An Introduction to Anaerobic Digestion of Organic Wastes

Final Report

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EXECUTIVE SUMMARY

Anaerobic digestion is a process which breaks down organic matter in simpler chemicals components without oxygen. This process can be very useful to treat arising organic waste such as:

- sewage sludge
- organic farm wastes
- municipal solid wastes
- green/botanical wastes
- organic industrial and commercial wastes

Before being digested, the feedstock has to undergo pre-treatment. There are various types of pre-treatment depending on the feedstock. The purpose of such treatment is to mix different feedstock, to add water or to remove undesirable materials such as large items and inert materials (e.g. plastic, glass) to allow a better digestate quality, a more efficient digestion and it will avoid failure in the process.

The digestion process itself takes place in a digester, which can be classified in relation to the temperature, the water content of the feedstock and the number of stage (single or multi-stage). Each digester has its characteristics and properties and thus can be more suitable for a specific feedstock. There are at the present more mesophilic (35^{o}C) than thermophilic digesters (55^{o}C) but the difference tends to decrease. There used to be more wet digesters than dry digesters but there is no clear trend anymore. Multi-stage processes aim at optimizing digestion and improving control of the process by separating stages of digestion. Only a few of these digesters are used at the present time. Finally, the batch processes are less expensive and less complex but there are also less efficient.

The by-products of anaerobic digestion, biogas and digestate, can be used in order to create a source of incomes. Biogas can be upgraded, most of the time by removing the carbon dioxide and the water vapour, and then, used in a CHP unit to produce electricity and heat. The digestate can be used as a fertilizer or further processed into compost to increase its quality.

Anaerobic digestion is helped but also limited by legislation. The main UK policies in favour of anaerobic digestion are the Climate Change levy and the new Renewable Obligation. Every premises aiming at treating waste should apply for a waste management license. There are also regulations concerning specific waste such as animal by-products and sewage sludge.

The financial aspect of anaerobic digestion includes the capital and the operating costs. Capitol costs are quite high but the source of incomes coming from the sale of electricity, heat and digestate allows important benefits.

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1.1 History of anaerobic digestion

Historical evidence indicates that the anaerobic digestion (AD) process is one of the oldest technologies. However, the industrialization of AD began in 1859 with the first digestion plant in Bombay. By 1895, biogas was recovered from a sewage treatment facility and used to fuel street lamps in Exeter, England. Research led by Buswell [ref. 1] and others in the 1930s identified anaerobic bacteria and the conditions that promote methane production. As the understanding of the AD process and its benefits improved, more sophisticated equipments and operational techniques emerged. The result was the used of closed tank and heating and mixing systems to optimize AD. Regardless of improvements, AD suffered from the development of aerobic treatment and low costs of coal or petroleum. While AD was used only for the treatment of wastewater sludge digestion, developing countries such as India and China embraced the technology. Small-scale AD systems were mostly used for energy and sanitation purposes. Numerous failures were reported [ref. 1]. Nevertheless, technical improvements and increasing energy prices have led to a diversification of the waste treated and larger size AD plants.

In recent times, European countries have come under pressure to explore AD market for two significant reasons: higher energy prices and increasingly stringent environmental regulations. AD facilities usually have a good record in treating a wide spectrum of waste streams such as municipal, agricultural or industrial waste. Some facilities have been in operation for over 20 years. More than 600 farm-scale digesters operate in Europe, where the key factor is simplicity. In addition to farm-scale digesters, Europe leads in large centralised AD systems [ref. 2].

1.2 General process description

There are two possible aims of using AD. It can be used either to treat biodegradable wastes or produce saleable products (heat/electricity, soil amendment). Energy crops can be grown and then used for AD. In this case, the aim is to produce as much biogas as possible and a good quality soil amendment. Nevertheless the most valuable use of AD is to combine both waste management and by-products use. Especially for waste management, it is unlikely that AD will be a viable treatment without using the biogas and the digestate. Their qualities will vary depending on the feedstock and its contamination. The use of biogas and digestate can also involve further treatments, such as composting of digestate.

The process of AD can be further divided into four stages: pre-treatment, digestion, gas upgrading and digestate treatment (see figure 1).

The level of pre-treatment depends on the type of feedstock; e.g. manures need to be mixed, whereas municipal solid wastes (MSW) are sorted and shredded.

The digestion stage takes place in the digester. There are many types of digesters with different temperature, mixing devices, etc… The digestion can be either dry or wet depending on the solid content (see chapter 1.4.1). Thus the feedstock can be mixed with water and other appropriate liquid wastes such as sewage sludge or re-circulated liquid from the digester effluent [ref. 1].

The biogas produced during the digestion stage has to be upgraded because it contains impurities that can damage boilers or engines. Hydrogen sulphide and water vapour need to be removed for boilers and combined heat and power units. Removal of carbon dioxide will be required if the gas is to be used as natural gas or vehicle fuel [ref. 4].

The scheme below (figure 1) shows the general process of a co-digestion plant. The co-digestion means that two different types of waste are mixed. It can sometimes improve the digestion stage (see chapter 4.4.2).

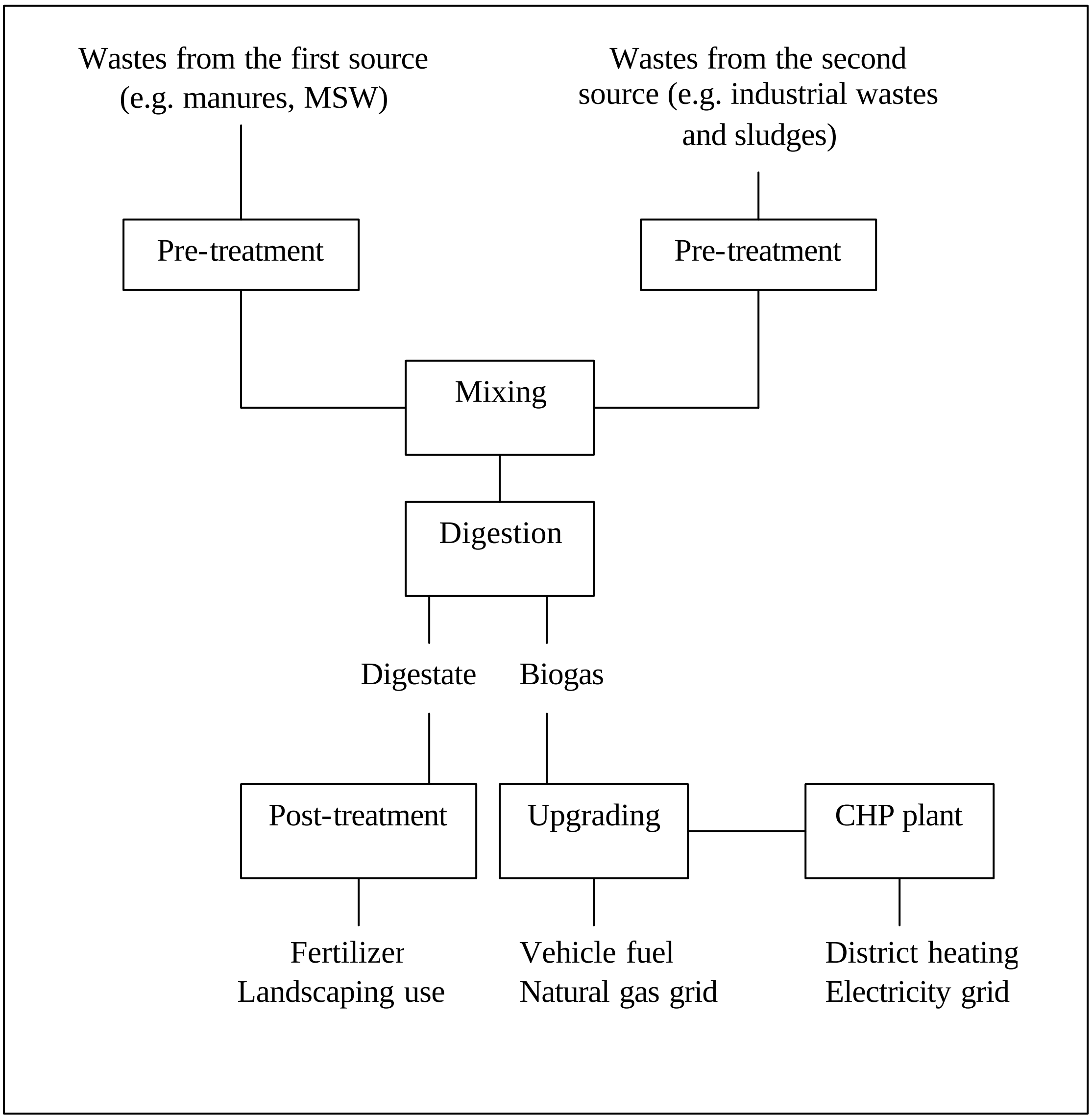

Figure 1: General process for an AD codigestion plant.

1.3 Biological process

Anaerobic digestion is a naturally occurring process of decomposition and decay, by which organic matter is broken down to its simpler chemicals components under anaerobic conditions. Anaerobic microorganisms digest the organic materials, in the absence of oxygen, to produce methane and carbon dioxide as end-products under ideal conditions. The biogas produced in AD-plant usually contains small amount of hydrogen sulphide (H_2S) and ammonia (NH_3), as well as trace amounts of other gases [ref. 3].

The science underlying AD can be complex and the process is best understood if split into the three main stages: hydrolysis, acidogenesis and methanogenesis.

During hydrolysis, the fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as fatty acids, amino acids and sugars. The complex polymeric matter is hydrolyzed to monomers, e.g. cellulose to sugars or alcohols. The hydrolytic activity is of significant importance in wastes with high organic content and may become rate limiting. Chemicals can be added during this step in order to decrease the digestion time and provide a higher methane yield.

In the second stage, acetogenic bacteria, also known as acid formers, convert the products from the first stage into simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid, butyric acid, propionic acid and ethanol.

Finally, methane is produced during methanogenesis by bacteria called methane formers in two ways: by means of cleavage of two acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. The acetate reaction is the primary producer of methane because of the limited amount of hydrogen available [ref. 1].

It is important to note that some organic materials, such as lignin, remain effectively undigested, as of course do non-organic inclusions within the waste.

