Internalising Environmental Benefits of Anaerobic Digestion of Pig Slurry in Norfolk

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Abstract

Hypothesis: The current financial climate works against the installation of anaerobic digesters on farms in the UK. However, if environmental benefits such as emissions of greenhouse gases are internalised, this technology may appear economically viable.

Project Design: The economics of establishing an anaerobic digester at a specific pig farm in Norfolk were investigated. A sensitivity analysis was undertaken by a series of cost benefit analyses, to study how the financial situation changes according to various factors. A monetary value was placed on the emissions reductions, and this was included in a new figure for 'annual benefits'. Values were found by calculating the reduction of:

Carbon dioxide emissions from electricity generation, avoided by energy production from this carbon-neutral renewable resource.

1) Nitrous oxide emissions from the application of fertiliser, avoided by the increased availability of nitrogen for plants from digested slurry.

2) Carbon dioxide emissions from electricity generation, avoided by the decreased demand for the production of energy-intensive fertiliser.

3) Methane emissions from slurry storage, avoided by the containment of the slurry.

Nitrous oxide and methane were converted to carbon dioxide equivalents. The current market price of carbon dioxide emission reductions from BP Amoco's internal market was used.

It was considered how internalising these external benefits would affect the financial viability of a digester at the farm, and also the economics of digesting the pig slurry from farms in Norfolk with more than 1000 pigs.

Main results: The digester was most likely to be profitable if there was a developed market for the fibre. Internalising the environmental benefits resulted in the net present value (NPV) of the farm digester increasing from £13351 to £475311. If the government paid 50% grants for 60 digesters in Norfolk, the environmental benefits would give this investment a NPV of over £3.5 million, although if the savings from avoided carbon dioxide from fertiliser production were not factored in, the NPV is negative.

Conclusion: The results found here support the hypothesis.

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Internalising Environmental Benefits of Anaerobic Digestion of Pig Slurry in Norfolk

1 Hypothesis

The current financial climate works against the installation of anaerobic digesters on farms in the UK. However, if environmental benefits such as emissions of greenhouse gases are internalised, this technology may appear more economically viable.

2 Introduction

Anaerobic digestion (AD) is the microbial decomposition of an organic matter in the absence of oxygen to produce 'biogas', consisting of methane (CH_4), carbon dioxide (CO_2) and water. The undecomposed solid matter (the 'digestate') can be separated into fibre and a liquor. The biogas can be used for heating water or to produce electricity. It is a renewable energy and therefore reduces CO_2 emissions. The fibre is a soil conditioner, and can be sold as an alternative to peat. The liquor is rich in nutrients and is used as a substitute to inorganic fertiliser. The use of this technology therefore has many benefits, and could play an important role in the move towards sustainable development.

2.1 The Resource

There are over 700 000 pigs in Norfolk, 10 % of the total for England (MAFF, 1998). This means a potential annual biogas yield of 9.5 million m^3 and an electricity output of 12.8 GWh.

An increasing number of pigs are kept in outdoor accommodation where their waste is mostly left on the ground and decomposes aerobically. There are two basic management systems for pigs living indoors: straw-based and slurry-based. The manure that arises from straw-based systems is not often used as a feedstock for AD because the straw needs chopping and it may cause pipe blockages (Higham, pers comm). Slurry-based systems were more popular in the 1970s, but are now on the decline due to perceived welfare problems (Dunnings, pers comm). With this system, the muck and urine fall through slats in the floor and are collected in a lagoon below.

The storage conditions of this slurry favour anaerobic conditions, and this type of decomposition causes an odour nuisance for those living in the vicinity of the farm. The slurry

has a high Biological Oxygen Demand (BOD) which can result in ground water pollution. AD can reduce the odour from slurry by up to 80% (Practically Green website), and creates an integrated management system which lessens the likelihood of pollution.

It has been estimated that the total accessible energy resource from wet livestock waste is around 3 TWh/year or 1-2% of UK electricity demand (ETSU, 1994, pp230-232 cited in Tipping, 1996).

2.2 The Technology

AD occurs in four stages:

1. the organic matter is hydrolysed to soluble compounds
2. the soluble compounds are fermented to volatile fatty acids
3. acetogenesis forms hydrogen, CO_2 and acetate
4. methanogenesis produces biogas.

This process is shown in Figure 1.

2.2.1 Types of digester

The most common on-farm digester in the UK is the continuously stirred tank reactor digester (CSTR). This involves an above-ground vessel that is usually circular to facilitate mixing. They are initially filled, and waste is removed and added regularly. They can be stirred with a rotating blade or by recirculation of the biogas. The latter type is becoming more popular due to its increased reliability. (Chesshire, pers comm).

In Europe the CSTR also predominates, making up 35% of digesters. The next biggest group are the plug flow digesters. These are not stirred. Waste is added regularly at one end and overflows at the other. 17% of the AD units in Europe are of this sort (AD-NETT website). Pig slurry is not deemed suitable for this type of digester, due to its lack of fibre. (AgStar, 1999, p1-3) In more temperate climates, a lower level of technology can be applied with an unheated covered lagoon digester.

Research and Development projects often point to the increased yields obtained from more advanced AD technologies, such as two-stage digesters. In one step digestion of solid wastes, problems may occur if the substrate is easily degradable. A population increase of the faster growing bacteria at the beginning of the process can lead to a build up of volatile fatty acids, a pH drop, and inhibition of the whole process. This is not a problem for substrates such as plant

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matter, where the presence of tough vegetable matter such as lignin means that hydrolysis is the rate limiting step. Mesophilic CSTR digestion of silage showed a slightly better performance than the two-stage process (Edelmann *et al* 1999).

Figure 1: The Stages of AD

Process	Material	Bacteria
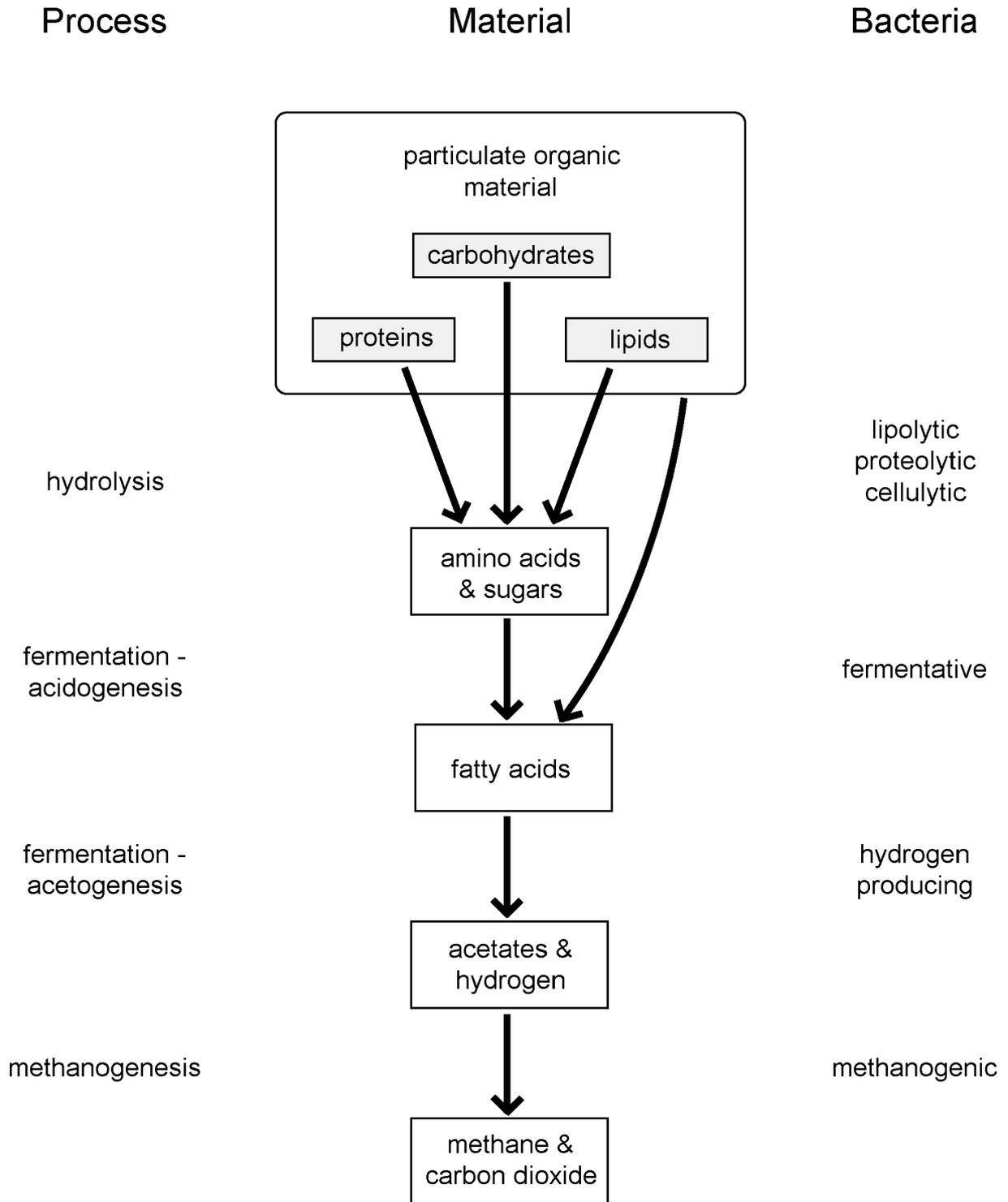
The practical running of these new technologies remains unproven in the field. Two-stage digesters can become in effect two separate normal digesters (Chesshire, pers comm). In practice, low technology digesters can be more reliable and therefore more economical. Roger White, owner of a pig slurry digester in Britain, has taken out all the more technical parts of his digester as they have failed, and now measures the temperature with a thermometer tied to a stick.

Digestion can operate at three different temperature ranges, each with distinct types of bacteria. Figure 2 shows the proportions of digesters in Europe at different temperatures.

Figure 2: Temperature Range of Digesters in Europe (Source: AD-NETT website)
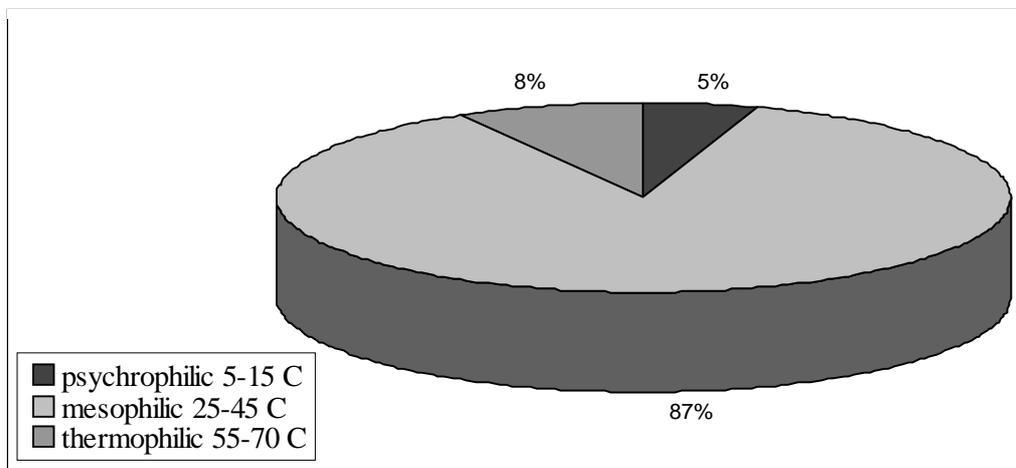
Mesophilic digestion tends to be more robust and tolerant than the thermophilic process, but gas production is less, larger digestion tanks are needed, and sanitation, if required, is a separate process. Residence time in thermophilic digesters is shorter, and they generally offer higher methane production, faster throughput and a higher level of pathogen and virus destruction. However, they do need more expensive technology, greater energy input and a greater degree of operation and monitoring (AD-NETT website).

A study by the University of Manchester found that thermophilic reactors generated similar amounts of biogas and methane per gram of total solids removed, but batch times were typically only 64% of those for a mesophilic reactor. The overall result of these differences was that the thermophilic process was 1.5-2.5 times more efficient than the mesophilic process. (University of Manchester,1987)

However, the extra energy needed to heat the digester is not always balanced by the increased yield. Because of this, another study found that thermophilic digesters were always less satisfactory than mesophilic digesters. (University College, Cardiff, 1986)

In particularly cold countries such as Canada, there has been some interest in psychrophilic anaerobic digestion. Experiments with conventional mesophilic and thermophilic digestion in Canada had not been successful due to high capital and operational costs. AD units were not energy efficient during sub-freezing winter temperature. Psychrophilic AD was found to be effective, reducing the pollution potential of pig slurry by removing 59-78% of the soluble chemical oxygen demand (Masse *et al*, 1999).

2.3 Feedstocks

It is possible to use a variety of feedstocks in a digester. These can come from agriculture, communities or industry. Agriculture accounts for the largest potential feedstocks and most current applications. Energy crops, algal biomass and harvest remains may be used as well as animal wastes. Biodegradable Municipal Waste (BMW) can come from communities near the digester, and can be treated there instead of landfilled. A large variety of wastes from industry can be used, including those from food processing, the sugar industry, the cosmetic industry and from slaughterhouses/ rendering plants. (Steffen *et al*, 1998, p3).

Municipal Solid Waste (MSW) as a whole can also be digested, however the main problems concern contaminants such as glass that may damage the digester and greatly decrease the value of the compost. Large capital costs lessen the attraction of this type of waste management system. The use of source-separated BMW decreases the likelihood of contamination, but perhaps not by enough to convince the consumer that the compost is a viable alternative to peat. One of the main concerns would be the effect of heavy metal contamination on plants.

Figure 3 shows the proportion of different types of the predominant feedstocks of digesters in Europe. Digesters are usually fed with more than one feedstock. The predominant feedstock was that defined as contributing more than 50% for each plant (AD-NETT website).

Figure 3: Feedstocks of Digesters in Europe

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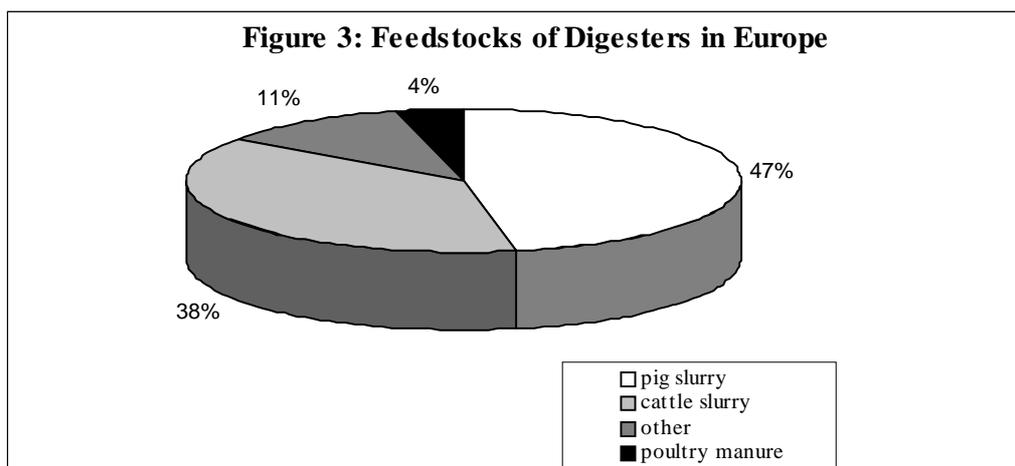
The database kept by Vicky Heslop shows that in Britain, the main feedstock is cow slurry. This may be because one of the main reasons for interest in digestion is worry over an odour problem and relations with neighbours. Family businesses are more concerned about this than commercial farms, and this type of small-scale business more commonly keeps cows than pigs (Murcott, pers comm).

