Exploring the viability of small scale anaerobic digesters in livestock farming

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SUMMARY

This report explores the viability of small scale anaerobic digestion for livestock farming where there is a need to deal with animal manure and slurry in a manner that minimises the emission of greenhouse gases. Dairy farming for example is dominated by small herds of animals, the slurry from which must be managed efficiently for the farm and to maintain high standards of health in a cost effective manner. AD is an acknowledged technology for farming operations that affords a high standard of manure management, the production of high quality biofertiliser and also the possibility of generating energy for own use as well as export.

The report is aimed at energy policy and decision makers as well as WWTP operators and was produced by IEA Bioenergy Task 37, an expert working group that addresses challenges related to the economic and environmental sustainability of biogas production and utilisation.

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Exploring the viability of small scale anaerobic digesters in livestock farming

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Executive Summary

Worldwide GHG emissions from livestock supply chains are estimated to produce 7.1 gigatonnes of carbon dioxide CO_2 equivalent (CO_{2e}) per annum. This represents 14.5% of all human-induced emissions. Of the total, storage and handling of manure represents 10 per cent (FAO, 2013a). On-farm anaerobic digestion (AD) of manures has significant potential to capture methane as a renewable energy source and, as a consequence, to reduce net global GHG emissions.

Animal manure, however, is a massively under-exploited biomass resource but presents many challenges in any attempt to harness its full potential. This is attributable in part to the low energy density of the material, and also arises because agriculture worldwide is comprised of relatively small units of production. If the benefits are to be realised, strategies need to be developed for on-farm AD whatever the size of the farm. In many countries, subsidies are used as an inducement to encourage such actions on account of its high capital cost.

The use of methane from agricultural biomass not only removes a direct source of GHG emissions, but also displaces the use of fossil fuels in terms of fertiliser and energy production, thus further reducing net GHG emissions. When livestock manures are used, there are other environmental benefits including better nutrient management which should be taken into account. These include:

- Improved air quality from the replacement of fossil fuels, wood and peat
- Biofertiliser availability in the form of digestate
- Resource efficiency (recycling of nutrients)
- Reduced odours
- At least 90% reduction of pathogens harmful to animal, human and plant life
- Reduction in weed seeds

Overall this creates a circular economy based on zero waste of resources

The purpose of this report

- To assist farmers who are considering the adoption of AD either to improve the overall productivity of the livestock enterprise or for farm diversification. It aims to provide the farmer with an overview of the types and designs of anaerobic digesters that are available and the factors which can affect both the capital and operating costs.
- To provide policy makers with an illustration of the capital and operating costs for farm-based anaerobic digestion that will allow assessment of the effectiveness of legislation and its impact on the adoption of AD technology.

The methodology

Four scenarios for a dairy farm of 100 milking cows are considered in order to demonstrate the extent to which energy prices, incentives and capital grants can influence the cost of GHG reduction through the use of AD for slurry management. All costs used in the examples are for illustration only and can be replaced with those appropriate for individual countries and farms. It is assumed throughout that cost calculations are based on best practice in plant design and management including digestate application. The outcomes can be used by policy makers and regulators for guidance in making decisions that will maximise the potential contribution from AD towards meeting internal and external targets for the reduction of greenhouse gas (GHG) emissions.

Concluding remarks and the way ahead

AD is a multi-purpose process. It reduces the GHG emissions from the storage of the livestock manure. The recovered biogas replaces oil, kerosene or wood as fuels and in doing so reduces the release of particulates and toxins into the atmosphere. As a consequence, their detrimental effects on human health are reduced, while the reduction or elimination of pathogens during the process can lead to improved human health as well as animal health and productivity. These small scale plants wherever they are located can usually be integrated into a wholly sustainable farming system for the reduction of pollution to land, air and water.

Extensive investigations at the international level all reach the same conclusion that AD is the most effective, indeed recommended technology for the removal of methane emissions from storage of livestock manure. There is a cautionary note that the AD process could potentially increase the amount of ammonia which can be released from the digestate into the atmosphere. This, however, is a matter for best practice management and therefore not an insuperable problem. It can be resolved in the main by gas tight storage of the digestate, as well as by the timing and method of application of the digestate to land as a biofertiliser. The cost calculations assume best practice in the plant design and management.

There is a different attitude and psychology to the use of AD when it is used as a basic farm process to enhance the productivity and monetary value of slurry. Dairy farmers generally need a simple, efficient and minimal cost system for dealing with slurry, and preferably one that reduces net cost to the farm. The investigations show that a small AD system can meet this need. For the farmer, the avoided costs and a predictable level of expenditure on energy, for example, are as important as any additional income from outside sources. This factor must not be overlooked in any evaluation of these small plants. Nevertheless, there is still the underlying dependence on the relationship between capital cost, energy prices and incentives, quite apart from any extra costs incurred to meet national regulations.

Conclusions to this effect have been reached by a number of studies made over the last three decades. There has been considerable progress in understanding process management and plant design since many of these studies were undertaken. It is, however, an oversimplification to assert that high levels of incentives are needed to offset the high capital costs of such plants.

The driving force behind the incentive systems adopted by national governments is to encourage renewable energy production as for example in Europe to replace the use of fossil fuels and so remove the sources of the GHG emissions. These incentives have and still are fulfilling that purpose. However, they fail to recognise the full environmental benefit which AD can offer. They have not been favourable therefore to the development of anaerobic digestion at a small scale (or indeed any scale) and especially manure based plants simply because these have been geared to electricity production which involves further complexity and investment in generation capacity. To tackle the issues of agricultural GHG emissions, the approach used shows a lead as to how AD, as the acknowledged best available technology for the reduction of GHGs from manure, can also be achieved without the combined heat and power (CHP) option where it fulfils the needs for heating or cooling within the buildings of the farmstead as a whole rather than the dairy in isolation.

Widespread adoption can drive the cost of small scale AD plants down through innovation, development and production and, where incentives are present, can allow support so that such plants can be fitted into the existing farming system, rather than having to alter the farming system in order to accommodate the digester and the incentive scheme.

Given the stimulus of a favourable combination of capital cost, energy price and incentive at the outset, there is a win for the policy maker and a win felt in the pocket of the farmer.

1. Introduction

The type of farm animal waste depends on the species, the type of housing, the feeds used and the quantity of water which the animal consumes. The solids content of the waste depends on whether animal bedding material is mixed with the excrement, as well as on the effectiveness in diverting rain water and washing water from the slurry or manure storage. Where the waste has a high solid content and is stackable, it is commonly referred to as manure, and where it is free-flowing, it is referred to as slurry.

Anaerobic digestion (AD) takes place when organic material decays in the absence of oxygen. When this is carried out in a controlled environment of airtight tanks, covered lagoons or covered ponds, this is known as a biogas plant or AD plant. The main benefits of AD are:

- *Reduced emissions from manure management*
  AD of manures and slurries can contribute significantly to reduce agricultural pollution and minimise GHG emissions from fugitive methane emissions. As much as 30% of the current emissions of CH_4 and N_2O associated with manure management could be mitigated by full deployment of current technology, including anaerobic digestion and composting (European Commission, 2010a). However, some studies indicate that the operation of a biogas plant on these low energy density materials gives only a marginal or negative return on capital investment (MAF, 2008; Leuer *et al.*, 2008).

- *Methane capture and use as a clean fuel, both to replace fossil natural gas and more polluting solid fuels*
  Reduction in GHG emissions, either directly or indirectly through fossil fuel displacement, is rarely considered as a criterion for providing financial subsidies for digester operation as a manure management tool and means of improving farm efficiency. In most cases, the subsidies are heavily weighted towards energy output, especially electricity. This encourages the use of high energy value feedstocks, including purpose-grown crops. Yet by far the greatest non-crop agricultural biomass resource is animal slurry and manure. In the European Union (EU), for example, estimates indicate annual tonnages around 1.4 billion tonnes (European Commission 2010b) a total annual GHG flux of 661 Mt CO_{2e}.

- *Biofertiliser availability in the form of digestate*
  The nitrogen content in the digestate after the AD process has enhanced availability in comparison with untreated animal manure and can offset in whole or in part the need to use chemical fertilisers which have a high energy demand in their production. When applied to land, digestate also has a lower potential for the release of nitrous oxide, a more powerful greenhouse gas than that from untreated slurry (Amon *et al.*, 2006).

- *Resource efficiency (recycling of nutrients)*
  All nutrients contained in the feedstock pass into the digestate and are available therefore to be recycled back to the land in the form of biofertiliser. This biofertiliser is used to replace mineral fertilisers.

If the EU is used as an example, the average number of livestock units (LSU) on individual farms is less than 100, yet about 70% of all agricultural land in the EU is used for livestock farming (European Commission, 2010a). Effective management of EU manure and slurry therefore requires technology at an appropriate scale for individual farms, or the operation of the technology by consortia of farmers working together. An example of feedstock quantities needed for a digester with an output of 100 kW electrical is shown in Table 1. In the case of dairy cow slurry, this would require almost 1,000 cows housed all year round or more than 6,000 pigs. The same output could be achieved from the digestion of a crop such as maize grown on a land area similar to that needed for a herd of 100 milking dairy cows.

Animal slurry has already been depleted of much of its energy in the animal gut, whilst food waste and maize are both high in energy-rich carbon components which have not been degraded. These two factors make the digestion of animal slurries a challenge because of the high volumes of material which need to be handled for the relatively small amount of energy recovered. However, it costs livestock farmers to store, handle and recycle these materials in any case and the AD process makes the material easier to handle whilst returning benefits in terms of fertiliser and energy. The area required to produce the daily quantity of maize needed to support a 100 kWe CHP will vary with the variety and as well as the soil and weather conditions. The area required to produce the daily quantity of maize needed to support a 100 kWe CHP assumes a yield of 40 t per hectare; thus, 0.19 ha would be required on a daily basis to produce the 7.6 tonnes of maize required, with nearly 70 hectares required to produce the year's supply. The food waste figure assumes weekly collection of 2.1 kg per household.

Yet energy output, frequently expressed in the form of electrical energy (kWe), is usually the sole basis of current AD financial evaluations. It is therefore not surprising that manure or slurry digestion rarely proves to be attractive in terms of electricity production; for example, a 'typical' livestock farm of 100 dairy cows only has an electricity generating capacity of approximately 10 kWe.

This brochure therefore focuses on different options which could be available to make the digestion of livestock slurry more attractive for the farmer than the present systems or status quo of slurry/manure management. It also highlights other advantages which digestion can offer, such as reduced GHG emissions, farm energy substitution, efficient nutrient recycling, and other environmental benefits, all of which could be the source of additional financial benefits.

Note:
Throughout this brochure, costs are expressed in GBP (£) as the currency of the lead IEA Bioenergy Task member country authors, in this case, the UK. For convenience, the GBP conversion rates of all members of the Bioenergy Task 37 countries are listed in Appendix A.

Table 1 Comparative units required to operate a 100 kWe CHP each day

Feedstock	Feedstock needed (tonne/day)	Daily Units needed	Unit
Dairy slurry	46.4	928	head
Pig Slurry	68.4	6240	head (sows)
Food waste	8.1	26,963	household collections
Maize silage	7.6	0.19	Hectares/day

Source: Derived from Tompkins (2011); FNR (2010)

2. Small scale farm AD

For present purposes, attention is focussed on livestock farms, with particular examples drawn from the dairy sector. Figure 1, based on the European member countries of IEA Bioenergy Task 37, shows that most farms have less than 50 hectares of usable agricultural land area (UAA).

The amount of land required to support livestock depends upon climate, average temperatures, soil type, drainage, water availability and other factors. For dairy herds, a common assumption in a cool temperate climate such as the UK, is that 0.5 ha of grass or other forage crop is required to support 1 cow, equivalent to one livestock unit (1 LSU). A herd with 100 milking cows therefore requires at least 50 ha. Each herd is also likely to include younger animals referred to as so 'followers'. The total herd size with 100 milking cows therefore is likely to be around 166 animals, with a land requirement of about 70 ha. Figure 2 shows that, with the exception of the UK and Denmark, average herd sizes are less than this in the selected Task 37 member countries.

In the United States, the average dairy herd size is about 133 cows, even though there is a growing trend towards confined animal feeding operations (CAFOs) with units of more than 1000 cows (Shields, 2010). The reality is that individual farms have the capacity to generate small amounts of electrical power, typically from about 3.9 kWe to 100 kWe, respectively for herds ranging from 39 to 1000 cows. If herds are housed for only part of the year, this poses further challenges, because either the AD system would only run for part of the year or further feedstocks would need to be found.