1.4 Conditions and variables influencing AD

There are several conditions and variables that must be applied in order to obtain a proper breakdown of the organic compounds. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the AD efficiency. Some of these parameters are discussed briefly in the following section. Further details on the digester characteristics will be discuss in the chapter 3.

1.4.1 Total Solid content

There are three different ranges of solid content: low solid (LS) AD systems contain less than 10% Total Solid (TS), medium solid (MS) from 15-20% and high solid systems (HS) range from 22-40%. When increasing the total solid content, the volume of the digester decreases, due to lower water requirements.

The advantages of both wet and dry digesters will be discussed later on, as well as their suitability for different feedstocks [ref. 1, 3].

1.4.2 Temperature

Anaerobic digestion can occur under two main temperature ranges:

- Mesophilic conditions, between 20-45°C, usually 35°C.
- Thermophilic conditions, between 50-65° C, usually 55°C.

The optimum temperature of digestion may vary depending on feedstock composition and type of digester, but in most AD processes it should be maintained relatively constant to sustain the gas production rate.

Thermophilic digesters are more efficient in terms of retention time, loading rate and nominally gas production, but they need a higher heat input and have a greater sensitivity to operating and environmental variables, which make the process more problematic than mesophilic digestion.

The sterilization of the waste is also linked to the temperature. The higher it is the more effective it is in eliminating pathogens, viruses and seeds [ref. 1, 3].

1.4.3 Retention time

Retention time is the time needed to achieve the complete degradation of the organic matter. The retention time varies with process parameters, such as process temperature and waste composition. The retention time for waste treated in a mesophilic digester ranges from 15 to 30 days and 12-14 days for thermophilic digester [ref. 5].

1.4.4 pH

The optimal pH values for the acidogenesis and methanogenesis stages are different. During acidogenesis, acetic, lactic and propionic acids are formed and, thus the pH falls. Low pH can inhibit acidogenesis and pH below 6.4 can be toxic for methane-forming bacteria (the optimal range for methanogenesis is between 6.6 and 7). An optimal pH range for all is between 6.4 and 7.2 [ref. 3].

1.4.5 Carbon to Nitrogen ratio (C: N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C: N ratio. Optimum C: N ratios in anaerobic digesters are between 20 and 30. A high C: N ration is an indication of a rapid consumption of nitrogen by the methanogens and results in a lower gas production. On the other hand, a lower C: N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C: N ratio of the feedstock materials can be achieved by mixing waste of low and high C: N ratio, such as organic solid waste mixed with sewage or animal manure [ref. 1, 3].

1.4.6 Mixing

Mixing, within the digester, improves the contact between the micro-organisms and substrate and improves the bacterial population's ability to obtain nutrients. Mixing also prevents the formation of scum and the development of temperature gradients within the digester. However excessive mixing can disrupt the micro-organisms and therefore slow mixing is preferred.

In case of co-digestion, the different feedstocks should be mixed before entering the digester to ensure a sufficient homogeneity [ref. 1, 3].

1.4.7 Organic loading rate (OLR)/ Volatile Solids (VS)

OLR is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR, results in low biogas yield due to accumulation of inhibiting substances in the digester slurry (i.e. fatty acids). Under such circumstances, the feeding rate of the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failure due to overloading. OLR is expressed in kg Chemical Oxygen Demand (COD) or Volatile Solids (VS) per cubic meter of reactor. It is linked with retention time for any particular feedstock and anaerobic reactor volume [ref. 1, 3].

Volatile Solids (VS) represents the organic matter in a sample which is measured as solid content minus ash content, as obtained by complete combustion of the feed wastes. VS comprise the biodegradable VS (BVS) fraction and the refractory VS (RVS). High VS content with low RVS is more suitable for AD.

2 Anaerobic digestion processes

2.1 Pre-treatment

The pre-treatment of feedstock for AD involves:

- removing the non-biodegradable materials, which are not affected by digestion and take up unnecessary space
- providing a uniform small particle size feedstock for efficient digestion
- protecting the downstream plant from components that may cause physical damage
- removing materials which may decrease the quality of the digestate [ref. 1].

A great variety of pre-treatment processes are available and the selection must be done regarding to prices, feedstock, process operations.

While the pre-treatment process for manure is most of the time limited to grit removal or mixing with other organic wastes, it can be more complex with municipal solid wastes. Grit is composed of heavy mineral matter such as sand and gravel, which may accumulate in the bottom of the digester.

The pre-treatment for municipal solid wastes consists in separating the recyclable or non-digestible wastes from the organic wastes. It can be achieve either by source separation, where undesirable wastes are removed at the source, or by mechanical separation for mixed municipal solid waste. Source separation has a significant effect upon the quality of the digestate because very few contaminants should be present in theory. However, source-separated wastes may require some physical processing.

Mechanical pre-treatment leads to a lower quality digestate. The removal of all contaminants is not possible especially for the smaller fraction such as heavy metals. The resultant fraction is thus more contaminated. It is mainly used for municipal solid wastes when source separation is not possible. It can consist of:

- Manual sorting, which can be used to remove contrary materials such as batteries, large items, bricks and others inorganics.
- Rotating trommels or other type of screen to remove oversize items
- Hammermill for size reduction of the waste
- A hydropulper (figure 2)[1]

In order to shred and mix the waste, a rotating drum can be used. It is a horizontally mounted, rotating steel cylinder. The rotation of the drum leads to a breakdown of the softer components by particle collision and attrition as they repeatedly contact the drum wall and the harder elements in the mixture [ref. 6].

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1 The hydropulper is an adaptation of a paper industry product for use with MSW. It is a wet process using the hydraulic forces to break down the organics, and to wash and separate the non-organics. The light fraction (plastics, wood, textiles, etc…) floats and is taken out of the process by a hydraulically operated rake dipping into the suspension. The heavy fraction settles down and is removed through a lock mechanism at the bottom of the hydropulper. Then the organics are passed through an 8 mm sieve which allows them to be pumpable and also to degrade more readily at this smaller size [ref. 3].

Figure 2: hydropulper [ref. 7]

These are only some of the mechanical pre-treatments available; there a numerous processes such as magnetic separation, fluidised bed screening/vibrating tables…For further information, look at: Anaerobic digestion, a detailed report on AD of MSW by the Institution of Wastes Management (IWM) AD working group and.

2.1.1 Sterilisation

Thermal sterilisation (or pasteurisation) of co-substrates or digestate can be required when using specific feedstocks (see chapter 7.4.1.2 about animal by-products legislation). Thermophilic temperature ranges within digesters cannot generally be considered sufficient for a reliable sterilisation. An EU-initiative to improve the present situation of biodegradable waste management, the guideline "Biological treatment of bio-waste, second draft" (ref.32) states that the wastes should undergo either:

- thermophilic digester operation (i.e. 55°C guaranteed for 24 hours with a residence time of at least 20 days), or in case of mesophilic digestion
- pre-treatment of substrates at 70°C for 60 minutes or,
- post-treatment of digestate at 70°C for 60 minutes or,
- composting of the digestate.

2.2 Types of Digesters

Anaerobic digesters can be classified into the following categories:

- single-stage
- multi-stage
- batch

The temperature range of the digestion, mesophilic or thermophilic, as well as the solid content also define the type of reactor used.

2.2.1 Single stage low solid (SSLS)

This process has been used for decades in the stabilization of sludge from the treatment of wastewater.

The advantages offered by SSLS are operational simplicity and technology that has been developed for a much longer time than high solid systems. Cheaper equipments (pumps, pipes…) can also be used for handling slurries, relative to solid materials. This advantage is however balanced by the higher investment costs resulting from larger reactor with internal mixing, larger dewatering and necessary pre-treatment steps.

Specific care must be taken for pre-treatments because during the digestion, the heavier fraction and contaminants sink and a floating scum layer forms resulting in the formation of three layers in the reactor. The heavier fraction settles at the bottom and may damage the propellers whilst a floating layer accumulates at the top and disrupts effective mixing. The accumulation of the heavier fraction can damage pumps, and therefore it is advisable to 'clean' the feedstock as much as possible prior to loading the reactor. Thus the pre-treatments involve the removal of coarse particles and heavy contaminants. Removing the heavier fraction, whilst at the same time retaining as much of the biodegradable content, can be quite a challenging task particularly for mechanical-sorted Organic Fraction of Municipal Solid Waste (OFMSW). These pre-treatments cause a loss of 15-25% of volatile solids (VS), with corresponding decrease in gas yield.

The predominant reactor is the continuously stirred tank reactor (CSTR), which has a stirring mechanism to ensure that the digestate is continuously mixed and completely stirred.

The occurrence of short-circuiting in CSTR is a technical drawback. Short-circuiting is the passage of a fraction of the feedstock with a shorter than average retention time. It diminishes the biogas yield and most importantly, it impairs the proper hygienization of the wastes. Thus it could be necessary to pasteurize the wastes after digestion.

The wastes need to be mixed with water to obtain a low solid content, thus leading to high water consumption. It can be a problem on economical and environmental criteria; however, mixing the wastes with sewage sludge or with the recycled liquid from the dewatering step can be a suitable solution.

Recycling the liquid pressed form the digestate, also called liquor, will achieve some recycling of acclimatized bacteria as well. This recycling can be done only if the ammonia content of the liquor is not too high because it inhibits the anaerobic digestion [ref. 1, 8].

2.2.2 Single stage high solid (SSHS)

The advances of the HS technology resulted from research undertaken during the 1980's that established higher biogas yield in undiluted wastes. While most of the plants built until the 1980's relied on wet process, the new plants built during the last decade are evenly split between wet and dry systems. However, no clear technology trend can be observed at this moment.

In dry systems, the fermenting mass in the digester has a solid content within a range of 20-40%. With this high solid content, the main problem with the process is in transport and handling. The feedstock is transported by conveyor belts, screws and powerful pumps especially designed for highly viscous streams. This equipment is generally more robust and expensive than that of LS.

The pre-treatment step is much simpler with HS because the system has a greater intolerance for impurities such as stones, glass or wood. Only the coarser impurities need to be removed before digestion, e.g. > 40 mm. Thus it can be suitable for treating the mechanically-sorted OFMSW which contains approximately 25% by weight of heavy inerts. It also decreases the loss of organic materials during pre-treatment steps.

