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International Fertiliser Society

ANAEROBIC DIGESTION OF FARM MANURES AND OTHER PRODUCTS FOR ENERGY RECOVERY AND NUTRIENT RECYCLING

by

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Proceedings 632

Paper presented to the International Fertiliser Society
at a Conference in Cambridge, on 10th December 2008

P O BOX 4, YORK YO32 5YS
UNITED KINGDOM

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ISBN 978-0-85310-269-4
(ISSN 1466-1314)

ABSTRACT.

Anaerobic digestion comprises a sequence of naturally occurring bacterial processes that breakdown complex, organic compounds in the absence of oxygen. At the final stage of the process, methanogenic bacteria produce a gaseous mixture of methane and carbon dioxide commonly termed biogas. Thus from an industrial and, more recently, an agricultural viewpoint, the process has the advantages of stabilising organic wastes and manures, with potential for reducing risks of pollution, and of yielding a renewable source of energy in the form of biogas. Simple, family sized digesters have been used to provide gas for cooking etc for many years in warmer climates. Large-scale plants in temperate regions, including the UK, were developed for the treatment of municipal sewage. Energy crises, together with concerns over the environmental impacts of intensive farming, have created much interest in on-farm anaerobic digestion plants. Most of these, including the most recent, are of the continuous stirred tank reactor (CSTR) design. An insulated tank is heated and mixed, and feedstock, such as livestock manure, food processing or other organic wastes, or specially grown crops, is fed in to it on a regular basis each day. Digested material (digestate) flows, or is pumped, out at the same rate. Biogas production is related to the composition of the feedstock, the operating temperature and the digester retention time. For most on-farm digesters, temperature is controlled within the range optimum for mesophilic bacteria (20-40°C) and retention time (the average time feedstock is in the digester) is between 10 and 30 days. Biogas does not readily compress, so storage is difficult, but can be burnt in a boiler for hot water or in an engine to produce power. Combined heat and power units (CHP) provide both heat, via recovery from engine cooling, and electricity via a generator. Digestion reduces chemical and biological oxygen demand (COD and BOD), so reducing the potential for water pollution, and level of odour and pathogens associated with organic feedstocks. It also decreases dry matter content and increases the proportion of nitrogen in inorganic forms available for plant uptake and so increases fertiliser value.

Government incentives, whereby electricity companies are obliged to purchase electricity from renewable supplies in support of policies on climate change, have boosted the economics of anaerobic digestion. High capital cost of plants and regulatory issues still present challenges to developments in the UK.

Keywords: anaerobic digestion, biogas, livestock manures, plant nutrients, renewable energy.

CONTENTS

1. INTRODUCTION.

Anaerobic digestion (AD) is a naturally occurring process in which bacteria break down organic matter in the absence of oxygen. Related processes occur in a wide range of natural environments including anaerobic mud in marshes and bogs, in soils and in the digestive tract of ruminant animals. The microbial processes involved are complex and involve predominantly strictly anaerobic bacteria. At the final stage of the process, specialised methanogenic bacteria produce a gaseous mixture of methane and carbon dioxide, commonly called biogas, which can be used to fuel gas fires, boilers or engines.

The potential to stabilise organic wastes, and hence reduce risks of pollution, and to produce a source of energy in the form of biogas has stimulated interest in the process over many years. The first recorded digestion plant was built in Bombay, India in the mid 19th century. There has long been interest in the process in developing countries because digestion of locally available organic wastes, such as cow dung, could provide biogas relatively cheaply. The combination of a warm climate, allowing the process to proceed without additional heating, the social and economic structure of countries such as India and China and the development of simple 'family size' digesters meant that huge numbers of people could use biogas for family cooking etc. and the digested material, or digestate, for fertiliser. In India, for example, the Gobar gas schemes dating from the 1950s made small, non-heated, non-automated digesters a practical possibility for millions of people.

In the Western world, the septic tank was developed as a simple form of digester in the mid 19th century for treating human sewage but with no attempt to collect the gas. An important development occurred in the 1890s when a septic tank was developed with provision to collect biogas and use it for street lighting in Exeter. Later, engineers at the Birmingham sewage works pioneered the use of the gas in internal combustion engines for large-scale generation of power (Hobson *et al.,* 1981). Large-scale plants all over the world use anaerobic digestion primarily for treating sewage, with biogas being used to heat the digester and to provide power to run the plant. Smaller installations used the gas for digester heating but flared off surplus gas. Apart from times of shortages, during the war or more recent energy crises for example, biogas has not been able to compete successfully with more convenient and cheaper fuels for widespread use.

In the 1970s, interest turned towards the use of anaerobic digestion for the treatment of livestock manures. At this time it was recognised that with the increase in size and number of more intensive livestock units, pollution from manures, ignored or negligible till then, could become a serious problem and controlled by legislation. There was an expansion of research and development on both laboratory and pilot plant scales, further encouraged by the first oil crisis of about 1974. This provided the stimulus for the construction of 10 – 15 full sized installations on farms in the UK and others in Europe and the USA. Although those in the UK received considerable interest and were technically successful, unattractive economics were a barrier to further uptake. This was largely due to high capital cost of the installation and difficulties in matching the supply of biogas from the digester and the demand for it from normal farming operations. Also, it must be recognised that anaerobic digestion was new, unfamiliar technology to farming so investment in and operation of a plant was not to be taken lightly.

The outlook for the application of the process in agriculture has changed again in recent years. There is certainly even more concern over national and global environmental issues such as climate change. Anaerobic digestion has a role to play here in capturing methane, a very potent greenhouse gas, from livestock manures and in providing a renewable alternative to fossil fuels. Through breaking down complex, organic nitrogen compounds to simpler forms that can be readily taken up by crops, the process increases the potential value of the digestate as fertiliser and saves on increasingly expensive bought fertilisers. Developments in machinery comprising a biogas engine and alternator for electricity generation to provide both heat and power, means that earlier difficulties in matching energy supply and demand on farms can now be overcome. Furthermore, government incentives to supply renewable sources of electricity to the national grid have markedly improved the economics. It is also recognised that gas yields from livestock manures are limited and that the efficiency and economics of the process on farms can be greatly improved by including other, readily degradable sources of organic matter, such as food wastes and crops, in the material fed to the digester.

This paper outlines the microbiology of anaerobic digestion, the design, operation and performance of on farm digesters and discusses the use of biogas and digestate. We also outline the role of the process in helping alleviate environmental issues, incentives for uptake on farms and the current economic outlook from a UK perspective.

2. MICROBIOGICAL PROCESSES.

Anaerobic digestion comprises a complex sequence of microbial processes involving several different groups of bacteria. The bacteria are predominately strictly anaerobic with the efficient metabolism of each group being dependent on the others.

2.1. Methane production.

The process of methane production can be divided into three main stages, a particular group of bacteria being associated with each stage. A fourth subsidiary group may also be included (Hobson, 1981; Hobson *et al.,* 1974). The main stages are illustrated in simplified form in Figure 1, overleaf.

Stage 1 (Hydrolysis). Degradable organic substances (carbohydrates and lipids) are converted to simpler soluble compounds. Initially, complex compounds are hydrolysed by exocellular enzymes produced by the bacteria. The resulting simpler compounds are then further broken down by fermentation to volatile fatty acids (VFAs), mainly acetic, proprionic and butyric acids. The fermentation is usually biased towards the formation of acetic acid. Some carbon dioxide (CO_2) and hydrogen (H_2) are also produced at this stage.

Stage 2 (Acetogenesis) At this stage, obligate hydrogen producing acetogenic bacteria metabolise mainly the proprionic and butyric acids to additional CO_2, H_2 and acetic acid. A fourth subsidiary group of bacteria *(Stage 4)* may convert some of the CO_2 and H_2 to more acetic acid. The bacteria responsible for this stage of the process are active over a wide temperature range from 3 to 70°C, with an optimum around 30°C.

Stage 3 (Methanogenesis) The third stage bacteria are the most important, being those that metabolise acetic acid or $CO_2 + H_2$ to methane (CH_4). About 70% of the methane is produced from VFAs, mainly acetic acid, and the remaining 30% from CO_2 and H_2O (Smith and Mah, 1966). The latter pathway is important in removing H_2 because, if concentration increases above a minimal level, acetic acid production decreases leading to less methane production.

Methanogenic bacteria are slow growing and very sensitive to environmental conditions. They are specific to temperature ranges, being classified as psychrophilic (lower than 20°C), mesophilic (20-40°C) or thermophilic (higher than 40°C). Digesters in the UK are most commonly operated in the mesophilic range. These bacteria are strictly anaerobic so molecular oxygen will kill them. Even inorganic compounds containing oxygen, such as nitrates (NO_3), will inhibit their growth. They are also very sensitive to pH and are inhibited if this falls below 6, leading to a build up of VFAs in the digester.

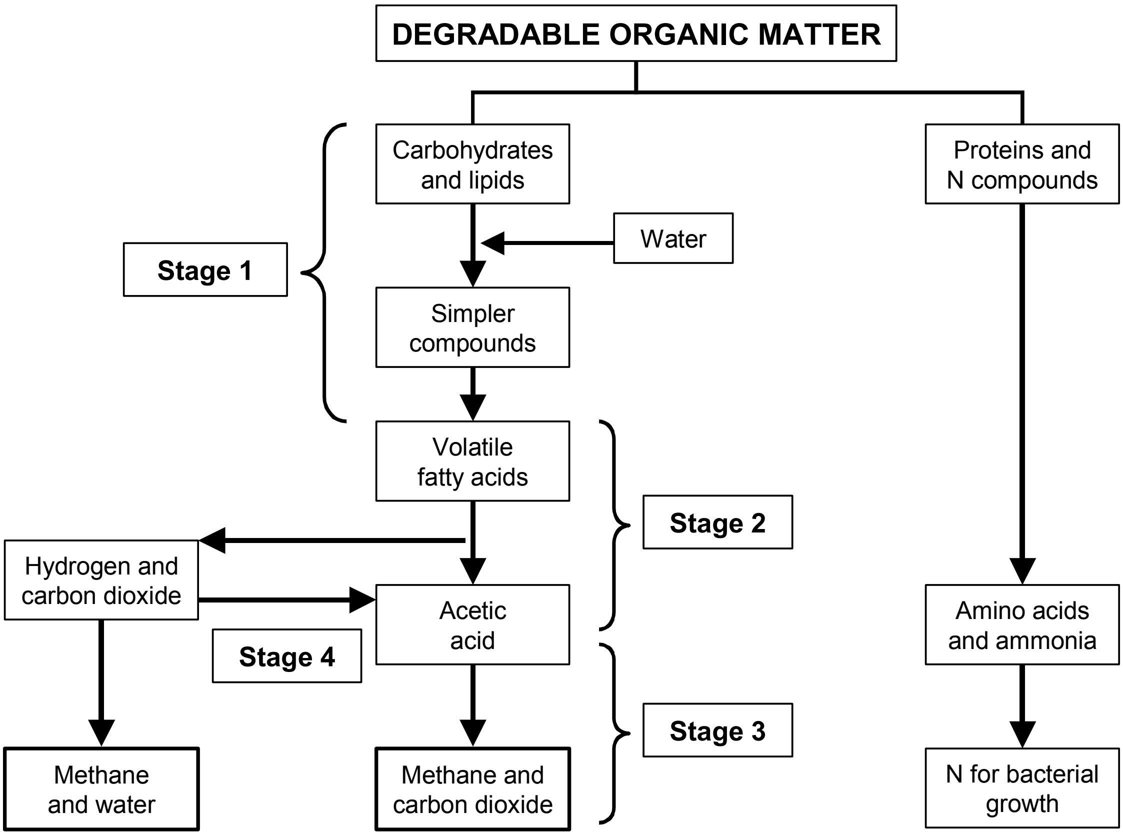

Figure 1: *The main stages in anaerobic digestion (from Hobson and Richardson, 1985).*

