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U P D A T E

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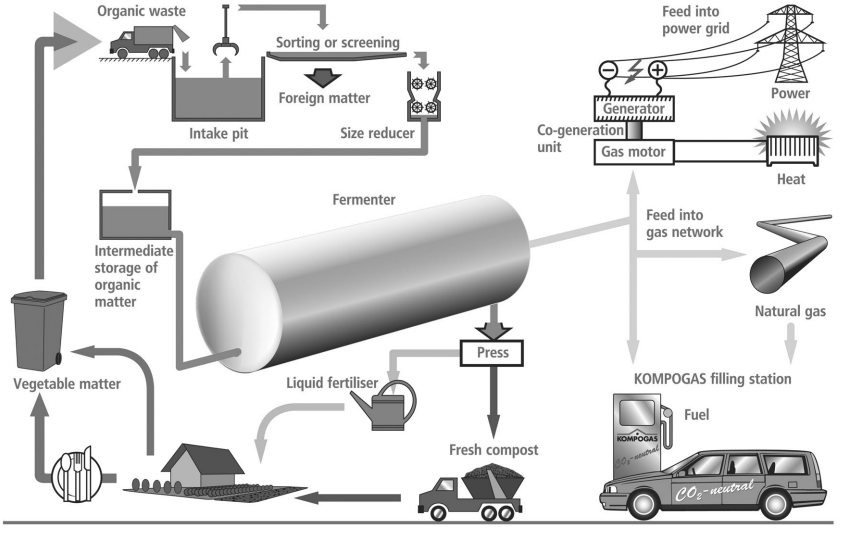
Biogas Production and Utilisation

Anaerobic digestion (AD) is the most promising method of treating the organic fraction of municipal solid waste (MSW) and other organic wastes. Anaerobic bacteria convert the biomass into a biogas or landfill gas that can be used to generate energy. This paper provides an overview of the status of AD. It collates policy issues which influence the deployment of AD technology, facility design concepts, energy, economic, and environmental issues relating to AD. It is a summary of the work completed within Task 37 and was compiled by Dr Arthur Wellinger, the Task Leader. The material has been sourced from a number of Task publications which are available on the Task website www.novaenergie/iea-bioenergy-task37/index.htm

Introduction

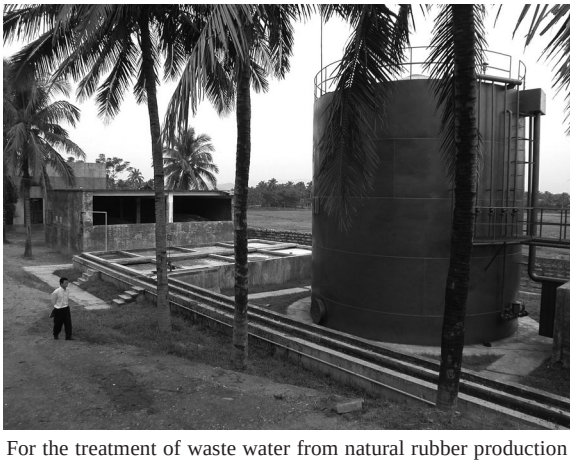
Around the world, pollution of the air and water from municipal, industrial and agricultural operations continues to grow. The concept of the 'four R's', which stands for Reduce, Reuse, Recycle, and Renewable energy, has generally been accepted as a useful principle for waste handling.

The emission of CO_2 and other greenhouse gases (GHG) has become an important issue, particularly since Russia has ratified the Kyoto Protocol which came into force on 16 February, 2005. Governments and industries are therefore increasingly on the lookout for technologies that will allow for more efficient and cost-effective waste treatment while minimising GHG. The CO_2-trade will even further increase the need for CO_2-neutral technologies.