Due to the viscosity, plug-flow reactors are used. The advantages are that it is technically simple and no mechanical devices need to be installed inside the reactor. Because no mixing occurs within the digester, wastes must be mixed with digestate to provide adequate inoculation.

With plug-flow digesters, no short-circuiting can happen as there are no moving parts. Feedstock is added at one end, thus pushing the digestate. The reactor is also smaller because no water is added, so that the heat required in order to maintain the temperature in the digester at a constant level is less important [ref. 1, 8].

2.2.3 Multi-stages processes

The development of multi-stage AD processes aimed at improving AD by having separate reactors for the different stages, thus providing flexibility to optimize each of these reactions. Typically, two reactors are used, the first for hydrolysis/liquefaction-acetogenesis and the second for methanogenesis. In the first reactor, the reaction is limited by the rate of hydrolysis of cellulose; the second by the rate of microbial growth.

The two-reactor process permits a certain degree of control of the rate of hydrolysis and methanogenesis. For instance, microaerophilic conditions can be used to increase the rate of hydrolysis, by supplying a small amount of oxygen in an anaerobic zone. The main advantage of the two-stage system is the greater biological stability it affords for very rapidly degradable wastes like fruits and vegetables. With such feedstocks, the slower metabolism of methanogens relative to acidogens would lead to inhibiting substances of acids in one-stage digester.

In multi-stages digestion, a distinction must be done between the reactors with and without a biomass retention scheme in the second stage. The aim of biomass retention is to achieve high cell densities of methane-forming. The reason for using this criterion is that the retention of biomass within the reactor is an important variable in determining the biological stability of the digester.

There are two basic ways to achieve biomass retention. The first one is to raise the solid content in the reactor by uncoupling the hydraulic and solid retention time, e.g. recirculation. The second one is attached growth, also known as "fixed film reaction". The microbes, responsible for conversion of the organic matter, are attached to an inert medium such as rock, or plastic in the reactor. An important requirement to be met in such reactors is the removal of suspended solids after the first stage. A common reactor used for biomass retention is the Upflow Anaerobic Sludge Blanket (UASB) reactor. The UASB reactor, wherein anaerobic microflora accumulates as granules, is suitable for treating liquid effluent with high levels of organic acids at high organic rates.

As the consequence of the higher biomass concentration, greater resistance towards inhibiting chemicals is achieved. The drawback, for attached growth, is that removing suspended solids before methanogenesis will decrease the gas yield.

Multi-stage processes are also classified in Low Solids processes (MSLS) and High Solids processes (MSHS).

The multi-stages low solids processes are plagued with similar problems as those of SSLS reactors, such as short-circuiting, foaming, formation of layers of different densities and expensive pre-treatment. In addition, the MSLS processes are technically more complex and thus require a higher capital investment.

The increased technical complexity of two-stages relative to one-stage systems has not always lead to a higher rates and yields. In fact, the main advantage is the greater biological reliability for wastes which cause unstable performance in one-stage systems.

All types of multi-stage systems provide some protection against the fluctuation of OLR. Systems with biomass retention ensure stable performance with wastes excessively charged with nitrogen and others inhibitors.

At the present time, multi-stages systems represent only 10% of the current treatment capacity [ref. 1, 8].

2.2.4 Batch process

In batch systems digesters are filled once with fresh wastes and allowed to go through all the degradation steps sequentially in the dry mode, i.e. at 30-40% TS. The leachate, collected at the bottom of the reactor, is continually re-circulated

There are three types of batch processes:

- single stage system
- sequential system
- upflow anaerobic sludge blanket (UASB) reactor

2.2.4.1 Single stage system

The single-stage system involves re-circulating the leachate at the top of the same reactor, which is equivalent to a partial mixing.

2.2.4.2 Sequential system

The sequential system comprises two or more reactors. The leachate from the first reactor, containing a high level of organic acids, is re-circulated to the second reactor where methanogenesis occurs. The leachate from the methanogenic reactor, containing little or no acids, is combined with pH-buffering agent and re-circulated to the first reactor. This guarantees inoculation between the two reactors, which eliminates the need to mix the fresh waste with seed materials.

2.2.4.3 Upflow anaerobic sludge blanket (UASB) reactor

The third type of system is the hybrid batch-UASB process, which is very similar to the multi-stage process with two reactors with biomass retention. The difference is in the first reactor which is a simple batch reactor.

Batch processes are technically simple, less expensive than other processes and more robust. However, they have a larger footprint as the height of batch reactors is 5-fold less (this lower height allows avoiding compaction of the waste inside the reactor, which inhibits the digestion) and the OLR 2-fold less than plug-flow dry reactor, for instance. They also achieve a lower gas yield. At the single-stage batch system in Lelystad for instance, The Netherlands, the gas yield is 40% lower than that obtained in continuously one-stage wet system [ref. 1, 8].

2.2.5 Mesophilic/thermophilic process

Traditionally, AD plants have operated in the mesophilic range as it was difficult to establish and maintain high temperatures within the digester. This digestion process is well understood, requires less heat to sustain the operation (it is generally self-sustaining) and it is said to be more robust and stable due to the larger diversity of bacteria. However, thermophilic systems generally operate at a faster rate, 12-14 days rather than 15-30 days for mesophilic range. They achieve a higher methane production and more effective sterilisation. The disadvantages are more expensive technologies, greater energy input and a higher degree of operation and monitoring.

The precise choice of system is a balance between many specific conditions for the location and application of the digester.

It is, however, important to note that for certain feedstocks there is a legal requirement for the digestate to be sanitised (in some cases, this requires heating the wastes to 70°C for an hour). Thus, thermophilic process could become more common because, having heated the wastes, there is an energy balance argument supporting the use of the energy produced to maintain thermophilic operating temperatures.

Nowadays, there are still more mesophilic plants but the difference between mesophilic and thermophilic plants tends to decrease [ref. 1, 3, 9, 10].

2.2.6 Case Study

There are at the present time, in Europe, numerous companies able to provide turnkey biogas plants or to work only on a specific step such as conception, engineering etc. Each company has developed its own processes with their specific pre-treatment steps and digester characteristics; however the processes of AD plants remain very similar. As an overview, a case study the one-stage BTA process is described below [ref. 11].

Case study: the single-stage BTA process

The process consists of two major steps: mechanical wet pre-treatment and biological conversion (see figure 3 below).

In the waste-pulper the feedstock is mixed with recirculated process water. Contaminants like plastics, textiles, stones and metals are separated effectively and gently without any handsorting by means of a rake and a heavy fraction trap. From the contained organics a thick pumpable suspension (pulp) is produced which can be easily handled and digested.

An optional but essential further component of the process is the grit removal system which separates the still remaining finest matter like sand, little stones and glass splinters by passing the pulp through a hydrocyclone. Thus the plant is protected against increasing abrasion.

Then the so called one-stage digestion takes place, fermenting the produced pulp within one single step in one mixed fermentation reactor. The biogas produced is used in a CHP unit while the digestate can be dewatered and composted.

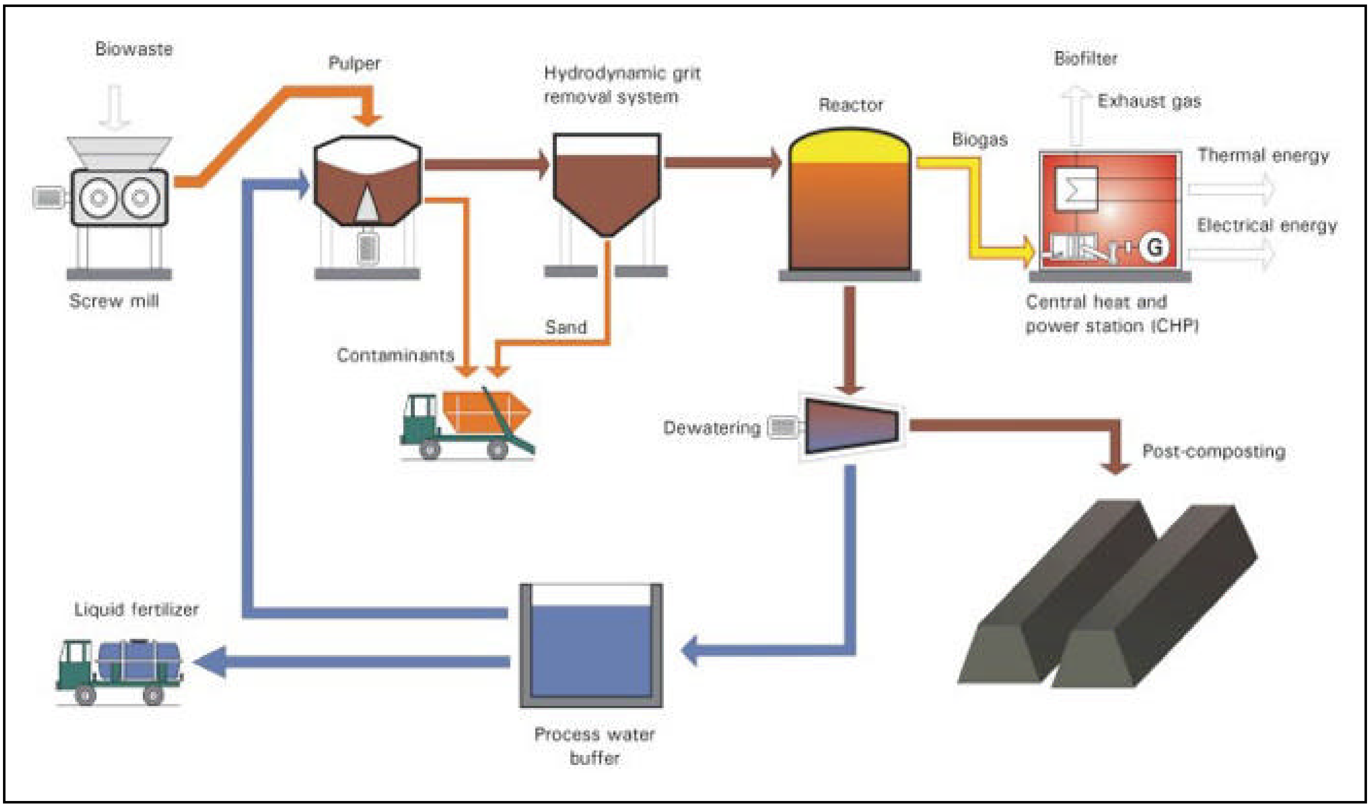

Figure 3: single-stage BTA process.