2.2. Additional processes.

Nitrogen, which is necessary for the growth of bacteria in the digester, is obtained by the activity of so called proteolytic and deaminative bacteria on the organic compounds containing protein and non-protein nitrogenous compounds. These compounds are initially broken down to amino acids that are then deaminated to give ammonia. Most of the bacteria can utilise both amino acids and ammonia but methogenic bacteria can only use ammonia for cell synthesis. However, free ammonia (NH_3) acts as a much more potent inhibitor of methane production than ammonium (NH_4^+) ions so it is important to maintain the correct equilibrium in a digester. Excessively high nitrogen contents in organic matter can slow down the digestion process. Highest methane production is obtained when organic material fed into the digester has a C:N ratio between 13:1 and 28:1.

Sulphate reducing bacteria are also present in digesters so sulphides can be produced from sulphates and from the breakdown of amino acids. High concentrations of sulphides can inhibit methanogenic bacteria (Lawrence and McCarty, 1964). Lactate fermenting bacteria are also present and produce some acetic and proprionic acids. A consortium of bacteria is thought to be involved in the complete breakdown of fibres although lignin is not normally affected.

3. BIOGAS.

Biogas is produced at the final stage of the process and can be burnt in a boiler, to produce heat, or in an engine so saving on fossil fuels. It is a mixture of CH_4 and CO_2, together with smaller proportions of other gases, that is saturated with water vapour. The exact composition of biogas depends on the nature of organic material that is digested and the conditions under which this occurs. Typical ranges are given in Table 1.

Table 1: *Composition of biogas*.

Gas	% total by volume
Methane	55 – 75
Carbon dioxide	25 – 45
Hydrogen sulphide	0.1 – 1.5

On average, biogas can be expected to contain about 60% CH_4 and 40% CO_2 and to have a calorific value of about 25 MJ/m^3 compared with about 40 MJ/m^3 for natural gas. Its energy density is low compared to other agricultural fuels such as petrol, diesel oil and LPG so storage is disproportionately expensive. Methane does not liquefy at temperatures above - 82.3°C so, unless a cryogenic system is installed, biogas must be restricted to large volume gaseous storage. Although it is explosive only over a fairly narrow range of mixtures with air (6 – 12% air by volume in biogas), this is critical both to its controlled combustion, in boilers or engines for example, and the prevention of explosions.

3.1. Using biogas.

There are four ways in which biogas can be used in a farm environment:

1. Burning in conventional types of boiler to produce hot water. Biogas can also be used in flued cookers or other heating devices. Without further cleaning, it is not suitable for hot air heaters where combustion products are released directly to the working environment, or crop dryer, due to the presence of sulphur dioxide.
2. Conversion to electric power by means of an engine generator set.
3. Conversion to heat and power by using an engine generator set design to produce both power and usable heat. These are called combined heat and power units (CHP).
4. Burning as an automotive fuel, after compressing it, in vehicles with suitably modified spark-ignition or diesel engines.

The first option is reliable and relatively inexpensive using, for example, domestic boilers modified by installing larger jets and electronic ignition or a propane pilot flame to cope with the inferior combustion qualities of biogas compared with natural gas. Boiler conversion efficiencies are normally in the 70 – 80% range. However, there is only limited requirement for hot water on most farming enterprises and, even if it is used for domestic heating, supply is likely to exceed demand at times of the year.

Internal combustion engines can be used to convert biogas energy into mechanical power that can be used directly for driving pumps etc or electricity generators. Spark ignition or diesel engines can be used but the latter requires some diesel to initiate combustion. The main problem is rapid deterioration of copper based engine components (bearings, distributors, ignition leads etc) cause by hydrogen sulphide (H_2S) in biogas. This can be avoided by suitably modifying engines or by installing equipment for scrubbing the hydrogen sulphide from the biogas before use.

The introduction of the Energy Act 1983 enabled low voltage private generators to supply the UK National Grid via a two-way meter and be paid for the electricity supplied. This together with recent government incentives for provision of renewable energy (see later) makes generation of electricity from biogas an attractive proposition, overcoming the problems of matching energy supplied by the digester with that used on the farm.

Option 2 above is a relatively inefficient way of using biogas because much of the energy is dissipated as heat from the engine. Today, the focus is on the use of CHP units. These not only convert biogas to electricity but also recover usable heat from the engine cooling jacket, exhaust and generator to give energy conversion efficiencies of 85% or more.

It has long been feasible to run vehicles on biogas. (Picken and Soliman, 1985; Buttner and Maurer 1982). However, biogas is not an easily transportable fuel because of its low energy density relative to liquid fuels. It is not easily liquefied, nor can be held in liquid form without 'boiling off'. A technically feasible, but expensive option, is to install equipment for removal of CO_2 and H_2S from the biogas followed by high pressure compression. The nearest equivalent is running vehicles on LPG but much larger cylinders are needed for methane and have to be carried in the vehicle to give the equivalent mileage.

Whilst the use of biogas in a farm environment is usually limited to the four options outlined above, there is growing interest in adding biogas, after necessary purification and modifications, into the national gas grid. Such a move has several key advantages including the ability to market gas on a much wider, regional or national scale. The use of the national grid to move gas to urban areas also opens up the opportunity to make better use of the heat generated via a CHP unit.

4. DIGESTATE.

The digested material leaving the digester, the digestate, is of a similar volume to that fed into the digester but different in physical, chemical and microbiological composition.

4.1. Mineral content and fertiliser value.

The anaerobic digestion process, as described in detail earlier, relies on a three-stage process involving enzymes and bacteria to break down organic matter. While the primary commercial aim of this digestion process is the production of biogas and ultimately renewable energy, the quality and management of the spent feedstock, commonly termed digestate, is very important.

The very nature of the digestion process means that significant changes occur in the properties of the feedstock during digestion. The whole degradation process has the impact of reducing the levels of solids within the original feedstock resulting in a significant reduction in the total solids content of the digestate compared to the original feedstock. The breakdown/conversion of organic matter into biogas does not impact on the overall mineral content of the feedstock. As a consequence the total nitrogen, phosphate, potash and other minerals content does not alter during digestion even though the availability of these minerals may well improve.

The bacteria involved in the organic matter digestion break down organic nitrogen in to readily plant-available nitrogen, mainly ammonium-N (NH_4^+). This has the potential to be taken up rapidly by plants, usually following transformation to nitrate (NO_3^-) in soils, but also to be lost to the environment either as ammonia gas (NH_3) or via leaching as nitrate.

In a similar manner, there is potential for organic phosphate to be broken down into more water soluble, and hence more plant available forms. This more readily available phosphate can be used to replace inorganic mineral fertiliser.

Whilst the increase in the availability of plant nutrients offers significant opportunities to use digestate as tactically applied crop fertiliser, risk of losses to environment should be taken into account when planning digestate management.

Changes in the mineral composition of livestock slurries following digestion are well illustrated by data from farm digesters in Europe and the USA collated in 2007 (Anon, 2007) and summarised in Table 2.

Table 2: *Changes in nutrient content of livestock slurries following anaerobic digestion (comparison between digester input and output expressed as % except for pH units).*

	DM %	**N-total** %	**NH_4-N** %	**P_2O_5** %	**pH**	**COD** %
Mean	-25.6	-0.8	25.7	0.7	0.4	-29.9
Range	-10 to -60.3	0 to -14.3	8.7 to 40.0	-12.7 to 18.0	0.3 to 0.5	-9.0 to -61.3
Observations	12	16	18	10	11	12

The data in Table 2 illustrate that relatively consistent physical and chemical changes occur during digestion. Regardless of the dry matter (DM) content of the original slurry feedstock, DM content was reduced as a result of digestion due to organic matter breakdown and the transformation of carbon to methane and carbon dioxide.

The total nitrogen content of the feedstock did not appear to alter significantly during digestion and there was no consistent effect on the total phosphate and potash. However, there were always increase in NH_4-N content and, to a lesser extent, in pH. This was considered to be due to the breakdown of organic nitrogen during the digestion process. The mean increase in NH_4-N was about 26% although there was a wide range in reported values. The availability of phosphate increased in some digesters but decreased markedly in others, indicating that change in the plant availability of phosphate during digestion is not consistent. There was a consistent reduction in the Chemical Oxygen Demand (COD) for all the digestates . The consistently lower scores for digestates when compared to the original feedstocks reflect the considerable degradation of organic matter within the digesters. As a result digestates tend to be far less damaging to a water environment than the original raw feedstocks. The COD was typically reduced by 30% during digestion but again there was a large variation between digestates.

Although these data clearly illustrate the potential changes during digestion, the points relating to the influence of feedstock quality and retention time highlighted earlier must also be taken into account. For these reasons, plus the fact that the digestion process is incredibly dynamic being based on microbial activity, standard values or averages should never be used as a substitute for actual and regular digestate analysis. It is clear, however, that the main factor influencing the fertiliser value of digestate is that of the digester feedstock. High mineral content feedstock will yield high mineral content digestate and vice versa.

4.1.1. Slurry-only feedstock.

For on-farm digesters, where the feedstock is primarily dairy or pig slurry, the total nutrient content of the digestate will be similar to the original slurry as in Table 3.