When using source separated MSW the cycle can be fully closed. The organic material is recycled to land and the energy produced meets the process energy requirements of the plant as well as providing a transport fuel. (Courtesy Kompogas)

One technology that can successfully treat the organic fraction of wastes is AD. When used in a fully-engineered system, AD not only provides pollution prevention, but also allows for energy, compost and nutrient recovery. Thus, AD can convert a disposal problem into a profit centre. As the technology continues to mature, AD is becoming a key method for both waste reduction and recovery of a renewable fuel and other valuable co-products. Worldwide, there are now approximately 150 AD plants in operation and a further 35 under construction using MSW or organic industrial waste as their principal feedstock. The total annual installed capacity is more than five million tonnes, which has the potential to generate 600 MW of electricity. Waste managers have found that AD provides environmental benefits allowing waste disposal facilities to meet increasingly stringent regulations. Controlling odour and recovering nutrients are major drivers in their decision making.



For the treatment of waste water from natural rubber production in Hainan, China, a hybrid filter was applied where the lower part of the vessel works like a UASB reactor and the upper part is filled with plastic bodies. The UASB reactor is the most wide spread system for the treatment of industrial waste water. (Courtesy Nova Energie)

The use of AD for sewage sludge stabilisation is well established and the use of AD as a (pre-) treatment step for industrial wastewater is increasing rapidly, to the point where there are now more than 2,500 vendor-supplied systems in operation or under construction throughout the world. Over 30 types of industry have been identified as having wastewaters amenable to AD treatment, including processors of beverages, chemicals, food, meat, milk, pulp and paper, and pharmaceutics.

Benefits of Anaerobic Digestion

There are a number of benefits resulting from the use of AD technology.

Waste Treatment Benefits
- Natural waste treatment process
- Requires less land than aerobic composting
- Reduces disposed waste volume and weight to be landfilled

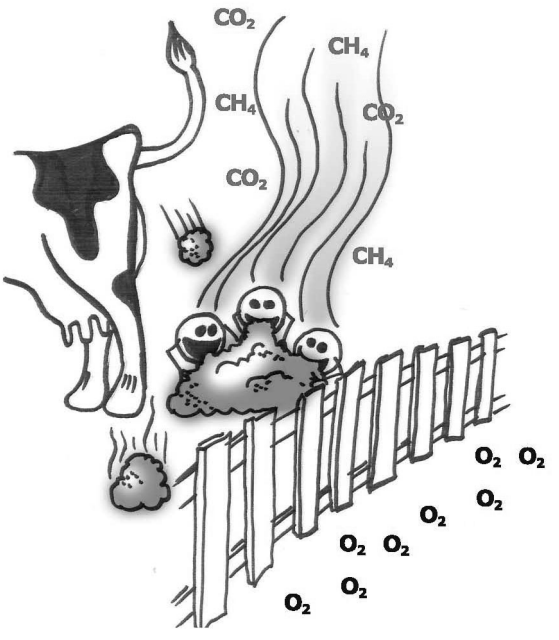
Energy Benefits
- Net energy producing process
- Generates high quality renewable fuel
- Biogas proven in numerous end-use applications

Economic Benefits
- Considering the whole life-cycle, it is more cost-effective than other treatment options

Environmental Benefits
- Significantly reduces greenhouse has emissions
- Eliminates odours
- Produces a sanitised compost and nutrient-rich liquid fertiliser
- Maximises recycling benefits

The Anaerobic Digestion Process

In the absence of oxygen, anaerobic bacteria will ferment biodegradable matter into methane and carbon dioxide, a mixture called biogas. Approximately 90% of the energy from the degraded biomass is retained in the form of methane. Hence, very little excess sludge is produced. Biogas is formed solely through the activity of bacteria.



Biogas is formed through the activity of a variety of different bacteria. The major products are the digestate which is an excellent fertiliser and the methane which is an energy carrier. (Courtesy Arthur Wellinger)

The AD process occurs naturally in the bottom sediments of lakes and ponds, in swamps, peat bogs, intestines of ruminants, and even in hot springs. Methane formation is also the process which stabilises landfill sites. The widespread natural occurrence of methane bacteria demonstrates that anaerobic degradation can take place over a wide temperature range from 10°C to over 100°C and at a variety of moisture contents from around 50% to more than 99%.

The potential to operate digesters at temperatures above 50°C makes the AD process particularly interesting for promoting hygiene. In addition to temperature, the anaerobic chemical environment multiplies the sanitation effect.

In evolutionary terms, anaerobic bacteria are very old, certainly much older than their aerobic counterparts. The anaerobic bacteria presumably first appeared before oxygen was a major part of the atmosphere. This accounts for their inability to process lignin, as woody plants had not yet evolved.