3 By-Products

AD is a cost-effective way to manage biodegradable waste because it produces biogas and digestate. The use or sale of both can provide great financial incomes. However, in order to obtain the maximum value from these products, further processing may be necessary. In some case, energy crops are also used for AD. The aim is then to produce lots of biogas (to generate electricity) and a good soil amendment.

Depending on which purpose AD is used for, the key factors of the process are different. For instance, if the aim is to produce as much biogas as possible, the key factors should be the total solid content.

3.1 Biogas

3.1.1 Biogas composition

Biogas produced during anaerobic digestion 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 and oxygen (O_2) are occasionally present in the biogas (as detailed in Table 1). Usually, the mixed gas is saturated with water vapour and may contain dust particles and siloxanes [ref. 12].

The composition of biogas is different from the one of natural biogas but it is quite similar to landfill gas. Landfill gas often contain significant amounts of halogenated compounds and occasionally the oxygen content is high when to much air is suck during the collection on the landfill . The calorific value is 36.14 MJ/m^3 for natural gas and 21.48 MJ/m^3 for biogas.

The composition of biogas is naturally linked to the waste composition and can thus vary.

Constituents	Units	Natural Gas	Biogas	Landfill gas
Methane CH_4	Vol%	91	55-70	45-58
Ethane C_2H_6	Vol%	5.1	0	0
Propane C_3H_8	Vol%	1.8	0	0
Butane C_4H_{10}	Vol%	0.9	0	0
Pentane	Vol%	0.3	0	0
CO_2	Vol%	0.61	30-45	32-45
Nitrogen (N_2)	Vol%	0.32	0-2	0-3
Volatile Organic Compounds (VOC)	Vol%	0	0	0.25-0.50
Hydrogen (H_2)	Vol%	0	0	Trace to less than 1%
Hydrogen Sulphide (H_2S)	ppm	~1	~500	10-200
Ammonia (NH_3)	ppm	0	~100	0
Carbon Monoxide (CO)	ppm	0	0	trace

Table 1: Composition of biogas, natural gas and landfill gas [ref. 12]

3.1.2 Gas utilisation

Biogas can be used for all applications designed for natural gas, subject to some further upgrading, as not all gas appliances require gas of with the same quality standards [ref. 4].

Biogas can be use for heating using **boilers**. The heat has many applications such as being used in the plant or producing water vapour for industrial processes. Boilers do not have a high gas quality requirement. It is preferable to remove the hydrogen sulphide because it forms sulphurous acid in the condensate which is highly corrosive. It is also recommended to condense the water vapour in the raw gas. Water vapour can cause problems in the gas nozzles. Removal of water will also remove a large proportion of H_2S.

Biogas is also used in **Combined Heat and Power** (CHP) units. Gas engines do have the same quality requirements as boilers, except that the H_2S content should be lower. In biogas engines the NO_x emissions are usually low because of the CO_2 in the gas. CO concentration is often more a problem. However, from an environmental point of view, CO is less of an issue than NO_x because it is rapidly oxidized to CO_2. CHP units are a good way to produce efficiently both electricity and heat for the AD plant. For instance, heating of the digester and sterilization of the digestate can be done using this heat. The remaining electricity can be sold to the national grid. This is actually the most popular way of using the landfill gas in the UK.

In case of use of the raw biogas, the distance from the plant and the gas user must be taken into account. Indeed, the cost of piping the gas can be prohibitive. If no potential users are located in the surroundings, the biogas should be use on site in a CHP unit or upgraded for use as a vehicle fuel or for distribution of electricity via the natural gas grid.

The utilisation of biogas as a **fuel for vehicles** requires the same type of engine as those used for natural gas. However, the gas quality demands are strict. Thus the biogas needs to be upgraded in order to obtain:

- A higher calorific value, (vehicles can operate over longer distances)
- A consistent gas quality for safe driving and engine operation.
- No enhancement of corrosion due to high levels of hydrogen sulphide, ammonia and water.
- A gas without any mechanically damaging particles.

In practice it means that the methane content should be increased to 95% and the gas should be compressed. Upgraded biogas is considered to be one of the cleanest fuels with minimal impact on the environment and human health. Although, such operations can involve a high cost; there are many examples of schemes across Europe where biogas is upgraded on a commercial basis. For instance, biogas plants in Fangel (Denmark) or Holsworthy (UK) are selling electricity to the grid.

The methane contained in the biogas can also be used as a fuel for **Fuel cells**. Fuel cells are power generating systems that produce DC electricity by combining fuel and oxygen (from the air) in an electrochemical reaction. There is no intermediate process which first converts fuel into mechanical energy or heat. Therefore fuel cells have extremely low emissions. In principle, fuel cells operate like a battery but, unlike a battery, it does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied. In a first step the fuel is converted to H_2 which is then converted to direct electric current. The by-products of the reaction are water and CO_2. Conversion efficiency to electricity is expected to exceed 50%. There are five different technologies but, currently, only phosphoric acid fuel cells are commercialised. A number of power plants are operating in Japan and in the USA with a practical electrical efficiency of 41%. However the technology is still too expensive.

3.1.3 Gas upgrading technologies

A number of gas upgrading technologies have been developed for the treatment of natural gas, landfill gas, town gas, however not all of them are recommended for the application with biogas because of the price and/or environmental concerns [ref. 4].

3.1.3.1 Carbon dioxide removal

Removal of carbon dioxide enhances the energy of the gas either to reach vehicle fuel standard or natural quality gas. At the present time, four different methods are used commercially to achieve it:

- water scrubbing
- polyethylene glycol scrubbing
- carbon molecular sieves
- membranes separation

Water scrubbers (figure 4) are used to remove carbon dioxide and hydrogen sulphide, since these gases have higher water solubility than methane. The absorption process is purely physical. The water used can be regenerated and recirculated but the most efficient method is to use cheap water such as water from a sewage treatment plant and thus not need to recirculate it.

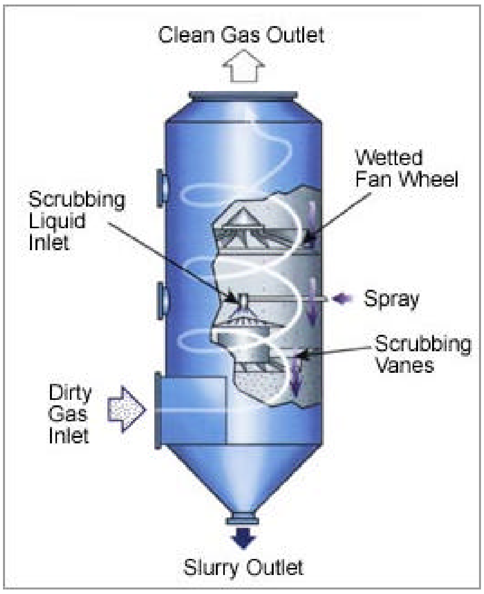

Figure 4: example of wet scrubber [ref. 34]

Polyethylene glycol scrubbing is a physical process like water scrubbing. The difference is that carbon dioxide and hydrogen sulphide are more soluble in this solvent and therefore smaller quantities of scrubbing media are required. In addition, water and halogenated hydrocarbons are also removed when scrubbing biogas with polyethylene glycol. This scrubbing is always done with recirculation.

In **carbon molecular sieves**, molecules are adsorbed in the cavities of the molecular sieve but not irreversibly bound. The selectivity of adsorption is achieved by different mesh sizes and/or application of different gas pressure. When the pressure is released the compounds from the biogas are desorbed.

There are two basic gas purification **membrane** systems. One is the high pressure gas separation which uses gas on both sides of the membrane. The membranes (made of acetate-cellulose) separate the small polar molecules such as carbon dioxide, moisture and hydrogen sulphide. In the low-pressure gas liquid adsorption separation, a liquid absorbs the molecules diffusing through the membrane. The essential element is a hydrophobic microporous membrane separating the gaseous from the liquid phase. The molecules from the gas stream, flowing in one direction, which are able to diffuse through the membrane, will be absorbed on the other side by the liquid flowing in counter current.

3.1.3.2 Hydrogen sulphide removal

Hydrogen sulphide must be removed in order to avoid corrosion. The most common methods for hydrogen sulphide removal are [ref. 4]:

- air/oxygen dosing to digester biogas
- iron chloride dosing to digester slurry
- iron oxide
- activated carbon
- water scrubbing
- NaOH scrubbing

Biological desulphurisation of biogas can be performed by micro-organisms. Most of the sulphide oxidising microorganisms belong to the family of *Thiobacillus* and it is essential to add stoichiometric amounts of oxygen to the biogas.
Air/oxygen dosing to biogas digester is the simplest method of desulphurisation. It consists in addition of oxygen or air (2 to 6% air in biogas) directly in the digester or in a storage tank serving at the same time as gas holder. Measures of safety have to be taken to avoid overdosing of air because biogas in air is explosive in the range of 6 to 12% depending on the methane content.
In large digestion plants, there is often a combined procedure of water scrubbing and biological desulphurisation.

Iron chloride dosing to digester slurry consists in feeding iron chloride directly to the digester slurry or in a pre-storage tank. It reacts with produced hydrogen sulphide to form iron sulphide salt (particles). This method is very effective in reducing high H_2S level but less effective to attain low and stable levels such as for vehicle fuel demands.

Iron oxide (or hydroxide) also reacts with H_2S. The reaction is slightly endothermic (minimal temperature of 12°C) and the biogas should not be too dry since the reaction needs water. The iron sulphide formed can be oxidised with air so that the iron oxide is recovered. This process is highly exothermic. Usually an installation has two reaction beds. While the first one is desulphurising the biogas, the second is regenerated with air. Iron oxide wood chips or iron oxide pellets can be used.

Activated carbon is also used to adsorb sulphur. H_2S has to be converted before into sulphur and water, in presence of air which is added to the biogas.

Scrubbers are described in chapter 3.1.3.1.

3.1.3.3 Halogenated hydrocarbon removal

Halogenated hydrocarbons cause corrosion in the CHP engines to the extent that manufacturers specify maximum limits of halogenated carbons in biogas. They can be removed using a pressurised tube exchanger filled with specific activated carbon. Small molecules like CH_4, O_2 and N_2 pass through while larger molecules are adsorbed.