Particular research attention has been given to pig slurries because these pose serious pollution problems but could be digested to give a gas yield of 0.3-0.45 m^3/kg, compared to a lower rate for cattle waste at around 0.2m^3/kg (Ader Associates, 1981). This higher yield is mainly due to the higher fat content. As a percentage of total solids, pig slurry has 7.0-12.3% fat, while cow slurry has 3.5-7.5% (Steffen *et al*, 1998, p21).

Different types of animal housing result in large variations of total solids (TS) content in slurry. If too much water is added from washing the lots, the feedstock may only have 2-5% TS. This is more likely to make the application of a digester system uneconomic, due to the need to heat the digester (Steffen *et al*, 1998, p10).

2.4 The products

2.4.1 Biogas

Biogas is a 'sour gas' in that it contains impurities which form acidic combustion products. Most digesters will produce a gas with 0.3-2% hydrogen sulphide (Practically Green website). If care is not taken, this gas can corrode the generator in which it is used. However, gas cleaning is expensive and so it is rarely used for on-farm units (BABA Ltd, 1987, Mees, pers

comm). Another option is to add ferric chloride to the feedstock which inhibits the production on hydrogen sulphide. However, this is very expensive and causes other problems such as corrosion of pipework by chlorine and it can kill valuable micro-organisms in the downstream processes (Practically Green website).

If the gas is used intermittently in a generator, a supply of mains gas should be connected to the generator so that it can flush out the biogas at the end of the session. This prevents corrosive elements such as the hydrogen sulphide from condensing inside the generator. Specialised gas Combined Heat and Power (CHP) units are very expensive. In Germany and Denmark diesel generators are now used. Costs are lower because it is a more standard piece of equipment. Maintenance costs are lower than for the CHP units used in this country which are more prone to erode. The diesel generators use 10% diesel fuel which lubricates the system and protects it from erosion. (Heslop, pers comm)

2.4.2 Liquid fertiliser

This product of AD is more acceptable than raw pig slurry for a number of reasons. It is practically odour free, the lower viscosity means that it is easier to spread and does not coat the leaves of plants, and nutrients are more readily available to the crop.

Digestion transforms the organic bound nutrients in the slurry to a mineral form. This is most significant for the nitrogen, where the organic form is metabolised to ammonium (NH_4^+). Ammonium is directly available for the crops when it is applied to the fields. The rest of the organic nitrogen must be mineralised by soil bacteria before it is available for the crops, which is the reason why organic fertilisers have a lower efficiency than mineral fertilisers (Klinger, 1999).

2.4.3 Soil Conditioner

After the digestate is separated, the fibre can be marketed as an alternative to peat. Its market acceptance will depend on the feedstock used. Pig slurry fibre will be free of many of the contaminants that might be found in MSW, but it does have a high zinc and copper concentration (see under 2.5.3 Heavy Metals).

The value of this fibre depends greatly on the development of its market. A greater number of AD units on farms may increase awareness and the acceptability of this product.

2.5 Current problems involving agricultural pollution

The traditional mixed farm is a closed system which produces few external impacts. However, today's economic climate favours specialisation and intensification (Conway and Pretty , 1991, p275). To compete with imports from countries with lower costs, farms need to produce their commodities in the most efficient way. This has led to an increase in intensive farming. Animals are concentrated in certain areas of the country, producing manure in large quantities, away from arable land which could potentially make use of it. The high nutrient load in this waste means that there is a very large national pollution load from livestock. In the UK, this is equivalent to the waste generated by 150 million people (Conway and Pretty , 1991, p276).

2.5.1 Air Pollution

Agriculture contributes to climate change through the production of certain greenhouse gases such as methane and nitrous oxide (N_2O). In Ireland, agriculture accounts for one third of greenhouse gas emissions and therefore it is under political pressure to reduce its impact (Heslop, pers comm). Livestock production is also one of the main sources of ammonia to the atmosphere.

Methane

Methane has a global warming potential (GWP) 21 times that of CO_2 (IPCC, 1995). In agriculture, the predominant source of methane emissions is bacterial activity in the guts of cattle. This accounts for 85.1 kilotonnes of methane per year. The pig industry's annual release is 22.5 kilotonnes. This is mainly because of the anaerobic decomposition which can occur during slurry storage. (Meeks *et al* 1999, p 39-40)

The Intergovernmental Panel on Climate Change (IPCC) reports that to stabilise atmospheric methane concentration at 1990 levels, global emissions need to be reduced by 15-20% (Houghton *et al*, 1990). AD contains methane emissions from animal wastes, and converts it into CO_2 which has a lower GWP and which can be absorbed by plants and kept within the terrestrial carbon cycle.

Nitrous Oxide (N_2O)

This gas is a potent greenhouse gas and depletes ozone. It has a high GWP 310 times that of CO_2. Annual agricultural emissions of N_2O are currently estimated to be about 100,000 tonnes.

Denitrification in soils is the principal source (Houghton *et al*, 1990, p26) and this process is increased by fertiliser application. Fertilisers also contribute to emissions through nitrate leaching and ammonia deposition. Around 45% of agricultural emissions are caused directly or indirectly by the use of synthetic nitrogen fertilisers. However this is an area of active scientific investigation and considerable uncertainty still surrounds these numbers (Wilkins, pers comm).

The atmospheric concentration is now 8% greater than in the pre-industrial era, and is increasing at a rate of about 0.2-0.3% per year. The major sink for N_2O is photolysis in the stratosphere, resulting in a relatively long atmospheric lifetime of about 150 years. To stabilise concentration at today's levels, an immediate reduction of 70-80% of the post-industrial additional flux is needed (Houghton *et al*, 1990, p27).

There is a suggestion that anaerobically treated slurries produce less N_2O than equivalent raw slurry, although this is unproven (Tipping, 1996, p122). The main contribution of AD to this problem is through the increased efficiency of the slurry as fertiliser. This could reduce inorganic fertiliser use. Each tonne of applied inorganic nitrogen results in the emission of 0.0297 tonnes of N_2O, and this can be averted through the increased use of organic manure and slurry (Wilkins, pers comm).

Ammonia

Ammonia releases to the atmosphere have local and regional effects. At a local level, ammonia can cause health problems at high concentrations (e.g. within animal housing buildings), and can cause odour nuisance. On a global or regional basis, ammonia deposition from the atmosphere can cause damage to natural vegetation and soil by nitrogen enrichment and acidification. This in turn may alter the nature of the vegetation, and so damage the ecosystem (Tipping, 1996, p129).

Ammonia is released directly from buildings where animals are housed, from slurry or manure storage systems and from fields after spreading. Agreement was recently reached concerning a Europe-wide protocol to curb ammonia emissions (ENDS, September 1999, p44). AD can contain emissions while the slurry is in the digester rather than in open storage. However, digestion lowers the pH which can result in a higher ammonia loss when it is land-spread, although research shows that ammonia volatilisation depends more on the time that the slurry remains on the surface before incorporation in the soil, than it does on whether the slurry has been digested (Tipping, 1996, p132).

2.5.2 Water Pollution

A National Rivers Authority report stated that pollution incidents caused by pig slurry accounted for approximately 10% of reported agricultural pollution incidents. They were principally due to "inadequate storage capacity, structural collapse, poor management and over-application to the land (NRA, 1992, cited in Tipping, 1996, p135).

Animal waste can contribute both phosphates and nitrates to water sources. Both are needed for algal population growth, but phosphorus is usually the limiting factor in freshwater systems. Animal farms are responsible for 17% of the phosphate loading to water courses in the UK This is the same proportion as from arable agriculture (Conway and Pretty , 1991, p200).

The price of inorganic fertilisers are low, they are easier to apply than livestock waste, and nutrients contained in them are readily available to growing plants. Farmers therefore prefer to apply these mineral fertilisers, and dispose of the livestock waste in other ways (Conway and Pretty , 1991, p275).

When organic manure is used, it is very difficult for farmers to adjust their fertiliser use accurately. As previously discussed, much of the nutrients in slurry and manure are locked up in their organic form. This can be slowly released over some years, so the farmer may overcompensate by applying too much mineral fertiliser. This can result in an overloading of nutrients such as nitrates, which may be leached into water systems.

2.5.3 Heavy Metals

Copper is added to feed to accelerate growth by increasing food conversion rates. Zinc is added for the same purpose, and to counteract the toxicity which might be caused by high copper concentrations. The majority of these additives are excreted. Pig slurry is therefore high in copper and zinc, and these can accumulate in the topsoil and part of the crops. No serious effects of this have been observed in the UK, although care must be taken with grazing sheep due to their particular susceptibility to copper toxicity (Conway and Pretty , 1991, p309).

2.5.4 Odour

The smell of farmyard manure is not normally perceived as offensive, but the odours from modern, intensive livestock systems are far removed from what is considered a traditional "good country smell". (RCEP, 1979, cited in Conway and Pretty , 1991, p291). The difference is due to the uncontrolled anaerobic decomposition of the slurry in storage, which gives off

over 77 compounds. These include volatile fatty acids, organic acids, phenols and organo-sulphide compounds. When the slurry is spread, it gradually oxidises and the smell disappears. If the slurry could be spread every few days, the odour problem would not occur. However, storage is necessary because spreading is not allowed under certain conditions which may result in water pollution.

2.6 The Benefits of AD

(Adapted from the AD-NETT website)

Energy balance

A properly designed and operated AD plant can achieve a better energy balance (taking emissions from transport into account) than many other types of energy production. This means that it consumes less energy per delivered unit of electricity.

Reducing greenhouse gases and fossil fuel use

CO_2 produced from AD is from 'short cycle' carbon, i.e. the carbon in the organic matter was recently sequestered from the atmosphere. Therefore energy produced from this process is not considered to contribute to climate change.

AD aims to contain methane emissions.

The use of the liquid fertiliser and fibre as a contribution to fertiliser regimes can reduce fossil fuel consumption in the production of synthetic fertiliser.

The decreased fertiliser use also reduces N_2O emissions

Reducing demand for peat

Peat extraction damages rare peatland ecosystems. The fibre produced by the AD process can be used as a soil conditioner, in some instances as an alternative to peat. However, they are not strictly comparable because peat is nutrient free.

Reducing odour

AD can reduce the odour from farm slurries by up to 80%.

Efficient electricity distribution

Nationally, transmission losses are 7% of electricity generated (ETSU, 1997, p50). Power production near to where it is consumed will reduce these losses.

Improving farm waste management

Establishing an AD project does not eliminate wastes, but it does make them easier to manage.

Even after digestion, slurry still has twenty times the pollution potential of raw domestic sewage (DTI, 1993a). However, a reduction in BOD and dry matter minimises the chance of creating soil anaerobic conditions and reduces the pollution of drainage water after field application of digested slurry. This reduction in BOD can be as high as 90% (SEPA, 1999).

Volatile fatty acids (VFA) in pig slurry can damage crops, which makes it unpopular with farmers. Digestion reduces the concentration of VFAs from thousands of parts per million, to about 250 ppm (Gornall, 1999).

The AD process stabilises slurries so that they do not putrefy or create odour. This allows them to be stored much easier and for longer.

Slurry handling costs are reduced because the liquid fertiliser is easier to spread than slurry. It can be pumped through existing irrigation equipment pipes, instead of tankered on to the land. Lightweight equipment which is more likely to be owed by the farm can be used, which can avoid contracting costs. This also reduces crop damage.

Reducing spread of weeds and disease

AD destroys virtually all weed seeds, so digested slurry can be spread with minimal risk of weed spread, reducing the need for costly herbicide and other weed control measures.

Financial benefits

Indicated above, there are many potential savings to be made from an AD project. Also, residues can be converted into saleable products such as electricity and soil conditioner.

Local economic development

AD can contribute to rural regeneration by creating or maintaining jobs on farms and in local support businesses. It can stimulate new industries, for example fish farms or local greenhouses may be able to use local heat produced by AD projects.

2.7 The Current State of the AD Industry

2.7.1 World-wide

AD plants are mostly concentrated in the Majority World, where simple systems bring direct benefits to the owners. The biogas can be used directly for cooking, which can have a direct environment impact by decreasing the demand for other fuels such as firewood, and reducing deforestation.(Fulford, 1988)

India and China have the most developed biogas industries. In China in 1989, there were 4.5 million on-farm digesters. Both countries have large populations of stabled animals; China with pigs, and India with cattle. They both now have extensive government programmes to co-ordinate the uptake of this technology after earlier failures due to unreliable digester plants being built (de Groot, 1989).

In the developed world, rising oil prices in the 1970s triggered an interest in AD. A minority of the digesters built at this time are still working, but many failed early, often due to poor system design (AgStar, 1999, p1-5)

Digesters fit into three categories:

1) small scale, on-farm digesters,

2) community digesters, shared between 20-30 farms,

3) large scale 'centralised anaerobic digesters' (CADs), which can digest a whole range of feedstocks, including industrial wastes, municipal solids wastes and agricultural wastes.

The first two types are more common in the Majority World. Community digesters in particular are popular in India and Nepal, where each household may have only one or two cows. Although costs are lower, due to less automated equipment and simpler designs, digesters are still often only marginally economic (Fulford, 1988).

The high capital costs involved in building a CAD mean that they are far more likely to be found in the developed world.

2.7.2 In Europe

AD-NETT is a European network of interested parties which exchanges information about AD. Its website has a database with information about Europe's AD units. This shows that 50% of AD plants are small, on-farm schemes. The remainder are roughly split between medium and large facilities. (AD-NETT website)

AD technology in other European countries has benefited much from government support. For example, subsidies in Denmark are 20-40% of investment costs (van Hauwaert, 1999). Other European governments have invested in this technology to a greater extent in line with their general encouragement of renewables, or due to the nature of their denser populated countries where water pollution control is more of a priority (Heslop, pers comm)

Germany has the largest number of digesters in Europe, with over 900 farm plants. Denmark has 19 centralised and 20 on-farm plants. Other countries with AD experience include Britain, Austria, Switzerland, Italy, Sweden and Finland (Heslop, 1999).

2.7.3 In Britain

On a large scale, AD is widely used in the UK for waste water treatment (Ader Associates, 1981). There is less development of AD in the agricultural sector. England has 25 on-farm plants (Higham,1997).

Apart from a few recent exceptions of digesters built with government research grants or with a NFFO contract, no on-farm digesters have been built since MAFF stopped their grant scheme in 1994 (Murcott, pers comm).

Seven contracts for electricity have been awarded to AD projects under the Non-Fossil Fuel Obligation (NFFO). Electricity prices agreed range between £0.0513 and £0.07 per kWh (Heslop 1999, p14). None has actually been built yet, but one CAD project in Devon has received 50% grant assistance from the Government and the EU, and it is expected to come on-line this year (Heslop 1999).

2.8 Legislation Affecting AD

A range of new and forthcoming environmental legislation may encourage the technology of AD. These include the climate change levy, the Integrated Pollution Prevention and Control (IPPC) and the Landfill Directive. Government targets, such as its political commitment to reduce its CO_2 emissions to 20% of 1990 levels by 2010, and to increase its proportion of

electricity from renewable sources to 10% by the same date, may mean an increased interest in AD as a way of meeting these targets.