Available Feedstocks for AD

Sewage Sludge

Digestion of sewage sludge provides significant benefits when recycling the sludge back to land. The digestion process sanitises and also reduces the odour potential from the sludge. Typically between 30 and 70% of sewage sludge is treated by AD depending on national legislation and priorities. In countries like Sweden and Switzerland limitations for the field application of sludge have been introduced. However, AD is still considered an important step since it produces renewable energy and improves the ability of the sludge to settle which makes it easier to dry.

In less developed countries, direct AD is the only treatment of waste water. If the digester is adequately designed and the retention time of the water is long enough, the quality of the treated water can be excellent.

Agricultural Wastes

Digestion of animal manure is probably the most widespread AD application worldwide. It produces a valuable fertiliser as well as biogas. Today, more and more organic industrial waste materials are added to the manure which brings increased gas production and creates an additional income from the gate fee. In countries like Denmark, Austria and Germany the easily degradable wastes are becoming scarce and farmers are looking for alternative substrates (energy crops) such as corn, barley, rye or grass. In Germany the income from electricity produced from biogas made from corn is higher than using the same crop to feed fattening beef. Germany and Austria receive higher feed-in tariffs when the biogas is produced with crops.

Cattle manure is an excellent substrate for biogas production. The yield is not the highest, however it guarantees a high methane content of up to 63% and makes the process more stable. (Courtesy Nova Energie)

Industrial Wastes

Organic solid wastes from industry are increasingly treated in biogas plants. Even if some of the substances might be difficult to digest as a sole substrate, in mixture with manure or sewage sludge they don't pose any problem. The combined digestion of different wastes is called co-digestion.

Most of the waste products from the food industry have excellent gas potential and therefore are in demand by plant operators. Until recently the industry paid the operators reasonably high gate fees (up to 35 Euro per ton) to accept the waste products. Now, the operators are starting to pay for the waste materials with the highest gas potential like fat and vegetable oil. With current high feed-in tariffs they can easily recover the cost of these wastes.

AD of industrial waste waters is becoming a standard technique. Whilst AD is only an initial stage in the treatment of high quality water discharge, it can significantly reduce the cost and size of plant compared to wholly aerobic treatments.

Animal By-products

The inefficient treatment of slaughterhouse waste or improper use of products produced from it led to the pandemic occurrence of animal diseases throughout Europe. The EU has therefore introduced rigorous regulations on the collection, transport, methods and procedures of treatment, and further disposal of animal by-products, as well as the use of or trade in the products (Regulation (EC) No. 1774/2002). The Swiss Government also released a comparable regulation.

The new EC regulation (No. 1774/2002) on the utilisation of slaughterhouse waste strongly favours biogas production however, under very precisely defined conditions that guarantee high standards of hygiene. This also includes the collection of the waste material. (Courtesy Extraktionswerke Bazenheid)

The waste material is classified in three categories: Category 1 products bear increased risk for human and animal health (BSE, foot and mouth disease, etc.) and have to be incinerated. The Categories 2 (perished animals or animals slaughtered, but not intended for human consumption, milk and colostrums, manure as well as digestive tract content) and 3 materials (meat-containing wastes from the foodstuff industry, slaughterhouse wastes of animals fit for human consumption, catering waste) are strongly recommended for biogas production after sanitising. The special requirements of slaughterhouse waste mean it is particularly well suited for large co-digestion plants.

Municipal Solid Wastes

Organic wastes from households and municipal authorities provide potential feedstock for anaerobic digestion. The treatment of clean source separated fractions for recycling of both the energy content and the organic matter is the only method in which the cycle can be completely closed. In most of the participating countries, the source separation of MSW is actively encouraged. This includes separation of the putrescible organic fraction, also known as 'green waste' or 'biowaste'. Experience has shown that source separation provides the best quality feedstock for AD. The digested material is a valuable fertiliser and soil improver, especially after aerobic post-treatment. Where source separation has been widely introduced, the results are encouraging.