3.1.3.4 Siloxanes removal

Organic silicon compounds are occasionally present in biogas which can cause severe damages to CHP engines. They can be removed by absorption on a liquid medium, a mixture of hydrocarbons compounds with a special ability to absorb the silicon compounds. The absorbent is regenerated by heating and desorption.

3.2 Digestate

Anaerobic digestion can be seen as a method to treat the organic wastes but, in order to extract the maximum recovery value from these wastes, the digestate should have a useful purpose and benefit should be derived from its production. Its main advantage is that it has a high nutrient content. Its quality should be acceptable for purpose such as soil amendment or landscaping. Digestate quality can be asses on 3 criteria: chemical, biological and physical aspects. The chemical aspects of quality management of digestate are related to the presence of:

- heavy metals and other inorganic contaminants
- persistent organic contaminants
- nutrients (NPK)

Agricultural wastes can contain persistent organic contaminants such as pesticide residues or antibiotics. Industrial organic waste, sewage sludge and household waste can contain aromatic, aliphatic and halogenated hydrocarbons, PCBs, PAHs…

According to their origin, organic waste can contain hazardous matters, which can result in new routes of transmission of pathogens and diseases between animals, humans and the environment. The quality control of this type of biomass is therefore essential in relation with the biological treatment. The main problems are related to:

- pathogens
- seeds
- transmissible spongiform encephalopathy (TSE)

The presence of impurities in the digestate can cause a negative public perception of the AD technology, aesthetic damage to environment, increase the operational costs. The most frequent physical impurities are:

- plastic and rubber
- metal
- glass and ceramic
- sand and stones
- cellulosic materials (wood, paper…)

The contamination of the digestate inevitably depends upon the nature of the feedstock (wastes), the nature, the pre-treatments applied and the biological treatment (digestion) itself. For the digestion of MSW, source segregation is more efficient than mixed collection because mechanical pre-treatments are not as effective in removing contaminants as is the elimination of potential contaminants at source.

In the case of pig farms, copper can be added to the food to accelerate growth by increasing food conversion rates. Zinc is added for the same purpose and to counteract the toxicity caused by high copper concentration. These heavy metals will be found in the pig slurry, thus it is important to monitor their levels in the digestate because reduction of heavy metals is not feasible and limits have to be respected in each country [ref. 13].

The European commission have suggested limit values for composts and digestates in the Working Document on Biological Treatment of Biodegradable Waste [ref. 35].

3.2.1 Use of digestate

Anaerobic digestion draws carbon, hydrogen and oxygen from the feedstock. Essential plant nutrients (N, P, and K) remain largely in the digestate. The composition of the fertilizing agents depends on the feedstock and can therefore vary [ref. 41]. The availability of nutrients is higher in digestate than in untreated organic waste. Nutrients (N-P-K) are mineralized to allow improved plant uptake. For instance, digestate has 25% more accessible NH_4-N (inorganic nitrogen) and a higher pH value than untreated liquid manure [ref. 39]. It reduces the odour nuisance by about 80%. The use of digestate also benefits the humus balance in the soil. Thus it can be used fertilizer or soil amendment in agriculture, landscaping [ref. 13]. Such use permits the creation of a nutrient cycle and maintains or improves soil structure due to the application of organic matter.

The use of digestate depends on its quality as well as the type of plant producing it. For instance farm scale and even large-scale co-operative agricultural digesters use the digested slurry without further treatment as a fertilizer on farm land. Depending on local regulations and conditions, spreading is often allowed exclusively on the farmland of the farmers operating an AD site. The amount of co-substrate permitted in manure digestion can also be restricted. Strict limits also exist for the total annual application of nitrogen and heavy metals introduced into the soil. Large scale commercial AD plants, especially those processing MSW, may find it worthwhile to further process the digestate to increase its value or appeal to new markets.

The digestate may have to be dewatered and thus separated into two fractions: the fibre and the liquor. For instance, dewatering and drying of the digestate in agricultural operations can eliminate the need for spraying completely, leading to a reduction in application costs and permitting much better "targeting" of land nutrient deficiencies [ref. 40].

The fibre is bulky and contains a low level of plant nutrients. It can be used as a soil conditioner and as a low grade fertiliser. It can be used as an alternative to peat as well, although it does not have exactly the same characteristics as peat (which is nutrient-free). Further processing of the fibre, such as through composting could produce good quality compost.

The liquor (liquid effluent) contains a large proportion of nutrients and can be used as a fertiliser. Its high water content facilitates it application through conventional irrigation methods, representing an advantage over compost as it can be applied throughout the crop cycle. The liquor is generally used on the farms on which it was produced. However consideration has to be given to the application time so that nitrogen, which is more readily available after digestion, is taken up by the crop and not leacheted into soil and subsequently groundwater. Nonetheless, it has advantages over raw manure applications, as the ammonia uptake by plants is higher than for organic nitrogen. A potentially wider market has yet to be fully developed such has use in hydroponic systems or to grow aquatic weeds or fish [ref. 25]. Many AD plants also reuse the liquor in their process.

The use of fibre and liquor from AD plants has led to improved fertiliser utilisation and therefore less chemical consumption in cropping systems. The most important advantage of organic fertilisers is their participation in the natural nutrient cycle, while inorganic fertilisers are additional to it [ref. 14].

3.2.2 Composting of digestate

In order to obtain a high quality product, with a higher value, the digestate can be processed into compost. It would ensure a complete breakdown of the organic components as well as fixing the mineral nitrogen onto humus-like fraction, which would reduce nitrogen loss. As an additive to composting process, it provides a good source of nitrogen for speeding up the process. At the same time, it enriches the compost in phosphorus and micro nutrients like Mg and Fe [ref. 41]. The water content of the digestate is also interesting for moisture management in the composting process. A private company, Unisyn Biowaste Technology (USA), operating both AD and composting processes, uses anaerobic digestate to enhance its compost [ref. 15].

4 Types of facilities

There is a wide range of facility types, which differ in location, size, feedstock and process employed. The characteristics of the facility have to be carefully chosen in each specific case.

4.1 On-site or Centralised Anaerobic Digestion (CAD) plant

Until recently, the application of anaerobic digestion of organic waste and wastewater was typically an on-site process, dealing with a single waste or wastewater. Although this type of plant can be found in industrial locations they are also very common on-farm. These systems are generally simple in design and require limited maintenance. The operational temperature is normally 35°C and the solid content is invariably less than 5%.

CAD plants approach differs fundamentally in that central locations are used to process material arising from various sources within a defined geographical area. The initial objective of CAD plant was to centrally treat the animal manure and slurry arising from adjacent farms, with better process control, economical advantages and greater operational efficiency. It was realised that AD could be used for co-digestion of manure with other organic waste generated within the immediate region of the plant (sewage sludge, food-processing waste and waste water, OFMSW, industrial waste). These type of plant significantly increase biogas productivity and can enhance overall commercial viability. Furthermore it provides additional revenue from the gate fees.

CAD plants are well-developed in Denmark where they are generally operated by a local farmers' cooperative or by a private energy utility companies [ref. 13, 14].

4.2 Co-digestion

There are several advantages to co-digestion of animal manures and slurries with others organic wastes.

- The primary advantage is the enhancement of the biogas yield per m^3 of reactor, with consequent financial benefits for the plant operator.
- Solid wastes are converted into pumpable slurries when mixed with liquid manure. This can result in easier handling both in the digestion process and afterwards.
- Co-digestion results in more efficient digestion of certain organic materials. This may also be due to other synergistic effects of the mixed digestion process.
- When organic wastes are accepted for co-digestion in an AD plant, the operator usually assumes responsibility for the end-use of the digestate,
- Co-digestion can help achieving a better NPK ratio by blending different organic wastes. The value of the digestate as a fertilizer is thus enhanced.

The main disadvantage is the dependency of large CAD plant on the availability of organic waste for financial viability (gate fees, biogas production). The growth in the number of CAD plants in Denmark, for example, means that CAD plants are now competing with each others for access to high biogas generating potential wastes coming from sources other than farms [ref. 13].

4.3 Size and Capacity of the digester

In 1998, The Biogasworks [ref. 2] listed 130 plants worldwide and 45 process suppliers of capacity varying from 500 to 300,000 tons/year for different waste streams.

The technology of anaerobic digestion is now well developed and the size of commercially available digesters ranges from 70m^3 to 5,000m^3. The size of the tank will be determined by the projected volume and nature of the waste to be handled and the temperature and retention time in the digester. Some indicative tank dimensions are given in Table 2 [ref. 16].

Organic waste digester (tons per day)	Volume (m^2)	Height (m)	Area (m^2)
50	800-1,500	8-10	75-150
150	2,200-3,500	10-12	180-360
350	4,700	10	470
450	7,700	15	513

Table 2: Digester size and the volume of organic wastes processed

Digesters with a volume of less than 250 m^3 can operate successfully on farms. Whereas most tanks are constructed from glass coated steel, these small digesters are often made of glass fibre reinforced plastic. If the plant treats an important quantity of wastes, several digesters can be used. For instance, the Holsworhty biogas plant designed by Farmatic Biotech energy Ltd. uses two 4,000 m^3 tanks for the digestion step. It processes 146,000 tonnes per annum of cattle, pig and poultry manure plus organic food waste [ref. 17].

In Germany, farm-scale biogas plants are well-developed. There were approximately 2,000 on-farm digesters by the end of 2002. Their sizes depend on the size of the farms; therefore manure inputs are comprised between 1000 m^3/year (generated by hundreds of animals) and 70,000 m^3/year (generated by thousands of animals). The smallest biogas digesters have a volume between 50 and 150 m^3, medium-sized are between 500 and 1500 m^3 and larger ones are between 1000 and 5000 m^3 [ref. 15].

For sewage sludge, AD is suitable for all the sludge coming from wastewater treatment plant with a biological treatment. However, it is generally used in plants with a catchment area equivalent to 30,000 inhabitants or more. Smaller amount of sewage sludge could be used for co-digestion. Table 3 shows some sizes of digesters regarding to the population equivalent [ref. 16].

Population Equivalent	Daily sewage throughput (m^3/day)	Total digester volume (m^3)
7,000	1,000	180
21,000	3,000	380
30,000	4,500	800
60,000	9,000	1,350
200,000	30,000	3,400

Table 3: some illustrations of the relationship between sewage throughput and tank volume

For the treatment of MSW, experience in Europe indicates that roughly 15,000 to 20,000 tonnes per annum is the minimal quantity at which the anaerobic digestion of MSW and similar wastes becomes financially viable [ref. 3].