Table 3: *Standard total nutrient content of livestock slurries (kg/m^3).*

Manure	Nitrogen N	Phosphate P_2O_5	Potash K_2O
Dairy cow slurry	3.0	1.2	3.5
Beef cattle slurry	2.3	1.2	2.7
Pig slurry	4.0	2.0	2.5

Using the average values identified in Table 2, the concentration of plant available nitrogen in slurry would be expected to increase from 50% to 75%post digestion (Table 4).

Table 4: *Anticipated readily plant available nitrogen (REN) in digested slurries (kg N/m^3).*

Manure	Total nitrogen	REN pre digestion	REN post digestion
Dairy cow slurry	3.0	1.50	2.25
Beef cattle slurry	2.3	1.15	1.73
Pig slurry	4.0	2.0	3.0

4.1.2. Mixed feedstock.

Where digesters are fed feedstocks comprising mixtures of different organic materials (co-digestion), the digestate will contain the total minerals of this mix. Knowledge of the nutrient content of feedstocks as well as the proportions fed at any one time is, therefore, useful when attempting to predict the fertiliser value of digestate. Table 5 shows the changes in nutrient content of the digestate from a digester over time as the feedstock was changed from a mixture including 57% of dairy slurry in 2004 to the present day when no dairy slurry is used. Data for dairy cow slurry are included for comparison. Note that NH_4-N accounts for over 75% of the total N (TN) in digestate compared with only 50% for undigested slurry.

Table 5: *Changes in nutrient content (kg/m^3) of digestate due to changes in feedstock.*

Year	Total nitrogen	Ammonium NH_4-N	NH_4-N as % total N	Phosphate P_2O_5	Potash K_2O	DM %
2004*	6.6	5.0	75.8	3.3	4.5	5.8
2008**	8.2	6.3	76.7	0.6	1.0	2.2
Dairy slurry	3.0	1.5	50.0	1.2	3.5	6.0

** Feedstock in 2004, 57% dairy cow slurry, 19% blood, 11% food waste, 8% chicken manure, 5% other non-farm waste.*

*** 2008 feedstock contains no dairy cow slurry.*

4.1.3. Influence of retention time on digestate composition.

As discussed later, for continuous stirred tank reactor (CSTR) digesters, feedstock is usually added regularly throughout each 24 hours and digestate is removed either via pump or gravity just as often. As a result the level of feedstock/digestate in the digester remains static. This continuous in and out process results in the inevitable removal of digestate in many different stages of digestion. Some will have been fully digested, having been in the digester for a considerable time and some will be completely undigested having only been added to the digester that same day. While some limited digestion, and biogas production, continues in digestate storage tanks, the rate will inevitably slow down as the temperature of the feedstock/digestate reduces. It follows that the average retention time of feedstock within the digester has significant impact on breakdown of organic matter and subsequently the availability of nutrients and the COD/BOD of the digestate.

Average retention time within a digester will also be influenced by the management of an individual plant. When calculating the economics of any particular biogas plants managers will inevitably take note of the fact that the rate of biogas production is not consistent throughout the time feedstock is being digested. Biogas production peaks early in the digestion process and then reduces as time progresses. For plants with plenty of digester capacity, and consequently potential for long feedstock retention times, maximising biogas yields per tonne of feedstock may be targeted. In complete contrast, AD plants with limited digester capacity may choose to shorten the average retention time of feedstock in order to make the most or the rapid rates of biogas production early within the process and, as result, maximise the rate of production per unit of digester capacity. The business plan of the managers of a particular AD facility will therefore significantly impact on the average retention time and ultimately digestate quality.

A further issue affecting the retention time of feedstock within a digester is the rate of gritting or silting up. Over time a digester will partially fill with settled-out inert solids such as grit. This inert solid uses up digester capacity and if feedstock feed rates is not altered to take into account this reduced overall digester capacity retention time will inevitably be reduced and rate of digestion compromised.

As outlined earlier digestion alters the physical properties of feedstock. The longer the digestion process the greater the alteration and vice versa. The longer the retention time the more available the nutrients contained within it will become. An understanding of the average retention time of feedstock in the digester will therefore impact on the fertiliser value of the digestate.

4.1.4. Post digestion losses of nutrients.

The digestion process increases the amounts of readily available nutrients and, whilst this presents a greater opportunity to use this nutrient effectively, it also increases the potential to lose nitrogen, either as ammonia gas during storage and spreading to land or via nitrate leaching, and phosphate via water and soil particle movement across fields.

The benefits of store covers have been proven to reduce considerably the loss of ammonia during storage (Hansen *et al.,* 2004) and for this reason most digestate stores now tend to be covered.

Table 6: *Monthly relative loss of nitrogen from covered and non-covered stores with four slurry types. (% initial N content) (Hansen et al., 2004).*

Storage period	**Store cover**	**Undigested slurry**	**Digested slurry**	**Separated undigested slurry**	**Separated digested slurry**
		% of initial nitrogen content lost per month			
9 Jan 2002 to 1 May 2002	Covered	0.8	0.9	-	-0.1
20 Mar 2003 to 6 May 2003	Uncovered	2.5	4.4	6.1	4.4

Preventing the loss of valuable and potentially polluting nutrients during and after spreading to land is more difficult. On the positive side, the lower DM nature of digestate compared to the original feedstock encourages very rapid infiltration into the soil. It is reasonable to assume that, in a similar manner to other slurries, rapid infiltration/incorporation into the soil will reduce the loss of ammonia gas. Furthermore, the use of trailing hose, shoe and injection equipment has also been shown to further reduce NH_3 losses to air during spreading of slurries and it can be assumed that this reduction in ammonia loss would also occur when these relatively new and novel techniques were used to spread digestate.

Table 7: *Ammonia loss following land application via trailing hoses to spring barley. Losses expressed as a % of NH_4-N applied.*

Year	**Undigested slurry**	**Digested slurry**	**Separated undigested slurry** (liquid fraction)	**Separated digested slurry** (liquid fraction)
	Losses as % of ammonium N applied			
2002	27	22	-	26
2003	46	34	23	18

Ammonia losses following application of slurry to land @ 30 m^3/ha via trailing hose to spring barley were measured by Danish researchers (Hansen *et al*, 2004). The lowest losses were from the digested and separated slurry, probably due to the quicker infiltration into the soil of the lower DM digestates and separated slurries. Nitrogen losses to ground water are more difficult to control. Unless application rate, and as a consequence nutrient supply, can be matched with crop uptake the potential of nutrients to be lost via leaching and surface run-off is significant. Digestate spreading should ideally take place in the spring when maximum uptake of nutrients is taking place. Pre drilling, spring application is best completed using injection equipment or by rapid incorporation into soil. Post drilling, dribble bar, trailing hose and trailing shoe machines should be used to place slurry on the surface of the soil or a growing crop.

Data from 11 trials with digestate and 15 trials with pig and cattle slurry (Sommer and Birkmose, 2007) clearly illustrate the potential to capitalise on the high available nitrogen levels in digestate via the use of trailing hose and injection equipment. (Figure 2). The Danish Advisory Service is now actively promoting the benefits of using high NH_4-N digestate as a crop fertiliser.

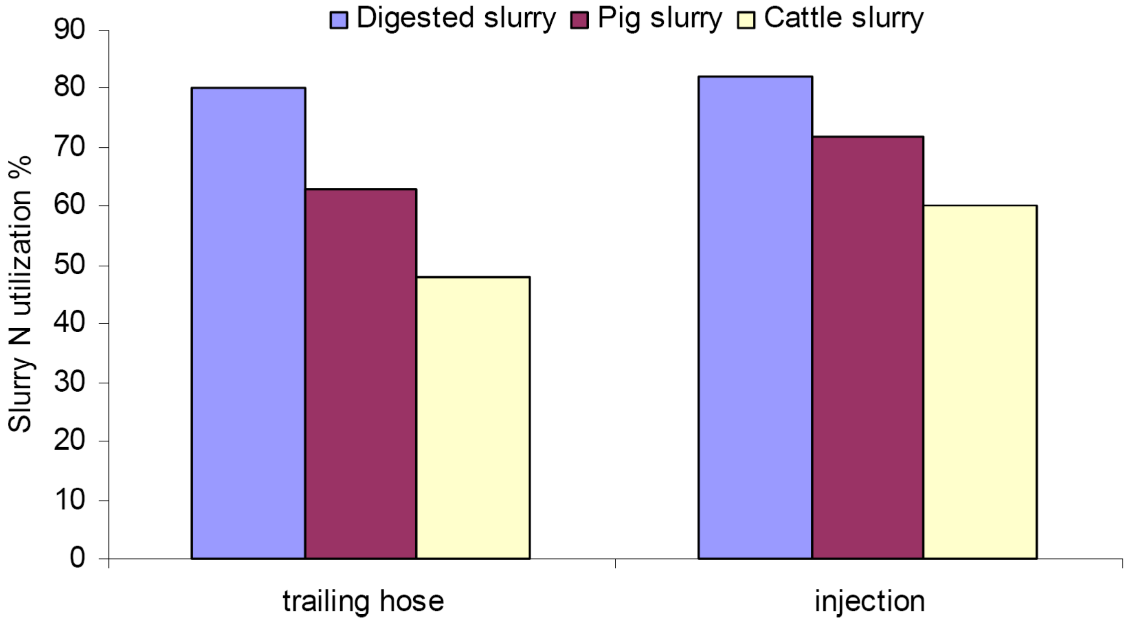

Figure 2: *Crop utilisation of nitrogen in digested slurry compared with pig and cattle slurry in field trials with the Danish Advisory Service.*

Dutch work (Schröder and Uenk, 2006) suggests that the high levels of available nitrogen in digested slurry allow it to be used more like inorganic fertiliser than is possible with undigested slurry. There appeared to a slightly larger residual effect of undigested slurry in the following years. (Figure 3).