Odour free storage and efficient collection of source separated waste are the key components for a successful introduction of an MSW system. (Courtesy TEKES)

Alternatively, the unsegregated wastes or the 'grey waste' after separation of the 'biowaste' can be treated to gain the biogas from the waste as well as stabilising it to prevent further problems in landfill. The latter technologies are called mechanical biological treatment (MBT).The EU has set the goal of reducing the amount of organic waste to landfill by 65% by 2014. Some countries have completely banned the disposal of untreated organic waste.

Dry Continuous Digestion of Source Separated Waste

This concept involves a continuously-fed digestion vessel with digested material with a dry matter content of 20-40%. Both completely-mixed and plug-flow systems are available. Mixing is achieved by the introduction of compressed biogas through jets at the bottom of the digester. Plug flow systems rely on external recycling of a proportion of the outgoing digestate to inoculate the incoming raw feedstock. There are systems with vertical plug-flow and horizontal plug-flow.

One of the successful processes of solid waste digestion is the horizontal plug-flow digestion at thermophilic temperatures (55°C). (Courtesy Nova Energie)

Most of the dry systems are operated at thermophilic temperatures between 52 and 57°C which allows an optimal degradation rate at a reasonably short retention time of 15 to 21 days. Above all, the high temperatures allow sanitation of the digestate. The horizontal plug-flow system was the only single stage concept which passed the severe type test according to the German bio-waste ordinance with regard to hygiene.

The dry systems have a very favourable demand for process energy. The horizontal plug flow system requires only 20% of the electricity produced from biogas to operate the plant, including the pre-treatment process of material size reduction and sorting out undesirables.

Farm-scale Biogas Production

Farm-scale digestion plants treating primarily animal wastes have seen widespread use throughout the world, with plants in developing and technically advanced countries. In rural communities small-scale units are typical; Nepal has some 50,000 digesters and China is estimated to have 8 million small-scale digesters. These plants are generally used for providing gas for cooking and lighting for a single household.

In more developed countries, farm-scale AD plants are generally larger and the gas is used to generate heat and electricity. These farm-scale digestion plants are simple stirred tank designs that use long retention times to provide the treatment required.

In Germany more than 2,000 farm-scale biogas digesters are in operation; Austria has approximately 120, and Switzerland 69.Two designs are prevailing throughout Europe: the so-called rubber top digester, and the concrete top digester usually built in the ground. Both have a cylindrical form with a height to diameter ratio of 1:3 to 1:4. They are intermittently mixed tank reactors with hydraulic retention times (HRT) of the waste in the digester of 15 to 50 days. The longer HRT applies where an energy crop is used as a co-substrate or even the only source of energy.

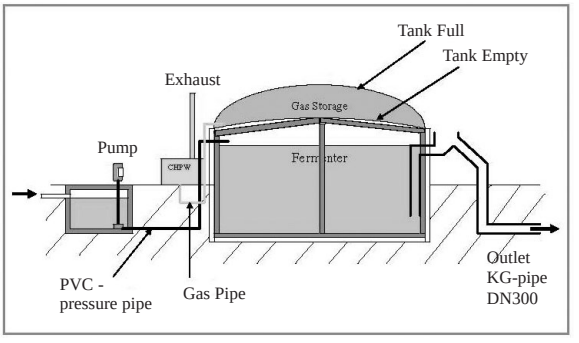
There are digesters with a single and a double membrane cover. The advantage of the rubber top digester is the price. A membrane is cheaper than a concrete cover. At the same time, the membrane serves as gas storage whereas concrete top digesters need additional gas storage. On the other hand, the latter are easy to insulate and can take high snow loads offering clear advantages in mountain areas. Often rubber top digesters give problems of odour emission when the rubber (usually black) is inflated due to heating by the sun.

In Vorarlberg, Austria, it is mandatory to cover the digester with a rigid top. Often the rubber membrane is then placed on the post-digester (without heating) or the storage tank. (Courtesy Nova Energie)

Virtually all of the plants use the biogas for electricity production in combined heat and power plants (CHP). Most of them use at least part of the heat for the digester, as well as for hot water for the stables and the farm dwelling.

The size of the digesters has steadily increased over recent years. In Germany the average installed electric power increased from 50 kW in 1999 to 330 kW in 2002. A comparable development but at a lower level was observed in Austria and Switzerland where the installed power increased from 45 to 65 kW.