Centralised AD plants in Denmark are used by farmers to treat mainly manure with other waste, such as tannery waste, waste from fish industry or intestinal content from abattoirs. The amount of waste treated ranges from 10,000 to 200,000 t/year and digester capacities varies from 750 m^3 to 7,200 m^3 (3*2,400 m^3) [ref. 14].

The surface area of an AD plant varies from 3,000 m^3 for a capacity of 5,000 tons/year to 15,000 m^3 for a capacity of 100,000 tons/year.

5 Advantages and disadvantages of anaerobic digestion

5.1 Advantages

AD contributes to reducing the greenhouse gases. A well-managed AD system will aim to maximise methane production, but not release any gases to the atmosphere, thereby reducing overall emissions. AD also provides a source of energy with no net increase in atmospheric carbon which contributes to climate change.

The feedstock for AD is a renewable source, and therefore does not deplete finite fossil fuels. Energy generated through this process can help reducing the demand for fossil fuels. The use of the digestate also participates to this reduction by decreasing synthetic fuels use in fertiliser manufacturing, which is an energy intensive process.

AD creates an integrated management system which reduces the likelihood of soil and water pollution to happen, compared to disposal of untreated animal manure/slurries. The treatment can also lead to a reduction up to 80% of the odour and it destroys virtually all weed seeds, thus reducing the need for herbicide and other weed control measures.

On a financial aspect, the advantage of AD is to convert residues into potentially saleable products: biogas, soil conditioner, liquid fertilizer. It can also contribute to the economic viability of farms by keeping costs and benefits within the farm if the products are used on-site [ref. 5].

5.2 Disadvantages

AD projects, as with many developments, will create some risks and have some potential negative environmental impact. These need to be removed wherever possible or at least minimised.

AD has significant capital and operational costs. It is unlikely that AD will be viable as an energy source alone and therefore must be seen as an integrated system. It is likely to be cost effective for those who can use the other products of AD: better waste management, fertiliser.

All waste management systems create traffic movement. This can become a problem in CAD plants and alternative methods of transport should be investigated as transport greatly influences costs and emissions. The location of the plant should be chosen carefully so that distances travelled are minimised between the production of the feedstock, the storage tanks and the digester. Nuisance for the neighbourhood has also to be taken into account.

About health and safety, there may be some risks to human health with the pathogenic content of the feedstock but it can be avoid with an appropriate plant design and feedstock handling procedures. There may also be some risks of fire and explosion, although no greater than for natural gas installation.

Larger CAD plants may have some visual impact, although the digester can partially be sunk into the ground to reduce visual impact and make it easier to load. Landscaping solutions are also possible [ref. 5].

6 Suitable wastes for anaerobic digestion

Anaerobic digestion is suitable for treating:

- sewage sludge
- organic farm wastes
- municipal solid wastes
- green/botanical wastes
- organic industrial and commercial wastes

6.1 Industrial wastes and wastewater

Organic industrial waste includes a wide range of waste materials from industrial and commercial operating. These organic wastes, in solid or liquid form, may form a suitable feedstock for AD.

Potential feedstock from commercial waste source includes catering waste from hotels and restaurants. These wastes contain high moisture content, thus causing problems for incineration, but are suitable for AD. Further treatment (pasteurisation) may be required.

Anaerobic digestion for treating industrial wastewater is increasing rapidly. Over 30 types of industries have been identified with having wastewater amenable for anaerobic digestion, for example, in food and drink preparation and processing organic chemicals, pharmaceutical and fermentation industries. It is suitable for industrial waste water with COD content up to 50,000 mg/l. and it is preferable to use AD for water with a COD value in excess to 2,000 mg/l., because aerobic treatments can be prohibitively expensive due to the supply of large quantities of oxygen [ref. 18].

Many of these industries use AD as a pre-treatment step to lower the sludge costs, control odours, and to reduce the costs of final treatment at a wastewater treatment plant.

For instance, the pulp and paper industry generates large volumes of highly heterogeneous waste water containing compounds from wood or other materials, process chemicals as well as compounds formed during the process. Anaerobic treatment is used as the pre-treatment so that less energy is needed in the aerobic treatments to meet the discharge standards. The excess sludge production will also be low [ref. 19].

Industrial waste and wastewater usually come from [ref. 20]:

- food/beverage industry
- starch industry
- sugar industry
- paper processing
- slaughterhouse (gastrointestinal wastes)
- chemical industry
- pharmaceutical industry
- dairies
- cosmetic industry
- fish oil and fish processing residues

These are only a few examples of the possible use of AD in industry but they are the main possibilities.

6.2 Sewage sludge

Sewage sludge from biological treatment plants is a highly active material which quickly starts fermenting on anaerobic conditions. It is usually delivered in liquid form at approximately 5% TS or dried to 20-25% TS. Anaerobic digestion has become a standard for the treatment of sewage sludge because of its low operational costs. It is also suitable to improve dewatering capability, renders it safer for land application and to obtain energy. Sewage sludge has long been treated with AD and it is a well-established technology.

In co-digestion plants, the addition of sludge to the organic fraction of MSW will increase the nutrient level as well as adding moisture content. The addition of 5% sewage sludge to MSW has been proved to give good process performance and reactor stability, but better anaerobic digestion performance has been achieved with a feedstock of 80:20 ratios MSW: sewage sludge [ref. 20, 21].

6.3 Farm waste

Installation of AD digesters for cattle, pig and poultry manure/slurry treatment at individual farm level dates from the early 1970s. Nowadays, it is a standard technology in upgrading of biowaste from agriculture. In Denmark, 75% of the biomass treated in the CAD plants is manure. It represents the larger amount of the waste treated by AD and also the most current applications.

Animal waste, which is the predominant waste material in agricultural digestion, is an inhomogeneous material with total solid content between 2% and 12%. The predominant number of digesters is therefore of the type of a continually stirred tank reactor (CSTR, wet process).

The advantages of AD for manure treatment include an odourless digestate that can be spread on the land without odour nuisance. This digestate has also a significant fertiliser value, so that it can be used for landspreading or injection into the soil. However, post-treatment may be required where the manure production is in excess of the quantities required by the farmers or where nitrate levels are already high.

The agricultural wastes suitable for AD are:

- Manure/slurry from cattle, pig and poultry
- Harvest remains and garden waste
- Farmyard manure on small farm

Farmyard manure typically consists of manure mixed with the beddings (straw, wood shavings…). The straw absorbs the manure resulting in dry matter contents ranging from 10 to 30%.

The biogas production is not the same depending on the feedstock as seen in table 4 below.

Feedstock	C/N ratio	Biogas yield ($m^3.kg^{-1}$ VS)
Pig slurry	3-10	0.25-0.50
Cow slurry	6-20	0.20-0.30
Chicken slurry	3-10	0.35-0.60

Table 4: Characteristic of agricultural slurries.

Every feedstock can contain some unwanted or inhibiting substances. The table below shows the different characteristics of slurries.

Feedstock	Unwanted substances	Inhibiting substances	Frequent problems
Pig slurry	Wood shavings, bristles, sand, straw	Antibiotics, disinfectants	Scum layers, sediments
Cow slurry	Bristles, straw, wood, soil, NH_4^+	Antibiotics, disinfectants	Scum layers, poor gas yield
Chicken slurry	NH_4^+, grit, sand, feather	Antibiotics, disinfectants	NH_4^+ inhibition, scum layers

Table 5: Problems linked with agricultural slurries [ref. 20].

Straw, especially long particles can cause considerable scum layer formation which is difficult to control during digestion. Straw also involves a poor digestion; however, if the particle size is small enough it can improve the biogas yield.

Wood shavings have a poor anaerobic biodegradation and can cause blockage of pipes.

Grit and sand will precipitate in the digester and thus cause process failures. Chicken manure can be considerably contaminated with sand when chicken are kept in open feedlots.

NH_4^+ ions inhibit the digestion in high concentration.

An important criterion for implementing an AD treatment plant is the quantity of feedstock available for digestion. Pig manure is often collected in the form of slurry, which contains high amounts of water. If the TS content is lower than 5%, the application of AD system might not be economic. In some cases, the manure is collected using scraper systems, thus resulting in higher solid content of 5-10%.

Cow manure is often collected with scraper system; hence dilution with water is minimal. Depending on location and operational tradition cows often spend long periods of time grazing on pastures. Reduced overall manure collection must therefore be considered in economical evaluation [ref. 13].

6.4 Municipal solid waste

The anaerobic digestion of municipal solid waste is, technically, perfectly feasible. However, one of the fundamental issues is whether the organic waste should be collected separately or whether mechanical segregation of the whole waste should be part of the treatment process. Source segregation does not mean that the waste does not contain any unwanted materials. In reality glass, plastic and other materials will always have to be removed. However if the process is well designed and carefully run, then a high quality product can be achieved.

The main disadvantage is that source separation has to be implemented. This involves new containers and vehicles for the collection, thus, the costs are always higher than the traditional single collection vehicle methods, except if it is part of an integrated source segregated collection system. Subsidies can help installing source separation. It also requires significant promotional efforts to raise public awareness and there will always by a sector of the public that will not participate.

Anyway the "cleanliness" of the waste stream should be define regarding to the purpose of the AD plants. If the plant is intended to maximise the output of methane, mixed collection is suitable. If the purpose is to produce a high quality digestate, then the purity of the waste is very important.

Studies have shown that the heavy metals contents were higher in mixed collection digestate than in source segregation digestate. Digestion of mixed MSW is not currently widespread. The Steinmuller-Valorga plant in Amiens, France, is treating unsorted MSW. It produces low quality soil improvers for agriculture, which they disposed of for free [ref. 3, 9].

6.5 Green waste

Green wastes are garden and parks waste. This material may be source separated at civic amenity sites, or produced through local authority or commercial horticultural and grounds maintenance activities. Generally it needs to be shredded to give a more homogeneous feedstock. It may contain woody lignin components which, whilst not readily biodegradable, do not necessarily detract from the value of the digestate produced.