There are different digester designs which could be used for slurry/manure digestion on individual farms that aim at:

- Simple and cost effective plant technology
- Ease of operation
- Dependable quality of products (heat, electricity, biofuel, biofertiliser)

Several plant constructors offer specially designed small-scale digestion systems which aim to keep investments and operating costs low. A list of suppliers of small-scale biogas plants is published on the website of IEA Bioenergy Task 37 (Task 37).

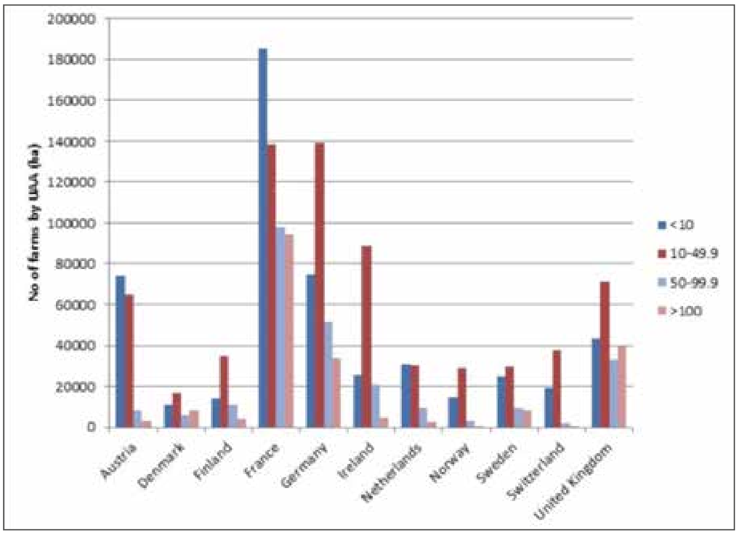

Figure 1 Distribution of farm size (ha) in selected IEA Bioenergy Task 37 member countries
Source: Compiled from European Commission (2012a)

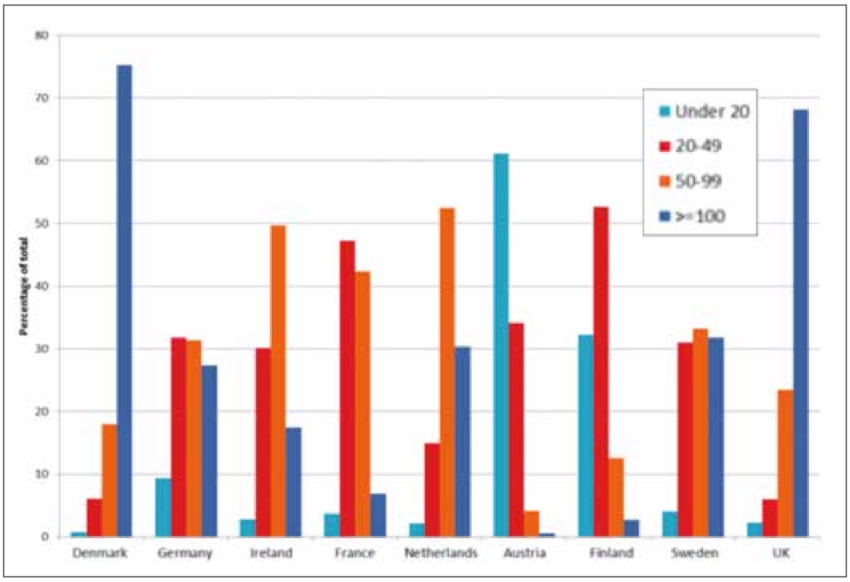

Figure 2 Comparative number of dairy cows per farm in selected countries
Source: Derived from European Commission (2012b)

3. Examples of anaerobic digestion technologies and operating conditions

Figure 3 shows a schematic diagram of an agricultural biogas plant which receives animal slurries or manures. Co-feedstocks may be added, such as residues of animal feedstuff, spoiled silage or crops from the farm itself or imported from elsewhere. Typically in the EU and North America, the biogas produced is likely to be used in a combined heat and power (CHP) unit to generate both electricity and heat, although it can also be used in a boiler for dairy and farmhouse heating or for cooling. Energy is required to maintain the digester temperature and for operation of any electrical equipment, such as for digester mixing. The second output from the digester is digestate, a biofertiliser (Lukehurst *et al.*, 2010). Digestate has a similar volume to the original feedstock, but has a lower organic carbon concentration. Whole digestate can be separated into liquid and fibre portions for storage and for various applications.

Examples of design approaches to farm digesters are given below. These range from simple covered lagoon systems to factory pre-fabricated turn-key installations.

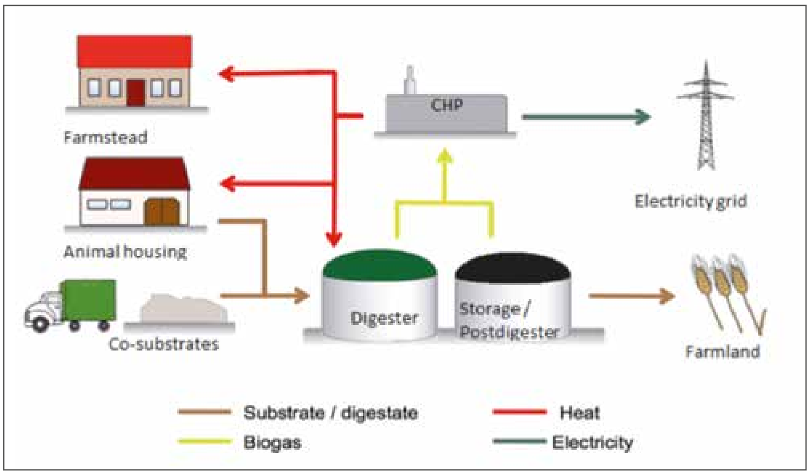

Figure 3 Schematic layout of a typical agricultural biogas plant (with CHP)

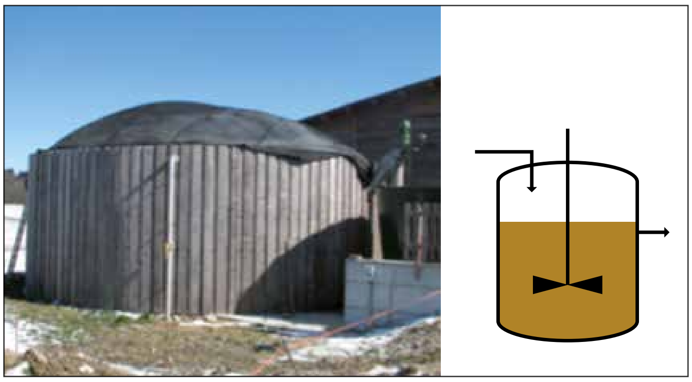

Figure 4 'CSTR' digestion system at Saugealles Fermes, Switzerland (Photo: EREP SA)

3.1 Continuously stirred tank reactor (CSTR)

The continuous stirred tank reactor (CSTR) describes a digester in which the contents are completely mixed and the digestate is displaced by the addition of fresh feedstock. This is supplied continuously to give steady and uniform conditions within the reactor tank. Most digesters of this type are in fact fed only intermittently or semi-continuously, but this usually provides conditions similar to continuous feeding. For this type of digester, an average dry matter content of the feedstock needs about 10% total solids (TS) to facilitate pumping. For this reason, feedstocks with a TS content >15% are sometimes considered unsuitable for this type of digester (Görisch and Helm, 2006). In practice, however, provided hydrolysis and conversion of the feedstock solids are effective, an appropriately-designed CSTR AD plant is suitable. For example, maize silage (~30% TS) or domestic food waste (~25% TS) are commonly used as feedstocks for CSTR digesters. In fact, since 80% or more of the feedstock solids are converted to biogas, the actual solids content within the digester is typically <6% and it can be kept fully mixed. A schematic representation of a CSTR and an example of a farm digester of this type are shown in Figure 4.

3.2 Plug-flow digester

In an ideal plug flow digester (also known as a reactor), the input feedstock passes through a defined path and will exit after a predetermined time with no intermediate mixing of the tank contents. This means that, as fresh feedstock enters, it pushes existing material through the digester as a ‘plug’ with the result that the oldest inputs are driven out at the discharge end of the digester. In practice, an ‘ideal’ plug flow plant is not feasible and some in-tank mixing will inevitably occur. Some individual designs incorporate moving floors or helical screws so as to move the material slowly through the digester in relation to the rate of fresh feed addition. Plug-flow digesters are usually configured with a high length-to-breadth (or diameter) ratio and operate with high total solids content (>15% TS). The feedstock is added at one end of the tank and digestate removed at the other end. Figure 5 shows a plug-flow system which uses gas mixing in a circular tank with cylindrical internal baffles designed to increase the path length between inlet and outlet: the inner compartment with the domed roof is used as storage for biogas.

There are also low-cost plug-flow systems without any internal mechanical means of moving the plug forward. This type is mainly used with slurry feedstocks. With these designs the reaction zone and gas collection are combined, either in a sealed and reinforced plastic or rubber bag, or by using a gas-tight cover over a lined or impervious lagoon excavated in the ground. The most common application of these is for digestion of pig and cattle manure and they are often operated at ambient temperatures in warmer climates (Figure 6), for example in New Zealand (MAF, 2008) and Brazil (Bley, 2013).

3.3 Feedstock and digester operating conditions

For small scale farm slurry based systems, feedstock pre-treatment should be kept to a minimum. However, pre-treatment equipment will be needed if the feedstock has a high percentage of straw or other fibrous material. In this case, it should be chopped before it is fed to the digester, as the long fibres increase the risk of floating layers which can form an undesirable crust on the liquid surface. Furthermore, bulky feedstocks can cause

Figure 5 Upflow (top picture) and plug (lower picture) flow examples of digesters (Photo: Top: ITAIPU Binacional, Brazil; Bottom: Marches Biogas)

Figure 6 Lagoon and bag type digestion systems (Photo: top: C. Lukehurst; bottom: C. Bley)

obstruction to pumps and pipes and are slow to degrade.

If feedstocks, such as agri-industry residues or food waste are imported onto the farm, sufficient reception and suitable storage space must be provided to contain the material and prevent nuisance and/or pollution of surface or ground waters. In many countries, regulations or codes of practice are stipulated. Where both high TS and slurry feedstocks are available, mixing tanks or mixing pits can be used for homogenisation of the material before it enters the digester. This avoids the need for a separate feeding system for high dry matter content feedstocks.

Some feedstocks may pose a risk to human or animal health. If this is the case, national regulations are likely to apply, as for example the Animal By-products Regulation in the EU (ABPR, 2009).

Various physical, chemical or biological pre-treatments are available on the market. These are intended to maximise methane yield. The cost effectiveness and energy requirements of these should be evaluated carefully before they are incorporated into the design, as they may only be cost-effective on large-scale plant. Methods for feedstock pre-treatment are the subject of a separate IEA Bioenergy report (Montgomery and Bochmann, 2014).

3.4 Digester temperature

Manure-based digestion systems are most commonly operated in the mesophilic range (30°C to 40°C), although it is also possible to operate at thermophilic temperatures of 50°C to 65°C, though 55° C is the optimum temperature for the methane formation. Higher temperatures are not usually applied (Angelidaki and Ahring *et al.*, 1984). The choice can have a significant influence on the digestion process:

- The higher the temperature, the faster the degradation of the organic matter. Thermophilic digesters require shorter retention times and therefore smaller digester volumes can be used.
- Thermophilic digesters give better pathogen inactivation, and operation above 55°C at a guaranteed retention time can partially satisfy the requirements of the European Animal By-products Regulation (ABPR, 2009). It also removes the need for a pre- or post-pasteurisation if materials are imported onto the farm.
- Thermophilic digesters are usually more sensitive to changes in process conditions (e.g. temperature, pH, feed rate) with the consequence that, if not well-managed, they can under-perform. This leads to a reduction in biogas production or even a breakdown of the biological system in extreme cases.
- The equilibrium of free ammonia with ammonium ions ($NH_3 \leftrightarrow NH_4+$) is dependent on pH and temperature in the digester. The higher the operating temperature, the greater the risk of inhibiting the efficiency of the digestion process through free ammonia toxicity.
- There is an energy demand associated with heating the feedstock from its storage temperature to the digester operating temperature. The greater this differential, the higher the heating requirement of the digester. Small-scale digesters also have a higher surface-area-to-volume ratio with proportionately higher heat losses. When low methane potential feedstocks such as manure are used, the energy demand and loss from the system are critical design considerations.