Quite commonly, the manure is collected in a feed tank where other soluble substrates can be added such as distillery, and potato slops, whey, etc. Provided the feed tank is equipped with a strong macerator, solid substrates can also be added. However, the limitation is the pumping capacity, which usually ends at a dry matter content of around 12%. In newer plants the solid material is added directly to the digester either with screw feeders from the top or by piston pumps below the liquid level in the digester.



In Europe more than half of the new agricultural digesters are built with a rubber membrane cover which serves at the same time as gas storage. (Courtesy Nova Energie)

Large-scale Centralised Co-digestion

Modern developments in agricultural waste digestion produced the concept of centralised anaerobic digestion (CAD) where many farms cooperate to feed a single larger digestion plant. The wastes provided are principally agricultural manures and biogenic waste materials from industry, but in some cases small amounts of industrial and municipal wastes are also treated. There are significant benefits from using these cooperative arrangements in terms of nutrient management and economics, but this does require that barriers of confidence in quality control and sanitation are overcome.

Centralised Anaerobic Digestion (CAD) has been developed in Denmark and is spreading into a number of European countries like UK. This Holsworthy plant started operation in 2002. (Courtesy Nova Energie)

The idea of CAD was first trialled in Denmark where there are now 20 plants in operation, all with manure as the major substrate. Denmark was soon followed by Sweden, where waste water treatment plants started to use co-substrates in their AD tanks. Today, CAD has become a standard technology which is used in most European countries as well as in Asia and the USA. There are two major drivers which helped to promote co-digestion:

- Digesters in waste water treatment plants are usually oversized. Addition of co-substrates helps to produce more gas and consequently more electricity at only marginal additional cost. The extra electricity produced covers the energy needs of waste water treatment at a reasonable cost.
- Agricultural biogas production from manure alone (which has a relatively low gas yield) is economically not viable at current oil prices. Addition of co-substrates with a high methane potential not only increases gas yields but above all increases the income through tipping fees.

Generally co-digestion is applied in wet single-step processes such as intermittently-stirred tank reactors. The substrate is normally diluted to dry solid contents of around 8 to 15%. Wet systems are particularly useful when the digestate can be directly applied on fields and green lands without the separation of solids.

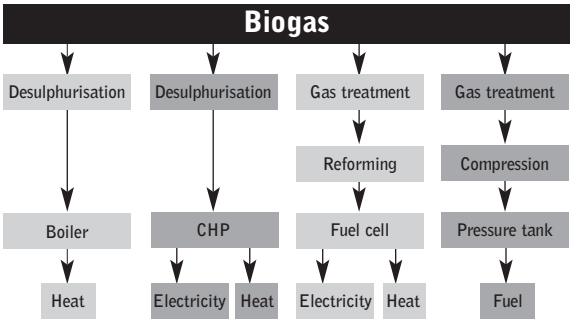
Large-scale industrial plants usually have more favourable economics. Typical examples (e.g., digester volumes of 4,650 - 6,000 m^3) have payback times between 3 and 10 years. However the pre-condition for economic success is still careful design, layout, and operation as was shown by a recent survey of 17 large-scale Danish centralised agricultural biogas plants.

The merits of CAD are:

- Improved nutrient balance for optimal digestion and good fertiliser quality
- Homogenisation of particulate, floating, or settling wastes through mixing with animal manures or sewage sludge
- Increased, steady, biogas production throughout the seasons
- Higher income from gate fees for waste treatment
- Additional fertiliser (soil conditioner)
- Renewable biomass production for digestion ('energy crop') as a potential new income for agriculture

Biogas Utilisation

Biogas produced in AD-plants or landfill sites is primarily composed of methane (CH_4) and carbon dioxide (CO_2) with smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_3).Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated or halogenated carbohydrates, oxygen, and siloxanes are occasionally present in the biogas. Usually, the mixed gas is saturated with water vapour.



Biogas can be used in all natural gas appliances given a certain upgrading of the gas quality (Courtesy P. Weiland, FAL)

Biogas can be used for all applications designed for natural gas. Not all gas appliances require the same gas standards. There is a considerable difference between the requirements of stationary biogas applications and fuel gas or pipeline quality. Boilers do not have a high gas quality requirement. Gas pressure usually has to be around 8 to 25 mbar. It is recommended that H_2S concentrations are reduced to values lower than 500 ppm.