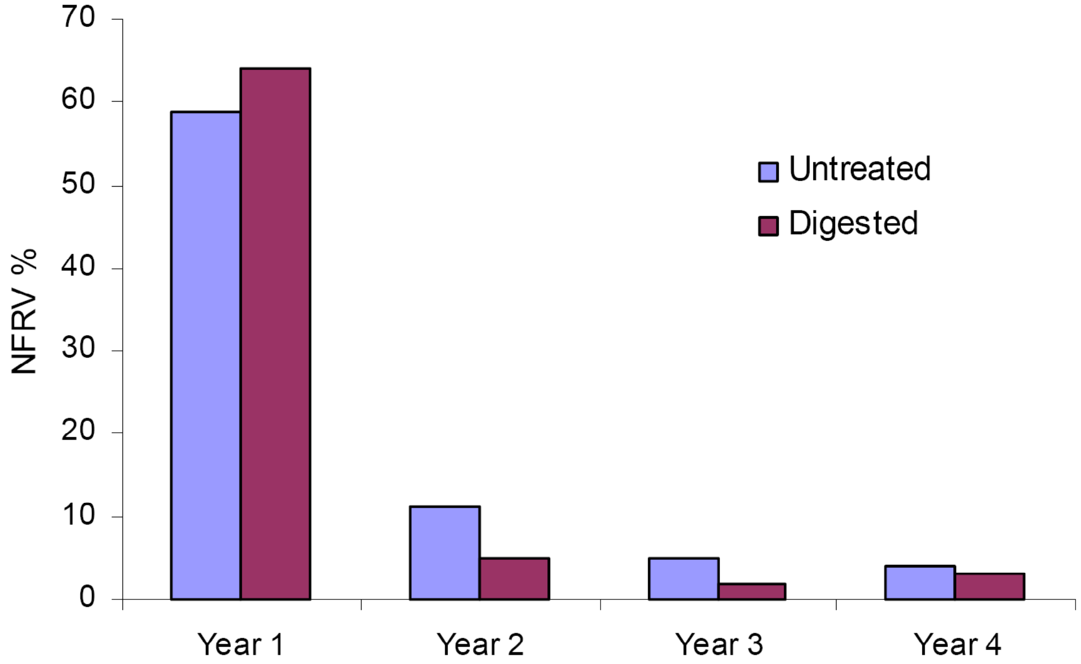

Figure 3: *Impact of anaerobic digestion on the nitrogen fertiliser replacement value (NFRV) of cattle slurry over four years following application.*

4.2. Reduced potential for water pollution.

The potential of organic effluents, slurries etc to pollute water is commonly described in terms of biological oxygen demand (BOD). This is a measure of the potential for removal of oxygen from water through the metabolism of micro-organisms. Chemical oxygen demand (COD), a measure of the oxygen consumed by oxidation of both microbial degradable and inert organic matter, is often used because it is a more rapid and more precise measure than BOD. The data in Table 2 indicate a consistent reduction in the COD for livestock slurries, reflecting the considerable degradation of organic matter within the digesters. The COD was typically reduced by 30% during digestion but again there was a large variation between digestates.

Anaerobic digestion has long been used as a treatment process for municipal sewage prior to discharging a treated, non-polluting final effluent to a watercourse. The problem with treatment of livestock slurries is that BOD and COD are much higher than for sewage. BOD, for example, is commonly 20,000 – 30,000 mg/l oxygen for slurry compared with about 400 mg/l for municipal sewage. Hence, the reductions achievable by anaerobic digestion is insufficient to meet standards required for discharge direct to water so spreading on land remains the only practical option.

4.3. Odour reduction.

It is established that anaerobic digestion of slurries reduces their characteristic odour though the breakdown of a range of the organic compounds responsible for offensiveness, including phenol, p-cresol, 4-ethylphenol, indole, skatol and fatty acids. (Velsen, 1981). The concentration, or strength, of odour in the air after spreading slurry has also been measured by olfactometry. Using an olfactometer, the threshold value of odour in air was measured after spreading undigested and digested pig slurry onto land. The threshold value is the number of dilutions with clean air after which 50% of a panel of people cannot distinguish the sample air from clean air. Some results are given illustrated in Figure 4. (Harreveld, 1981). This illustrates that the odour from digested slurry is not only lower than that from undigested initially, but is also detectable for a much shorter period after spreading – for about 16 hours compared with 3 days in these experiments.

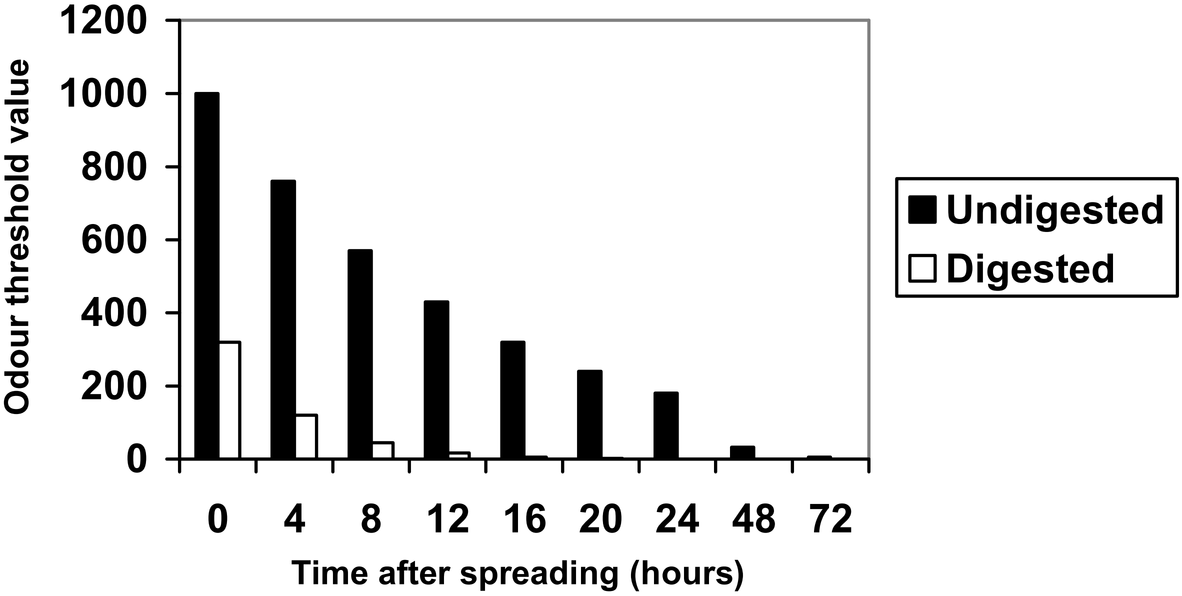

Figure 4: *Odour threshold values measured after spreading undigested or digested pig slurry.*

4.4. Greenhouse gas emissions.

The three main gases arising from human activities that are responsible for the greenhouse effect and subsequent climate change are CO_2, CH_4 and nitrous oxide (N_2O). In the UK, agriculture accounts for about 7% of the total greenhouse gas emissions. The main greenhouse gas is CO_2 accounting for 84% of UK emissions. Agriculture accounts for only 1% of CO_2, mainly from combustion of diesel fuels in tractors etc, but 36% and 67% of CH_4 and N_2O emissions, respectively. Compared to CO_2, CH_4 is 23 times more potent as a greenhouse gas than CO_2 and N_2O 296 times so these two gases are likely to have a disproportionately large impact on climate change.

About 85% of agricultural methane emissions are derived from rumen fermentation and are difficult to mitigate without changes to animal nutrition.

The remainder arise mainly from livestock manures. Agricultural N_2O emissions come mainly from nitrogen transformations in soils. Anaerobic digestion has the advantages of significantly saving on use of fossil fuels, and hence reducing national CO_2 emissions, but also avoids release of CH_4 from livestock manures to the environment. More considered use of the digestate as nitrogen fertiliser, particularly with regard to the rate and time of application to land, will help lower emissions of N_2O.

5. DIGESTER DESIGN AND OPERATION.

There is a wide range of digester designs, the choice of design being dependent on the characteristics of the organic material to be digested (feedstock), the reasons for the installation, climate and economics. Many types of digester are designed primarily as a treatment process for various dilute effluents and are not suitable for livestock slurries and other agricultural digester feedstocks because of their relatively high solids content (Table 8).

Table 8: *Suitable feedstock solids content for different types of digester (Rozzi and Passino, 1985).*

Type of digester	Feedstock solids content kg TS/m^3
Continuous stirred tank reactor (CSTR)	25 - 100
Plug flow	30 - 120
Anaerobic contact	0.5 - 20
Upflow anaerobic blanket	0 - 2
Packed bed	0 - 5
Fluidised bed	0 - 5
Batch	50 - 200

Long, once through, horizontally inclined digesters, termed plug flow digesters, are capable of digesting feedstocks with high solids contents. Although relatively inexpensive, such digesters are often associated with operational problems, including formation of scums and crusts that interfere with the breakdown of solids and with gas release when used for agricultural feedstocks. Batch digesters are also suitable for use on farms, can be relatively easy and cheap to construct but also suffer from operational disadvantages. CSTR type digesters are the most practical design for medium to large scale installations in temperate regions.

5.1. Continuous stirred tank reactors (CSTR).

Although CSTR units vary greatly in detailed design, they have a number of components in common. A typical plant is represented in Figure 5.

The size of the digester itself is determined from knowledge of the volume of material, or feedstock, to be digested and the required retention time. This describes the average time the feedstock stays in the digester. For a 20-day retention time, for example, a volume of fresh feedstock equivalent to a twentieth of the digester volume would be added whilst the same volume of digestate was removed. It follows, therefore, that the longer the retention time, the larger the digester required per unit volume of feedstock to be digested.