For most manure-fed farm digesters, where pasteurisation is not a legal requirement, mesophilic AD allows satisfactory degradation with reduced energy demand compared with thermophilic AD.

3.5 Mixing system

The movement of the feedstock in digesters is an important consideration, as it facilitates the distribution of micro-organisms and heat in the digester tank. In a CSTR, this feature is inherent in the design which includes a mixing system. In plug flow reactors, it is necessary to mix fresh feedstock with digestate to ensure biological activity and to pre-heat before entry into the digester. In batch fed digesters, continual inoculation and heat transfer is maintained through percolation of recycled digestate through the digesting mass.

Variations on CSTR designs are most commonly used for manure digestion and these can be supplied with three main types of agitation: mechanical, hydraulic and pneumatic (gas mixed).

- **Mechanical agitators** are propellers or paddles which mix by rotational movement. They are susceptible to abrasion by materials such as grit and sand which can enter the digester as soil mixed with manure-based feeds, or as contaminants of co-digestion feedstock which may contain metals and glass. Mechanical agitators can also be fouled and seriously damaged by materials that wrap around them. In a farm situation, this might include items such as binder twine or even plastic film.

- **Hydraulic agitation**, or jet mixing, creates a strong hydraulic current through the digester which induces mixing. In practice, digestate is withdrawn and returned through a nozzle under pressure. An advantage is that the mechanical equipment is located outside the digester and is more accessible for repair and maintenance. There is a risk that the device could be clogged by dense or fibrous digestate .

- **Pneumatic agitation**, or gas mixing, functions by injecting biogas under pressure through nozzles located in the bottom or sides of the digester. The rising gas bubbles lead to different density gradients in the tank which bring about mixing. Gas mixing can be carried out using fixed or moveable gas tubes, depending on plant design.

All mixing systems can, to varying degrees, be sensitive to actual solids concentration and fibrous feedstocks. It is possible to employ a combination of technologies: for example, gas mixing can be used as well as hydraulic jet mixing. As the energy consumption and therefore the cost implications (See Section 5) for agitation can be very high, it is vital that the technology is chosen and scaled appropriately for the size of the digester and type of feedstock.

Figure 7 Digester feeding options; Gravity feed of manure into the tank – top photo: S. Baumann; Feedstock augered directly into a digester – bottom photo: A Bywater

3.6 Digester process control

Control of the AD process can vary from an extremely simple system to one that is highly automated. At its simplest, feedstock can be moved into a storage tank or lagoon through a simple weir system for mixing. Thereafter the feedstock is discharged into the digester (Figure 7, top). This procedure can be controlled by a simple timer. As an alternative, the feedstock is scraped by tractor into a loading area, from where it is screw-fed directly into the digester (Figure 7, bottom), whilst an output screw removes digestate to a separator so that liquid and solid digestate fractions can be recovered for separate storage.

It is also possible to implement fully automated process control which can further simplify the work of the operator and allow independent running of the plant during weekends and holiday periods. Where possible, even for small plants, some automation is recommended as it can help to limit the daily labour requirement. Even with full automation, however, the design should include the option of manual control in case of unexpected events, e.g. if a unit of the plant breaks down. Process monitoring in biogas plants is described in detail in a separate IEA Bioenergy publication (Drosg, 2013).

Figure 8 Gas storage in a flexible roof (top) and in a double membrane gas holder (bottom) (Photos: B.Drosg (top); A. Bywater (bottom))

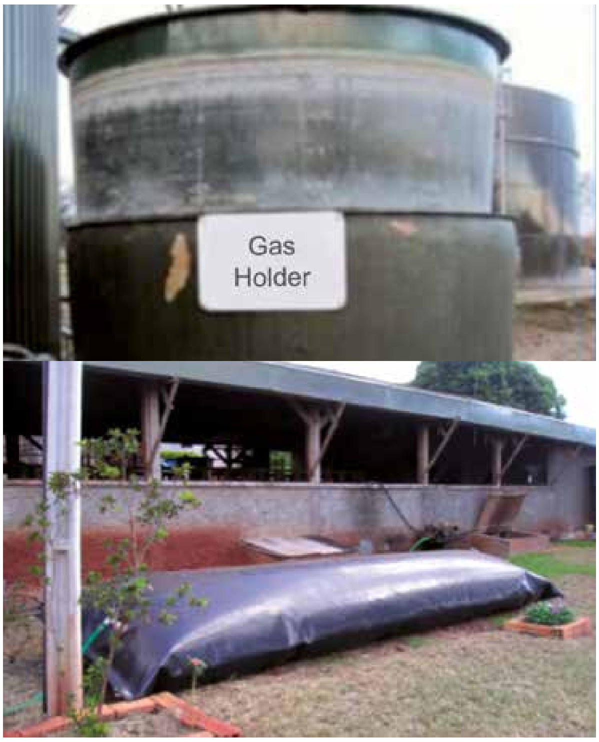

Figure 9 GRP bell-over-water gas holder (top) and simple gas bag storage at a Brazilian farm (bottom) (Photos: A. Bywater (top); D. Baxter (bottom))

3.7 Storage and Use of AD Products

3.7.1 Biogas Storage

Although biogas is produced continuously, fluctuations and peaks occur and it is common practice to provide buffer storage capacity both to dampen this effect and to take into account the variable demand from biogas utilisation (e.g. boiler, CHP or upgrading unit).

A common method of storing biogas is inside the digester. For example, a double membrane flexible roof can be used, with the outer skin being inflated using a compressor and the inner skin expanding and contracting according to the gas production and consumption rate. Although convenient, this design can be susceptible to heat loss through the roof if it is not insulated. This may be a major concern in small-scale plant or where outside temperatures are very low. A flexible membrane roof is shown in Figure 8.

External gas storage can be a simple bell-over-water configuration (Figure 9, top) which effectively acts as a process buffer and requires no energy to operate. Separate flexible double-membrane gas holders can offer a convenient and price-efficient solution but, like double-membrane tank gas storage, they have a small electricity demand in order to maintain a minimum gas pressure in the system. A gas bag (shown in Figure 9, bottom) also provides a low cost storage solution. In India, for example, very small bags are used to carry the biogas for sale in the local market.

3.7.2 Biogas use

Before use, biogas ideally needs to be dried and H_2S removed. There are three main uses: combustion in a boiler for space heating or cooling, cooking or water heating; combustion in an engine to give combined heat and power (CHP); and upgrading to biomethane for use as a vehicle fuel or for gas grid injection.

By far the most common of these alternatives in Europe and North America is the use of CHP either for localised electricity use (off grid) or for connection to the grid. This brings additional income to the farm, with further utilisation potential of the heat recovered from the CHP engine. In many cases, however, this heat is not utilised because of the extra infrastructure requirements. CHP units are available with low output power ratings which could meet the needs of farms with manure-based digesters, although these smaller units tend to be less efficient than larger ones. For 20 and 100 kWe output, electrical conversion efficiencies may be 30% and 40%, respectively (measured values, ASUE, 2011).

Upgrading biogas to biomethane requires removal of CO_2 to achieve a methane (CH_4) concentration of typically >96%. This significantly improves the energy density of the gas and makes it usable in appliances designed for natural gas. Subject to local regulations, it can be injected into the gas grid or used off-grid in local applications. Biomethane is also used as vehicle fuel and provides better environmental performance than either liquid fossil fuels or indeed liquid biofuels (Persson and Baxter, 2015; Svensson, 2013). There are also opportunities for on farm use of upgraded biogas. There is growing interest in the development of small-scale upgrading equipment. Conventional upgrading technologies such as water scrubbing, pressure swing adsorption (PSA) and membranes are already available, but are still generally considered expensive at the 0-100 Nm^3/hour scale.

3.7.3 Digestate storage and post-treatment

Discharge of the digestate is the final stage of the AD process. From CSTR type digesters, the digestate is in a liquid form and can be discharged into an existing slurry storage tank or lagoon. In contrast, digestate from digesters designed to process high TS feedstocks is more like compost. The size and type of the storage required and the length of the storage period before land application depends on national legislation as well as on geographical factors such as soil type, winter rainfall, crop rotation, etc. In temperate parts of Europe, for example, the storage capacity must accommodate 4–9 months of digestate production (Lukehurst *et al.*, 2010).

Digestate does not form a natural crust like raw slurry and therefore fixed or flexible tank/lagoon covers should be used. These will help to avoid nutrient losses and pollution through ammonia emissions (ADAS and SAC, 2007) and prevent dilution by rainwater. The use of this type of system also allows residual methane to be captured which improves the plant‘s energy balance. Where full covers are not feasible, a floating cover of lightweight expanded clay aggregates (known as LECA clay pebbles) can also be used, but these can be less effective.

On most farms, digestate is used as fertiliser without any further treatment and is applied to the land with the same equipment that is used for slurry or for solid manure. Some farms, however, use screw or belt press separators when the liquid and dry matter is used for different purposes (as in the application of slurry). With a screw press, the resulting dry matter content of the solid fraction is 30-35% and the liquid fraction contains 3-7% dry matter. This type of equipment can reduce the required storage tank volume by as much as 29%. The equipment is relatively low cost, efficient and robust. Digestate processing and nutrient recovery are described in a separate IEA Bioenergy publication (Drosg *et al.*, 2015). Selection of AD technology and how it is operated will determine both capital and operating costs which are considered in the farm context in Section 5.

4. Environmental Benefits of Anaerobic Digestion

The viability of a farm AD plant, whether a small-scale slurry/manure based plant or a farm diversification enterprise, generally focuses on financial performance in terms of return on capital investment. However, a significant underlying factor in agricultural policy globally is the need to reduce GHG emissions from manure storage. In consequence, environmental factors must also form part of the total assessment.

4.1 Abatement of greenhouse gas emissions

Total annual GHG emissions from the European agricultural livestock sector are about 661 Mt CO_{2e} of which 15-19% could be prevented through technically achievable mitigation solutions including AD (European Commission, 2010a). Manure management is responsible for emissions of about 87 Mt CO_{2e}/year which amounts to 13% of the total. Two-thirds of this (55 Mt CO_{2e}/year) are derived from methane gas emitted from storage systems. The remainder (32 Mt CO_{2e}/year) is in the form of N_2O gas emissions. The installation of treatment processes to stabilise slurry/manure under controlled conditions, either aerobically or anaerobically, is recognised as the most cost-effective means to reduce these emissions. Moreover, AD has the added benefit of capturing methane which can be used to replace fossil fuels for heating or cooling and/or the production of heat and power.

4.2 Direct avoidance of GHG emissions

FAO (2013b) recommends the use of AD to capture and utilise methane emissions from manure as well as to generate renewable energy and enable sanitation, especially in developing countries. The purpose of this section is to illustrate how small scale AD can contribute to these objectives. For illustration, the calculations below are based on the daily production of slurry from a dairy herd of 100 milking cows. It is assumed that the slurry can be collected and stored and therefore that the herd is housed for all or part of the year. Where climatic conditions are favourable and agricultural practice is outside grazing, excreta will be deposited directly on the pasture. Even during this outdoor grazing period, some excreta will be deposited in or around the milking parlour and could be collected.

The GHG savings and potential energy production have to be calculated pro rata to the weight of total and volatile solids load of slurry produced. The actual quantity reflects the breed and body weight of the animal, the nutrient content of the feed, the stage in the lactation and the milk production (NRCS, 2008; US EPA, 2012). As an example, dairy cows which produce between 5,000 and 9,000 litres per lactation also produce about 55 kg to 64 kg of undiluted slurry/day (Defra, 2010). The following illustration assumes that 55 kg/head/day (TS of 13.9%) can be collected, equal to 5.5 tonnes/day for 100 milking cows (derived from US EPA, 2012). In reality, it is likely that a certain volume of water which has been used in the parlour may have been added to the slurry that reaches the digester, although this should be minimised. If it is assumed, for example, that 10 kg water/cow is added, this would take the total weight of the feedstock (slurry plus dirty water) for digestion to 6,477 kg for TS of 11.8%. Any contributions from heifers (10-24 months) and young stock under a year old are ignored in this example. It follows that the 100 milking cows would produce 764 kg of total solids per day, of which around 636 kg (83% of total solids) are volatile solids (VS). The specific methane potential of dairy slurry lies in the range 0.110 – 0.275 m^3/kg VS (FNR, 2010) and a proportion of this will be produced in any storage tank, pit, pond or lagoon systems. Unless this methane is collected, it will escape to atmosphere as a fugitive emission. The amount will depend upon a number of factors, including the type of storage system, the temperature and the time that the material is stored. For the purposes of calculations below, the specific methane production of undiluted dairy slurry is taken as 0.15 m^3/kg VS.