The current momentum of renewable electricity coming on line suggests that the target of 10% by 2010 is unlikely to be met. It would require 500MW of net capacity to come on stream every year, but just 90MW were added in 1997 (ENDS, February 1999). To achieve the target set, the Government will need to give a greater encouragement to renewables. However, some accuse it of threatening the renewable industry with a change in electricity trading arrangements. It is now unlikely that there will be another round of the Non-Fossil Fuel Obligation (NFFO) which have given renewable energies a guaranteed price for their energy. However, the proposals for a new electricity trading arrangement (NETA) have been heavily criticised for their potential adverse affect on the renewable industry. Someone from the British Wind Energy Association renamed this arrangement "Never Expected Ten per cent Anyway" (ENDS, August 1999).

The climate change levy is an energy tax, which will be applied to certain groups of high energy user from April 2001. In response, the Confederation of British Industry has published proposals for the UK's first emissions trading scheme (ENDS, October 1999). This could theorectically benefit owners fo digesters, if they could be paid for the reduction in emissions which result from their project.

The forthcoming implementation of the EC Directive 96/61 on Integrated Pollution Prevention and Control (IPPC) will mean that farmers will have to look more seriously at their waste management practices. This may facilitate a spread of AD technology, although other waste management options involve far less capital and are simpler to run. It will affect pig units with more than 2000 pigs over 30kg or 750 sows. They will be required to reduce emissions to air, land and water, based on the following general principles:

1. Prevent pollution using Best Available Technique (BAT)

2. Minimise waste

3. Conserve energy

4. Prevent accidents and limit their environmental consequence

5. Clean-up of site when activities cease

A range of BATs will be recommended, and AD may be on this list, although this is unlikely to be the cheapest option for many farmers (Larkmann, pers comm).

The Landfill Directive adopted by the EC in April 1999 sets targets for reducing the amount of BMW which is landfilled. Under this directive, by 2010 the UK must reduce the total weight of BMW going to landfills to 75% of the 1995 total. One option to meet this target is the anaerobic digestion of BMW. Farms with digesters could be paid a 'gate fee' to accept and treat this waste.

2.9 Farming trends

Over recent years, farming has moved away from traditional, mixed systems to more intensive practices. Intensified crop production requires more fertiliser than is available from traditional sources. Livestock production is often on small areas of land, so disposal of the associated wastes is becoming increasingly difficult.

The pig industry is currently in crisis, losing £2.5 million a week on a national scale. Small businesses are less likely to be able to break even during this time, and are going out of business at a greater rate than the larger farms (Farm manager, pers comm). This is quickening the current trend towards larger farms. Between 1993 and 1998 the average size of pig herds increased from 398 to 504. However, total numbers of pigs are gradually declining. The total number of pigs in England declined by 10.6% between June 1998 and June 1999.

2.10 Objectives of the Study

There are a number of scientific papers concerning experimental biogas yields under various conditions, in different types of digesters, and with a variety of feedstocks. In the UK there have been some governmental studies about the practicalities and the economics of AD, but none have internalised the environmental benefits as this study attempts to do. Neither did an extensive search of scientific journals find any research attempting to put a monetary value on the environmental benefits of AD.

The main study on this subject to be commissioned by MAFF, is about Centralised AD. A fact sheet from the DTI states, "In general, suitable farm waste occurs in too small quantities on individual farms for it to be exploited as a source of energy" (DTI, 1993b). However, although there was a large degree of uncertainty, a report by AEA Technology found that under the best scenarios, on-farm digestion could be more of a cost effective measure to reduce methane emissions than CADs (Meeks *et al*, 1999).

This project focuses on the small-scale digestion of farm waste. This is primarily because there is evidence that the pollution from transport involved in CADs outweighs the environmental benefits (Tipping, 1996). Furthermore, on-farm digesters follow the government's proximity principle of dealing with waste near to source. (DETR, 1999), and are therefore more in line with sustainable development.

2.11 Terminology

2.11.1 Pig Terms

On a slurry-based system, such as the farm in question, sows stay on straw in the 'dry sow house' until one week before farrowing. They then give birth in the farrowing house, which has slats in the floor and is over a lagoon of slurry. The piglets, in danger of being squashed, are encouraged to stay away from their mother when not feeding. This is done with an infrared farrowing lamp, to keep the temperature inside their hutch warmer. The piglets stay there until they are 5.5 kg in weight. They are then termed 'weaners', and move to the 'flat decks', which is also a slurry-based system. The flat decks are heated, and each week the rooms decrease by 2°C, until just above ambient temperature. The weaners stay there for 4-5 weeks. After this, they are 'store pigs', and move to the rearing shed, which is on straw and is not heated. At 12 weeks old they become finishers and move to the finishing house - another slurry based system. There they grow from 35 kg to 105 kg.

2.11.2 Financial Terms

Businesses have both internal and external costs. Internal costs, such as paying wages and buying equipment, are borne by the company. External costs, such as polluting the atmosphere or a river, may be paid for by society, for example by adverse health effects or through higher water bills. The Polluter Pays Principle, attempts to ensure that those responsible for environmental damage pay to mitigate its consequences. Economic theory states, that if this were always possible, it would result in a 'socially optimal' level of pollution. Market failure exists when a company uses and degrades an unpriced environmental resource, which imposes no internal cost on the firm, but does create an external cost for society (Turner *et al*, 1994, p75).

2.11.3 Energy terms

One kilowatt hour (kWh) equals 1 kilojoule per second for an hour, i.e. 3600 kJ, or 3.6 MJ.

1 MWh equals 3.6 GJ.

1 GWh equals 3.6 TJ.

2.11.4 Other Terms

The terms synthetic fertiliser, mineral fertiliser and inorganic fertiliser are used interchangeably in this text.

Part 1: The economic viability of an Anaerobic Digester at a specific pig farm

3 Aim

To investigate the sensitivity of the project's economic viability to a range of situations.

4 Introduction

The economic viability of a digester at a pig farm near Swaffham was investigated. This farm has 8500 pigs (piglets through to finishers) on just 3.5 acres. It is owned by a feed company. It has no arable land, and has to pay contractors to remove the slurry and spread it on nearby farms. The farm is situated in a Nitrate Vulnerable Zone (NVZ). At certain times of the year and especially when conditions are wet, the slurry has to be transported outside of the zone at considerable expense. It has no gas supply, and relies upon electrical heating.

Figure 4: Options for anaerobic digestion
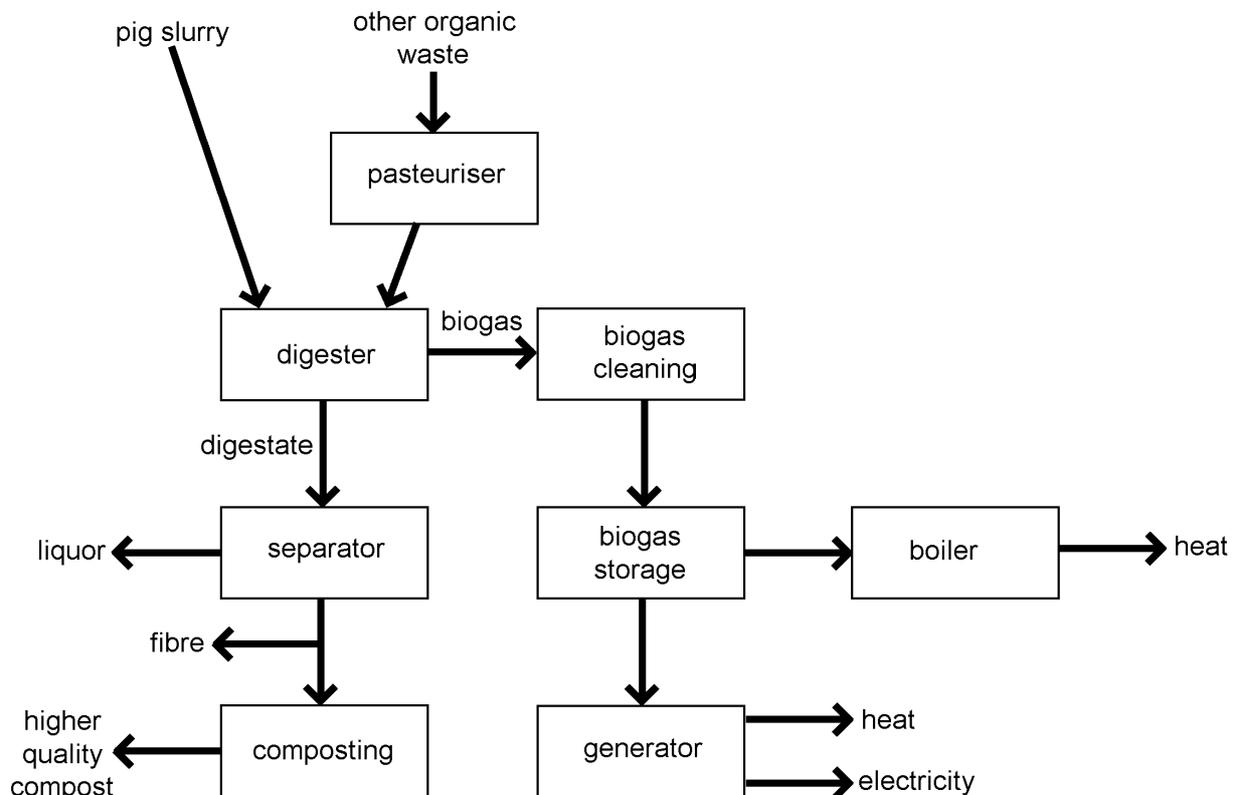
As shown in the Figure 4, the basic components of AD are the digester itself and a boiler.

An electricity generator adds significantly to the capital costs, but may be a more suitable use of the energy if there is not a sufficient heat sink for the hot water. A CHP unit is a more efficient use of the energy. One m^3 of biogas would typically give 2.5 kWh of heat from a boiler, 1.7 kWh of electricity from a generator with 30% efficiency, or 1.7 kWh of electricity and 2 kWh of heat with a CHP unit.

A separator allows the fibre to be marketed, and reduces the volume of the liquor that needs to be disposed of. A mixed farm would benefit from the extra ease of handling of the nutrient-rich liquor which can be pumped instead of spread, and which is a more effective fertiliser than the undigested slurry. This benefit to the arable farmer is unlikely to be translated into an economic profit for a pig farm disposing of its slurry. It is possible that other farms would be more willing to accept the waste in this form, but this is difficult to quantify.

The financial success of a digester is likely to depend on whether full use can be made of its products (British Biogen website). The marketing of the fibre by-product has great potential, and failure to realise this will have a large influence on the economics of the plant. However, a significant investment is needed for the infrastructure required to compost the digested fibre to a high quality with a good market price, and there is great uncertainty about the money that can be made from this better quality fibre in a largely undeveloped market.

If the farm is to accept other organic waste, it may need a pasteuriser for health and safety reasons.

5 Method

A farm visit and follow up research provided the necessary information to input into a cost-benefit analysis (CBA) spreadsheet. The CBA calculates the Present Value of the costs and benefits for each year of the project by applying a certain discount rate. This discount rate reflects the depreciation of the value of money. The year in which payback occurs is that in which the cumulative Net Present Value (NPV) becomes positive. The Internal Rate of Return (IRR) is the discount rate at which the NPV is zero.

The data required were:

Capital costs:

- Anaerobic digester with boiler

- CHP unit

- Fibre separator

- Composting equipment

- A change in the infrastructure of some of the heating system

Operational costs:

- Electrical needs of the digester

- Repairs and maintenance

Annual savings

- Heating of the flat decks

- Heating of residential houses

- Electricity purchases

- Disposal of slurry

Annual benefits

- Fibre

- Gate fees for accepting other waste

5.1 Discount Rate

Two discount rates of 6% and 15% per year have been adopted in this study. This follows the rationale used in 'Cost Effectiveness of Options to Reduce UK Methane Emissions' (Meeks *et al*, 1999, p14). The first reflects the nominal risk-free yield on government bonds, which is often used to indicate an appropriate discount rate. Across the EU, yields are typically between 5.4% and 7.3%. The DETR generally adopt a discount rate of 6% per year, following the recommendations of the 1997 HM Treasury Guide.

However, this investment has quite a high risk, with many uncertainties regarding operational costs and annual benefits. If this capital were used for an alternative high-risk investment, it would expect a higher potential rate of return. The second discount rate of 15% reflects the opportunity cost. This is the return an investor would expect from an equivalent investment of this capital with the same level of risk.

5.2 Sensitivity analysis

The baseline scenario for this study used the most realistic values and chose the options that maximised the profit for the farm. To calculate whether an individual factor increased or decreased the economic viability of the project, the baseline CBA was altered three times. Firstly this excluded the CHP unit and electricity savings, then the separator and fibre sales, and lastly the cost of installing hot water pipes in the flat decks, and the savings from this were included.

A variety of scenarios were then compared to investigate the sensitivity of changes in various situations. These were the following:

1. More expensive cost of the digester

2. Longer project lifetime

3. Pessimistic value of the fibre with no investment in a separator, to extremely optimistic fibre sales with separator and composting equipment.

4. No reduction in slurry disposal costs, to no negative value for the slurry

5. Cheaper to more expensive operational costs

6. Gate fees for accepted waste

7. More efficient bacteria

8. Higher electricity price

5.3 Values for the CBA

Table 1: Values used in the scenarios

	Baseline scenario	Values used in analysis	Location of analysis
Capital costs			
AD unit and boiler (£)	90000	45000, 64000, 90000, 105000, 150000, 300000	Scenarios 1a-f
CHP unit (£)	25000	0, 25000	Baseline Scenario
Separator (£)	15000	0, 15000	Baseline Scenario, Scenario 2a-e
Composting equipment (£)	0	0,16500	Scenarios 2a-e
Concrete under compost (£)	0	0,12279	Scenarios 2a-e
Hot water pipes in the flat decks (£)	0	0, 20000	Baseline Scenario
Operational costs (£)	7000	2000,6200, 7000, 10000	Scenarios 3a-d
Annual savings			
Savings from heating flat decks (£)	0	650	Baseline Scenario
Savings from heating residential houses (£)	1200	n/a	n/a
Savings from electricity (£)	10138	6a-c: 10138, 253877, 296189 7a-b: 10138, 13540	Scenario 6a-c, 7a-b
Slurry disposal (£)	4630	0-25000	Scenario 4a-e
Annual benefits			
Fibre sales (£)	5791.7	0, 5792, 20685, 72000, 100000	Scenario 2a-e
Gate fees (£)	0	6000	Scenario 5a-c
Other factors			
Digester lifetime (years)	15	15-20	Baseline Scenario
Discount rate	6%, 15%	n/a	n/a
Efficiency of bacteria (% VS destroyed)	40% VS destroyed	40%, 60%, 70%	Scenario 6a-c
Electricity price (£)	0.0599	0.0599-0.08	Scenario 7a-b

5.3.1 Capital costs

a) AD unit and boiler, and separator

The size of the digester was calculated following the method described by Meynell (1982, p82). His review of working digesters indicates that organic loading rates vary between 0.8-3.2 kg of volatile solids (VS) per m^3 of digester per day, and is generally 2.8 kg VS/m^3/day. By choosing this latter figure as a preliminary design loading, the digester will be sized in approximately the correct range. It is better to oversize than to undersize, in case of an increase in the amount of waste or estimating errors, and this also ensures that the waste will be digested properly.

Pig slurry produced under this type of regime is typically 5% total solids (TS). 75% of that is VS (Chesshire, pers comm). The farm produces 22.7 m^3 of slurry per day.

$$22.7 \times 0.05 \times 0.75 \times 1000 = 851 \text{ kg VS/day}$$

At a loading of 2.8kg VS per m^3 of digester, 304m^3 (851/2.8) would be the correct size, with a range of 266-532m^3. This would have a retention time of 23 days, which is within the correct range (Meynell 1982, p82). This figure was confirmed by an equipment supplier, who agreed that a 300m^3 digester would be needed for this size of farm (Chesshire, pers comm).