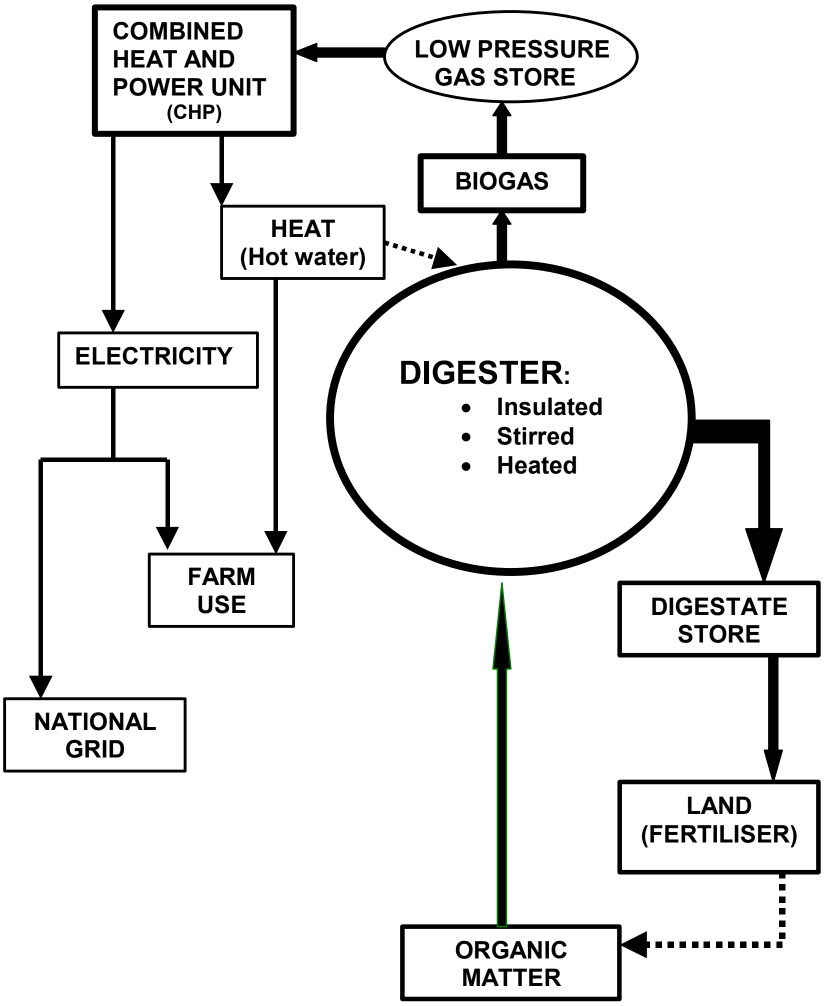

Figure 5. *Representation of continuous stirred tank reactor (CSTR) type of anaerobic digestion plant for operation on farms.*

It may be an above- or below-ground tank, built most commonly of concrete or vitreous enamelled steel sheets. It is insulated to reduce heat loss and often includes heat exchangers to raise the temperature of the feedstock to the required operating temperature. This is usually done by using some of the hot water produced from burning the biogas in a boiler, or from a CHP unit. It is important to keep the heat transfer surface below about 50°C so that the bacteria are not killed.

Provision for mixing the contents is needed to prevent the formation of a floating layer or sediment, to ensure that the bacteria come into contact with fresh feedstock and to ensure an even and optimum temperature throughout the tank.

Equipment, for example a positive displacement pump, is required to feed fresh feedstock into the digester and for digested material (digestate) to flow or be pumped out and to maintain a constant level in the digester.

Some form of storage is needed for biogas, albeit short term if the gas is continually used to run an engine or CHP unit, to even out fluctuations in daily production of biogas and the demand for it. Storage can take the form of a flexible lid on the digester, a gasometer type gasholder or a separate low pressure storage vessel or bag.

A storage tank for feedstock is usually included, again with a mixing device, to ensure material fed into the digester has as constant a consistency as feasible. This is especially important where feedstocks comprise more than one type of organic material e.g. livestock slurry together with industrial or processing wastes, crops etc. Choppers for green plant material are essential when these or crop wastes form part of the feedstock. Similarly, storage is provided for digestate so that there is control over when and where it is spread on land and used as a fertiliser.

A biogas boiler or CHP unit is required to supply heat for the digester and to utilise the biogas as outlined above.

5.2. Operating conditions.

Digester operating conditions are important to both the efficiency and economics of AD plants. Feedstock, retention time and temperature are important to optimising biogas production and ensuring adequate stabilsation of organic matter.

5.2.1. Feedstock.

Organic materials subject to digestion, including livestock manures, food and industrial wastes and crops, are complex in composition and contain a wide range of constituents which break down at different rates and yield different amounts of biogas. For example, 1 kg glucose if broken down completely would yield no more than 0.75 m^3 of gas whereas 1 kg of a fatty acid, such as palmitic, would yield about 1.4 m^3. It is, therefore, difficult to predict gas yield without digesting representative samples in a laboratory digester. Such prediction is made even more difficult when mixtures of feedstocks from different sources are digested. Gas yields are commonly expressed as volume/unit weight of volatile solids (VS). This is because VS is easy to measure, being the proportion lost on combustion, and is a rough measure of the amount of material that is biodegradable.

Some approximate yields of biogas from a range of potential feedstocks for a farm digester are given in Table 9, overleaf.

Table 9. *Some comparative biogas yields from various digester feedstocks (from KTBL, 2007).*

Feedstock	**Biogas** l/kg VS	**Biogas** m^3/t fresh	**% CH_4 in biogas** %
Pig slurry (6% DM)	400	19	60
Cattle slurry (8%)	280	18	55
Poultry manure (46% DM)	500	169	65
Maize silage (32% DM)	580	178	54
Sugar beet	700	148	51
Grass - fresh	310	54	70
Grass silage (25% DM)	560	123	54
Wheat straw	252	208	55
Milk	750	35	53
Vegetable residues	350		
Municipal sewage	450		

VS = volatile solids.

As is to be expected, biogas and methane yields and are generally greater from pig than from cattle slurries because the latter will have undergone partial anaerobic digestion in the rumen. Research with farmscale digesters has shown that mechanically separating cow slurry and using the liquid fraction as the digester feedstock can increase relative biogas yields (Pain *et al.,* 1984) as illustrated in Table 10.

Table 10: *Biogas yields from mechanically separated and unseparated cow slurry.*

Retention time days	**Separated slurry** (liquid) 4.4% DM		**Unseparated slurry** 7.2% DM	
	l/kg TS	l/kg VS	l/kg TS	l/kg VS
20	280	340	204	255
15	251	305	ND	ND

TS = total solids, VS = volatile solids.

Using the data in Table 10, it can be estimated that 1 t of unseparated slurry would yield 14.6 m^3 of biogas. Separation could be expected to remove about 18% by weight of the slurry as a solid fraction (Pain *et al* 1978), leaving 0.82 t of liquid for digestion. Hence, at 20 day retention time in the digester, gross gas yield would be reduced to 10.1 m^3. However, since gas yields for separated slurry were only slightly lower at the shorter 15 day retention time, it would be possible to reduce the size, and hence cost, of the digester. Separation also has the advantages of yielding a liquid that is easier to pump and mix in the digester, with less risk of blockages and solids settlement and improved fertiliser value.

Yields from silages are high because they contain relatively large quantities of volatile fatty acids that are precursors to methane production. Hence there is much interest in using these materials as digester feedstocks, perhaps mixed with livestock slurries (co-digestion), when biogas production is the main objective.

The key factors influencing biogas yields from digestion of crops are species, variety, time of harvesting, mode of conservation and pre-treatment of biomass. Optimum composition of feedstock for anaerobic digestion will be different from that required for livestock feed because, for example, cellulose break down is about 80% in the latter compared with 40 – 60% in the former.

Using laboratory-scale batch digesters, Amon *et al.* (2007a) compared methane yields from a wide range of crops including maize, winter wheat, triticale, winter rye, sunflower and grass. They concluded that the highest methane yields were obtained from maize, followed by small grain cereals and sunflowers. For maize, varieties with high biomass yields harvested in the vegetative stage milk to wax ripeness gave the highest methane yields per hectare (Amon *et al.,* 2007b) as illustrated in Figure 6. Similarly, the best results were obtained from digestion of the whole plants.

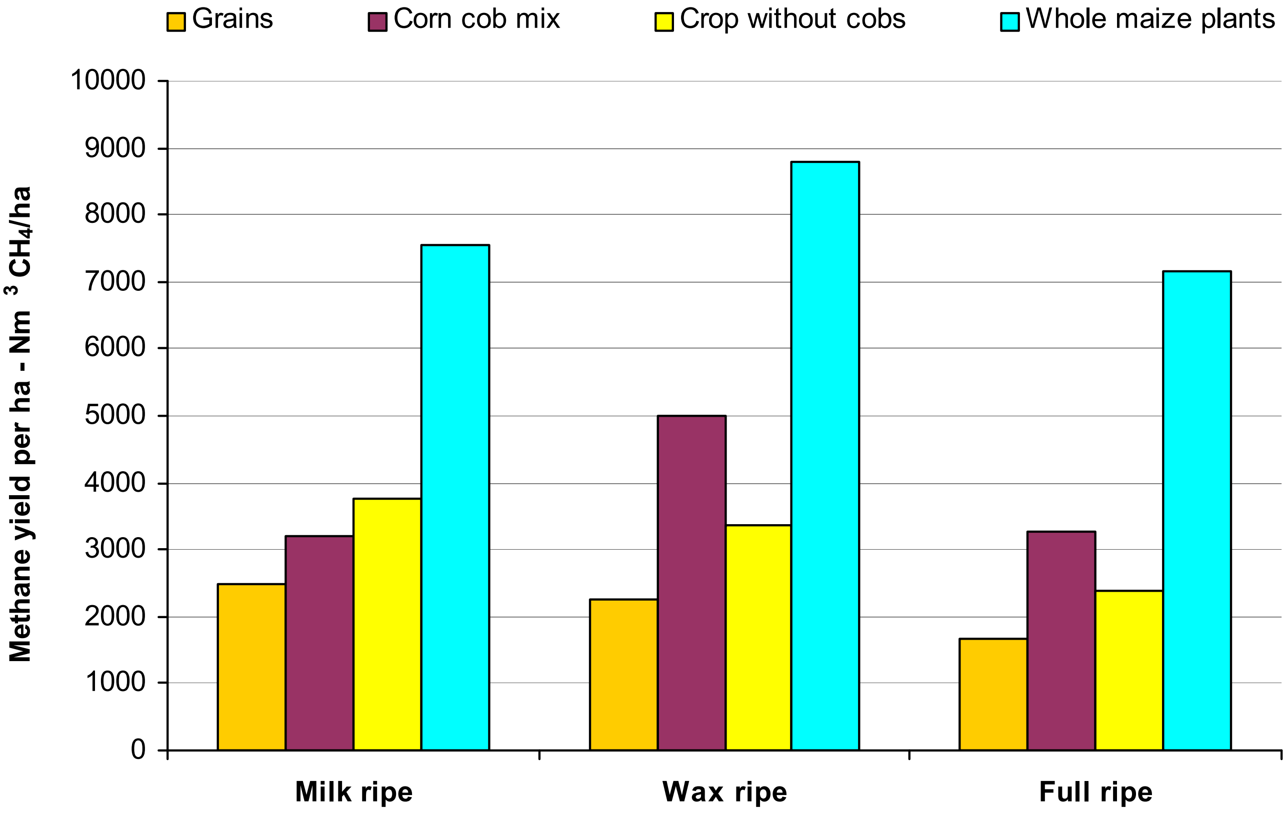

Figure 6: *Methane yields from anaerobic digestion of maize at different stages of ripeness. (Amon et al., 2007b).*

For cereals, fast growing varieties harvested as for whole-crop silage gave the highest methane yields. Variety was also important because methane production appears related to the crop oil composition.