According to LCA studies by Styles *et al.* (2014) for each tonne of dairy slurry dry matter fed into a biogas plant, the emission of 1.45 tonnes of CO_{2e} can be avoided, primarily through avoided manure storage, but

Table 2 Indicative CO_2 equivalent for potential avoided natural methane emissions during storage

	Unit	Daily
Undiluted slurry output from 100 milking cows (excluding water of 1000 kg)	kg	5477
kg of volatile solids assuming the slurry VS concentration is 83% of TS (or 11.62% of the wet weight)	kg	636
Potential methane production based on a specific methane potential 0.15 m^3/kg VS	m^3	95
Proportion of methane (13%) by volume (Nm^3) in biogas expected from long term natural digestion (IPCC Tier 2 approach) at 12°C	Nm^3	12
Convert methane to kg at STP (0.715474) for mass expected from long term natural digestion	kg	9
Mass CO_{2e} based on CH_4 being 25 times more potent as a GHG compared to CO_2	kg CO_{2e}	222

also through replacement of mineral fertiliser, grid electricity and use of heating oil. This is equivalent to a "carbon credit" of 3.27 kg CO_{2e} per kWh net electricity generated and compares with an achievable carbon credit of 0.49 kg CO_{2e} per kWh electricity generated from other renewable energy sources that achieve GHG avoidance only through electricity replacement.

Methane loss from storage is taken from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The Guidelines use three approaches (Tiers) to the calculations of the emissions based on the level of detail available. The figures used in Table 2 are based on a Tier 2 method, where more detailed information is available. The estimate is calculated for liquid slurry at 12°C with a natural crust cover and uses a specific methane yield (B_0 value) of 0.15 m^3/kg VS, i.e. 6.36 kg VS per head. The calculated contribution to GHG emissions as CO_{2e} from such a dairy herd based on anticipated methane loss is shown in Table 2. This value would be higher if the stored slurry did not form a natural crust cover in the slurry store. The annual loss would depend on the number of days of storage.

On the basis of these assumptions, the use of the digester as a standard piece of farm equipment has the potential to avoid emission of 222 kg CO_{2e} per day from 100 milking cows. The captured methane is the fuel used to generate energy to operate the digester and to have a surplus for other on farm uses. An element of care needs to be applied to the estimates above as these relate to the characteristics of the undiluted slurry which can vary from day to day. If the local temperature rises higher than the prevailing average, then the quantity of methane emissions can increase.

4.3 Indirect avoidance of GHG emissions

In addition to the direct avoidance of fugitive methane from slurry storage, anaerobic digestion also reduces GHG emissions through fossil fuel substitution by offsetting the emissions which would otherwise have resulted from the production or use of fossil fuels and power generation from fossil carbon. In this section, this offset is calculated based on the use of the biogas as a replacement for:

- Fuel/heating oil for hot water and domestic heating only
- Grid electricity/CHP

On the basis of the above, the undiluted daily slurry output from a herd of 100 milking cows is 636 kg/day volatile solids or 6.36 kg/cow. However, even if the slurry is diluted, the volatile solids and the output of biogas will remain the same, provided that digestion conditions are not changed. The calculated energy recovered from the slurry is shown in Table 3.

Table 3 Data used for the calculation of indicative CO_2 reduction

	Unit	Daily
Volatile solids from 100 milking cows/day	kg	636
Total methane production	Nm^3	95
Total energy value of methane @ 35.7 MJ/m^3	MJ	3408
Total energy value of methane (1 MJ = 0.2778 kWh)	kWh	947

Table 4 Effect of water addition on the TS and VS of dairy cow slurry

Water input per cow	L /day	0	10	20	30	40	50	60	70
TS cattle slurry	%	13.9%	11.8%	10.2%	9.0%	8.1%	7.3%	6.7%	6.1%
VS	%	11.6%	9.8%	8.5%	7.5%	6.7%	6.1%	5.5%	5.1%

Any water addition has the effect of reducing the hydraulic retention time of the digester which, in extreme cases, could lead to a washout of the methane producing organisms. Of more concern, however, is the effect that dilution has on the amount of heat needed to process the slurry in the digester. Biogas used for heating the digester is obviously not available for other uses where it can take the place of fossil fuel. Table 4 shows how the TS and VS concentration of the slurry is affected by water addition. If it is assumed in all further calculations that 10 kg of water are used per cow for cleaning before milking and thereafter makes its way into the slurry, by the time the slurry reaches the digester this takes the effective total solids concentration to 11.8% and volatile solids to 9.8%.

The retention time in the digester will become critical if the TS of the slurry drops to around 6%. Dilution will not produce more biogas, but it will increase the heat required to maintain the digestion process and there will therefore be less biogas to displace fossil fuel use. Therefore, it is important to minimise water ingress into small digester systems.

Table 5 Indicative CO_2 reduction attributable to fuel oil replacement (EF = emissions factor)

	Unit	Daily
Energy value of methane which remains after digester heating; used to replace fuel oil	kWh	495
Total CO_{2e} emissions avoided from use of biogas (methane) to replace heating oil based on an EF of 0.269 kg CO_{2e} / kWh (DECC, 2013)	**kg CO_{2e}**	**133**

4.4 Use of the biogas for heat-only

The daily energy required to heat 6.5 tonnes of slurry and water from a temperature of 8.45°C (the annual average temperature in the UK) (derived from Jain, 2013) to 40°C is 237 kWh. The daily heat loss from the example digester is 73 kWh. This assumes the same annual average temperature and a digester construction of concrete, insulated with polyurethane, and with a U value of 0.51 W/m^2/°C (derived from Jain, 2013). The U value relates to the rate of heat loss (formally, the U value is the coefficient of transmission). The U value does not allow for actual heat losses through pipework, imperfections in insulation, thermal bridging and variations in digester design. Such thermal losses make a significant difference on these smaller digesters and the actual heat losses are likely to be higher than the theoretical values. A U value of 0.51 W/m^2/°C (watts per square metre per degree centigrade) represents a total process heat requirement (feedstock and losses) of 294 kWh. This is 36% of the total post-boiler energy production of 805 kWh. A U value of 0.66 W/m^2/°C has been used in the following calculations in order to reflect actual heat losses. These are typically in the region of 40% (Bywater, 2011; pers. communication Murcott, 2013).

In the calculations below it is assumed that the digester volume is 130 m^3, with a surface area of 146 m^2, and that it is fed at a rate of 5 kg volatile solids/m^3/day. This gives a retention time of 24 days. The energy remaining for further use is 495 kWh. If this energy in the form of biogas is used as a direct replacement for fuel oil on the farm, further GHG savings would be made. Again, bearing in mind that the digester may run all or part of the year, sufficient economic use for the heat would need to be found and this is discussed in Section 5.

The above parameters are used in Table 5 to show the daily CO_{2e} emissions which can be avoided when biogas is used to replace heating oil.

4.5 Use of the biogas for CHP

The calculation below is based on a CHP of approximately 11 kWe. This is taken to have an electrical efficiency of 31% and heat recovery factor of 93% and to operate with a load factor of 91% or 8000 hours/year. For present purposes this figure is used in the calculations in Section 5, but in practice the engine performance will depend on the quality of biogas and the amount of degradation of components during operation, which will affect the requirements for maintenance. The time taken for maintenance will be reflected by the expertise available on the farm (see Section 5.2.2).

The GHG savings for renewable electricity vary between countries and the fuel mix of the electricity which it replaces. It is assumed that the heat available after feedstock and digester heating is used to replace fuel oil. In Table 6 below, an EF of 0.45376 kg CO_{2e}/kWh is used as the basis for the electricity calculations, with a range in IEA Task 37 countries of 0.0022 kg CO_{2e}/kWh (Norway) to 0.67222 kg CO_{2e}/kWh (Germany) and a world average of 0.662353 kg CO_{2e}/kWh (Brander *et al.*, 2011).

The results above show that 133 kg (Table 5) and 186 kg CO_{2e} per day, respectively, could be saved if the biogas is combusted in a boiler to produce heat only or in an engine to produce combined heat and power (CHP).

Table 6 Illustration of daily reductions in CO_2 equivalent with an 11 kWe CHP

	Unit	Daily
Replacement of grid electricity: Electricity generated from 95m^3 methane/day (From Tab. 2 above) at 31% efficiency and 91% Load Factor (LF)	kWh	264
Total CO_{2e} saved by electricity substitution from a renewable source (0.45376 kg CO_{2e} /kWh) (a)	kg CO_{2e}	120
Heat generated from 95m^3 methane/day at 93% thermal efficiency and 91% load factor	kWh	555
Deduct the energy used for digester heating	kWh	310
Total heat available to replace heating oil	kWh	245
CO_2 emissions displaced from use of biogas to replace fuel oil based on an EF of 0.269 kg CO_{2e}/kWh (b)	kg CO_{2e}	66
Total CO_2 equivalent emissions displaced by CHP (a) + (b)	**kg CO_{2e}**	**186**

None of the GHG calculations above take into account any potential fugitive emissions of methane from the digestion process itself or from gas utilisation equipment.

4.6 GHG savings from synthetic fertiliser replacement

The fertiliser savings depend on the amount of nutrient in the animal diet, the conversion efficiency in the rumen and that which remains in the faeces and urine. The AD process does not change the amount of total nitrogen (N), phosphorous (P) or potassium (K). Based on the manure characteristics used in the previous sections, a milking cow excretes 0.29 kg/day of total nitrogen, (US EPA, 2014). The proportion of total N available to the next crop can vary from 0.10 kg - 0.14 kg depending upon its availability; e.g. 36% (Defra/DECC, 2011) or 50% (FNR, 2009), respectively. Frost and Gilkinson (2010) highlight the need for a cautious approach in any attempt to establish fertiliser savings. For example, at the Agri-Food and Biosciences Institute in Northern Ireland daily samples over a whole year were taken of both dairy cow slurry fed into the digester and digestate from the storage tank. The total N and available N varied both in the slurry and in the digestate from one day to another. The aggregated results showed a 20% increase in the ammonium nitrate which when applied to land is immediately available for plant uptake.

It follows that the additional availability of N could reduce some of the requirement for imported fossil fuel based nitrogen fertiliser and the corresponding CO_2 equivalent emissions associated with its manufacture. Emission factors (EF) for N fertilizer production vary widely depending on the fossil fuel used (Wood and Cowie, 2009; European Commission, 2013). The calculations below use an EF value of 6.172 kg CO_{2e}/kWh N (European Commission, 2013) for the production of urea (46% ammonium nitrate). The potential savings are given in Table 7.

Table 7 Indicative daily avoided emissions from the replacement of synthetic N fertiliser

	Unit	Daily
Total N in the slurry @ 0.286 kg/cow x 100 cows	kg	29
Available N in the slurry @ 36% of total N	kg	10
Increase in readily available N after digestion: 20%	kg	2
Avoided CO_{2e} emissions using European average EF of 6.172 kg CO_{2e}/kg N for urea (including transport)	kg CO_{2e}	13

Source: Derived from: Defra, 2010; US EPA, 2012; Frost and Gilkinson, 2010.

The time span over which slurry can be collected can vary considerably. In a cool climate, cows may be housed approximately 185 days a year (Defra, 2010) and return from pasture for milking. Under these conditions Defra (2010) estimates that 60% of the annual excreta can be collected (19% during the grazing period). In this situation, 2.8 tonnes of CO_{2e} emissions potentially could be avoided. If the herd is housed throughout the whole year, the yearly emissions saving would amount to 4.6 tonnes.