Five manufacturers of AD equipment in the UK were asked for the cost of this size of digester with a boiler and fibre separator. Estimates ranged from £105 000 to £300 000 (Chesshire, Gornall, Maltin, Mees and Murcott, pers comm)

The cheapest quote was used for the baseline scenario. Separators can be purchased for £12-15 000 (Heslop, pers comm). Therefore, scenarios 1c-f use the range of values, less £15 000. Scenario 1a is with a 50% MAFF grant of the £90 000 digester.

In 1996 a pilot project was started to produce an 'Anaerobic Digestion Kit' with a detailed construction manual and a video. It was hoped that this would allow the farmer to do more of the work, with a reduction in capital cost by up to 20% (West Wales Task Force, 1996). Although this project was not realised, scenario 1b investigates what effect it could have had on the project. For simplicity the 20% reduction in capital costs was deducted from the price of the AD unit.

b) CHP unit

Three of these manufacturers also gave quotes for CHP units. Two were for £75 000 (Chesshire, and Gornall, pers comm) and the third was for £25 000 (Heslop, pers comm). The latter was for a diesel generator which is cheaper because it is not a piece of specialised equipment, but is mass produced. It has the added advantage of not being corroded by the hydrogen sulphide because the 10% diesel needed to run with it, acts as a lubricator.

c) Composting equipment

The capital costs involved in setting up this infrastructure were investigated from a variety of sources. Roger White is the only pig farmer in Britain with a digester who markets his fibre as compost. He has been very successful with this enterprise, which is a major source of income for his farm. The costs he reported for composting the 1-1.5m^3/day which comes from 4.5m^3 slurry produced by the pigs, were:

5 x 30m polytunnel	£500
self-built turning machine	£3000
second hand bagging machine	£1200

It was not appropriate to directly scale this up because the equipment was bought 4-6 years ago, and for the larger throughput, a turning machine purchased from a municipal sewage works would be more suitable. It could not be assumed that a suitable second hand machine would be available to bag the fibre, and a new one would cost around £4000 (White, pers comm).

Barry Woodcock, a supplier of composting equipment, said that the following were needed to turn the compost:

120-140 horse power tractor	£30-40 000 new
Creep speed gearbox in the tractor (allowing a speed of 3-4 metres per minute)	£15 000 to convert a tractor without this
turning machine	£16 500

The farm has a 112 horse power tractor which does have a creep speed gearbox, and this was considered adequate. Therefore the turning machine was the only extra equipment cost. It was decided that the polytunnel would not be needed, because Barry Woodcock's advice was that because of East Anglia's low rainfall, it is acceptable to keep the compost outside.

The area that Roger White requires for one fifth of the slurry output of the farm in question was scaled up. A depth of 0.25m is needed (Betamy, pers comm). Two suppliers of concrete were contacted to investigate the price of covering the area required for the composting. The lower price was then used.

$$190m^3 \text{ at } £64.6/m^3 = £12279$$

It was assumed that the laying of this concrete is relatively simple and could be done by employees at the farm, not resulting in overtime. Therefore, the costs involved in producing a high quality fibre were:

Separator	£20 000
Concrete	£12279
Turning machine	£16 500
Bagging machine	£4000

d) Hot water piping

It was originally presumed that savings could be made from converting the heating system of infra red lamps in the farrowing shed to hot water. However, Stephen Betamy from the Farm Energy Centre said that retrofitting pipes is not feasible in this case. It is possible in the flat decks, but it is three to four times more expensive than other heating methods, and only marginally cheaper to run. Retrofitting these pipes in the flat decks would cost around £5000 for the equipment, and £15 000 for the labour. This value was used to investigate the best baseline scenario.

5.3.2 Operational costs

The proponents of this technology suggest that labour costs do not have to be taken into consideration because daily maintenance can be incorporated into the routine of the farm. Accordingly the costs of attending to the digester for an average of one hour a day have not been accounted for.

Roger White reports his annual costs for his 75m³ digester as:

£300 for repairs and maintenance

£100-400 electrical costs

£40-50 insurance

Therefore, scaling this up slightly, a very low estimate for the running costs, given a large amount of expertise on the farm and a low technology system, is £2000. This is similar to the experience of Walford College, Shrewsbury, which has $300m^3$ digester (ETSU, 1997, p52).

The Good Practice Guidelines for AD (ETSU, 1997, p27) state that the running costs for an on-farm project are likely to be £7-10 000 per year. The AD-NETT website suggests £6200. Therefore, ETSU's lower estimate of £7 000 was used for the baseline scenario, and the effect of more optimistic and pessimistic scenarios was investigated in scenarios 3a-d.

5.3.3 Annual Savings

a) Heat and Electricity Production

The biogas production was calculated in two ways:

Method 1

40% of the VS are destroyed and converted into biogas. Conventional wisdom is that $1m^3$ of biogas with 60-65% methane is produced from approximately 1 kg VS (Chesshire, pers comm). This approximation was used, although a mass balance shows that slightly more VS is needed.

$$\text{1 mole at STP occupies } 0.0224m^3$$

$$\text{1 mole of } CH_4 = 0.016kg$$

$$\text{1 mole of } CO_2 = 0.044kg$$

With 60% CH_4 and 40% CO_2:

$$\text{1 m}^3 \text{ of biogas} = 0.6 \times 0.016/0.0224 + 0.4 \times 0.044/0.0224 = 1.21kg$$

With 65% CH_4 and 35% CO_2:

$$\text{1 m}^3 \text{ of biogas} = 0.65 \times 0.016/0.0224 + 0.35 \times 0.044/0.0224 = 1.15kg$$

Method 2

ETSU (1997, p18) and the Practically Green web site state that 26 m^3 of biogas are produced from each tonne of pig slurry, assumed to have total solids content of 9%. This method gave a result that was 73% more than the yield from Method 1. The former method was therefore chosen, because it gave a more conservative estimate, even given the potential underestimation of the quantity of VS needed for each unit of biogas. This method was also considered more suitable because the assumption of 9% total solids involves little or no dilution. The slurry from

the pig farm in question has some water from cleaning out the sheds and from the drinking water for the pigs. Five per cent TS was thought to be a more realistic assumption for this pig farm.

The Good Practice Guidelines state that $1m^3$ of biogas would typically give the following (ETSU, p18):

- electricity only: 1.7 kWh of electricity (assumed conversion efficiency of 30%)

- heat only: 2.5 kWh of heat (assumed conversion efficiency of 70%)

- combined heat and power: 1.7 kWh electricity and 2 kWh heat

It is more economical for the generator to be running at peak times, saving £0.0599 per kWh rather than £0.0245. However, this will mean that during start-up, the generator will be running for about an hour before producing electricity. If it runs for 5 hours a day, 80% of the predicted electricity will be available (Tovey, pers comm). Although usually it would be beneficial to run it for longer periods, which would be more efficient, this ratio was used to err on the side of caution.

Table 2 shows the yearly energy output from digester with the latter two options.

Table 2: Energy produced from the farm's slurry

m^3 of slurry	8297
TS (kg)	414831
VS (kg)	311123
VS destroyed (kg)	124449
m^3 biogas	124449
Boiler only:	
kWh heat	311123
CHP:	
kWh heat	248899
kWh electricity	211564
kWh electricity available (80%)	169251

If the generator runs for 5 hours a day during peak time, the 169 251 kWh of electricity at £0.0599 it produces every year would save the farm £10 138.

For the baseline scenario, the efficiency of the bacteria was taken to assume that there was 40% VS destroyed (Chesshire pers comm). This was a conservative estimate. A different method gave a biogas yield which was 73% higher. Other sources state that the amount of VS

destroyed is between 40-60% (e.g. ETSU, 1997). Added to this, there is a possibility that over the next few decades, the bacteria in digester will adapt to its environment, and this may result in more efficient strains (Chesshire, pers comm). Therefore efficiencies of 40%, 60% and 70% were used in these scenarios 6a-c - the former two being the published range, and the latter being a hypothetical optimistic value.

> With 60% VS destroyed, 253 877 kWh are available - a saving of £15 207.

> With 70% VS destroyed, 296 189 kWh are available - a saving of £17 742.

The farm has a high electricity demand throughout the year. In June 1998, there was the lowest demand of the summer, of 22299 kWh at peak rate throughout the month. This is equal to a daily demand of 743 kWh at peak rate. With 70% VS destroyed, 811 kWh per day can be produced. The deficit of a use for this electricity was only slight, and only for one month of the year. Therefore this small detail was not taken into account.

Scenarios 7a-b looked at a possible variation in electricity price. The government has a target of 10% electricity from renewable sources by 2010 (DTI, 1999). It has the option of encouraging renewable energy with a fixed high price for electricity. Scenario 7a took the baseline price of £0.0599, scenario 7b had a price of £0.08 per kWh. The second price was chosen because this was the value given in the Walford College case study (ETSU, 1997, p53). It meant that the electricity would have a annual value of £13 540.

b) Energy needs

Whether full use of this energy can be made is a crucial issue for the viability of this project. James Murcott, the main manufacturer of AD equipment in Great Britain suggests that the increased capital costs from a CHP unit mean that its purchase would have a detrimental effect on the economics of the plant. He states that practically all the digesters running in the UK do not generate electricity. However, as discussed above, this farm relies on electrical heating, and does not have the infrastructure to benefit from the output of hot water. Another issue is the three to four factor difference between the summer and winter heat load (Betamy, pers comm). Although heating is minimal in the summer, many of the electrical needs such as the fans, the wet feed pump and the slurry pump, remain largely unchanged.

(i) Heating needs

There are four residential houses attached to the farm. Together, they spend about £1200 per year on oil (Farm manager, pers comm). Using the Digest of UK Energy Statistics, values were

obtained for the cost and energy value of oil. £1200 would relate to an energy use of 13.8 tonnes of oil, which is 149GJ per house. This is significantly more than the annual consumption for an average house, of 70GJ. As seen in Table 2, the yearly heat output is 248 899 kWh, which equals 896GJ. This is more than ample for the heating needs of the houses. Just over one third of the heat is left. This is equivalent to the heating needs of the digester (ETSU, 1997).

In one of the CBAs to calculate the best baseline scenario, the flat decks have been fitted with hot water pipes, and the savings from heating these rooms are included.

The flat decks consist of 10 rooms in a well-insulated building. Weaners are moved there from the farrowing shed, where they stay for four to five weeks. They begin at a temperature of 28°C, which is decreased by 2°C every week. The manager reported that the flat decks are warmed with a 3 kW heater in each room, which is on for approximately 26 weeks per year. This uses 13 104 kWh per year. Given an electricity price of £0.0599 for 17 hours a day, and £0.0245 for the remaining 7 hours, this means a yearly saving of £650.

Although the heating needs of the houses and the digester will be concentrated in the winter, for the purposes of this calculation it is assumed that the heat from the CHP can meet these needs.

(ii) Electricity needs

The farm's electricity bills for 1998 were obtained. They showed that even in the summer, the daily electricity demand still exceeds the generator's potential output. Therefore for the baseline scenario, it was assumed that the 169 251 kWh of electricity would be produced during the day when the cost of electricity is £0.0599 per kWh.

c) Slurry Disposal

The farm spends £25 000 a year in contractor fees for the disposal of the slurry. Digestion slightly reduces the volume, and separation would reduce it further. The farm is situated in a NVZ, and at certain times of the year, slurry has to be transported up to 30 miles away. The main part of the cost is the transport. If it could always be spread nearby, 60% of the costs would be saved (Farm manager, pers comm).

The increased amount of nitrogen readily available for the plants after digestion may mean that nearby farmers are more willing to accept it. It is easier for them to adjust for the useful

nitrogen content, so they can reduce the amount of mineral fertiliser applied, and the limits imposed in the NVZ will not be exceeded. However, it was not possible to quantify the result that this increase in acceptability of the digestate would have. It was only possible to calculate savings on the basis of volume reduction. The Good Practice Guidelines for AD states that digestion removes 2-4% of the mass of the slurry, and separation a further 7-25% of the digestate (ETSU, 1997, p22). The reduction in volume and therefore the saving for the baseline scenario, was taken as an average between the two ranges of estimates.

$$97\% \times (7\% + 25\%)/2 = 18.52\% \text{ reduction in cost}$$

$$18.52\% \times 25\,000 = £4630$$

Mass does not directly relate to volume, so this is an approximation. However given the expectation that digestion would result in reduced slurry disposal costs, also for the other reasons mentioned, it was thought necessary to include some measure of this. A range of value from no reduction in disposal costs, to a 100% reduction, was used in scenarios 4a-e. The latter scenario assumes that arable farmers realised the value of the liquid fertiliser, and pay the contractors themselves.

5.3.4 Annual Benefits

a) Fibre sales

Roger White sells 15 kg/40 litre (0.04 m^3) bags of compost direct to consumers, for £4.80 each (equivalent to £160/tonne uncomposted fibre).

Desmond Godson from British Biogen said that the fibre probably has no value, or is only worth £10/tonne.

The separated fibre is 7-25% of the mass of the original pre-digested slurry (ETSU, 1999, p22). Therefore, at £10/tonne, the 8 296.6 tonnes of slurry digested per year would give an income of £5808-£20 742. The lower value was chosen for the baseline, because there was a need to be cautious considering that the fibre may have no value, and the extent of its positive value depends on enthusiastic marketing.

In scenario 2a, no infrastructure was invested in, and the fibre has no market value. Scenarios 2b-2e had the added capital costs of the turning machine and concrete (see 5.3.1, Composting Equipment). Extra running costs were not included because it was assumed that the marketing and management of the compost could be absorbed into the daily routine of the farm. Roger

White reported he spent half to one hour a day on this, and occasional whole days to prepare for mass deliveries in the spring and autumn. The farm secretary agreed that this amount of work could feasibly be done by those already employed at the farm, without involving overtime.

Scenario 2b had the same value for fibre sales as the baseline, assuming that 7% of the mass of the slurry ends up as fibre worth £10 per tonne. 2c assumes that the higher percentage of 25% of the slurry can be sold as fibre. 2d-e presume that the extra investment in composting equipment significantly increases the value of the fibre to £4.80 per 40 litre (0.04 m^3) bag, as Roger White sells his for. His pigs produce 4.5 m^3 per day, which after separation provides 1-1.5 m^3 of fibre for composting. This volume reduces by half during the composting process. Taking the lower estimate of 1 m^3, a daily throughput of 0.5m^3 of compost would result in 0.5/0.04 = 12.5 bags a day. This is over 4500 bags a year, although Mr White only sells 3000.

The farm in question produces 5 times the amount of slurry. If it managed to market the same proportion of compost as Mr White, it would make 5 x 3000 x £4.80 = £72 000. This scenario is shown as 2d. This results in a very short payback period of 4 years, which may be acceptable to business. However it is unlikely that such a large amount of compost could be marketed at such a price. Mr White sells his directly to the consumer, and this may not be feasible with 5 times the quantity to unload. Realising this potential would need great marketing skills, enthusiasm and imagination. The farm being investigated may not have the necessary time, skills or inclination.

Scenario 2e shows how favourable a project this would be with a developed market for the fibre. If all the theoretical 22 815 bags of compost could be sold at £4.80 each, then the yearly earnings could reach £109 500. This is highly unlikely due to the undeveloped state of the market for this product, and the distribution costs that would be involved.

b) Gate fees

The Landfill Tax currently stands at £10 per tonne of non-inert waste. This is set to rise in the coming years (Parfitt, pers comm). This means that organic waste has a negative value for the business sector. Many of these wastes, especially those from the food industry, will be suitable for digestion. Oils and fats actually greatly increase biogas production. It is possible that businesses could pay the owner a price below the Landfill Tax to accept this waste. Local

Authorities which need to meet targets set by the Landfill Directive for the reduction of the BMW sent to landfill, may also want to pay a digester owner for disposal of organic waste.