It is important to establish and maintain the organic loading rate for all feedstocks. This is the amount of organic matter, usually expresses as kg of VS, fed per m^3 of digester working volume each day. Although increasing organic loading rate will, up to a point, increase gas yield, excess can lead to overload and subsequent inhibition of methanogenic bacteria or toxicity.

5.2.2. Retention time.

Retention time is the average time the feedstock remains in the digester. For CSTR digesters it is defined as the digester working volume divided by the mean volume flowing in, and hence also out, of the digester. Thus for a 20 day retention time, for example, a volume equal to a twentieth of the digester working volume will flow in and out of the digester each day. The optimum retention time is dependent on the feedstock to be digested – the lower the degradation rate of the feedstock, the longer the retention time. The degradation rate of the main organic compounds increases in the following order: cellulose –> hemicellulose –> protein –> fat –> carbohydrate. Feedstocks containing higher concentrations of fats, such as pig slurry, therefore, require lower retention times than those, such as cattle slurry, that contain more cellulose and hemicellulose because of the nature of the diet of the animals. Although gas yield increases with increased retention time, the relationship is not linear but similar to that illustrated in Figure 7.

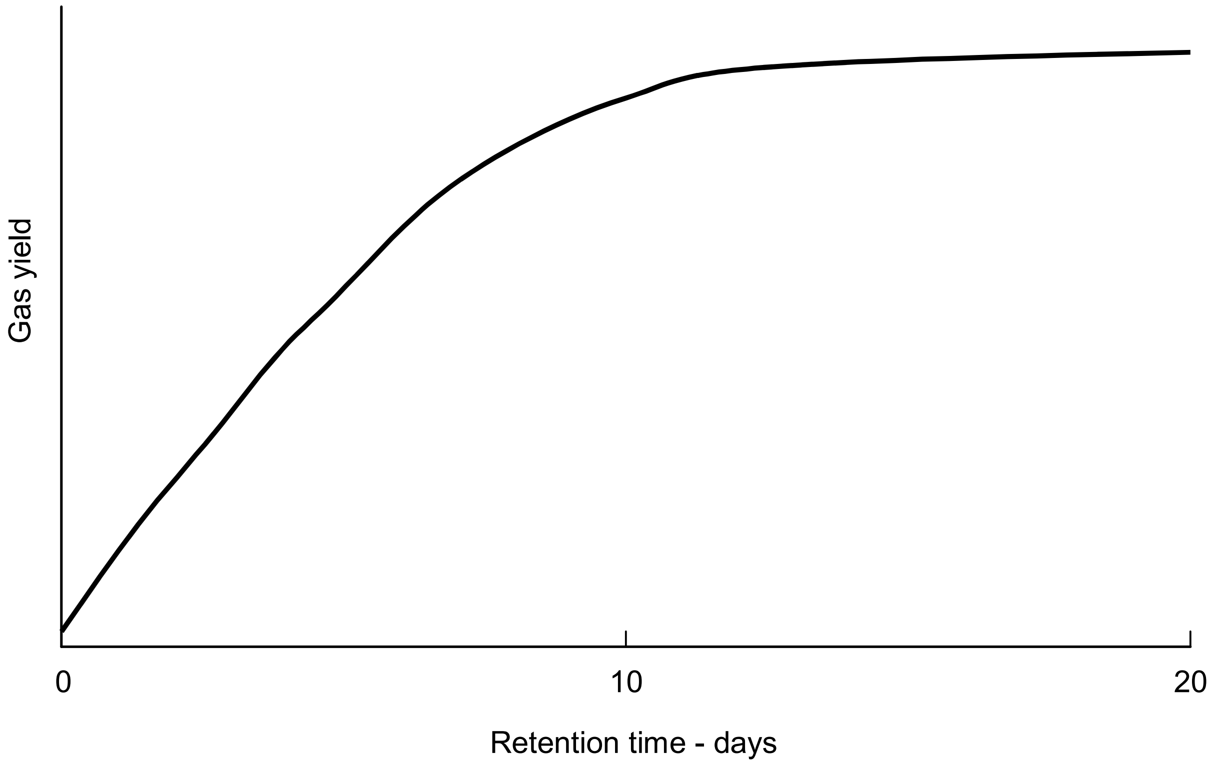

Figure 7. *Typical relationship between biogas yield and retention time.*

On the steep part of the curve increase in retention time results in a large increase in gas yield whilst at longer retention times the increase is much less. Increased retention time for the same volume of feedstock means a larger digester and higher cost. Hence, it is important to determine the optimum, economic retention time for the specific digester feedstock. For pig and cattle slurry, this is about 10 and 20 days, respectively.

5.2.3. Operating temperature.

As discussed in Section 2.1, farm digesters in temperate regions are usually operated in the mesophilic temperature range (20 – 40°C). Thermophilic digestion (40 – 60°C) can give higher methane yields and more effective pathogen inactivation (Dohanyos, 2001) although the process tends to be less stable. The main disadvantage for farm digesters is that a disproportionately large percentage of the energy produced is required to heat the digester. In warmer parts of Europe, simple, low cost digesters operating in the psychrophilic temperature range (10 – 20°C) have been built (Burton and Turner, 2003), for example by fitting a floating cover to collect biogas from an existing slurry lagoon. However, biogas yields are relatively low and variable and long retention times are needed.

Within the mesophilic temperature range, gas yields increase with increasing temperature as illustrated in Figure 8 (Hawkes, 1985). This indicates that the optimum operating temperature for gas yield is about 35°C. However, since the major heating requirement in a digester is to raise the temperature of the feedstock, slurry at ambient temperature for example, it may sometimes be more economic to operate the digester at a slightly lower temperature. Hawkes (1984), for example, pointed out that with separated cow slurry the gas yield at 25°C was 87% of that at 35°C with a 15 – 20 day retention time, so making the lower operating temperature more economic.

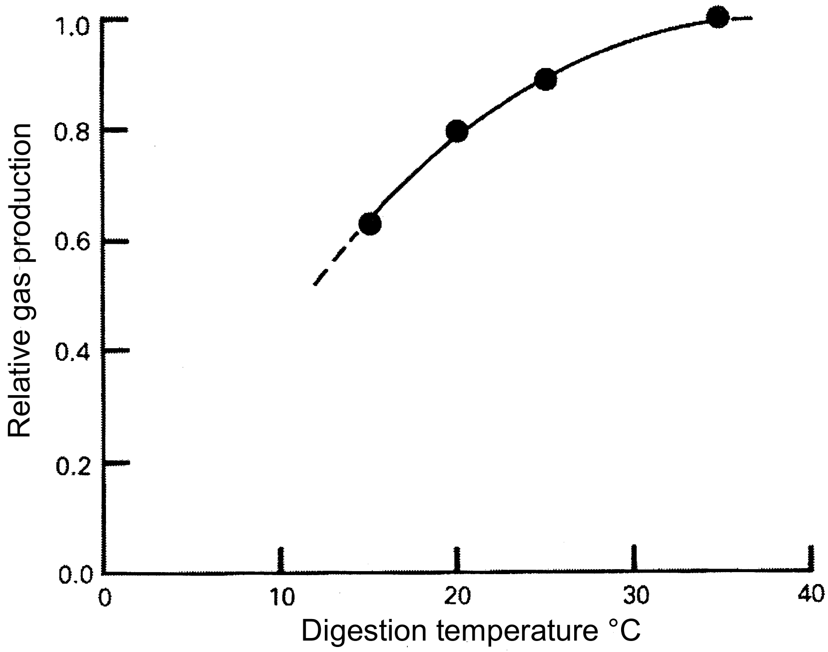

Figure 8. *Relationship between biogas yield and operating temperature for mesophilic digestion.*

5.4. Batch digesters.

As the name implies, batch digesters are operated on a discontinuous basis and can be used for thick slurries to semi-solids and solid wastes. They are relatively easy and cheap to build and are the most common type found throughout parts of Asia.

On farms, fresh feedstock is fed into the digester vessel together with an inoculum of digested material from a previous batch to provide a suitable population of micro-organisms. The digester may be heated for a couple of days and anaerobic digestion then proceeds for a three to four week period. Depending on the feedstock, gas production increases to reach a maximum after 10 – 14 days then reaches a steady state of about half the maximum. (Burton and Turner, 2003). The digester vessel is eventually emptied and refilled with fresh feedstock. The main disadvantage is the uneven gas production, although this can be overcome to some extent by operating several batch digesters together and filling at different times or using a semi-batch system. Here fresh feedstock e.g. livestock manure, is added as available and digested material removed at intervals. A further disadvantage of batch digesters is that loading and unloading facilities can be expensive and troublesome to construct and operate.

5.5. Anaerobic lagoons.

Unlike anaerobic digester installations on farms, biogas production is not the main objective of anaerobic lagoons. Some do have covers to collect the gas but yields are low. They do offer a means of long term storage and organic matter reduction for slurries and waste waters etc whilst retaining nitrogen and phosphate so that the end product is of value as fertiliser, for example through irrigation on to land. Since anaerobic lagoons are not heated, they are only suitable as a treatment process in warmer climates.

6. ECONOMICS AND GOVERNMENT INCENTIVES - UK.

An economic study of an early farm digester using cow slurry as feedstock (Oliver *et al.,* 1986), indicated that when financial returns were based solely on energy production, an AD plant for 200 cows could incur a loss of £50 p.a. Since then the economics have become much more attractive due to a number of changes. These include the use of combined heat and power unit for utilising the biogas, financial incentives for renewable energy supplies and the use of feedstocks comprising mixtures of slurry with other highly degradable sources of organic matter to increase gas yields.

The balance sheet for digestion will vary greatly from installation to installation and there is a range if issues that will impact on the economic calculation. Like any other business, the economics of biogas production can be split into the annual trading incomes/expenses and the capital costs associated with the initial and ongoing development. In this section the key trading income and expenses issues are discussed together with the capital costs and government incentives for AD.

6.1. Trading income.

There are four main financial outputs arising from an AD plant:

- Renewable Obligation Certificates.
- Electricity.
- Heat.
- Digestate.

6.1.1. Renewables Obligation Scheme.

The sale of Renewable Obligation Certificates (ROCs) under this scheme is likely to represent the largest single income stream for farmers investing in medium to large-scale AD plant.

This scheme places an obligation on electricity suppliers to source an increasing amount of their supplies from renewable sources over time. Implemented by the Department of Trade and Industry, the Scottish Executive and Department of Enterprise, Trade and Investment in Northern Ireland, the scheme is the main mechanism by which renewable electricity production is being supported and encouraged. It is administered by OFGEM that issues Renewable Obligation Certificates for each unit (kWh) of electricity produced from renewable electricity generation.