Table 8 Summary of potential reduction of CO_2 equivalent emissions

Avoided CO_{2e} emissions	
Heat only option:	
Slurry storage (Table 2)	222
Replacement of fuel oil (Table 5)	133
Replacement of synthetic N fertiliser (urea) (Table 7)	13
Daily total (kg CO_{2e})	**368**
Displaced or avoided per cow/LSU (kg)	***3.7***
From 60 % slurry recovery (Annual T CO_{2e})	**81**
From 100 % housing (Annual T CO_{2e})	**134**
CHP option:	
Slurry storage (Table 2)	222
Replacement of fuel oil and electricity (Table 6)	186
Replacement of synthetic N fertiliser (urea) (Table 7)	13
Daily total (kg CO_{2e})	**421**
Displaced or avoided (kgCO_{2e}) per cow/LSU	***4.2***
From 60% housing (Annual T CO_{2e}/year)	**92**
From 100% housing-365 days (Annual T CO_{2e}/year)	**154**

4.7 Estimation of the total savings in GHG emissions

The total daily CO_{2e} GHG abatement values are shown in Table 8 for an AD system which has been installed principally to improve slurry management. The conversion of the methane into heat and/or combined heat and power is the means to the end rather than the end in itself. Nevertheless, it demonstrates through the example of a herd with 100 milking cows the potential contribution to GHG reduction.

For both the farmer and the policy maker, the significance of the amount by which GHG emissions can be reduced by AD of slurry will become apparent in Section 6. For the policy maker, the impact is expressed as the marginal abatement cost (MAC) of GHG avoidance, and for the farmer, by the efficiency benefits costs which can be achieved. (See Section 5).

4.8 Emissions of nitrogen

Care needs to be taken in any attempt to compare the level of GHG emissions from the application of animal manure, in this example undiluted dairy cow slurry, with those from synthetic fertiliser or with digestate. The purpose of this section is to consider first nitrous oxide (N_2O) and thereafter emission of ammonia (NH_3) which is not a greenhouse gas, but nevertheless is a cause of air pollution.

4.8.1 Calculation of nitrous oxide emissions

The amount of N_2O released depends on the system of slurry/manure management. Nitrous oxide is a very powerful greenhouse gas, with a CO_2 equivalence factor of 310. It is formed in slurry storage tanks and in soil after the application of both fossil derived and natural organic nitrogen fertilizer. Production of N_2O during storage and treatment of animal slurry/manure occurs as a result of the combined nitrification and denitrification. Because N_2O production requires an initial aerobic reaction and then an anaerobic process, dry aerobic management systems are more likely to provide an environment favourable for N_2O production than wet slurry stores. However, it remains uncertain how much N_2O might be generated under these conditions. The tentative default IPCC emission factor value for a liquid slurry storage system is 0.001 kg N_2O-N per kg N excreted. While there is much uncertainty about N_2O generation in slurry/manure management systems, it is clear that there is no possibility of N_2O formation occurring while the liquid manure (slurry) is in the digester. Given the uncertainty, no N_2O savings have been included in the reduction of GHG attributed to the digestion of the slurry and application of the digestate.

4.8.2 Ammonia-N losses from volatilisation

There is evidence to suggest that AD increases the concentration of available ammonia-N compared with that in undigested slurry. In theory, this should lead to greater N losses from the manure/slurry management system and methods of application compared with use of undigested material. However, results in the literature for NH_3 losses during application are not consistent. A number of other factors are involved; including lower NH_3 emissions following narrow band application, attributed to the lower dry matter content of digested manure which gives better soil infiltration.

Sommer *et al.*, (2006) reported significantly higher NH_3 emissions after broadcast application of co-digested manure compared with untreated manure and this was believed to be due to the higher pH of digested manure. Both Amon *et al.* (2006) and Wulf (2002) also found significantly higher NH_3 emissions after spreading of digested cattle manure compared with untreated manure. Research in Canada (Crolla *et al.*, 2013) also found a much higher emission factor for digestate compared with slurry in one of their applications, but not in another. Losses are also reported to be short term and only continue until the digestate is incorporated into the soil. Other studies, including the work of Clemens *et al.*, (2006), and Pain *et al.* (1990), found no significant differences between digested and undigested slurries during application. In practice, nitrogen losses can be minimised by good farming management practices. These can include a 15 cm layer of lightweight expanded clay aggregates (LECA) placed over the slurry/digestate (ADAS and SAC, 2007) or a covered store, together with appropriate application timing and use of low-emission spreading techniques. The latter include:

- Soil injection; either shallow or deep
- Surface application, followed by immediate incorporation into the soil.

4.9 Odour emissions

Odour arises from volatile organic compounds in slurry, some of which are broken down during the AD process to form the biogas. As a consequence, less remains in the digestate to cause the odours (Birkmose, 2011). Laboratory and field tests to measure odour units (OU)/m³, for example, in Canada (Crolla *et al.*, 2013), Denmark and the UK (reported in Lukehurst *et al.*, 2010) compared digestate with untreated cow slurry. Tompkins, (2011), for example, records between 90% and 95% reduction of odour units. In Canada, simulation studies compared odour emissions from fresh and old digestate with raw slurry in spreading applications (Crolla, *op.cit*). The results demonstrated significantly lower odour for digestate compared with slurry when expressed both as a concentration (OU/m³) and as an odour flux (OU m²/second).

4.10 Reduction of pathogens

Major investigations in Denmark (Bendixen, 1994), Germany (Hass *et al.*, 1995), The Netherlands (van Overbeek and Runia, 2011), Sweden (Harraldson, 2008 and Zetterstrom, 2008) and in the UK (Tompkins, 2011) all show the effectiveness of AD in the reduction of at least 90% of slurry borne pathogens harmful to animal and plant health. The combination of temperature, presence of volatile fatty acids, pH and levels of nitrogen in the digester tank creates a hostile environment for the survival of animal and plant pathogens and also weed seeds.

Animal pathogens

For example, eggs and larvae of roundworms and gastrointestinal worms in cattle slurry do not survive more than 2 days at 35°C, while it takes just 7 days to destroy the larvae of lungworms. Public Health Authorities (Bendixen, 1994), for example in Denmark and Finland (see Appendix C), show that at least 90% *Streptococcus faecalis* (FS) do not survive after two days at a mesophilic temperature. If FS are killed, then the large number of bacteria less tolerant to heat are also killed.

The digestion process is equally effective in the inactivation of viruses which cause some of the common diseases in cattle and also in pigs. For example, the survival times range from 3 hours for bovine viral diarrhoea to 5 hours for Aujeszky's Disease (Botner, 1991) and 24 hours for infectious bovine rhinotracheitis.

In Section 5 it is not possible to establish the financial implications of the break in the pathogen cycle from animal to pasture and ingestion back into the animal in the short term. There is, however, anecdotal evidence that veterinary costs are reduced and that the overall level of herd health improves (See case study in Appendix C).

Plant pathogens

Scientific tests also confirm the effective destruction of most crop disease-spreading spores in a mesophilic digester operated at 35°C, and therefore the scope to reduce the risk of recycling plant disease (Zetterstrom, 2008; Harraldson, 2008; van Overbeek and Runia, 2011). Specifically, for example, the spores of *Fusarium oxysporum* which affect cereals and maize decline rapidly within one day in the digester and none are present in the final digestate. Laboratory tests also show that potato nematodes, Globula rostochiensis and G. pallida, do not survive after 4 and 5 days respectively in a digester at 35°C.

The degrees to which inactivation of pathogens as well as the eggs and larvae of parasites in the farm digester, which lead to animal and plant disease, has a twofold significance:

- The digester breaks the cycle of infection from animal to pasture and ingestion back to animal
- The digester provides a natural destructive process for pathogens, etc., which are becoming increasingly resistant to anti- bacterial and anti-viral drugs.

Weed seeds

Recent work by Johansen *et al.* (2013) confirms from laboratory tests that a digester, whatever its scale, is also effective in the reduction of seven common weeds which are competitive with arable crops. These include *Solidago canadiensis* (Golden Rod). *Avena fatua* (Wild Oat), *Sinapsis avensis* (Charlock) *Brassica napus* (Oil Seed Rape), *Amsinckia micranta* (Common Fiddleneck) and *Fallopia convovulus* (Bindweed) all of which are killed in less than a week. The seeds of *Chenopodium album* (Fat hen) survive in decreasing proportion up to 11 days, after which there are no viable seeds in the digestate. Johansen *et al.* (2013) notes that in developing countries, farmers can make use of all kinds of plant material, including roadside weeds, for energy production without the risk of spreading weed seed and parasites on to farmland via the digestate.

5. Financial viability

Irrespective of the type of AD plant, its financial viability depends on the balance between capital and operating costs, the income or the avoided expenditure from the use of the biogas, the added value of nutrients in the digestate and the quality and characteristics of the feedstock. In terms of energy balance for small scale AD, the design and operation must ensure that process load and heat losses are minimised in order to maximise availability of biogas for other uses.

5.1 Capital costs

In this section, no account is taken of any fiscal support for the purchase of the plant. The discussion is based on the actual capital costs of AD plants. These include civil engineering works, process equipment, storage tanks, electrical and mechanical parts, the biogas conversion technology and any connections to the gas, electricity or heat distribution networks. To these costs must be added all the costs incurred in feasibility studies, planning or permit application and any environmental assessment and licences. These extra costs can typically add 10 – 15% to the costs covered in a contractor's tender document (Anderson Centre, 2010).

It is important for the farmer to have some awareness of the spread of the capital costs and to consider the degree to which the selection of the digester design and feedstock can affect that cost. The first German study (FNR, 2005) estimated 45% (range 21-69%) of capital costs are attributable to civil works and tanks, 49% (range 34-65%) to mechanical and electrical equipment and installation as well as 6% (range 6-7%) to gas use technology, usually the CHP. The authors of these reports acknowledge, however, that there is little commonality in how costs are allocated between the first two categories. Civil engineering costs can also be substantially reduced on small-scale farm plants when it is possible to use existing farm machinery and labour for ground preparation and other construction work (see the Case Study in Appendix C). Grid connection costs which vary widely from country to country, as well as who pays the costs according to local/national regulations, and so are not taken into account in this report. Possible grid connection costs must nevertheless be taken into account by anyone planning a biogas project.

Capital costs can be expressed in various ways. These include the cost per kWe capacity or per m³ digester volume, or as in the US, as a cost per cow (Leuer *et al.*, 2008). The different ways in which costs are expressed, the different currencies used and the different periods over which construction occurs make estimation and comparison of the capital costs of AD very difficult. Thus, the discussion below focuses on examples of costs for three options and should be regarded as illustrative, rather than definitive:

- Electricity/CHP
- Biogas upgrading to biomethane
- Biogas use for heat

5.1.1 The CHP option

For the purpose of comparison, capital costs are expressed in a monetary unit per kWe and are based on data from over two hundred AD plants which range in capacity from 30 kWe to over 1 MWe. Those illustrated below are for plants which have been the subject of financial and technical surveys in Germany (FNR, 2005; FNR, 2009), Austria (Laaber, 2011) and France (Bastide *et al.*, 2010). The ranges of costs as well as average and median values are given in Table 9. These figures are based on currency conversion rates (Appendix A) and have not been corrected to take account of annual inflation. In the case of France 80 plants were identified

Table 9 Indications of range of capital costs of agricultural plants

Source	No. of plants	Range cost £/kWe	Average	Median
Germany (FNR, 2005)	59	£1,010 – £6,411	£2,677	£2,487
Germany (FNR, 2009)	61	£1,307 – £5,247	£2,646	£2,707
Austria (Laaber, 2011)	41	£1,979 – £4,748	£3,476	£3,327
France (Bastide, 2010)	30	£1860 – £8600	Not available	Not available
UK (Jain, 2013)		£3,000 – £6,915	Not available	Not available

(Bastide *et al.*, 2010), from which a sample of 30 were selected for more detailed analysis, the results of which are used in Table 9. Those for the UK have been collated from plant owners and constructers, as no formal data are available.

Care has to be taken in the use of these data, as the plants can vary widely in design and range in size from less than 100 kWe to more than 1 MWe capacity. For example, the median cost of the Austrian and German plants smaller than 250 kWe is £3,223/kWe while, contrary to expectation, the median cost for those smaller than 100 kWe is only marginally higher at £3,383/kWe. Further exploration of the costs reveals that there is greater variation between the highest and lowest costs of plant of a similar size than there is between all plants of either smaller than 250 kWe, or indeed below 100 kWe.

While such figures based on capital cost/kWe are sometimes used by a bank to evaluate a farmer's case for a loan to build a plant or at policy level to compare the cost of AD with other bioenergy technologies, it is unsafe to use them at their face value. It is not a comparison between like with like, even for plants of a similar size. For example, the high cost of some digesters in France is often attributable to the need for farms to install reverse osmosis for ammonia recovery in response to nitrogen overload in soils. Factors which contribute to cost variations include:

- Choice of feedstock and any pre-processing equipment
- Methane potential of the feedstock and its effect on digester volume
- Cost of grid connection
- Costs for compliance with national permitting, planning, bio-security and safety regulations

These are all important issues for prospective AD plant purchasers who need to know what is included in the offer price of a plant and the how the price can be minimised.