Combined Heat and Power Plants (CHP)

The utilisation of biogas in internal combustion engines (gas engines) is a long established and extremely reliable technology. Thousands of engines are operated on sewage works, landfill sites and biogas installations. The engine sizes range from approximately 12 kWe on small farms up to several MWe on large-scale landfill sites. A diesel engine can be rebuilt into a spark-ignited gas engine or a dual fuel engine where approximately 8-10% diesel is injected for ignition. Both types of engines are often used. Newest designs show electric efficiencies up to 41%.

In recent years new engine types have been developed such as hot fuel cells or micro turbines. Hot fuel cells have the potential to reach electric efficiencies of close to 50%. Molten carbonate (MCFC) or solid oxide fuel cells (SOFC) do not require CO_2 to be removed from the raw gas.

Micro turbines have far lower electrical efficiencies of 26 to 28% but they produce steam instead of hot water, which might be used for industrial purposes.

Biogas Fuel

The utilisation of biogas as vehicle fuel uses the same engine and vehicle configuration as natural gas. Worldwide there are more than 3 million natural gas vehicles and about 10,000 biogas driven cars and buses, demonstrating that the vehicle configuration is not a problem for use of biogas as vehicle fuel. However, the gas quality demands are strict so the raw biogas from a digester or a landfill has to be upgraded.

Worldwide more than three million gas vehicles are in operation, including an increasing number of taxis and buses. (Courtesy Swedish Gas Centre)

Sweden and Switzerland are the only countries where pure biogas is available as transport fuel. Generally it is advisable to feed the upgraded biogas into the gas grid which makes it available to densely populated areas. (Courtesy Swedish Gas Centre)

Biogas Upgrading

There are a number of compounds which have to be removed from biogas where they are present. Most often only water vapour and hydrogen sulphide are to be removed except when gas is compressed as vehicle fuel. Then it is recommended that CO_2 is also removed.

The following compounds might be present in biogas

- Water vapour
- Carbon dioxide
- Hydrogen sulphide
- Siloxane
- Aromatic compounds
- Air (oxygen, nitrogen)
- Halogenic compounds (chlorides, fluorides)

Water scrubbing is one of the six basic technologies to upgrade biogas to grid quality. It is particularly well suited for waste water treatment plants like the one in Kings County, Seattle, USA. (Courtesy Nova Energie)

When the gas is fed to the grid it has to meet energy standards which usually require 97% methane.

Upgrading of biogas is an important cost factor in the production of fuel gas. Typical costs for an upgrading plant treating 200m^3 per hour of raw gas is in the order of 1.5 Euro cents per kWh as was shown in a Swedish study (Margareta Persson, SGC, pers. comm.).

Future Prospects

As with all forms of bioenergy, the future looks bright for biogas technology. As a CO_2-neutral source of energy it will be increasingly used to meet the Kyoto Protocol commitments and to benefit from the CO_2-emission trade. Biogas is a flexible form of renewable energy that can produce heat, electricity and serve as a vehicle fuel. As well as energy, the AD process yields valuable fertiliser and reduces emissions and odour nuisances. It therefore can make a positive contribution to multiple goals in government programmes.

In Europe the European Commission has taken some important decisions to promote renewable energy in general and biomass in particular. By the year 2010 the average electricity production from renewable sources should be increased from 12% to 21%. Further more, fossil fuel consumption for transport should also be increasingly substituted by biomass to reach 8% by 2020. Sweden, for example, will achieve most of this requirement with biogas.

In the USA, especially in California, low emission cars are becoming an important issue. The project CalStart that is promoting the change in California, has rated biogas as the best alternative fuel before bio-ethanol and hydrogen for fuel cells.

Thanks to its simple, reliable and proven technology, AD has all the advantages to increasingly become one of the most efficient and economical sources of renewable fuel. It will become an important component of the suite of renewable energy technologies and fuels that will be required to substitute for diminishing oil supplies. AD has also been shown to be an economically viable technology for both small-scale rural applications in developing countries and for a range of scales in the developed world.

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