Table 11: *The level of renewable obligation on electricity supply companies in 2002/03 et seq.*

Year	Annual Renewables Obligation (%)
2002/03	3.0
2003/04	4.3
2004/05	4.9
2005/06	5.5
2006/07	6.7
2007/08	7.9
2008/09	9.1
2009/10	9.7
2010/11	10.4
	+1% per year until 2015

The support by electricity companies for renewable supplies will be increased each year as shown in Table 11. For each MWh generated by renewable means, such as AD, a Renewables Obligation Certificate is allocated. These certificates need to be produced by a supplier to show that they have met their obligation and financial penalties are applied if this is not done. Income raised from such penalties is reallocated to companies who have submitted ROCs, with the result that non-compliers are in effect doubly penalised.

The consultation document, released in May 2007, setting out the government proposals under the 2007 Energy White paper, listed AD as one of the emerging technologies which it hopes to encourage via the banding of ROC allocations. Within the consultation it was proposed that each unit (kWh) of electricity produced from AD would generate 2 ROCs, in effect doubling the ROC allocation and financial incentive to produce electricity in this way.

The nature of the financial arrangements for the scheme means that predicting the ongoing value financial of ROCs is difficult. If suppliers, via generators, meet their obligation then ROC values will be very low. If, as is currently the case, suppliers cannot meet their obligation the purchase value of ROCs will be high.

6.1.2. Sale of electricity.

Income from electricity sales either comes as a direct payment for that sold into the national or a locally set up grid, or as a result of savings made on core business electricity requirements as a result of self supply. Whichever option is chosen, the electricity generated earns ROCs that can be sold to suppliers with renewable obligations.

Using electricity produced from AD to offset that currently purchased from the national grid offers considerable and particularly good savings. The benefit results from the difference between the retail price currently paid for electricity purchased from the grid of £0.12/kWh, and the wholesale price of £0.06-0.08/kWh received for power sold into the grid. The difference between the two is significant and is one reason why high users of electricity tend to be interested in renewable energy production on site. The same difference in retail and wholesale prices makes the setting up of a local electricity 'private wire' grid, through which electricity can be sold to local customers, attractive.

6.1.3. Surplus heat.

As outline earlier, CHP units burn biogas to run a generator, which in turn produces electricity. Alongside this electricity production the unit produces a considerable amount of heat, primarily from the engine cooling, in the form of hot water. In the region of 50% of the potential energy in a feedstock is converted to heat in this way. This hot water has a theoretical financial value although in many situations realising this value in financial terms is difficult due to the rural location of most farm AD plants and the subsequent lack of local demand. Since it is possible to pipe hot water, or in fact biogas, siting a plant alongside another user, such as a greenhouse or market, offer the best opportunities.

6.1.4. Digestate.

Although the total mineral content of the feedstock is unchanged by digestion, the crop availability of these minerals is increased as described in 4.1 above. For example, the proportion of total nitrogen that is available for plant uptake in cattle slurry is about 50% increasing to around 75% following digestion. Hence, the potential financial value as an agricultural fertiliser and soil conditioner is increased when compared to undigested slurry. Although not as flexible as manufactured fertiliser, when nutrients are applied at rates and times matched to the nutrient requirements of crops, the financial value of digestate can be directly compared with the cost of using manufactured fertilisers. Recent significant increases in fertiliser prices have further increased the value of digesate. Although the nutrient content of feedstock can be used to predict the nutrient content of digestate, this approach is not a replacement for regular analysis of digestate.

6.2. Trading expenses.

The annual trading expenses associated with running a digester can be split into variable and overhead costs. Variable costs tend to rise in direct proportion to the output of the digester, the best example being the purchase of feedstock. The bigger the digester and the shorter the retention time, the more feedstock is needed. Overhead costs tend to be fixed and, in general, remain the same regardless of digester output, with perhaps the most obvious example being labour costs.

6.2.1. Variable costs.

Feedstock has the potential to be by far the biggest annual expense in any AD business. While potentially being the largest cost, AD feedstock can also be an important source of additional income if gate fees can be commanded for non-agricultural waste. On farm, organic manures, such as slurry are in effect free, but farm grown energy crops have a real cost. If purchased, there is the payment made to the independent grower or, if home grown, there are crop production costs plus an allowance for the opportunity cost of the alternative use of that land.

Consideration of the unit cost, or revenue, per tonne of feedstock should take into account of the differing biogas yields per unit of feedstock. For example although free of any charge, slurry has a comparably low gas yield compared to energy crops and off-farm food waste.

6.2.2. Overhead costs.

The overhead or fixed costs of running an AD plant are relatively low. Water and particularly electricity and heat requirements are minimal. Experience suggests that the relatively straightforward nature of the digester mechanics and the generally high build quality result in low maintenance and repair costs. The expense and inconvenience associated with shutting down, emptying and refilling a digester to allow repair/replacement of machinery mean that good build standards and ongoing maintenance are very important.

Labour requirements, and as a consequence costs, will vary depending on the level of plant automation. Key tasks are the addition of feedstock to the digester and the logistics of disposing of the digestate. Both elements can be mechanised to reduce physical labour input. Running an AD plant alongside a working farm offers real opportunities to improve the efficiency of farm labour use. Labour input is not directly linked to digester capacity making it a true fixed cost. As such digester capacity can have a big impact on the labour cost per unit of biogas. The bigger the digester the lower the unit cost of labour and vice versa.

6.3. Capital expenditure.

The capital cost of an AD plant is considerable and is often the biggest barrier to on-farm investment. Development costs include fees associated with the planning, building and commissioning of an AD plant as well as the actual building cost. Whilst these costs are inextricably linked to size/capacity of plant, the fact that all AD facilities require the same basic infrastructure means that true economics of scale can be achieved the bigger the plant becomes. In addition to size issues, the proposed feedstock sources can also impact on the capital cost. Farm waste or energy crop fed digesters require less equipment compared to those taking food and animal by product waste where pasteurisation and other specialist digester feeding equipment will be needed.

Approximate capital development costs are quoted at between £2,500 and £6,000 per KW of digester capacity.

6.3.1. Grid connection.

The capital cost, complication and time-consuming issues associated with connection to the UK national grid are considerable. Unlike some EU countries (e.g. Germany) connection to the grid is not guaranteed and considerable time and effort is needed to secure planning and other approvals. Capital cost of connection varies, being cheaper if lines currently cross the land and the distance between connection point and plant is minimal. Published costs indicate a range of £20,000 - £60,000 for connection and £20,000 - £30,000 per km (Burgess Salmon, 2008)

6.3.2. Capital funding.

Like any business venture, investment in an AD plant should only be made on the basis that trading income will cover all the costs associated with the project. In the case of AD, sales of electricity, ROCs, heat and digestate and possible gate fees for non-farm waste will all play their part in achieving this self-sufficient position. In addition, some capital grant and other incentives are on offer to further encourage investment. These include:

- Private Equity Finance:

  Private investors with or without the help of their banks are likely to be the main investors in on farm AD technology. Investors will seek strong and professionally run projects with the banks in particular looking for reasonable security to cover their commitment if things were to not go as planned.

- Commercial Private Equity Funds:

  Venture capitalists and investment funds are also likely to offer funding for well run projects. Other potential funders would be the utility companies themselves who in some cases have capital and are keen to invest if they can see the electricity produced can be used to meet the renewable obligation.

- Rural Development Agency Funding:

  Capital Grant funding should in the near future become available via the Rural Development Agencies who have been allocated considerable capital to support rural development including that of regional renewable energy production and the improved use of nutrients produced from the livestock sector. AD appears to fit very well within both these remits and it is anticipated that capital grants will be available for well thought-out AD plants in 2009. The capital for the RDA fund is the result of the reallocation of monies from direct agricultural support into more general rural development support.

- Enhanced Capital Allowances (ECA):

  To further encourage investment in energy saving technology, the UK government allows companies to offset up to 100% of the capital cost of such investment against business profit in the year of investment. The 100% allowance replaces the 25% per year standard allowance. The ECA will not reduce the level of tax paid in total paid but will help cashflow in the early years of a project by in effect delaying tax payments.

- Bio-energy Capital Grants Scheme:

  The Bio-energy Capital Grant scheme aims to support the installation of biomass fuelled CHP units in England. The scheme is run in rounds, the fifth of which is due take place in late 2008. This fifth and subsequent rounds during 2009 and 2010 will provide capital support for CHP unit installation including those associated with AD plants in commercial and community locations. Farmers are specifically named as potential recipients in the summary introduction to the scheme. Support of up to 40% of the financial difference between installing the biomass CHP unit compared to a standard fossil fuel alternative is offered.

6.4. Current economics of anaerobic digestion.

The current economics of UK anaerobic digestion plants have been studied recently (Kőttner *et al.,* 2008) using data from 7 farmer projects and one community-based project in Cornwall.

This very detailed and thorough project considered the capital and trading economics of the plants and made the following key conclusions:

- The size of a biogas plant has real and considerable implications on its profitability. Plants that are too small will not generate sufficient profit to dilute the fixed costs of the installation.
- The ROC and potential double ROC value is the major element of the trading income.
- Regular supply of feedstock, particularly livestock manure, is important to maximise the annual energy production of a plant and in turn dilute the plant fixed costs.

- Cost of feedstock be it in gate fees received, or purchase price paid, can have a massive impact on variable costs and ultimately profit of a plant.
- Regulations associated with certain waste feedstocks and digestate can be very expensive especially for low output plants.
- The use, and subsequent income earned, of surplus heat can significantly increase annual income and as a result profitability.
- Minimising capital development costs has the potential to cut annual depreciation charges with the result that profits are higher and overall returns greater.
- Grant funding, particularly for the smaller plants, is important to minimise initial capital requirements and ultimately capital depreciation costs.

While some have criticised the Cornish work, primarily because of its choice and the size of the farming scenarios, the project very much confirms the importance of understanding fully the financial implications of AD prior to investment. The project also highlights the need for careful siting of any proposed AD plant. A well thought-out location may ease issues associated with feedstock and digestate disposal thereby improving the potential sustainability of a particular project.

6.5. Ongoing developments.

The development of on farm AD has both logistics, e.g. planning, regulation and financial barriers to overcome. Key to overcoming these issues is the requirement for a major increase in the awareness of the technology amongst authorities and financiers. In order to address this need, the UK government launched the Anaerobic Digestion Demonstration Programme in July 2008.