5.1.2 Biogas upgrading to biomethane

A second option is to upgrade biogas to produce biomethane, although this is more often considered for plants with a high volumetric output of biogas. Typically, a digester for manure which serves 100 LSU is only likely to produce around 5-6 m^3/hour of biogas and upgrading units with a capacity less than 300 m^3/hour are still uncommon. This is evident in the list of upgrading plants on the IEA Task 37 website (http://www.iea-biogas.net). However, such small plants do exist, for example in Brazil (Figure 10), India (Vijay *et al.*, 2013), the UK and Finland. The 10-30 m^3/hour Finnish upgrading unit, developed and commercialised by Metener, is described in Appendix C. Upgrading units of this size could be suitable for farms, but the capital costs can range between £233,000 and £361,000.

Figure 10 Small biomethane upgrading plant in Brazil; top: pilot biomethane upgrading plant which serves a co-operative of 33 family farms with an aggregate of 100 LSU, **Capital cost:** £66,000, **Biogas throughput:** 5 Nm^3/hour (Photo: ITAPU Binacional, Brazil, 2014); bottom: biogas is transported through a pipeline to link the farms to a central CHP adjacent to the new upgrading plant.(Photo: Clare Lukehurst)

5.1.3 Biogas for heat

Instead of either CHP or upgrading, the simplest option is to use the biogas to replace fuel oil, bottled gas or electricity where this is used for cooking, heating and hot water or cooling. This third and globally most widespread option considers direct heat utilisation, in which the biogas is used to heat the digester to process the slurry and to displace the use of fossil fuels on the farm. This requires, as a minimum, a boiler as an integral part of the AD plant. A typical cost for a 25 kW cast iron boiler for a 100 LSU farm is £3,200 with an additional £300 for a heat exchanger. Operating costs should be in the range £300 to £1,000 for a twice yearly clean (Note: the lower operating cost is used in the calculations that follow).

Capital cost alone, however, is only one part of the equation and needs to be considered in relation to operating costs before any investment decisions can be made.

5.2 Operating costs

The purpose of this section is to focus on the level and range of operating and maintenance (O&M) costs which can occur and the extent to which they can vary from one plant to another and indeed between AD plant construction companies in the way in which they are set out in tender documents. Some quote the actual energy consumption for individual items of equipment and typical maintenance costs. Others express these costs as a percentage of total capital cost. For present purposes, the latter approach is adopted for the calculations in Section 5.3. This approach overcomes what are in effect costs specific to individual plants. In large measure, the operation and maintenance costs relate to the design and complexity of the plant. The areas of these costs are summarised in Table 10 below.

5.2.1 Digester related costs

Energy consumption is considered first in order to highlight those areas where plant design and management efficiency may be able to reduce these costs. The electricity used to drive the moving parts can either be supplied from an external source or from the CHP. If the latter, calculations from the survey data show that on the 41 farms for which data are available, the demand can vary between 5% and 20% of that which is produced with an average at 7.5% (FNR, 2009). In these cases, the higher demands are attributed to the amount of energy needed for specific feedstock preparation. The choice of equipment affects the process electricity demand.

Table 10 Elements of digester operational cost

Digester operation: • Energy consumption	• Electricity costs based on operational time and efficiency of equipment such as agitators or gas pumps, macerators, mixers, pumps, heat exchangers, automatic valves, blowers for flexible roofs and cushions to store gas (except bell over water configurations), digestate separators (if included)
• Routine maintenance	• Repair or replacement of pumps, pipework/valves, feedstock choppers and mixers, heating system, control system, digestate separators (if included) • Checks for fugitive emissions to prevent gas leaks (and loss of saleable output) • Monitoring and control system calibration, replacement and repair
• Gas use/conversion technology	• Gas cleaning or scrubbing and consumables • Servicing, parts replacement and maintenance • Major overhauls as specified in manufacturer's recommendations
General expenses • Finance related • Health & safety • Other	• Repayment of loans & interest charges, insurance, licences • Education and training/process management development, etc., • Soil, feedstock and digestate analyses, where required. • Consumables for process optimisation, where used

Labour and any feedstock costs must also be taken into account.

Routine maintenance costs of moving parts, pumps, mixers, macerators and other elements are similar to those of any other farm machinery and often of a preventative character. However, these costs will increased significantly if damage to equipment is caused by grit, stones and other debris in the feedstock.

5.2.2 Maintenance of the gas conversion technology

If a CHP unit is included, the supply company usually specifies the frequency and type of work which needs to be undertaken. The extremes are indicated below:

- Full maintenance contracts are available in which costs are cited at £1.05 and £1.25 per operating hour for 23 kWe and 30 kWe capacity engines, respectively. This contract covers remote control by the supplier, all consumables and spares, a guarantee of operating time and complete engine replacement after a given number of operating hours
- In contrast, farmers can undertake much of the engine servicing. In our analysis of German practice on the farms for which data are available (FNR 2009), the total (O&M) costs appear to be subsumed under the heading 'parts and maintenance' but relate to the plant as a whole and not specifically to the CHP. Nevertheless, it seems to be substantiated by the fact that only 10 out of 2,500 farmers who purchased a CHP also purchased a maintenance contract (Schnell Motoren, 2013).

The calculations in Section 5.3 use a figure for CHP servicing of £0.03 per kWh which has been derived from a number of supplier quotations and Jain (2013). This is based on 2008 data. It assumes that the farmer will do most of the CHP maintenance work.

The maintenance costs can also be exacerbated by the level of hydrogen sulphide (H_2S) in the biogas. This may not only invalidate a manufacturer's warranty, but can also cause damage through corrosion in the engine. Table 11 below shows examples of methods which can be used to minimise these problems and examples of their respective costs.

5.2.3 Boiler and heat system maintenance

In contrast to the costs which can be incurred for a CHP, the maintenance cost of biogas boilers is significantly less. For present purposes it is based on the personal knowledge from three companies with over 40 years' experience of the construction and maintenance of biogas plants and biogas boilers. The total cost of boiler and subsequent equipment servicing ranges in total between £300 and £1,000 for the twice yearly clean (Mulliner, 2013, Murcott, 2013, Chesshire, 2013).

5.2.4 Labour

Farm digesters need to be simple, easy to operate and to fit seamlessly into the daily labour routine of the farm. In fact, the time taken to operate a digester installed to improve the efficiency of slurry management can take no longer or even less time than the *status quo* – the farm's current system. If crops are included, as on most German farms, the length of time to manage the digester increases, with 40% to 55% of total digester labour time spent on feedstock preparation. Experience recorded on 32 Austrian farms showed a range between 1-2 hours/day for slurry only digesters, with a marginal increase on the farms where crops are co-digested with

Table 11 Comparative material costs for hydrogen sulphide removal*

Method	Cost £/Nm^3 of biogas	Cost £/kg
Air injection into the gas storage space	<0.001	n/a
Oxygen from a bottle	0.04	n/a
Iron oxide pellets for absorbing 0.3-0.5 kg/kg H_2S added to the feedstock	0.001	0.20
Ferric oxide pellets added to the feedstock	0.01	0.53
Active carbon absorbing 0.1-0.3 kg/kg H_2S as a biogas filter	0.023	2.72

*Derived from tender documents

the manure (Walla & Schneeberger, 2005). Some time may also be required where farmers are required to complete returns for compliance with statutory regulations. This can be quite time consuming.

The case study in Appendix C achieved very substantial labour savings where the biogas replaced wood chip heating.

5.2.5 Feedstock costs

Slurry only plants are unlikely to incur any significant additional costs because they are usually already equipped with much of the slurry handling equipment. They will have machinery or contract arrangements to spread the slurry/digestate but, in order to comply with best practice in digestate use, specialist equipment such as that used for shallow injection may need to be purchased.

If additional feedstocks are used, these will normally incur a cost. In the UK, for example, chicken or pig manure is often imported for its fertiliser value. Prices can vary according to local conditions and demand. If this same manure is digested prior to application, it may incur some storage or mixing costs. However, if the slurry is augmented by, for example, grass, maize silage or other crops in order to enhance the energy output, it will incur a production cost whether grown on the farm or purchased from outside. This needs to be taken into account. As an illustration, McInry *et al.*, (2011) recorded the variations in the production costs for grass silage of between £19 and £24 per fresh tonne when produced under different management systems. UK maize production costs ranged between £23 and £28 per fresh tonne in 2014 on yields of 37-44 tonnes/ha.

Such figures should be used with caution, as there can be losses between the field and silo and during the period of storage which can affect the methane yield and therefore the overall profitability. For maize, the highest gas yields can be obtained when it is fully ripe (Amon *et al.*, 2007; Amon *et al.*, 2012). However, if for example maize is used to lengthen a crop rotation, such as between the cereals and oil seed rape, there can be pressure to harvest early so that the next crop can be planted. In such cases, there can be a marginal reduction in its potential gas yield and, therefore, potential income (see Murphy *et al.* (2011) and Al Seadi *et al.* (2013) for further information on biogas potential from crops).

5.2.6 General expenses and external costs

General expenses include interest rates on capital borrowing, insurance premiums, operator training costs, general consumables, safety equipment calibration, checking and repair, laboratory tests, permitting/licenses and local or national taxation. A number of these costs are unrelated to the performance of the plant and will have to be met whether or not the plant is operational.

Plant and equipment depreciation is usually included in the financial assessment of an AD plant and it may be accounted for in many ways. One approach is to take into account the life of individual plant components such as the tanks, pumps and CHP. Typically, the life span of these components can range between 8 and 22 years, depending upon the projected life of the asset (NRCS, 2007; CAEEDAC, 1999). A simpler method is to take a straight-line depreciation for the plant as a whole, with or without a residual value. On farms where the prime function of the digester is to process slurry and therefore increase farm efficiency, digester depreciation is likely to be treated in a similar fashion to that of any slurry storage tank which is written off over a period of 20 years. The same approach is taken for repayment of any loan and the interest charges. In practice, the lifetime of some AD plants has proved to be much longer. In fact, there are a number of gas stirred digesters in the UK constructed in the 1970s, 1980s and 1990s which are still in operation (Bywater, 2011) long after their costs have been paid back.

5.3 Estimation of financial viability

For slurry management, the concept of financial viability has different meanings to different people. For the farmer, it is defined for present purposes as the ability of an AD plant to offer a long term improvement in the farm efficiency at no greater cost per cow than the current system of slurry storage (the status quo).

The purpose of this section is to compare the costs of the AD with the status quo where slurry is stored, for example in an open steel tank, and applied to land in accordance with national regulations. The example taken is for a 130 m³ digester serving a 100 cow milking herd and under what conditions slurry management can pay for itself or indeed make a profit.

5.3.1 Basis for the financial calculations

Before any attempt can be made to assess the potential viability of the small scale AD as a sustainable replacement for an open slurry store it is first necessary to take into account the cost of the plant, the source of capital and any income which may be forthcoming. The aim of this section therefore is to set out the assumptions upon which the financial analyses are made. These relate to the capital cost and revenue as well as the operation and management. The calculation of the latter draws upon experience in Austria and Germany (see Section 5.2), which has been reinforced with the knowledge of individual experts in the design, construction and operation of very small scale AD plants suitable for slurry only.

The total methane output produced from the slurry during digestion provides the starting point as the total methane resource produced. This is shown in Table 12. About 33% of the energy is used to process the slurry in the digester. Thereafter the greater proportion is either used for space and water heating /cooling or used to operate an 11 kW CHP engine for the length of the period during which the slurry or other feedstock is accessible.

Table 12 Data used as the basis for calculation of costs and income from energy sales.

	Unit (per day)	Daily output
Volatile solids in slurry[a]	kg	636
Total CH_4[a]	Nm³	95
Total energy value[a]	kWh	947
Process heat requirement[b]	kWh	310

[a] Derived from Section 5 Table 3
[b] Derived from Section 5 Table 4

The first step is to establish what the plant will cost and how the farmer will pay for it. There are many permutations as to how the funding package can be pieced together. However, the advice for present purposes given by the agricultural business section of a major bank provides the basis for the calculations. This advocates, as realistic, that 20% of capital is provided from the farmer's own assets, with the remaining 80% on loan as a farm/efficiency development from an agricultural lending bank. This loan would be repayable over 20 years in equal parts, secured against the asset value of the farm and subject to a bank's personal knowledge of the farmer's credit rating. An interest rate of 3.5% would apply as the same as that used for agricultural improvement schemes. Both the interest and depreciation also would then be accounted for in 20 equal instalments over the lifetime of the plant just as in the case of a slurry tank. In practice part of the capital cost may be secured from grant aid (See Section 7) or as interest free loans in those countries which offer this form of support but it is not included in the calculations below.