The AD-NETT website gives £6000 as an estimate for the income that could be made from the acceptance of organic waste (Higham, 1999).

However, to safely treat the organic waste, it would be preferable to install a pasteuriser which would cost an additional £12 500 (Heslop, 1999). Scenario 5a is the same as the baseline. 5b-c include the extra capital costs of a pasteuriser, and assume £3000 and £6000 from gate fees.

5.3.5 Other Factors

Although most sources state that AD units have a 15 year lifetime (e.g. Chesshire, pers comm, Godson, pers comm) some digesters in the UK have been running for over 20 years (Murcott, pers comm). A recent report by AEA Technology (Meeks et al. 1999) uses a 20-year lifetime in its analyses, but this study stayed with the weight of opinion. The history of failures in AD plants (Higham, 1997) suggest that this is a safer option, however, a preliminary calculation investigated how a longer lifetime would affect the economics of the project.

6 Results

6.1 Baseline Scenario

As seen below in Table 3, the baseline scenario does have a positive NPV with a 6% discount rate. However, for this level of risk, its IRR of 7.54% would not tempt many commercial investors. If the money needed to be borrowed from a bank, the interest rate may be higher than this return. The cost of capital for the company would therefore make enthusiasm for this project unlikely. In fact, the parent company of this farm demands a 39.5% annual return on investment, with payback within 3 years. This project has a yearly return of only 11.4%, and payback occurs in the 13th year. Therefore, although it is economically viable in the strict sense, with a positive NPV at 6%, it would be an unwise investment, especially given the considerable uncertainty regarding many of the variables, and the fact that the payback period is almost as long as the project's lifetime.

Table 3: The Baseline Scenario and its variations

	Baseline Scenario	20 year lifetime	without CHP unit	without separator	flat deck pipes
IRR	7.54%	9.51%	-0.69%	3.12%	6.51%
NPV 6%	13351	39294	-40687	-20627	5005
NPV 15%	-43694	-37613	-66280	-58182	-56677
Payback year	13	13	>20	>20	15

Figure 5: IRR and Payback Year of the Baseline Scenario and its Variations
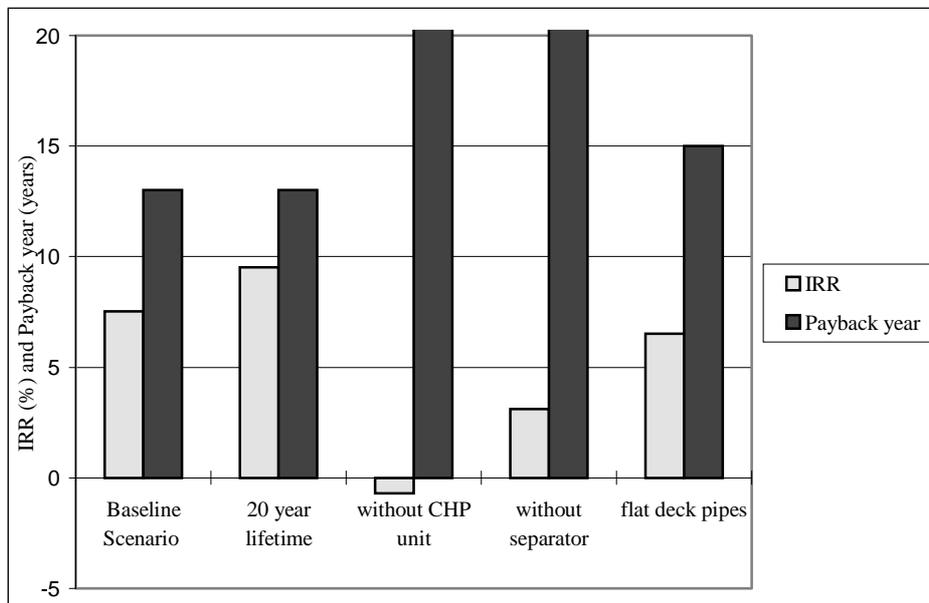
Figure 6: NPV at Discount Rates of 6% and 15% for the Baseline Scenario and its Variations
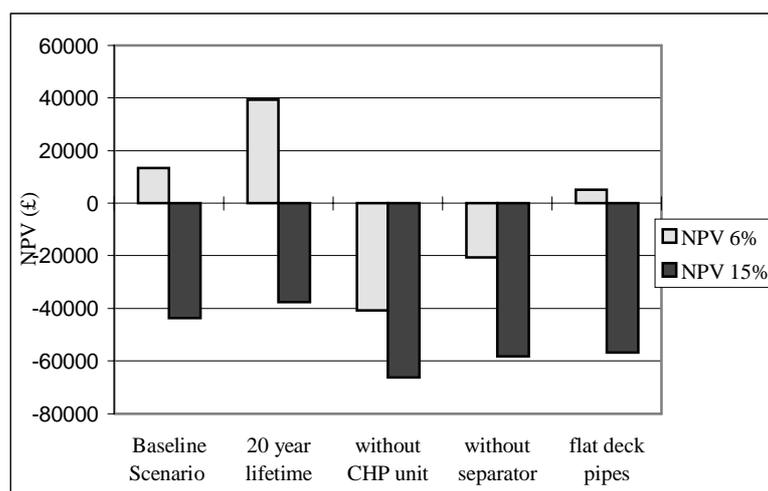
If the project lifetime was 20 years, the NPV at 6% is considerably greater, and the IRR is higher. All the other options had a negative impact on the overall result.

When a CHP unit is not purchased the reduction in annual benefits from no savings in electricity bills, are so significant that without them, the IRR after 15 years is negative. This means that payback occurs only in the 52nd year. Without electricity generation, full use cannot be made of the energy produced by the biogas, especially in the summer.

It was presumed that without a separator the digestate would have no value. As well as not benefiting from fibre sales, there would be less savings on the disposal of slurry. These significant benefits substantially outweigh the extra capital costs which are needed. The 15-year IRR for buying this equipment is 64.4%, and payback is in the 2nd year.

The small savings made from heating the flat decks with hot water do not justify the large capital costs involved. This is assuming that this heating will be completely covered from the generator's output. However, in the winter when the residential houses and the digester both have increased heating needs, this may not even be the case.

These results confirm that the options chosen for the baseline scenario were correct: To maximise the project's chances of success, a CHP unit and a fibre separator are needed.

6.2 Digester price

Scenarios 1a-f investigate the project sensitivity to changes in the price of the digester.

Table 4: Variations in digester price

	Scenario 1a	Scenario 1b	Scenario 1c	Scenario 1d	Scenario 1e	Scenario 1f
	50% MAFF grant	20% capital reduction	£85 000 digester	£105 000 digester	£150 000 digester	£300 000 digester
Cost of digester (£)	45000	64000	90000	105000	150000	300000
IRR	15.32%	11.37%	7.54%	5.83%	1.98%	-4.94%
NPV 6% (£)	58351	39351	13351	-1648	-46649	-196649
NPV 15% (£)	1306	-17694	-43694	-58694	-103694	-253694
Payback year (at 6%)	8	10	13	16	>20	>20

Table 4 and Figure 7 show that the project is quite sensitive to changes in its capital costs. The IRR is positive when the digester costs less than £200 000, although at this price, the NPVs are both negative. The NPV at 15% is negative for all values except for when there was a 50% grant. Even then, it value is only £1306, and payback occurs in the 8th year.

Figure 7 also shows that the NPV at 6% is only positive when the digester costs less than about £100 000. This means that without governmental support, only the very cheapest quote is in any way financially viable, unless other circumstances are different.

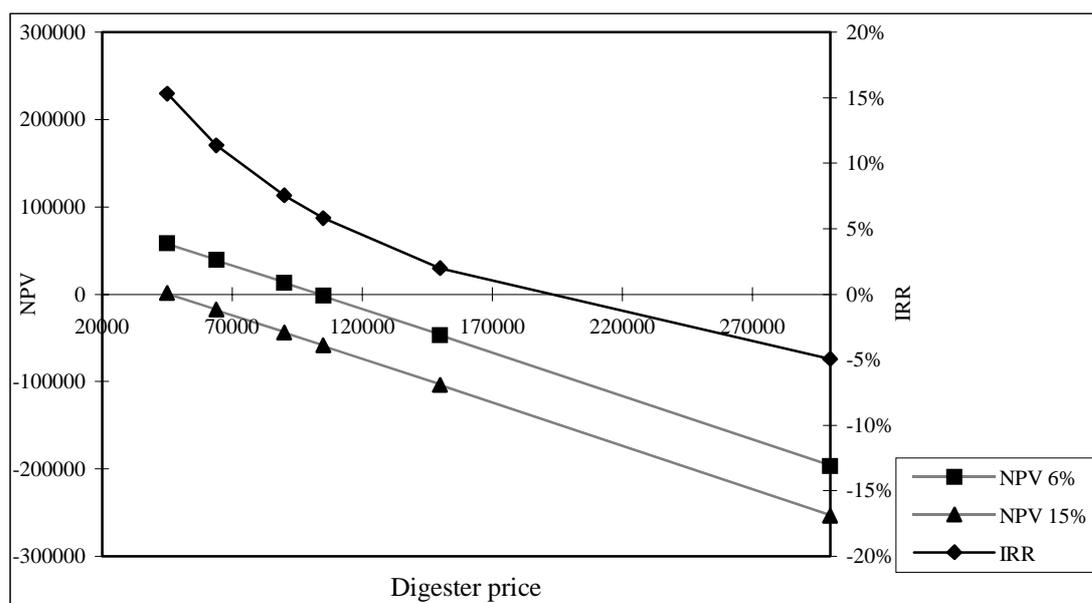**Figure 7: Cost of Digester Scenarios**

40

Table 4 and Figure 7 show that the project is quite sensitive to changes in its capital costs. The IRR is positive when the digester costs less than £200 000, although at this price, the NPVs are both negative. The NPV at 15% is negative for all values except for when there was a 50% grant. Even then, it value is only £1306, and payback occurs in the 8th year.

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6.3 Fibre sales

Scenario 2a-e involved examining how the results of the CBA changed according to fibre sales.

Table 5: Variations in fibre sales

	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 2d	Scenario 2e
Fibre cost (£)	0	5792	20685	72000	109500
IRR	-4.74%	4.12%	16.33%	49.62%	72.76%
NPV 6% (£)	-65583	-19428	125217	623604	987813
NPV 15% (£)	-85248	-76473	10612	310672	529948
payback year (at 6%)	>20	19	7	3	2

The smaller capital investment needed for scenario 2a did not make up for the lack of annual benefits from fibre sales. Scenarios 2b-2c had higher capital costs than the baseline scenario, due to investment in composting equipment. In scenario 2b, this extra investment did not pay off, sales were the same as the baseline, and the NPVs were both negative. Payback was longer than 15 years, but within a possible project lifetime of 20 years.

A more developed market for the fibre would have a great impact on the project's profits. The NPV at 15% is positive with sales above about £20 000. Scenario 2d, with sales proportionally similar to Roger White's, has a very healthy IRR which would mean a very attractive investment. Achieving the theoretical maximum profit from fibre sales is clearly unlikely, but if it were possible, the project would have a payback of just 2 years, with an IRR of 73%, and a NPV (6% discount rate) of nearly one million pounds.

Figure 8: Fibre Sales Scenarios
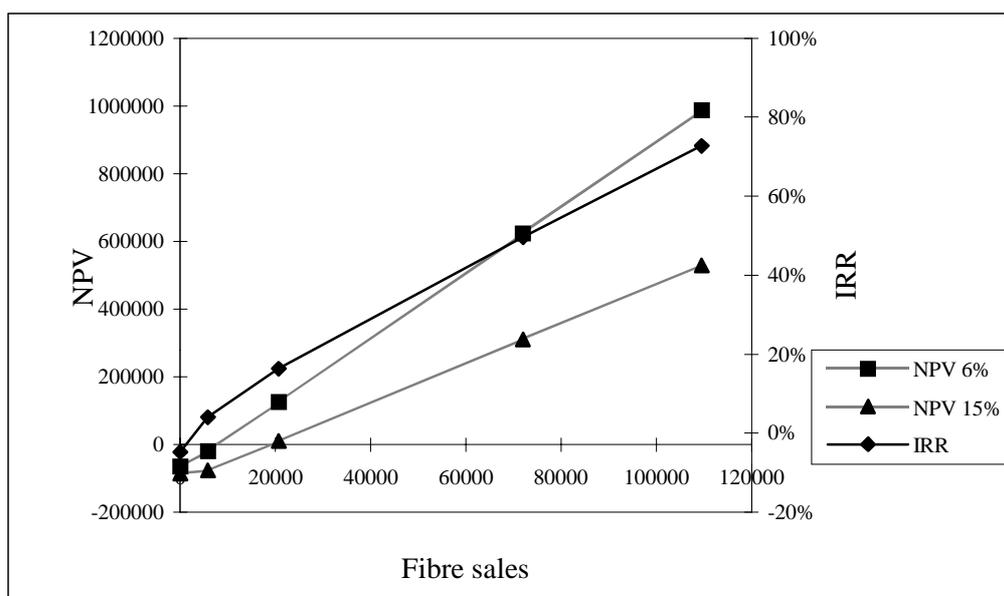
6.4 Operational costs

The effect of different running costs is examined by scenarios 3a-d. A variety of quotes for the yearly costs of repairs and maintenance had been given by equipment manufacturers and other sources. Figure 9 shows that the IRR is positive for all the situations, but the NPV at the 6% discount rate is only positive when costs are below £8000 a year. Under these circumstances, the NPV at the 15% discount rate is not positive whatever the running costs. The analysis is therefore not very sensitive to changes in operational costs.

Table 6: Variations in operational costs

	Scenario 3a	Scenario 3b	Scenario 3c	Scenario 3d
yearly costs (£)	2000	6200	7000	10000
IRR	12.66%	8.40%	7.54%	4.08%
NPV 6% (£)	61912	21121	13351	-15786
NPV 15% (£)	-14457	-39016	-43694	-61236
payback year (6%)	9	12	13	19

**Figure 9: Operational Costs Scenarios**
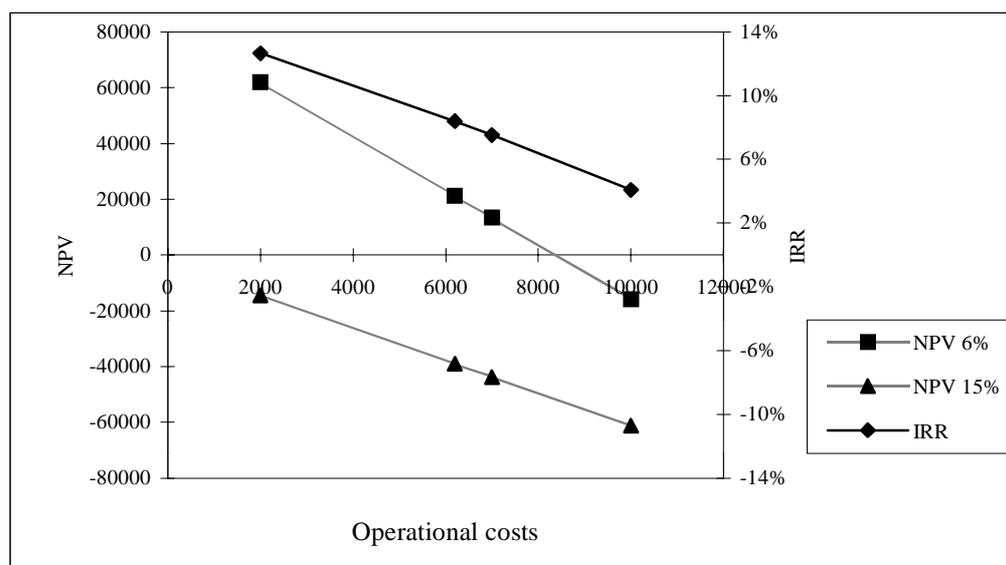
6.5 Variations in Slurry Disposal costs

Scenarios 4a-e feature different savings in contractors fees for slurry disposal. Scenario 4a shows that if no savings are made, then the IRR is only 2.02% and the NPVs are negative after 15 years at both 6% and 15%. Without a separator, it is possible that this might be the case, and even with a separator, little difference may be observed. Scenario 4b involves the saving made if the volume is reduced by only 9%. This is the lower estimate for the mass reduction of the digestate (ETSU, 1997, p22). Although strictly it is incorrect to assume that the mass balance can be directly used to predict changes in volume, the different savings in disposal costs here only give an indication to how the financial viability changes with decreasing costs. The actual savings chosen for the graph are not crucial. What can be seen from Figure 9 is that the project has a positive NPV at a 6% discount rate when savings rise above £3000. When there is a benefit of more than £12 000, the NPV at a discount rate of 15% is also positive.