The £10 million programme will fund between 3 and 6 projects aiming to improve the awareness and technical potential of biogas in the UK. The main themes of the programme are:

- Maximising the cost-effective production of biogas;
- Maximising the environmental benefits from the use of anaerobic digestion and its products;
- Maximising the potential of anaerobic digestion to reduce the carbon footprint of the food supply chain;
- Maximising the opportunity for the injection of bio-methane into the gas grid; and
- Maximising the potential of anaerobic digestion to reduce the carbon footprint of the water treatment infrastructure.

7. REGULATORY CONSIDERATIONS IN THE UK.

There is a wide range of regulatory issues that impact on the construction and operation of an AD plant in the UK. These include:

- Planning consent.
- Environmental Permitting Regulations.
- Animal By-Product Regulations.
- Nitrate Vulnerable Zones.
- Climate Change Levy and Climate Change Levy Exemption Certificates.
- Waste Resources Action Programme.

Although it is beyond the remit of this paper to discuss regulation fully, the main points that must be taken into account are outlined below.

7.1. Planning consent.

The development of any on-farm AD plant will require full planning permission primarily because it is seen as a waste treatment facility rather than an agricultural operation. Local authorities tend to view AD as new technology and as such require full detailed justification for the particular location of an AD plant. Key issues to consider when developing a planning application/justification include the impact of the proposed digester on traffic movements, air emissions, dust and odour, noise, water resources and visual intrusion.

7.2. Environmental Permitting Regulations (EP).

Of particular importance for an on-farm AD plant is the environmental legislation relating to the feedstock used and digestate produced by the digester. Environmental Permitting regulations combine what were the Waste Management Licensing (WML) and Pollution Prevention and Control (PPC) regulations and came into effect on the 6th April 2008. AD is only allowed on sites with an Environmental Permit (EP) or registered exemption (see Table 12, overleaf). If feedstock material contains food waste then the plant may also be subject to the Animal By-Products Regulations. Plants using slurry and other livestock manures as feedstock should qualify for exemptions from the Environmental Permitting requirements.

Application of digestate to agricultural land for agricultural benefit is exempt from EP regulations. This annual exemption has various spreading restrictions (proximity to watercourses, wells and abstraction boreholes etc) attached to it with the aim of minimising the risk of water pollution.

Where the intention is to spread up to 50 t/ha/yr of slurry, other manure or energy crops-based digestate for agricultural benefit (e.g. as fertiliser or soil conditioner), application for exemptions is easy and free. To spread between 50 and 250 t/ha/yr of slurry, other manure or energy crop derived digestate, application is still free but proof of the agricultural benefit will be needed. Similar agricultural benefit proof will be needed and a registration fee charged for spreading digestate containing non-agricultural waste.

Table 12: *Environmental permitting requirements for on farm AD plants.*

Activity	Exemption or permit needed
Anaerobic digestion of up to 1000 m^3 of waste: • At place of production. • Where digestate is to be used. • At a place occupied by the waste producer or digestate user. Storage of above waste to be digested.	Registered non-chargeable exemption from the EP Regulations.
Burning biogas in appliance with net rated input of 0.4 megawatts.	Registered non-chargeable exemption from EP Regulations.
Any other waste recovery activity including burning of biogas in an appliance with a thermal input above 0.4 megawatts.	Environmental Permit.

7.3. Duty of Care.

The Duty of Care controls apply to the producer, transporters and user of digestate. Duty of Care controls require waste to be treated responsibly and only transported or given to registered carrier or site with a written description or waste transfer note.

7.4. Animal By-Product Regulations (ABPR).

Digesters taking animal by-products, including waste feed containing animal parts, need to meet the ABPR regulations enforced by Local Authorities.

7.5. Renewable Energy Guarantee of Origin (REGO).

REGO electronic certificates are issued, per kWh, to registered generators of renewable energy to act as evidence of the renewable source of the power. The scheme is administered in the UK by OFGEM.

7.6. Nitrate Vulnerable Zones.

January 1st 2009 sees the introduction of the latest Nitrate Action programme. Under this programme areas of the UK are designated as Nitrate Vulnerable Zones (NVZs). Farmers within these NVZs have to follow a wide-ranging complex set of rules that impact on AD plants in relation to the use of digestate.

While the majority of the NVZ rules apply to the use of digestate in the same way as other organic manure, the following specific issues are of note:

- <u>Whole farm livestock manure N loading:</u>

  This, in effect, a restriction on stocking rate, applies only to livestock manure. Thus, the nitrogen contained within digestate derived from farm livestock manure will need to be taken into account when calculating the permissable farm livestock manure loading. The nitrogen contained in digestate derived from non-livestock manure feedstock will not.

- Field organic manure limit:

  This field limit within NVZs is set at 250 kg/ha N per year from organic manure. Nitrogen supplied from digestate must be taken into account when assessing compliance with this regulation.

- Closed periods for organic manures:

  Liquid digestate with high readily available nitrogen content of over 30% will be subject to the closed spreading periods in the autumn/winter.

- Field justification of nitrogen fertiliser:

  Available nitrogen supplied via digestate must be taken into account when calculating the need for additional inorganic nitrogen.

Digestates derived from non-farm, high nitrogen content feedstocks contain much higher amounts of nitrogen than most livestock slurries. This may well present problems in complying with permissible nitrogen applications to land and also in ensuring that nitrogen crop requirements are not exceeded.

7.7. Climate Change Levy (CCL).

In addition to the current regulations, the Climate Change Levy scheme and future Water Resources Action Programme (WRAP) protocol will inevitably have an impact on farm AD development.

Administered by OFGEM, the CCL is a levy charged to commercial and public sector organisations per unit of electricity they use. The aim of the CCL scheme is to encourage electricity users to improve energy efficiency and cut emissions of greenhouse gases. As a means of encouraging the use of renewable electricity, such as that produced by AD, companies using renewable electricity are exempt from paying the CCL via the Climate Change Levy Exemption Scheme (LECS).

7.8. Waste Resources Action Programme (WRAP) Quality Protocol.

The UK Environment Agency is currently working with the Waste Resources Action Programme (WRAP) to develop a Quality Protocol for digestate. At present digestate produced from non farm produced feedstock is treated as a waste hence spreading to land is subject to the waste regulations and is expensive and complicated.

The proposed Quality Protocol, which went out for consultation in the spring of 2008, will, if adopted, have the effect of regarding digestate as a product rather than a waste. Digestate could then be used, or indeed sold, as a fertiliser or soil conditioner with no waste disposal legislation requirements.

8. CASE STUDIES.

In the final section of this paper, we briefly outline two case studies of AD plants. The first, based on a dairy farm, uses livestock manures and specially grown energy crops to produce electricity to feed into the national grid. The second is a large centralised anaerobic digester (CAD) plant where, although initially based on digestion of livestock slurry from nearby farms, much of the income is based on receipt of fees for treatment of industrial waste.

8.1. On-farm biogas installation.

This unit is based on a dairy farm in Dorset. The first of its kind in the UK, this Biogas Nord UK plant was commissioned in July 2008. Based on a popular German model of on-farm anaerobic digestion technology, feedstock will be a mixture of both livestock slurry and dung plus energy crops including maize and grass silage. The digester is a single reinforced concrete tank with wall and floor heating with 2,888 m^3 capacity; electricity is produced by a 370 kWh combined heat and power (CHP) unit. Anticipated feedstock use in a 12 month period is 20,300 t, this being made up of 14,000 t of cattle slurry, 3,800 t of grass silage, 1,500 t cattle dung and 1,000 t whole crop maize.

Key output will be sale of electricity into the UK national grid. At present there is no obvious use for the heat being produced so it is currently being released into the atmosphere. It is also intended that the plant will used as a demonstration facility for the ongoing development of Biogas Nord UK.

The budget from this company predicts an annual return of 20.87% on the £1.225 million investment capital investment (Table 13).

Table 13: *Base year profit and loss budget (produced by Biogas Nord UK, October 2008).*

Income		**£**
Electricity (inc ROC value)	2,917,080 kWh @ £0.145 /kWh	£422,977
Variable costs	Feedstock and transport	£110,200
Overhead/fixed costs	Labour, insurance etc	£112,923
Total costs		£223,123
Net margin		£199,854
Return on capital		**20.8%**

Key issues are:

- Digester operation time, assumed to be 90% for this plant, is high compared with UK averages of 25-45% and the renewable Energy Authorities suggestions of 85%.

- Feedstock purchase cost, which will inevitably be dependent on the financial returns available from alternative land use options.
- Plant depreciation is assumed to be 22 years. If earlier replacement or an upgrade of machinery is necessary this would increase the depreciation cost considerably.

The capital cost associated with a project of this size is considerable. Higher returns or increased security of sustainable profits would obviously be possible if the initial capital development costs of the project could be reduced.

8.2. Centralised anaerobic digester.

This is operated by Andigestion Ltd at Holsworthy in West Devon. It comprises two 4,000 m^3 digesters and 2.7 MW CHP units for electricity generation. It is the UK's only centralised anaerobic digester. Historically run as a farmer co-operative, being built in 1998, the plant is now run as a private business. Up to 140,000 m^3 of organic material can be processed at the plant with feedstock including bakery, other food, abattoir, fish processing, cheese, and biodiesel wastes. Digestion of livestock manures, collected from 30 or so local farmers, was phased out as a feedstock in the summer of 2008.

In the region of 90% of the typical 800 - 1,000 MWh of electricity produced per month is sold to the national grid with the rest used to run the plant.

Digestate is spread to agricultural land via a series of on-site storage tanks using a dedicated truck and spreader machinery. The high nutrient content of the digestate offers a valuable opportunity for local farmers to replace manufactured fertiliser.

Digestate nutrient quality has changed over the years as a result of the feedstock changes associated with the phasing out of livestock manures. Total nitrogen levels have dropped only slightly but phosphate and potash levels have fallen considerably (Table 14).

Table 14: *Rolling 4 month nutrient content of Holsworthy digestate.*

Year	Units	Total N	Total P_2O_5	Total K_2O
April 2005	kg/m^3	7.78	1.09	3.15
April 2006	kg/m^3	7.15	1.03	2.88
April 2007	kg/m^3	6.28	0.65	2.38
April 2008	kg/m^3	6.68	0.35	1.48

This large scale AD plant continues to produce significant amounts of renewable electricity. Issues over the years have included odour, transport plant design problems and in, its early years financial challenges. One historic and ongoing challenge is dealing with developing environmental legislation.

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