Lignin is an important structural component in plant materials and constitutes roughly 30% of wood. The biodegradability of lignocelluloses materials can be increased by an array of physical/chemical processes. Such treatments are useful when wood and plant materials are to be degraded anaerobically. Nevertheless, it will increase the processing costs [ref. 3, 24].

7 Policy, legislation and regulation

There are many legislation and regulation applying on AD depending on the wastes treated, the type of facilities and the use of the by-products. As a waste management facility, an AD site has to be run with a license and some wastes, such as animal by-products, have to be treated with specific care. The application of digestate on land has to respect limits (see chapter 3.2.) and specific regulations also apply for potentially harmful feedstock, such as sewage sludge. In favour of AD, the electricity produced with the biogas involves that AD is part of the EU and UK policies on new renewable energy.

7.1 EU and UK policies

The European Union is also looking to combat the effects of CO_2 emissions across a number of initiatives [ref. 42]:

- European climate change program
- EU emissions trading scheme
- EU renewable energy policy
- Kyoto Protocol

The development of AD could be boost by legislation as well as good practice and sustainability. The key sets of EU legislation are [ref. 25]:

- Landfill Directive (EC/1999/31), which sets targets for the substantial reduction of biodegradable waste sent to landfill,
- Animal by-product regulation (see chapter 3),
- Draft Biowaste Directive, which is due to be prepared at the end of 2004. If it is adopted in its current draft, the local authorities will be forced to collect source separated food waste in order that the biofertiliser value of organic waste can be realised.

The UK government is also involved in developing renewable technologies through policies and legislation. The aims for the UK Government's policy on new and renewable energy are [ref. 42]:

- assisting the UK to meet national and international targets for the reduction of greenhouse gases;
- helping to provide secure, diverse, sustainable and competitive energy supplies;
- stimulating the development of new technologies necessary to provide the basis for continuing growth of the contribution from renewables into the longer term;
- assisting a UK renewables industry to become competitive for home and export markets and in doing so provide employment in a rapidly expanding sector;
- contributing to rural development.

There are two major incentives supporting UK policy for renewable energy:

- the climate change levy and,
- the new Renewable Obligation

Climate change levy applies to energy used in all industrial, commercial and public sectors, however, the electricity generated from renewable energy (e.g. AD) will be exempt from the levy.

The new **Renewables Obligations Scotland** (ROS) will be important for energy produce from biomass. It succeeds the Scottish Renewables Obligation (SRO) and the Non Fossil Fuel Obligation (NFFO) in providing a guaranteed market for electricity generated from renewable sources. The ROS is at the centre of the incentives for renewable energy. It requires licensed electricity suppliers to meet a specified proportion of their customer demand from electricity generated form "eligible" renewable sources. Eligible technologies are energy from landfill gas, sewage gas, hydro-electric, onshore and offshore wind, biomass, geothermal, tidal stream, wave, photovoltaic and energy from waste [ref. 26].

The ROS will benefit AD, particularly plants that are connected to national grid. It will be left to the energy suppliers to determine with whom to contract, and there will be no fixed contract or price, which will be a matter of negotiation between contracting parties [ref. 36].

7.2 Grant Funding

In order to support the ROS, capital grants are being made available by the Department of Trade and Industry (DTI) and the new Opportunities Fund [ref. 37]. It is aimed at "longer-term technologies", principally offshore wind and biomass projects. There are others incentives and sources of funding available within the UK and the EU. They are listed and described on the site www.novem.org/biofinance .

UK incentives include:

- Climate change levy exemptions
- Bio-energy capital grants scheme
- Community and household renewables scheme
- Community renewable initiative
- Energy crops scheme
- Bio-energy infrastructure scheme

7.3 Regulation

Some wastes have to be treated with specific care due to their nature and potential risks for the humans and the environment. There are regulations that state which wastes are suitable for AD and the way to handle, store, treat and dispose them. For AD, animal by-products and sewage sludge are especially regulated. The main concerns with animal by-products is the high risks of spreading diseases (e.g. foot and mouth), whilst for sewage sludge the concerns relate primarily to its application to land.

7.3.1 Regulation of process

7.3.1.1 Waste management licensing/permitting

An anaerobic digestion facilities handling controlled waste will require a waste management licence under the Environmental Protection Act 1990. The licence required for an AD plant would be a site licence, authorising the deposit, recovery or disposal of controlled waste in or on land.

Controlled waste means household, commercial or industrial waste. It includes any waste from a house, shop, office, factory or any other trade or business premises. It is controlled waste whether it is solid or liquid and even if it is not hazardous or toxic [ref. 27].

A licence has conditions to make sure that the authorised activities do not cause pollution of the environment, harm to human health or serious detriment to local amenities. Aspects likely to be covered by this will include acceptance, handling and storage of wastes, operation and monitoring of flare stacks and gas cleaning equipment, odour control, handling, storage and use or disposal of digestate and monitoring of pathogens. All licences require the production of a working plan to regulate site operations.

Planning authorities will wish to have regard to the following [ref. 16]:

- **Safety** considerations associated with the handling, transporting and burning of gas;
- Potential **odour** problems associated with the transport and storage of biodegradable matter, and during the digestion process;
- Biogas **emissions** to the atmosphere, including the flaring of excess gas;
- **Visual intrusion**, particularly by the digester tank and the gas flare;
- **Noise** from engines, generators, gas blowers, pumping equipment and traffic;
- **Liquid effluent** disposal and the protection of groundwater;
- **Traffic** resulting from the transport of wastes and subsequent by-products to and from the site.

A planning application for an anaerobic digestion facility could usefully include the following information:

- The location and design of plant and machinery including chimney height;
- Provision for storage;
- Vehicular access and vehicular movements;
- Provisions for dealing with noise and odour;
- Landscaping provisions;
- Security fencing and lighting.

7.3.1.2 Animal by-products

The new EU animals By-products Regulation (EC No.1774/2002) has applied since 1 May 2003. It permits the use of composting and biogas treatment for catering waste and others low risk (category 3) animal by-products.

Animal by-products are the parts of a slaughtered animal that are not directly consumed by humans, including dead on farm animals and catering waste (i.e. waste food originating from restaurants, catering facilities and kitchens) that contains or has been in contact with meat products, whether cooked or uncooked. Some of these products are used in animal proteins like meat-and-bone-meal, fats, gelatine, collagen, pet food and other technical products, such as glue, leathers, soaps, fertilisers etc. The alternative is their destruction, most often by incineration. There are three different categories of materials.

Category 1 materials (i.e. animal by-products presenting highest risk such as TSEs, residues of prohibited substance e.g. hormone used for growth promotion or environmental contaminants e.g. dioxins, PCBs) must be completely disposed of as waste by incineration or landfill after appropriate heat treatment.

Category 2 materials include animal by-products presenting a risk of contamination with other animal diseases (e.g. animals which die on farm or are killed in the context of disease control measures on farm or at risk of residues of veterinary drugs), and may be recycled for uses other than animal feeds after appropriate treatment (e.g. biogas, composting, oleo-chemical products, etc).

Only category 3 materials (i.e. by-products derived from healthy animals slaughtered for human consumption) may be used in the production of animal feeds following appropriate treatment in approved processing plants [ref. 28].

Animal by-products other than catering waste and, until 31 December 2005, some former foodstuffs must be treated to at least the EU standards, which are 70^{o}C for at least one hour in a closed vessel system. The maximum particles size should be 12 mm. In addition, high risk (category 2) animal by-products can be treated to this standard but only if they have first been pressure rendered to the 133^{o}C/3 bar/20 minutes standard.

7.3.1.2.1 Catering waste

Under the animal by-products Order 1999 (as amended), catering waste containing meat or products of animal origin had to be banned from contact with livestock (including wild birds), in order to avoid introduction and spread of serious animal diseases. Thus it prevented the use of animal by-products on land, treated or not (composting, AD…).

The EU regulation permits Member States to introduce national treatment standards for premises which treat only catering waste. The national standards are at least:

- 57^{o}C for 5 hours with a maximum particles size of 5 cm. or,
- 70^{o}C for 1 hour with a maximum particles size of 6 cm.

These standards do not applied to premises which treat other category 3 animal by-products, pressure-rendered category 2 material, or a mixture of catering waste with animal by-products or pressure-rendered category 2 material. This material must be treated to the EU standard as described in the previous paragraph.

7.3.1.2.2 Additional barrier

As well as the time/temperature treatment requirement, all systems must also contain at least one additional barrier, as described below.

Biogas plants must either:

- treat only meat-excluded catering waste or,
- following the treatment, store the material for a minimum of 18 days. Storage may include anaerobic digestion.

For example, a biogas plant could pasteurize the catering waste by treating it to 70°C for an hour (or 57°C for 5 hours), followed by an 18 days anaerobic digestion stage. Alternately, a biogas plant could only treat meat-excluded catering waste to the time/temperature standard alone. Both of these would comply with the two barriers requirements for the biogas plants.

All composting and biogas plants treating catering waste containing meat or originating from premises handling meat must be approved by DEFRA (Department for Environmental, Food and Rural Affairs) [ref. 29].

7.3.1.2.3 Approval for animal by-products treatment

Every premise dealing with animal by-products needs to obtain a validation by the State Veterinary Service (SVS). In order to obtain this validation, the operator should carry out a Hazard Analysis and Critical Control Points (HACCP). It is a process that identifies, evaluates and controls hazards which are significant for product safety. The recommended HACCP approach is [ref. 29]:

- Conduct a hazard analysis
- Determine the critical control points (CCP)
- Establish critical limits
- Establish a system to monitor control of each CCP
- Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control
- Document and record all procedures, corrective actions and verification results
- Establish procedures for verification, audit and review to confirm that HACCP is working efficiently.

When the HACCP system is defined, plant validation can take place. There are two stages:

- Pre-validation of the system by the manufacturer or the operator and,
- Validation of the site by the operator, to demonstrate that the system is capable of being operated properly at the specific site

For the pre-validation, the plant manufacturer or operator must provide evidence and data to demonstrate the system can comply with the requirements of the Regulation. These evidences will be assessed by the SVS, who will determine whether the system is sufficient.

Once it has been accepted by the SVS, the operator will also need to demonstrate that the system can be operated on their own site in a way which complies with the requirements of the Regulation. They will need to carry out a validation process for this and then submit a HACCP plan listing the system critical control point, how they will be measured and monitored to demonstrate compliance, and what corrective actions will be taken in case it is needed. Once the SVS has received and assessed the HACCP plan, and is satisfied that the system is capable in principle of meeting the requirements, they will inspect the site. The operator will have to demonstrate that he knows how to operate the system properly. If the SVS is satisfied, they will deliver a time-limited approval.