Table 7: Variations in slurry disposal costs

	Scenario 4a	Scenario 4b	Scenario 4c	Scenario 4d	Scenario 4e
slurry disposal savings (£)	0	2215	4630	7000	25000
IRR	2.02%	4.79%	7.54%	10.04%	26.20%
NPV 6% (£)	-31617	-10104	13351	36369	211190
NPV 15% (£)	-70767	-57815	-43694	-29836	75417
payback year (6%)	>20	18	13	11	5

Figure 10: Slurry Disposal Scenarios
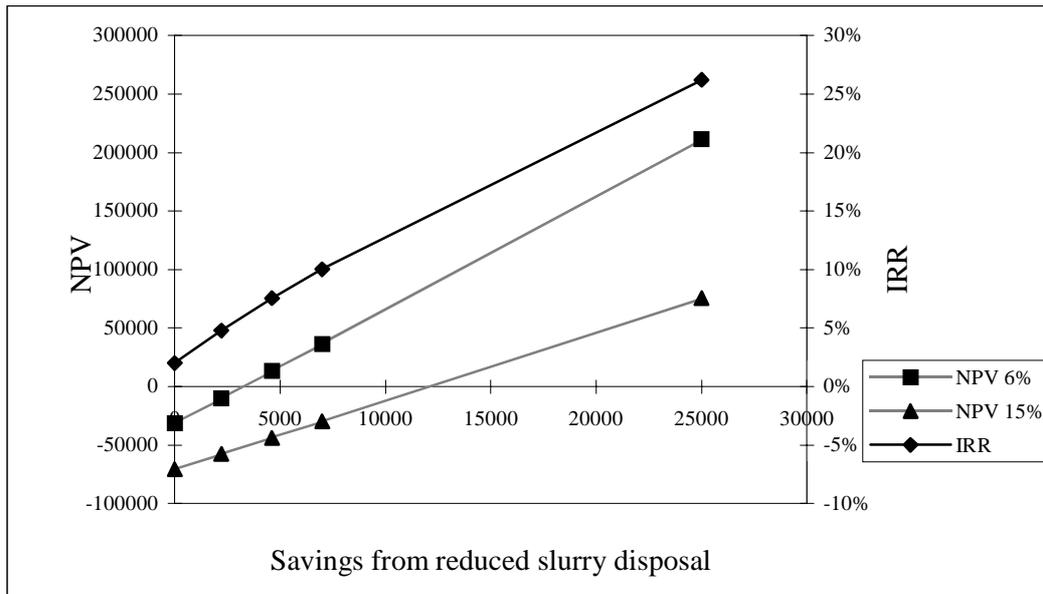
6.6 Gate Fees

Because the potential amount of money to be received in gate fees is not on the same scale as fibre sales, this analysis showed that the economics of the project were not particularly sensitive to these changes. Although the pasteuriser did pay for itself, and the IRRs are higher when one has been bought and waste is being accepted, they are still below 15%, and so the NPVs at this discount rate remain negative.

Table 8: Variations in money received as gate fees

	Scenario 5a	Scenario 5a	Scenario 5c
gate fees (£)	0	3000	6000
IRR	7.54%	9.08%	11.85%
NPV 6% (£)	13351	29988	59125
NPV 15% (£)	-43694	-38652	-21110
payback year 6% (£)	13	12	10

Figure 11: Gate Fees Scenarios
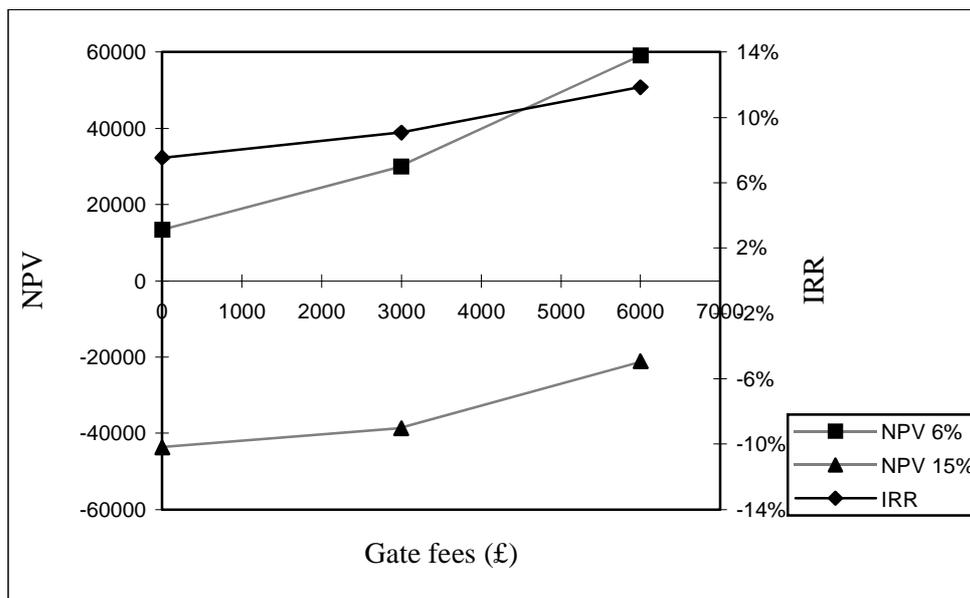
6.7 Efficiency of Bacteria

It can be seen from Figure 12 that these increases in efficiency increase the NPV and the IRR of the project. Scenario 6a is the same as the baseline. In scenario 6b, a 50% increase in the efficiency of the bacteria, has resulted in 468% increase in the NPV at a 6% discount rate. In scenario 6c, the IRR is just above 15%, so the NPV at this discount rate becomes positive near this point.

Table 9: Variations in the efficiency of bacteria

	Scenario 6a	Scenario 6b	Scenario 6c
bacteria efficiency (% VS destroyed)	40%	60%	70%
IRR	7.54%	12.72%	15.12%
NPV 6%	13351	62583	87199
NPV 15%	-43694	-14053	767
payback year (6%)	13	9	8

Figure 12: Bacteria Efficiency Scenarios
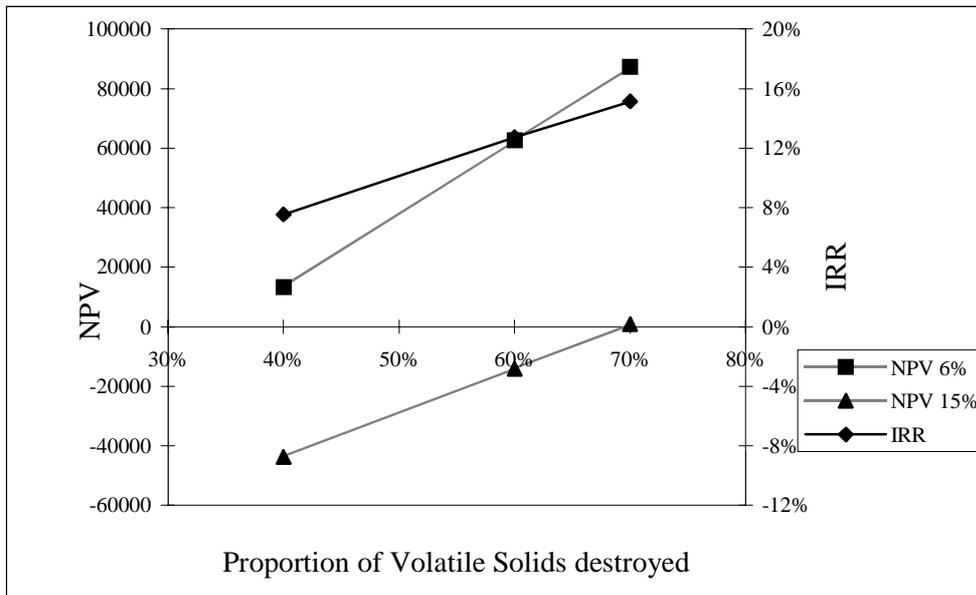
6.8 Electricity price

Table 10: Variations in electricity price

	Scenario 7a	Scenario 7b
electricity price (£)	0.0599	0.08
IRR	7.54%	11.08%
NPV 6% (£)	13351	46392
NPV 15% (£)	-43694	-23801
payback year	13	10

Scenarios 7a and 7b show how sensitive the project is to an increase in the price of electricity. If the price increased by just £0.0201, payback would occur in the 10th year instead of in the 13th. However, the IRR is still below 15%, and so does not make the project financially attractive.

Figure 13: Electricity Price Scenarios:
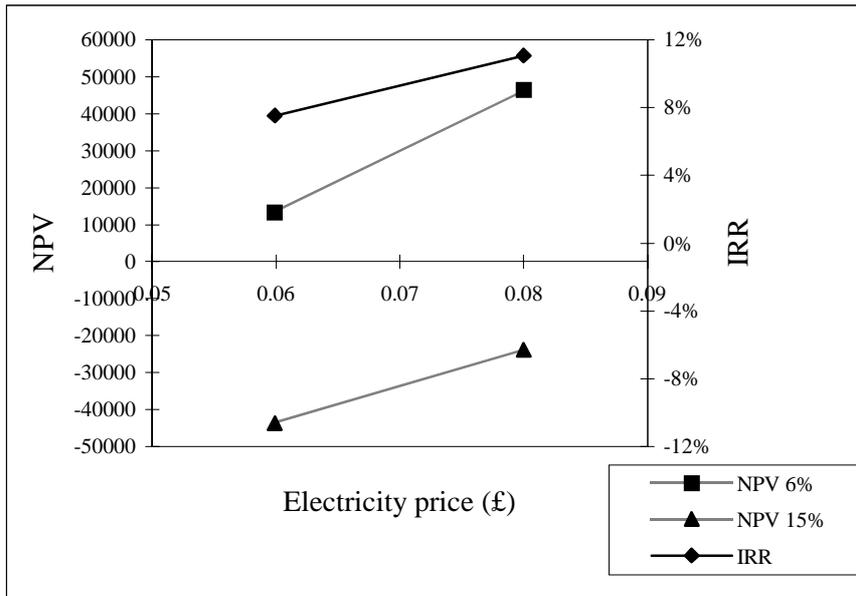
Part 2: The Environmental Benefits of Anaerobic Digestion of Pig Slurry Produced in Norfolk

7 Aim:

To investigate the environmental consequences of the digestion of Norfolk's pig slurry by calculating potential reductions in emissions of pollutants. To relate this back to the farm featured in Part 1, and to examine whether internalising the environmental benefits would change the economics of investing in a digester.

8 Method

The total environmental benefits from the digestion of pig slurry available from Norfolk farms of a suitable size were assessed. This was because, if the Government were to encourage AD, it might want to start in one area, where education and support could be concentrated and a market for the fibre could be developed. Therefore this study was done on a county rather than country scale. Norfolk has one of the highest densities of pig populations and a pilot study concerning agricultural waste gave an accurate figure for the quantity of pig slurry produced every year. This meant that it was an appropriate choice.

The MAFF June Census 1998 gave the proportion of animals on farms with less than 1000 pigs. This was deemed an appropriate threshold, because for smaller digesters, economic and energy costs per m^3 of digester are higher. The slurry from the smaller farms was not counted in the calculations regarding pollution savings.

The following benefits were quantified for Norfolk and for the individual farm:

- reduced emissions of CO_2, and SO_2 through the production of electricity from a renewable source instead of from fossil fuels.
- reduced emissions of N_2O, CO_2, and SO_2 from savings in the use of fertiliser.
- reduced CH_4 emissions from containing releases from slurry storage.

8.1 Emission Reduction from Electricity Generation: Method

The electricity that could be produced from the available quantity of slurry was determined using the first method from Part 1. The Digest of UK Energy Statistics (DUKES, 1999 p265)

gives the emissions of CO_2 and SO_2 for different types of power stations. It was assumed that coal-fired power stations would be the first to come off line as more electricity from renewable sources becomes available, so emissions from that source were used. The same assumption is used in Centralised Anaerobic Digestion, Review of Environmental Effects (Tipping, 1996). The data given in DUKES was for GJ of coal consumed rather than electricity produced. Therefore emissions were divided by the efficiency of a modern coal-fired power station, and multiplied by 3.6 to obtain values per MWh of electricity produced by Norfolk's slurry and by the farm.

Permit prices in BP Amoco's pilot internal CO_2 trading scheme have averaged \$20 (£12.44) per tonne. This value was used to put a price on the savings in CO_2 emissions. A report by the energy consultancy Ilex was roughly in agreement with this figure, stating that when international trading begins, (expected to be in 2008) a possible range of permit prices will be \$10-20 (£6.22-12.44) per tonne (ENDS, August 1999). It was not possible to find a value for the saving in SO_2 emissions.

8.2 Emissions Savings from Reduced Fertiliser Use: Method

The nitrogen content of the total slurry available for digestion in Norfolk and on the farm was calculated. A commercially undertaken analysis for the farm gave the nitrogen content as 3.9 kg/1000 kg. When manure is stored in the best possible manner to minimise losses, the nitrogen content is 4.5 kg/1000 kg (Irish Department of Agriculture and the Environment cited by Heslop, 1999). Therefore the former figure was used for the farm, and the latter number was optimistically used for Norfolk's total slurry.

Trials on cereals showed that undigested slurry had a nitrogen efficiency of 35-42%, and digested slurry had an efficiency of 79-101% (Klinger, 1999). This is a measure of how many kg of mineral fertiliser nitrogen would be needed to replace 100kg of total nitrogen in digested slurry. In field trials conducted by Ørtenblad, the nitrogen efficiencies of digested slurry applied under various conditions ranged from between 22% to 80%. The majority were between 50 and 70% (Ørtenblad, 1999). The results quoted by Klinger may therefore have been unusually high. The lower result for undigested slurry from this trial is used with an estimate of 70% efficiency for digested slurry. It is acknowledged that these two numbers do not have a large degree of scientific backing, but there have been few studies in this area.

The amount of synthetic fertiliser that is not used due to the increased efficiency of the digested slurry is determined by multiplying the difference in efficiencies with the total nitrogen content.

A local fertiliser supplier was telephoned, and the price per tonne of nitrogen was used to find out the economic savings resulting from the presumed reduction in fertiliser purchases. This information was used to consider how the economic situation would differ for the farm in Part 1 if it were paid for avoided fertiliser purchases.