For present purposes it is assumed there are two revenue sources from which the capital and operating costs are repaid – direct income from energy sales and/ or incentives and indirect from the avoided costs. The latter can be secured from the on-farm use of the biogas to displace fossil fuel based energy and the 20% increase in the amount of available N fertiliser (see Section 4.6). This otherwise must be purchased from an external supplier. Many AD plants which are developed for farm diversification, accept agricultural and agri-food industry residues for which the farmer receives a gate fee. This option however lies outside the scope of this brochure. The focus of this investigation is on the role of the AD as a sustainable system to replace open slurry tanks and from a policy viewpoint to reduce GHG emissions from slurry storage.

Any attempt to establish where and how an AD can benefit the farmer financially is a difficult undertaking and the results need to be used with care. The evidence which is presented below is for illustration and should not be taken out of context. The sensitivity analysis identified some 650 possible permutations. It is however, unrealistic to attempt to show the complexity of the factors involved, therefore for the purpose of illustration the interaction of three elements are explored in Tables 15-17. These are the effect of capital cost, energy prices and incentives. The impact of these three interrelated factors is exemplified through four scenarios. The assumptions which underlie the calculations are detailed in Table 13.

The '100 cow' farm slurry digester with or without CHP is now rare, therefore the capital and operating costs used in the Tables 18-20 are based on the best data available.

In the first three scenarios, it is assumed that all the land is used to support the dairy herd either for grazing or for the production of winter feed such as grass and/or maize silage, barley or fodder beet. In reality many farms at the end of the period of housing the cows may have 'left over' silage, sweepings of spilled animal feed or grain which can supplement the slurry. This, however, is difficult to quantify and for this reason is not taken into account. The calculations below can be regarded as a base or worse case situation. The 130 m³ AD plant is installed as an advanced slurry management and nutrient recycling system. It is considered as a standard piece of farm equipment just as a milking parlour or any other piece of farm machinery used to improve the efficiency of the farm.

Each country has its own incentives for the use of AD (see Section 6) and therefore all cost data used in the Tables below are specific to the particular examples. However, the method of calculation is transferable, so that the costs experienced on an individual farm, irrespective of its location, can be used in place of those used in the text examples. In reality, an individual farm may already have some form of slurry storage on which a loan may be at some stage

Table 13 Scenarios used for the cost calculations

Scenario 1 Specialist dairy farm with 100 milking cows housed **185 days**. Biogas combusted in a boiler. All land is used as pasture and for forage crops	Heat : (a) Incentive to process manure for removal of CH_4 from emission to atmosphere (b) Incentive for supply to dairy and average sized farmhouse	Assumes: All heat for beneficial use (a) Heat to process manure for removal of CH_4 from emission to atmosphere (b) Use of all saleable heat for dairy and household needs as well as livestock drinking water. Replacement of heating oil at £0.035/kWh/l^{-1} and incentive of £0.076
Scenario 2 The same specialist dairy farm but with slurry available **365 days**. Biogas combusted in a boiler. Land use as above	Heat: (a) **No incentive** to process manure for removal of CH_4 (b) Incentive of £0.076 for dairy and farmhouse replacement of heating oil only	Assumes: (a) Total dairy, domestic and livestock drinking water heat demand satisfied during the winter (185 days) as above and continued demand fo domestic and dairy hot water for further 180 days. Beneficial use of 77% of available heat to replace heating oil as above
Scenario 3 The same specialist dairy farm but with slurry available **365 days**. Biogas combusted in a 11 kW CHP (The cost and conditions of grid connection vary from country to country and therefore have not been included.)	Incentives for: (a) Electricity sold to the farm and house(s) and surplus sold off farm to the grid (b) Heat used on the farm	Assumes: CHP operates 91% of time at 31% efficiency. Farm electricity demand 40,000 kWh and replaces this amount bought in from grid at £0.11. Any excess exported to grid at £0.465/kWh. Incentive £0.1013/kWh for all electricity produced. All heat used to replace heating oil as above with an incentive of £0.076 /kWh
Scenario 4 100 cow milking herd on a mixed farm. Herd housed 185 days and slurry supplemented in summer with crop , etc. to maintain year round CHP operation	Electricity and heat incentives as above	Assumes: (a) Slurry available as in Scenario 1 (b) Supplemented with 736 kg of for example grass, maize, cereals, fruit and vegetables. (c) No extra land available to buy or rent therefore extra feedstock purchased at £40/tonne

of repayment. In the real situation therefore this will need to be taken into account in the farmer's own calculations but for illustration here existing loans are ignored.

5.3.2 The status quo – installation of a slurry tank

In practice, slurry storage can vary from a clay or high density polyethylene (HDPE) lined lagoon as the cheapest storage option, through to steel or concrete tanks which are more expensive. Open lagoons capture much more rainwater and this leads to higher spreading costs than for storage tanks. Although environmental legislation requires increasingly that slurry stores are covered, the assumption here is that slurry stores are open. Operational costs are estimated at 1% of capital cost and costs are incurred for mixing and pumping of slurry prior to spreading, but these costs could vary widely in practice.

In those areas where slurry storage is regarded as a "farm waste" the legal requirement for a given number of days of storage can be perceived as an extra financial burden, and for this reason is shown in red in Table 14. In practice it can be argued that slurry is really an asset when used as a biofertiliser, but for present purposes the total nutrient value both before and after digestion is assumed to be the same and therefore is not included in the financial calculations below. Although storage is still required for an AD plant, the associated cost can be reduced by covering the digestate storage which makes it possible to recover further biogas and keep out rainwater. It is also possible to reduce the size of the tank if the solids are separated. This is easier to do with digestate than with undigested cow slurry.

Table 14 Indicative cost for slurry storage

Capital cost installed [1]	£55,000
Assume 20% farmer's own capital	£11,000
Bank loan for 80% capital cost	£44,000
Yearly costs: Repayments of bank loan (at 3.5%) Depreciation over 20 years Maintenance cost @1% of capital cost	 £3,062 £2,750 £550
Total annual payment	**£6,362**
Cost per cow	**£63.62**

[1] Data provided by tank suppliers

5.3.3 Effect of variations in capital costs

Parameters for the 130 m³ base case 100-cow digester have been described above. These take into account the operating costs as a percentage of capital cost (see Section 5.2) as well as direct and indirect revenue streams which are specific for each scenario. For the purposes of the illustration, capital cost is defined as the ***total cost** of the installation including all the elements necessary to operate the system.* For present purposes this lies in a range between £100,000 and £300,000. It is acknowledged that in reality it may be difficult for a digester technology supplier to build the 100-cow digester within this range, without the benefits of volume cost reductions. However, it is on the assumption that such a situation can be achieved.

5.3.4 Effect of variations in energy prices

The background price of energy is a critical factor as to whether a digester is profitable, or at least of no greater cost than the status quo. Table 15 illustrates the 4 scenarios for an AD system with a capital cost at £100,000 to £250,000 where energy prices range from 50% to 200% of the June 2015 levels in the UK (shown as *100% in italics* in Table 15). The base case therefore is modelled for the avoided costs at £0.11 per kWh for electricity, £0.62 per kg N and £0.42 per litre (equivalent to 10.9 kWh) for fuel oil which amounts to £0.385/kWh. It is assumed for illustration that energy prices (electricity, oil and fossil fuel fertiliser – N) rise at the same rate, although in practice this may not be the case. The farm will replace its own needs of 40,000 kWh/year by generating its own electricity and export the rest (Scenarios 3-4). This figure is rounded up from a dairy farm use of about 1 kWh/cow/day (Trimble, 2009), and a farmhouse demand of approximately 3,300 kWh/year (Ofgem, 2011). For simplicity, it is also assumed that a proportion of the saleable heat (which is not used to process the slurry) from the boiler or CHP can be used during very cold winters, for example to heat drinking water for animals, although in reality this may not always be the case. In Table 15 three situations with regard to profitability are

Table 15 Effect of energy prices (electricity, fuel oil and fertiliser) on digester profitability

Scenario	1	2	3	4
Energy Cost	Slurry, 185 days housing, boiler with incentive on total heat	Slurry, 365 days housing, boiler, on saleable heat	Slurry, 365 days housing, CHP & incentive on eligible heat	Slurry, 185 days housing, CHP & heat, top up with crop in summer
£100K digester				
50%	£901	-£113	£6,937	£4,487
100%	£2,886	£2,647	£10,966	£9,040
110%	£3,283	£3,199	£11,772	£9,950
120%	£3,679	£3,750	£12,578	£10,861
130%	£4,076	£4,302	£13,384	£11,771
200%	£6,855	£8,166	£19,025	£18,144
£150K digester				
50%	-£4,883	-£5,897	£1,153	-£1,296
100%	-£2,898	-£3,137	£5,183	£3,256
110%	-£2,501	-£2,585	£5,988	£4,166
120%	-£2,104	-£2,033	£6,794	£5,077
130%	-£1,707	-£1,481	£7,600	£5,987
200%	£1,071	£2,382	£13,241	£12,360
£200K digester				
50%	-£10,666	-£11,681	-£4,630	-£7,080
100%	-£8,682	-£8,921	-£601	-£2,528
110%	-£8,285	-£8,369	£205	-£1,617
120%	-£7,888	-£7,817	£1,011	-£707
130%	-£7,491	-£7,265	£1,816	£203
200%	-£4,713	-£3,402	£7,457	£6,577
£250K digester				
50%	-£16,450	-£17,464	-£10,414	-£12,864
100%	-£14,466	-£14,705	-£6,385	-£8,312
110%	-£14,069	-£14,153	-£5,579	-£7,401
120%	-£13,672	-£13,601	-£4,773	-£6,491
130%	-£13,275	-£13,049	-£3,967	-£5,580
200%	-£10,497	-£9,186	£1,673	£793

Key to shading:

(dark green)	Farmer benefits: AD generates new income from slurry
(light green)	Farmer benefits: AD reduces the cost (£ per cow) of slurry storage compared with the *status quo*
(white)	No financial benefit: AD is a loss maker

highlighted and colour coded to facilitate interpretation:

If it is assumed that there is no change in operating cost or incentives, the effect of quite small variations in energy prices can make a significant difference to the potential viability of the plant. In all cases the installation of a digester can turn slurry into a financial asset if the digester can be installed for £100,000. Also it still reduces the cost of slurry storage per cow even when the capital expenditure increases to £150,000. If oil prices return to their January 2014 level when crude oil was $97 a barrel, roughly double that of July 2015, the slurry and heat only digesters at £150,000 can also yield an income of between £7,434 and £8,744, equivalent to £74.34 and £87.44 when the avoided cost of £63.62 per cow is also taken into account. Such benefit is dependent upon whether the incentive recognises the role of the digester in removal of the GHG or whether it only takes into consideration the saleable energy. At £200,000 the slurry only digester offers no financial benefit for the farmer unless the energy prices double. However, if the £200,000 system includes an 11 kW CHP which operates year round it can give a profit of £8,178 when the avoided costs are taken into account. It has in fact a greater potential than Scenario 4 if there is a need to supplement the slurry with imported feedstock. These calculations have not taken into account any effects of inflation.

5.3.5 Effect of variations in incentives

Differing heat incentive payments per kWh are examined first as shown in Table 16. Here the heat incentive varies from the base case (in italics) of £0.076 per kWh, and any changes are expressed as a percentage of this level.

Without the heat incentive the slurry only options are not viable despite their contribution to the reduction of GHG emissions. In contrast the effect of an incentive for heat with variations up to £0.152 shows how at the current level (£0.076) the heat only digesters offer a financially more attractive proposition for the farmer than the installation of an uncovered storage tank. Even at a 20% decrease in the incentive for heat the farmer is still financially better off than with an uncovered slurry tank, but only if the capital cost is kept below £150,000. At £200,000, possibly a more realistic level, the simple option where the AD readily fits into the existing farm operations it would need an increase of £0.03 incentive to make it worthwhile for the farmer to install the AD to prevent GHG emissions from slurry storage.