An application and inspection form for approval to treat animal by-products and/or catering waste in composting or biogas plant, can be found on the internet site of DEFRA. For further information, see the guidance on the DEFRA site as well.

7.3.2 Regulation for the application of digestate

7.3.2.1 Sewage sludge

In addition to having beneficial properties as a fertiliser and soil conditioner, sewage sludge can also be potentially harmful to the environment and health if not used appropriately.

In accordance with the requirements of the Urban Waste Treatment Directives (91/271/EEC) the disposal of sewage sludge to surface waters, including the sea, ceased in December 1998. In 2000, approximately 64% of sludge was disposed of to landfill compared with 3% in 1998. Only 20% of sludge applied to agricultural land in Scotland is stabilised by digestion before application, but this situation is set to change. In Scotland, the regulations are enforced by SEPA. Below is a summary of the requirements of the Sludge (use in agriculture) Regulations 1989 (as amended). Some of the requirements relate to the sludge producer and some to the farmer. Discussion of the requirements between farmers and sludge providers should be done to make sure they are being met [ref. 30]:

- Representative samples of sludge shall be taken after processing and before delivery to the user and analysed in accordance with the regulations. All soils must be sampled and analysed in accordance with the Regulations and the results be available before sludge is first applied and regularly thereafter.
- Sludge applications must not raise soil metals levels above the limits laid down in the Regulations.
- Sludge must not be applied if the soil pH is below 5.0.
- Sludge application rates in conjunction with other organic and inorganic fertiliser applications should match the crop requirements.
- No fruit or vegetable crops, other than fruit trees, shall be growing or being harvested in the soil at the time of use.
- Stock must not be grazed for at least three weeks after application.
- Fruit and vegetable crops, which are grown in direct contact with the soil and normally eaten raw, must not be harvested for at least 10 months after the application of the sludge.
- If untreated sludge (i.e. sludge or septic tank sludge that has not undergone biological, chemical or heat treatment, long term storage or a process to reduce its fermentability and health hazards) is applied to grassland, it must be injected and no sludge should remain on the surface.

The application on food crops of untreated sludge is no longer carried out in the UK because of a voluntary agreement in the terms of the sludge matrix. The Safe Sludge matrix is a table summarizing the possible use of sewage sludge regarding to its level of treatment and the agricultural use of the land. It can be found on this site: http://www.adas.co.uk/matrix/SSM.pdf .

DEFRA and the Scottish Executive are currently amending the Sludge (Use in Agriculture) Regulations 1989 to incorporate some of the requirements of the Safe Sludge Matrix.

8 Financial aspect

Before deciding to build an AD plant, the financial aspect of AD must be carefully considered and understood. These include:

- capital costs
- operating costs
- sources of income.

The capital costs are dependant on factors such as plant size and engineering, location, and waste composition. It is thus difficult to provide accurate costs without the specifications of the plant. Moreover each case is specific. For instance, plants treating MSW need to have expensive pre-treatments and these can differ regarding the degree of segregation you want to achieve or the goal of the project: e.g. recovery of recyclables, production of combustibles or high quality digestate. Even source-segregated MSW have to undergo pre-treatments has some inert materials are always present.

Operating costs include costs associated with staff, insurance, transportation, annual licenses, pollution abatement and control, and other maintenance.

Sources of income are likely to include revenue from the sale of electricity, heat sales, digestate (liquor and fibre) and gate fees. The gates fees are charges made for processing waste and are especially relevant to CAD plants. It is likely that it would need to be competitive with alternative waste management solutions available locally. Operators of AD plants should ensure that they have sufficient feedstock material to operate their plant at optimum capacity, in order to maximise the potential sources of revenue. Long-term contracts for the reception of waste (i.e. feedstock) and sale of energy and other by-products can contribute to maximising the sources of income.

Although it is difficult to provide accurate costs, it is possible to give an indication of the range of costs for an AD plant in relation to the type of waste treated and capacity. Some examples are outlined below:

- For an on-farm digester, the capital cost is likely to be between £100,000 and £200,000 for a capacity of about 3,000 tons/year. The operating costs should be around £2,000 (without labour).
- For larger plants, treating waste form several farms, capital costs vary from £500,000 for a capacity of 10,000 tons/year to £5,000,000 for a capacity of 200,000 tons/year. Operating costs are likely to be in a range between £31,000 and £530,000.
- For AD plants, treating the organic fraction of source-segregated MSW, capital costs vary from £3,000,000 for a capacity of 5,000 tons/year to £12,700,000 for a capacity of 100,000 tons/year. Operating costs are ranging from £127,000 to £953,000.

It is possible to calculate roughly the biogas production and thus the electricity and heat production of an AD plant in relation to the composition of the feedstock (for more detailed information, please see appendix 1). However such calculations are based on average values and they do not take the process parameters into account (type of digesters, temperature of digestion). Figures should be regarded as indicative values.

For instance, a large centralized AD plant processing 100,000 tpa of cow slurry, which represents approximately 8,000 cows, would produce:

- **3,110 MWh/y** or **31.1 kWh/tonne** of electricity
- **5,710 MWh/y** or **57.1 kWh/tonne** of heat

Considering a selling price of 4.5p/ kWh, the total income for a year for the electricity would be **£140,000**. The heat could be used for the process (digester heating, sterilization) and for many other applications.

For further information about selling electricity, see Scottish Renewables internet site [ref. 43]. The selling price is not fixed and depends on the agreement between the producer and the power supplier. The length of the contract is also very important.

9 GLOSSARY

Energy crops: they are specifically grown to produce some form of energy and are considered a type of biomass. Energy may be generated through direct combustion or gasification of the crops to create electricity, or through the creation of liquid fuels such as ethanol to be used in transportation vehicles.

Halogenated hydrocarbon: chemical compounds containing hydrogen, carbon, and either chlorine, iodine, or bromine. Vinyl chloride is an example of a halogenated hydrocarbon.

Hammermill: it is a speed machine in which waste is disintegrated into smaller pieces by fixed or swinging metal hammers.

Plug-flow reactor: the reactor is fed with the influent at on side, and the effluent is pushed to the other side depending on the digestion. No mixing occurs.

Town gas: in the olden days, town gas, often called manufactured or coal gas, was often made by baking coal in large airtight ovens (gas retorts). The gas bubbles from the hot coals were piped off and used as a household fuel. Natural gas has replaced town gas.

Seed material: material containing the bacteria required for digestion.

Upflow Anaerobic Sludge Blanket (UASB): Wastewater enters the bottom of the reactor vessel through the inlet distribution system and passes upwards through the dense anaerobic sludge bed. Soluble COD is readily converted to biogas which is rich in methane and an upward circulation of water and gasborne sludge is established. The specially constructed settler sections allow effective degasification to occur. The dense, granular sludge particles now devoid of attached gas bubbles sink back to the bottom establishing a return downward circulation.

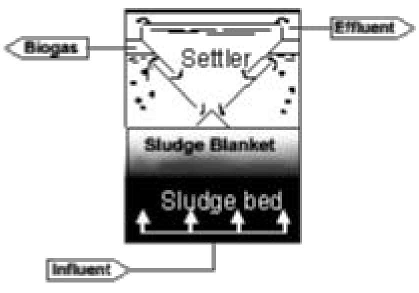

Figure 5: UASB scheme [ref. 38]

The upward flow of gasborne sludge through the blanket combines with the return downward flow of degassed sludge and creates continuous convection. This insures effective sludge to wastewater contact without the need for any energy consuming mechanical or hydraulic agitation within the reactor. The unique design of the reactor allows a highly active biomass concentration in relation to soluble organic solids passing through the sludge bed and is responsible for the very high loading rate (short hydraulic retention time) which can be achieved routinely [ref. 33].

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[ref. 43] www.scottishrenewables.com, see the report about financing renewable projects

11 APPENDIXES

<u>Appendix 1:</u> calculation of the electricity and heat production.

Feedstock	Total solids TS (%)	Volatile Solids VS (% of TS)	Biogas yield[4] (m^3/kg VS)[2]	CH_4 content (%)
Pig slurry	3-8[1]	70-80	0.25-050	70-80
Cow slurry	5-12[1]	75-85	0.20-030	55-85
Chicken slurry	10-30[1]	70-80	0.35-0.60	60-80
Leaves	80	90	0.80-0.95[3]	n.a.
Straw	70	90	0.35-0.45[5]	n.a.
Garden waste	60-70	90	0.20-0.50	n.a.
Food waste	10	80	0.50-0.60	70-80
Whey	1-5	80-95	0.80-0.95	60-80

<u>Table X:</u> characteristics of biogas regarding to the feedstock [ref. 13].

These figures are depending on several parameters: the total solid content can vary with the dilution of the waste (1) and the biogas yield is linked to straw addition (2), dry weight (3), retention time (4) and particle size (5).

<u>Example:</u>

A centralized AD plant is treating 100,000 tpa of cow slurry. It represents approximately 8,000 cows. The average value for each parameter will be used in the calculation, so:
TS= 8.5%, VS= 80% of TS and biogas yield= 0.25 m^3/kg VS

100,000*8.5%= 8,500 tpa of solids
So the VS content is: 8,500*0.80= 6,800 tpa
6,800,000 kg/y VS*0.25= 1,700,000 m^3 biogas/y

The amount of biogas produced per year is 1,700,000 m^3. That gives 194 m^3 per hour.
The electricity and heat production is:
With a calorific value of biogas of 22MJ/m^3,
194*22*10^6/3600= 1,185,946 W that is approximately 1,185 kW

So the power available for the CHP unit is 1,185 kW. Assuming that the CHP unit has a conversion efficiency of 30% for electricity and 55% for heat:
1,185*0.3= 355.5 kW
355.5*24*365= 3,110 MWh/y
The production of electricity will be **3,110 MWh/y.**
1,185*0.55= 652 kWh/y
652*24*365= 5,710 MWh/y

The production of heat will be **5,710 MWh/y.** This heat could be used for the process (digester heating, sterilization) and for many other applications.

It can be expressed in kWh/tonne as well; it gives **31 kWh/tonne** of electricity and **57 kWh/tonne** of heat.