A communication from MAFF indicated that the quantity of nitrogen fertiliser in tonnes applied should be multiplied by 0.0297 to obtain N_2O emissions, also in tonnes (Wilkins, pers comm). The global warming potential (GWP) of the N_2O is 310 times that of CO_2 over a hundred years (IPCC, 1995). The market value of the CO_2 equivalent was calculated according to the BP Amoco CO_2 trading price.

To produce 1 kg of nitrogen as inorganic fertiliser, 2 kg of mineral oil is needed (Haber Bosch System, cited in Klinger 1999). Although this is perhaps not a very precise figure, the energy value of oil is taken from DUKES to be 43.2 J/tonne (1999, p277), and the reduction in emissions from the decrease in demand for the energy-intensive production of fertiliser is considered.

8.3 Reductions in Methane Emissions: Method

When pigs are kept in outdoor accommodation, their waste is spread on the ground, and aerobic decomposition usually predominates. However, in intensive farming systems waste is stored in tanks and lagoons in liquid form. Their anaerobic conditions generally prevail, and methane is evolved.

Two factors can mitigate these emissions: Methane evolution can be avoided by ensuring that there is aerobic decomposition of the waste, or the methane can be contained and converted into CO_2. "Cost Effectiveness for Reducing UK Methane Emissions" reports that farm scale AD can reduce emissions by 20-50% (Meeks *et al*, 1999, p41). This is assuming some emission of methane due to further decomposition of the digestate on removal from the digester.

Meeks *et al* also give the annual CH_4 emissions arising from pig waste. The majority of these emissions are from slurry based systems (p39). Data about the proportion of pigs on slurry and

straw in different regions in England and Wales show how the percentage of its pigs on straw systems in East England compared to the rest of the country. East England was defined as the East Midlands, East Anglia and the South East. Data were available concerning the numbers of weaners and finishers in different types of housing. A weighted average was calculated to find the contribution Norfolk's slurry makes to the UK's total. This was because there was no record for Britain's total production of slurry, so the proportion of the UK's CH_4 emissions had to be calculated per pig on a slurry based system, rather than per m^3 of slurry. The weighted average took weaners to have a mean mass of 12.75 kg, and finishers to have a mass of 70 kg. This followed information from the farm visit, that weaners are 5.5-12 kg, and finishers are 35-105 kg. The number of pigs nation-wide housed with partly or fully stated floors was found by this weighted average, and this was used to find the average CH_4 emission per pig on a slurry based system. This was then applied to find the emissions for Norfolk pigs in slurry systems, and for the farm.

The GWP of CH_4 is 21 times that of CO_2 over 100 years (IPCC, 1995). The value of the CO_2 equivalent emissions reductions was determined using the previous method.

8.4 Cost-Benefit Analysis with Internalised Environmental Benefits: Method

The monetary value of the emissions savings was included in CBAs to examine whether internalising the environmental benefits greatly affects the viability of a digester at the farm in Part 1.

Due to the lack of confidence in the value of the energy needed to produce nitrogen fertiliser (see 8.2), two CBAs were undertaken. Scenario 8a refers to CO_2 reductions from electricity generation, methane reductions from containing releases, and N_2O reductions from decreased fertiliser use. In addition to these, scenario 8b refers to CO_2 reductions from decreased fertiliser production.

8.5 Cost Effectiveness of Digesting Norfolk's Slurry: Method

The costs of installing digesters at all the slurry-based pig farms in Norfolk with over 1000 pigs were put into a CBA along with running costs, economic and costed environmental benefits.

The proportion of farms with over 1000 pigs (MAFF, 1998), was multiplied by the number of pig farms in Norfolk. It was presumed that the proportion of large farms would not be

significantly different on the county level. Less than half of farms are slurry-based, (Dunnings, pers comm) so this number was then divided by two. This assumption is contradicted by the results from section 9.4, where it was found that less than 25% of pig waste from weaners and finishers in East England is in slurry form, compared to a 40% national average. However, although this indicates a smaller percentage of farms have slurry-based systems, it is not clear from these data how many. The assumption of digesters on 50% of Norfolk's pig farms with over 1000 pigs, is more cautious than the more favourable finances of supposing that this slurry could be digested in fewer, larger AD units.

The size of the digesters were calculated with the same method as in Part 1. It was assumed that this slurry also had 5% TS, and 75% VS. Although the digesters may vary in size between farms, the costs involved are mostly for the infrastructure, and so capital would be similar for each farm. An extra digester capacity of $100m^3$ would cost an additional £3-4000 (Mees, pers comm, confirmed by Heslop, pers comm). Mass production could significantly reduce the capital costs of the digester. Heslop has done some work in this field, and her figures for mass-produced $100m^3$ digesters are used in this situation, with an extra £4000 per $100m^3$ capacity.

The annual benefits for different farms could vary considerably, so fewer assumptions could be made. The farm in Part 1 had high slurry disposal costs because it was situated in a NVZ. Other farms may have a far smaller expenditure in this area. Forty per cent of farms in Norfolk are arable (Dunnings, pers comm), so they would directly benefit from the pumping rather than spreading of the slurry. However, it was not possible to assume by how much.

Energy needs also vary greatly between farms, particularly between those with different types of accommodation. Slurry-based systems use more energy for heating, so it was assumed that all these farms, like the farm in Part 1, would be using all their electricity produced at peak time rates. Farms are indeed likely to use all the energy produced by a biogas plant (Chesshire, pers comm). Data could not be found regarding the hot water needs of farms, or how many had residential houses nearby. Due to the higher infrastructure costs, less than 5% of farms have hot water pipes heating farrowing sheds and flat decks. This proportion is decreasing (Dunnings, pers comm). Therefore, although CHP units were used, and advice is that these are only viable when there is a heat sink (Betamy, pers comm), savings from heating were not costed in.

The presence of a number of digesters in Norfolk would increase awareness and the likelihood that businesses and Local Authorities would choose to dispose of their inorganic waste through paying farmers gate fees. However, because this system is not yet in place, too many uncertainties surround it. Therefore potential revenues from this source were not included.

The value of the fertiliser that the improved digestate could replace was calculated, and the 40% of this arising on farms with arable land was included.

Fibre sales were calculated in the same way as the baseline calculation for Part 1. It was assumed that 7% of the mass of the slurry would end up as fibre worth £10 per tonne.

Operational costs were taken as £7000 per year, as in Part 1.

A CBA was first done for the internal costs and internal benefits for the farmers (Scenario 9a). This was repeated as scenario 9b, with a 50% grant for the capital costs. Lastly, scenarios 9c and 9d were done for a government program, which paid for 50% of these capital costs, and benefited from the external factors of pollution reduction. Scenario 9c did not include the benefit from the reduction in fertiliser production, while scenario 9d did.

It was not possible to place a monetary value on many things, besides the SO_2 emissions already mentioned. The only article to be found regarding willingness to pay for avoided odour nuisance, was about diesel odour in an urban area in the USA. The study found that the average household would be willing to pay $75 a year to completely avoid all exposure to diesel fumes (Lareau *et al*, 1989). It was decided that given the differences in circumstances, it would not be appropriate to apply the findings of that study to this project.

The savings in fines due to water pollution from pig slurry were also considered. Only one pig farmer was fined for pollution during 1999. The fine amounted to £2860.74, and was for two incidents at £1000 each, and court costs (Aylward, pers comm). The limited nature of this information meant that it was very unlikely to truly represent the monetary value of water pollution in Norfolk by pig slurry. Therefore these costs could not be included in this section.

9 Results

9.1 Quantity of Available Slurry: Results

The MAFF June Census 1998 showed that 20.1% of pigs lived on farms that had under 1000 pigs. The proportion of pigs in indoor accommodation from farms with under 1000 pigs is very similar to the overall average. The smaller farms have 89.8% and 99.7% respectively of weaners and finishing pigs inside. The overall averages are 90.2% and 99.5%. Given this marked similarity, it seems a fair assumption that the proportion of farms using slurry based or straw based waste management systems will not radically contrast for differently sized businesses.

Therefore of the 786425 m^3 of pig slurry produced in Norfolk every year, (BDB Associates, 1998) 79.9% is available for digestion on farms with more than 1000 pigs. This gives a quantity of 628417 m^3.

9.2 Emission Reduction from Electricity Generation: Results

Table 13: Emissions of pollutants from coal fired power stations

	Emissions from coal-fired power stations, tonnes/MWh
CO_2	0.8684.
CH_4	0.0002
SO_2	0.0083
Black smoke	0.0006
NOx	0.0025
VOC	0.0002
CO	0.0023

Table 13 shows the emissions of various pollutants by MWh of electricity. The quantity of pig slurry generated in Norfolk could produce 12820 MWh of electricity every year. If this displaced production from coal-fired power stations, this would translate into a reduction of 11133 tonnes of CO_2 and 106.9 tonnes of SO_2. The CHP unit on the farm could produce 169.3 MWh of electricity per year. This would save 146.9 tonnes of CO_2 emissions, and 1.4 tonnes of SO_2.

At £12.44 per tonne of CO_2 saved emissions, avoided CO_2 from Norfolk's biogas production is worth £138 493, and from the farm's is worth £1828.

9.3 Emissions Savings from Reduced Fertiliser Use: Results

Table 14: Yearly savings from the reduction in N_2O emissions from reduced fertiliser use

	Norfolk	Farm
slurry (m^3)	693627	8297
nitrogen content of slurry (kg N)	3121321	32357
synthetic N equivalent of undigested slurry (kg N)	1092462	11325
synthetic N equivalent of digested slurry (kg N)	2184925	22650
saved application of synthetic N (kg)	1092462	11325
money saved (£)	88489	917
N_2O saved (tonnes)	32	0.34
CO_2 equivalent (tonnes)	10058	104
Value of CO_2 savings (£)	125125	1297

As described in the method, the nitrogen content of the slurry is between 3.9% and 4.5% by mass. The potential savings in synthetic fertiliser was the difference between the available nitrogen in undigested slurry, and that which had been made available by digestion. This difference (70% - 35% N efficiency) was equivalent to 35 kg of synthetic nitrogen per 100 kg of nitrogen in the slurry. At £81/tonne (/1000 kg), this reduction in fertiliser use would be worth £88 489 for Norfolk, and £917 for the farm in Part 1 if it were paid by the arable farmers accepting the slurry.

This saving in fertiliser use would reduce emissions of N_2O by 32 tonnes in Norfolk and 0.34 tonnes from the farm's slurry. Although this does not seem like a large quantity, the high GWP of N_2O (310 tonnes that of CO_2) means that this is worth £125 125 in Norfolk, and £1297 for the farm.

Table 15: Yearly savings from the reduction in CO_2 emissions from reduced fertiliser production

	Norfolk	Farm
saved application of synthetic N (tonnes)	1092	11.3
GJ saved	94389	978
MWh saved	339799	3522
Reduced CO_2 emissions (tonnes)	295089	3059
Value of CO_2 savings (£)	3670907	38054

One tonne of nitrogen fertiliser needs 86.4 GJ to produce it. (Twice the mass of oil is needed to produce the fertiliser, and the calorific value of the oil is 43.2 GJ/tonne - see method.) Therefore the energy saved by the annual reduction in fertiliser production was 94389 GJ for Norfolk, and 978 GJ for the farm. Reduced CO_2 emissions were calculated in the same way as in section 7.1. These were considerable, and had a value of £3.7 million for Norfolk, and £38 054 per year for the farm.

9.4 Reductions in Methane Emissions: Results

Table 16: Numbers of pigs on straw and slurry

	In Britain	In East England
Weaners on straw	656464	381736
Weaners on slurry	927597	304527
Finishers on straw	1549783	928303
Finishers on slurry	871743	259841
% Weaners on slurry	0.586	0.444
% Finishers on slurry	0.360	0.219

Table 15 shows that East England has a higher proportion of pigs on a straw-based system. The weighted average suggests that about 40% of waste from pigs in Britain is slurry and contributing to CH_4 emissions, compared to 25% in East England:

$$(58.6 \text{ x } 12.75 + 36.0\% \text{ x } 70)/82.75 = 39.5\%$$

$$(44.4\% \text{ x } 12.75 + 21.9\% \text{ x } 70)/82.75 = 25.4\%$$

The annual emission of CH_4 from the pig in the UK is 22500 tonnes (Meeks *et al*, 1999, p39). According to the MAFF June 1998 Census, there are 8 101 575 pigs in the UK. This means that the average emission per slurry producing pig is:

$$22500/(8101575 \times 39.5\%) = 0.00703 \text{ tonnes per year}$$

There are 714105 pigs in Norfolk (MAFF June 1997 Census). The 25% of these producing slurry will be responsible for the following amount of CH_4 emissions:

$$714105 \times 25.4\% \times 0.00703 = 1275 \text{ tonnes per year}$$

The slurry from the 8500 pigs on the farm will emit:

$$8500 \times 0.00703 = 59.8 \text{ tonnes per year}$$

A discrepancy was found when comparing this result to an alternative method. The proportion of Norfolk's slurry produced at the farm (1.06%) was very similar to its proportion of Norfolk's pigs (1.19%). In fact, it produces less slurry per pig than the average for Norfolk. This is surprising considering few of the pigs on the farm are on straw, while more than half of the pig farms in Norfolk produce no slurry (Dunnings, pers comm). Either one or both of the slurry estimates are inaccurate, or other farms in Norfolk are much less efficient at keeping water out of their slurry. If it is assumed that all pigs in the UK contribute equally to the emissions, then the average per pig would be:

$$22500/8101575 = 0.00278 \text{ tonnes per year}$$

and the emissions that the farm is responsible for would be:

$$8500 \times 0.00278 = 23.6 \text{ tonnes per year}$$

Between 20-50% of the CH_4 that would otherwise be emitted can be contained by AD (Meeks *et al*, 1999, p41). With Centralised AD, this can be increased to 50-70% if there was containment and collection of biogas that continues to be produced by the digestate. This is not as feasible for a farm scale digester - it is more likely to occur with CAD when economies of scale make post-digester collection more worthwhile.

Table 17: Annual methane emission reductions

	Norfolk	Farm
Emissions (tonnes per year)	1275	59.8
50% of this - potential saving	637.5	29.9
CO_2 equivalent	13388	628
Value of CO_2 saving (£)	166541	7811
20% of this - potential saving	255	12.0
CO_2 equivalent	5355	251
Value of CO_2 saving (£)	66616	3124
Average potential saving	446	20.9
CO_2 equivalent	9371	440
Value of CO_2 saving (£)	116578	5468

It can be seen that for the farm this has a more significant value that savings in CO_2 and N_2O emissions. However this calculation had a greater likelihood of inaccuracy. A variety of sources used for the data. The use of successive MAFF June Censuses for the numbers of pigs would not have had significant effect, but the application of data about straw and slurry accommodation in England and Wales to the whole of the UK, may have done. This measure may have also led to inaccuracy because data were only available for weaners and finishers, and these proportions were then applied to all ages of pigs.

9.5 Cost-Benefit Analysis with Internalised Environmental Benefits: Result

**Table 18: Variations when environmental benefits are internalised**

	Baseline Scenario	Scenario 8a	Scenario 8b
IRR	7.54%	16.87%	47.81%
NPV 6%	13351	105721	475311

NPV 15%	-43694	11918.3	234434
Payback year	13	7	3

Figure 14: Variations in IRR and Payback year when environmental benefits are internalised
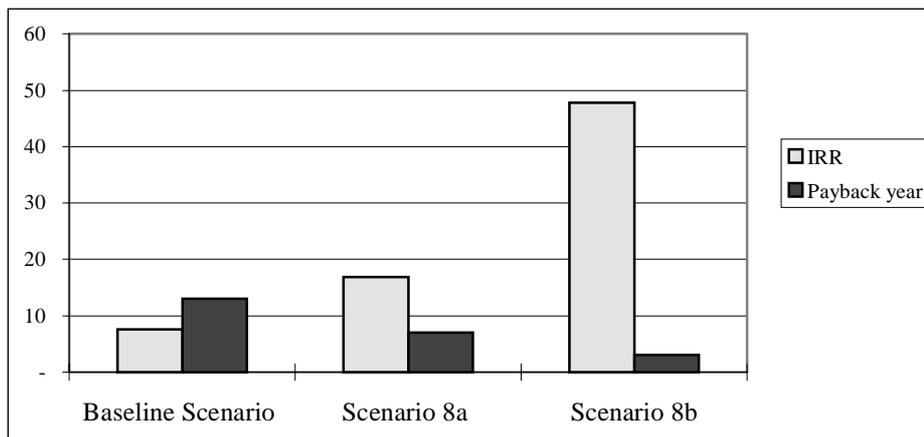
Figure 15: Variations in NPV at 6% and 15% discount rates when environmental benefits are internalised
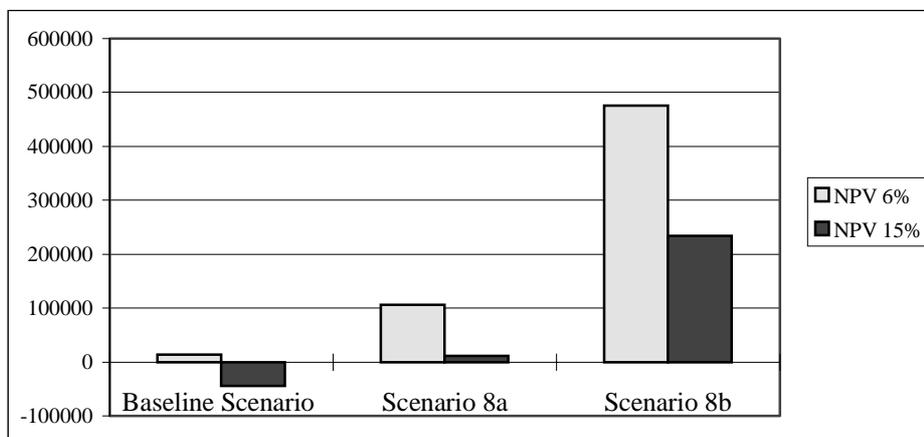
Figures 14 and 15 show what a large difference the internalisation of environmental benefits would make to this project. Even in scenario 8a without taking into account the reduction in emissions from less fertiliser production, there is a marked increase in the IRR from 7.5% to 16.9%, and the NPV at 15% becomes positive. The payback reduces from 13 years, to just 7.

Scenario 8b shows that when these energy savings from reduced production of fertiliser are included, the IRR increases to 47.8%, and payback takes only 3 years. Therefore, if this

theoretical internalisation were possible, this project would be very attractive, with a NPV at 6% of almost half a million pounds.

9.6 Cost Effectiveness of Digesting Norfolk's Slurry: Results

The 1998 MAFF June census shows that nationally, 8262 pig farms have less than 1000 pigs, and 1945 farm have more. If this percentage was translated to Norfolk's 621 pig farms, and divided by two for slurry-based farms, 59.2 farms are suitable for digesters. Therefore, the capital costs of £126 500 were multiplied by 60.

Table 19: Internalised environmental benefits for digesting Norfolk's slurry, at the farm

	Scenario 9a	Scenario 9a per farm	Scenario 9b	Scenario 9b per farm	Scenario 9c	Scenario 9d
IRR	6.80	6.80	20.3	20.3	107	5.58
NPV (6%)	405012	6750	4200012	70000	35550334	-102432
NPV (15%)	-2776512	-46275	1018488	16975	19893306	-1571848
payback year	14	14	6	6	1	16
payback year 15%	9	9	>20	>20	2	>20

Figure 16: IRR and Payback Year of Digesting Norfolk's Slurry, with Internalised Environmental Benefits Included to Different Extents
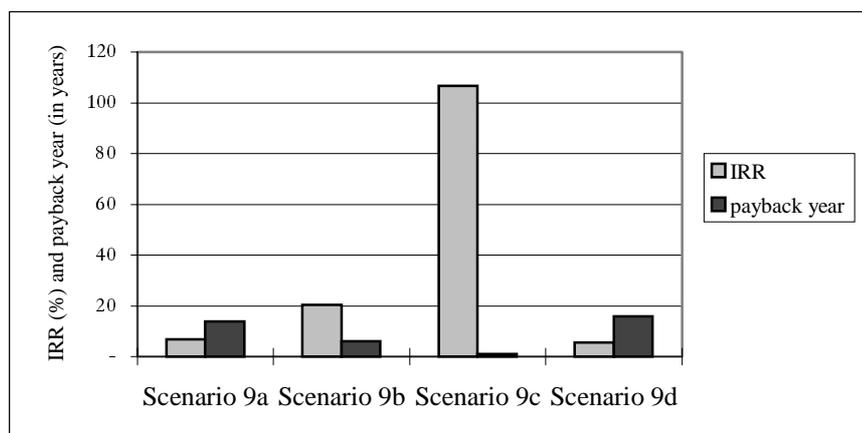
Figure 17: NPV at 6% and 15% Discount Rate of Digesting Norfolk's Slurry, with Internalised Environmental Benefits Included to Different Extents
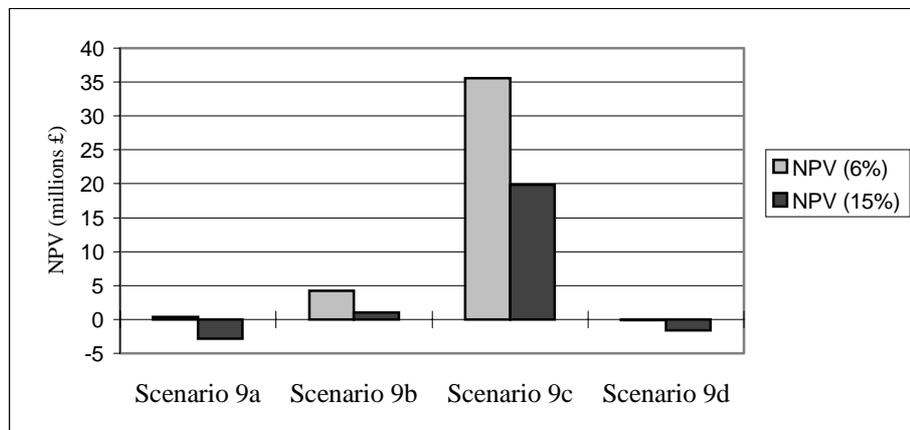

Table 19 and Figures 16 and 17 show the costs of digesting Norfolk's slurry under certain scenarios. Scenario 9a shows the internal costs and benefits for the farms. Because there were so many uncertainties regarding what benefits were applicable for all the farms, and so many were not included, the IRR is lower than the baseline scenario for the farm in Part 1, and payback is one year later. In 9b, with a 50% grant, this project would be viable for farms, with a positive value even at a 15% discount rate. Payback is within 6 years, which may tempt some farmers, especially given the other benefits.

When the emissions savings from decreased fertiliser production are taken into account, payback is within one year, and the NPV at 6% is over £3 million pounds. However, without this factor with its high degree of uncertainty, payback is only within 16 years – longer than the project's potential lifetime.

10 Discussion

The results show that for Part 1, taking the most realistic estimates, the project is viable if the cost of capital for the farm is less than the discount rate of 7.54%. This is most sensitive to the yearly revenue from fibre sales. The conservative estimate for these sales in the baseline scenario was less than the £14 000 which Roger White makes, with a farm a fifth of the size. A more developed AD industry would lead to greater awareness and acceptance of this product, which could increase profits and ease of marketing. Good fibre sales were the only way in which the payback period of 3 years that the parent company demands could be met. The project was also sensitive to the slurry disposal costs. If the liquid fertiliser ceased to have a negative value, this target could almost be reached, with a payback of 5 years. The situation would improve further if it had a positive value, but it would be difficult to market due to transport costs.

All the results would have appeared more favourable if a project lifetime of 20 years had been used. It is probable that the digesters would last this time, but 15 years was a safer estimate given the risks involved. Of the 45 units installed since 1975, only 25 are still operating. Some of the most common problems have been an inability to maintain a mesophilic temperature during the winter months, pipe blockages, digester pH instability and equipment failures. The two main causes of these problems have been inadequate design and lack of operator training.. Both of these problems are relatively avoidable, and farmers who still have plants find that they are running reliably. However, these past failures mean that AD has a bad reputation (Higham, 1997).

The economic situation is far from ideal for AD, given low electricity prices for renewable energy and an undeveloped market for fibre sales. The cost of taking out a loan or using money from the parent company was not investigated for this project, but are crucial to whether a project can be accepted. However, other barriers to the technology's dissemination also exist. These include social and technical factors and a lack of information. Social factors relate to a lack of enthusiasm for, and confidence in this technology. The two main causes of failure mentioned in the above paragraph both relate to a lack of technical expertise in this industry, although this situation is improving. This study showed a reasonable rate of return for this farm, although it does not benefit from some of the products of AD. Other farms could benefit greatly through avoided contractor costs by being able to pump the liquid fertiliser through

their irrigation equipment, and by the improved fertilising quality of the digestate. There is scope for an AD unit to be a sound investment for certain farms in the UK, and the fact that they are not being built, suggests a lack of information.

The calculations in Part 2 were on a theoretical rather than practical basis. It might never be practical to involve small businesses such as this pig farm in carbon trading. The environmental benefit that contributed most to the very high NPV in scenario 9d was the savings of CO_2 emissions from reduced fertiliser production. This relies on the assumption that farmers will decrease their use of inorganic fertiliser according to the increase in efficiency of the digested pig slurry. For this to happen, the government would need to carry out field trials about exactly how much the nitrogen efficiency improves by. Even with greater knowledge of this issue, farmers may be resistant to changing their behaviour, especially because the effectiveness of the liquid fertiliser will always be less predictable than mineral fertilisers. Inorganic fertilisers may be seen as more reliable and convenient, and it may still be in the farmer's financial interest to overapply nutrients to crops when fertiliser prices are low, the and there is a chance that underapplication will result in a poorer yield. Therefore the assumption regarding a decrease in fertiliser use will only become a practical reality with education of the farming community, or perhaps even legislation.

Part 2 does show, however, that if the government reinstated its 50% grant, economic conditions would be favourable for farms to invest in digesters. Taking into account some of the environmental benefits, this could be a very beneficial move for the Government to make. It is rare that an investment could have such an impressive return, with payback in just one year.

It was not possible to do a energy life cycle analysis of all the consequences of the digestion of Norfolk's pig slurry. Many factors were not taken into account in the calculations. It was not known how much energy is required to build the digester and its associated parts, although the AD-NETT website states that it requires less energy per unit produced than other sources of electricity. The 12.8 GWh that this AD on 60 pig farms could produce a year is not a large proportion of Norfolk's energy, but any production of renewable energy can be seen to displace the need for building new power stations, which have their own associated energy and financial costs.

Due to the uncertainty regarding what effect digestion may have on reducing the transport costs of the slurry disposal in Part 1, the environmental benefits that might result from this

were not calculated. There is also doubt about the effect that digestion would have on ammonia emissions and nitrate pollution of water. AD can help in the control of both factors, but other management techniques have a greater effect, so these were not accounted for.

The reduction of CO_2 emissions from using the heat from the CHP plant was not calculated, because it was considered a less important part of the environmental benefits, and as mentioned previously, the extent of the use of this energy was difficult to investigate.

A deeper investigation could look into more of these factors, although it is believed that the major ones are covered in this project, and a more in-depth analysis of these more minor factors would not significantly alter the results.

There was not a high level of accuracy for the estimates of heating needs of the farm. Quotes for equipment given by manufacturers were also not precise. However, it was considered that a high degree of precision was not appropriate for this study, especially given the rapidity in which each situation could change.

Because this project was of a more practical nature, it was not possible to rely on information given in published papers. It might not always be acceptable to rely on material from websites and personal communications. However, the websites referred to contained information by published authors and experts in the field, as well as those with practical rather than academic experience.

AD is typical of a renewable energy with proportionally high capital costs, which is negatively affected by high discount rates. There is an argument for applying negative discount rates to renewable projects. The logic is that a certain quantity of coal now, could be converted into a greater amount of useful energy if this was done with more efficient future technology. Applying this rate would mean that the significant decommissioning costs for nuclear power eliminates this option, and fossil fuel projects become more expensive. This means that renewable energy is given an economic advantage (Tovey, 1998).

However, this option goes against normal economic reasoning. A more feasible approach may be to pursue the internalisation of environmental costs and benefits. This has largely been done with nitrate pollution, where EU directives have placed more responsibility on the farmer. This tool of environmental economics is soon to be applied to major CO_2 producers, with the government's climate change levy. This will impose a price on emissions of CO_2, although it

will always be difficult to ascertain whether this market price reflects the true environmental costs.

AD may well have a place in this country's move towards sustainable development. It promotes economic, environmental and social development. It treats waste near the source, in line with the government's proximity principle, and returns nutrients back into the system, closing a cycle that would otherwise demand more inputs and create more outputs.

Although it is more economically viable at bigger farms, some market forces have worked against a greater implementation of AD in the livestock industry. The specialisation of farming, and the move away from traditional mixed farming systems, mean that farms will not themselves benefit from the improved fertilising quality of the digestate. Fewer farms are family owned and part of the rural community. One of the main motivations for investing in a digester is reducing the odour problem and improving community relations (Murcott, pers comm). This will inevitably be less of a priority for commercial farms whose owners have less of a sense of responsibility to the neighbours.

However, it is also argued that AD of agricultural waste is not completely in tune with sustainability because of its link to relatively intensive farming (Aubrey, 1998). Another trend which will work against the widespread implementation of AD in the pig industry, is the move away from slurry-based systems. This is due to perceived animal welfare issues, and has the advantage of a lower energy use for the farm. These trends could mean that there may not be a large resource base in the future for AD.

11 Conclusion

This study supports the hypothesis that although AD is not a financially attractive option for most farm owners today, it has a range of environmental benefits for society which have a significant value. It was only possible to put a market price on greenhouse gas emissions, which may not truly reflect the real value to the environment. With some of the environmental benefits internalised, the Net Present Value of the project at both the farm and the county level, increased considerably. Therefore it is concluded that the government should attempt to correct the market failure caused by the external costs of pollution being borne by society rather than the polluter. This could be done by reinstalling the 50% grant that had been provided by MAFF.

12 Afterword

This project presented more of a challenge than I had expected. The pig farm I had originally made an arrangement with, pulled out after I had spent a month preparing for the visit. The values needed for many of the calculations were not readily available in published form, as I had hoped. In fact, very little was published in this area to give me some guidance.

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14 Glossary

AD	Anaerobic digestion
BMW	Biodegradable Municipal Waste
BOD	Biological Oxygen Demand
CBA	Cost Benefit Analysis
CHP	Combined heat and power
DETR	Department of the Environment, Transport and the Regions

Discount rate - the rate at which money depreciates in value, taking into account

DTI	Department of Trade and Industry
ETSU	Energy Technology Support Unit; manager of the DTI's New and Renewable Energy Program
EU	European Union
GWP	Global Warming Potential
IRR	Internal Rate of Return - the discount rate at which the Net Present Value (NPV) is zero.
KWh	kilowatt hour
MSW	Municipal Solid Waste
NFFO	Non-Fossil Fuel Obligation
NPV	Net Present Value
NVZ	Nitrate Vulnerable Zone
STP	Standard Temperature and Pressure
TS	total solids
VS	volatile solids

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