In all the above discussions the key issue is to focus on the AD system as an alternative to an open slurry store. In that situation, all the values (shaded in green) offer the farmer a financially better option than his present situation, but of course the pro rata payments of any existing storage system will need to be taken into account. A key issue is for the digester suppliers to bring the capital costs down to below £200,000 and for incentives to remain constant for long enough to allow time for suppliers to move towards bulk production of simple systems.

The sensitivity analyses above illustrate the complexity and close interaction which exists between capital costs, energy (fuel oil/electricity) prices, the level of incentives and their impact on the financial viability of small scale farm digesters. For simplicity of illustration, the incentives offered by just one Task 37 member country are used in the Tables above. It is, however, important to demonstrate the variation in both the level and combinations of incentives which are experienced elsewhere (Persson and Baxter, 2015) and how these can affect the financial performance of a small AD plants. A capital cost of £150,000 is used as an illustration for comparison. All other factors remain constant.

Although both Germany (post July 2014) and Austria have higher incentives for electricity than the UK, the latter can also receive an incentive for any heat which

Table 16 Effect of heat incentive variations on digester profitability at varying levels of capital expenditure

Scenario	1	2	3	4
Heat incentive	Slurry, 185 days housing, boiler with incentive on total heat	Slurry, 365 days housing, boiler, on saleable heat	Slurry, 365 days housing, CHP & incentive on eligible heat	Slurry, 185 days housing, CHP & heat, top up with crop in summer
£100K digester				
0% (£0.0)	-£8,427	-£6,877	£4,950	£700
80% (£0.0608)	£623	£742	£9,763	£7,372
100% (£0.076)	£2,886	£2,647	£10,966	£9,040
120% (£0.0912)	£5,148	£4,551	£12,170	£10,708
140% (£0.1064)	£7,411	£6,456	£13,373	£12,375
200% (£0.152)	£14,198	£12,170	£16,983	£17,379
£150K digester				
0% (£0.0)	-£14,211	-£12,661	-£834	-£5,084
80% (£0.0608)	-£5,161	-£5,042	£3,979	£1,588
100% (£0.076)	-£2,898	-£3,137	£5,183	£3,256
120% (£0.0912)	-£636	-£1,232	£6,386	£4,924
140% (£0.1064)	£1,627	£672	£7,589	£6,592
200% (£0.152)	£8,415	£6,386	£11,199	£11,595
£200K digester				
0% (£0.0)	-£19,995	-£18,445	-£6,618	-£10,867
80% (£0.0608)	-£10,944	-£10,826	-£1,804	-£4,196
100% (£0.076)	-£8,682	-£8,921	-£601	-£2,528
120% (£0.0912)	-£6,419	-£7,016	£602	-£860
140% (£0.1064)	-£4,157	-£5,112	£1,805	£808
200% (£0.152)	£2,631	£603	£5,415	£5,812
£250K digester				
0% (£0.0)	-£25,779	-£24,228	-£12,401	-£16,651
80% (£0.0608)	-£16,728	-£16,610	-£7,588	-£9,980
100% (£0.076)	-£14,466	-£14,705	-£6,385	-£8,312
120% (£0.0912)	-£12,203	-£12,800	-£5,182	-£6,644
140% (£0.1064)	-£9,941	-£10,895	-£3,978	-£4,976
200% (£0.152)	-£3,153	-£5,181	-£369	£28

Table 17 Comparative financial performance in each scenario with different levels of national incentive

Scenario	1	2	3	4
Digester capital cost £150,000	Slurry, 185 days housing, boiler with incentive on total heat	Slurry, 365 days housing, boiler, incentive on saleable heat	Slurry, 365 days housing, CHP	Slurry, 185 days housing, CHP & heat, top up with crop in summer
Austria[1] @ £0.15	-£14,211	-£12,661	£3,867	-£383
Germany[1] (<75kw) Pre 07/2014 @ £0.20	-£14,211	-£12,661	£8,693	£4,443
Germany[1] (<75 KW) Post 07/14 @ £0.15	-£14,211	-£12,661	£3,867	-£383
Ireland (<500 KW) CHP @£0.12 Non CHP@ £0 .09	-£814	-£1,383	£8,096	£6,597
Switzerland[1] (<50 kW) @£0.36	-£14,211	-£12,661	£24,137	£19,887
UK[2] (<250 kW) £0.1013[2] CHP Heat incentive @ £0.076	-£2,898	-£3,137	£5,183	£3,256

[1] A heat incentive is available only for the CHP option

[2] See Table 15 for CHP

[2] From Table 15

is used beneficially. This makes the very small scale (11 kW) more attractive than the current tariffs in Germany and Austria where the median cost of plants below 100 kW is £2,707 and £3,327 (Table 9) respectively.

Table 17 illustrates how the use of the AD as an alternative to open tank slurry storage can be attractive with the appropriate level of incentive in those countries where the heat incentive is independent of that for electricity. The heat only option readily fits into the farming system without the need for land use change, acquisition of extra land or exposure to the risk of volatile prices for the purchase of feedstock from elsewhere.

The farmer benefits financially and the policy maker opens up a wider field from which to secure GHG reductions. Under current regimes which link any heat incentive to CHP, a huge untapped resource is potentially missed and wider recycling of this huge resource through AD technology for these many livestock farms cannot be realised. It is a 'win-win' for both the farmer and the policy maker. For the farm, it involves

- No change in dairy herd management
- No land use or landscape change
- Long-term energy security
- A long-term cushion against fossil fuel price fluctuations
- Non quantifiable benefits such as pathogen kill which is reflected in improvements in animal health and productivity. (See Appendix C - Case study of Kalmari Farm.)

The question then is how far incentives can help to reduce the estimated 87 Mt CO_{2e} from livestock manure management in Europe (European Commission, 2010a). The advantages of AD to process this huge, but dispersed quantity of manure could be exploited not only in Europe but worldwide.

6. Policy background

Since the mid-1990s, policy emphasis, especially in Europe, hinges on reducing the pace of climate change. For this purpose, incentives have been introduced to encourage the production of renewable energy, including that from AD. It has however, focussed particularly on electricity and biofuels. Ragwitz *et al.* (2007) evaluated the role of the incentives and the extent to which these were successful in stimulating production. It was shown that those EU governments which offered support per kWh and stability of support over several years resulted in the fastest growth of renewable energy

It is clear that an AD plant offers considerably more than renewable energy. In the case of the small scale farm plants, the purpose is to improve the productivity of the slurry as well as to increase the efficiency of the farm and to reduce GHG emissions. Prior to the emphasis on renewable energy, the European *"Council Regulation (EEC) No. 797/85 of 12 March 1985 on improving the efficiency of agricultural structures"* (European Commission, 1985) permitted capital grant provision for the installation of new or the improvement of existing farm equipment. This aimed *inter alia* to prevent pollution from farm effluent and provided the first stimulus for the use of AD for the improved use of animal manure. This is a similar situation, for example to that in Brazil (Itaipu Binacional, 2009) and many other countries (Global Methane Initiative, 2006).

However, this form of support in Europe was discontinued in 1994. In 1997, the EU *White Paper* (COM 97/500, European Commission, 1997) for a community strategy and action plan identified the need for all sectors of the economy, including agriculture, to contribute to national targets for the reduction of GHGs. The subsequent legislation and related incentives embraced AD as one of many technologies which could be used to help to meet mandatory targets. These thereafter provide the framework within which AD, irrespective of the scale of the plant, operates and include:

- EC 2001/77/EC (Renewable Electricity Directive, 2001) on the promotion of ***electricity*** from renewable sources in the internal ***energy market***. This sets the framework within which AD as one such technology operates.

- Directive 2008/98/EC (Waste Framework Directive, 2008) lays down the definitions of waste which *inter alia* apply to feedstocks such as the residues of agri-processing and food. It also sets the waste hierarchy which, among other things, directs biodegradable waste from landfill and towards composting, AD and energy recovery. The use of a landfill tax to drive the redirection of the waste serves as incentive to the advantage of large scale commercial AD plants to charge gate fees. Such plants lie outside the scope of this brochure.

It has already been illustrated (Section 4) on a daily basis how small scale AD for slurry storage on a farm with 100 milking cows can avoid emissions of greenhouse gases. Table 18 takes the calculations further to illustrate the contributions which can be made in a year by just one herd of 100 milking cows where the digester is installed as a slurry storage system. This demonstrates from a policy viewpoint the potential of what can be achieved when AD becomes a standard piece of farm equipment on a livestock farm.

Table 18 Potential contribution of small scale AD to the reduction of GHG emissions

Scenario	**1**	**2**	**3**	**4**
Energy Cost	Slurry, 185 days housing, boiler, incentive on total heat	Slurry, 365 days housing, boiler, incentive on excess	Slurry, 365 days housing, CHP & heat	Slurry, 185 days housing, CHP & heat, top up with crop in summer
Tonnes CO_{2e}/year	76	119	151	125

Table 19 Range and type of incentives within the Bioenergy task 37 member countries (NB. All incentives are given in the currency of the individual country. For conversion factors see Appendix A)

Incentive Type	Incentive	Details	Notes
Electricity related	Feed in tariffs (FIT)	Rates vary from country to country (See Persson and Baxter, 2015)	For currency conversion see Appendix A Currency in Euro except where otherwise stated
	Basic rates/kWe	Index-linked guaranteed price over a defined time period. Banded in relation to the kWe capacity with a higher level for smaller plants; e.g. UK £0.1013 /kWh for <250 kWe, Austria 0.1950 €/kWh for < 250 kW and minimum 30% manure; Denmark 0.056 €/kWh -minimum 50% fresh weight manure; France 0.1182-0.2110 €/kWh for AD plants; German tariff before July 2014, 0.25 €/kWh for < 50kWe and; **post** July 2014, 0.2373 €/kWh for <75 kWe **only and must use 80% fresh weight of manure**; Ireland 0.15 €/kWh for <500 kWe; Switzerland 0.28 CHF/kWh for <50 kWe; the Netherlands 0.07 €/kWh increases in 6 phases to 0.15 €/kWh (not kWe capacity limited).	After contract secured minimal risk except where e.g. poor digester management or feedstock failure. Payments can be supplemented where heat used beneficially (See CHP below)
	Electricity certificates	Names vary from country to country, number issued/MWh varies; purchased by users which cannot meet statutory obligation for carbon reduction. Bidding process/auctions, e.g. average price range 170-220 SEK/MWh in Sweden; £42/MWh in UK	Alternative to FITs; prices depend on supply and demand; adverse effect if large buyers install own renewable CHP and flood the market
	Commercial spot market sales at auction	Competitive bidding at auction can double or treble a wholesale price where electricity is exported to grid. Better suited to the larger producers; power purchase companies can act as a co-operative for sale of block supply from a number of small producers	Similar risk to supply and demand led bid price; Supplements the income derived from FIT incentive
	The 'virtual power plant'	Swiss innovation, serves 65 farmers who are already linked into a sales cooperative, manages small outputs, sells certificates, etc. through an intelligent control system with modern technology. (Mutzer, 2013)	Recent initiative; interest spreading among farmers; dependence on efficiency of the central management company
Supplement examplesv	Heat to increase CHP efficiency	Conditions attached to encourage beneficial use of heat; e.g. Switzerland 0.025 CHF/kWh for <50 kWe added to base rate tariff, but non-detachable from the CHP; UK £0.076	Moderate/high risk of tariff reductions during planning and building
	Agricultural bonus including manure	Germany prior to July 2014, no bonus for <75 kWe plants; for <150 kWe 0.06-0.08 €/kWh; post July 2014, basic bonus only dependant on crop and manure mix; Post July 2014, no bonus (See above) Switzerland 0.18 CHF/kWh for <50 kWe Norway 250 NOK/dry tonne manure	See also Table 20
Non CHP incentives	Biomethane feed into gas grid	Varies between countries; e.g. Sweden tax exemptions and consumption incentives; UK £0.068/kWh for gas to grid: voluntary support programme by Swiss Gas Association to achieve 399GWh biomethane in 6 years; for Netherlands (see Persson and Baxter (Eds), page 42, 2015)	Regular payments; can be reduced as policy targets met
	Heat only	E.g. £0.076 for producers with <200 kWth capacity, applies to domestic and business consumers in UK; Ireland 0.11 €/kWh for non-CHP application for <500 kWth; Netherlands total budget sum available	DECC, 2013
Tax incentives		Used to encourage biogas energy, eg exemption from carbon and energy taxes; value-added taxes on renewable electricity sales; priority allocation for parking places, etc. In the Netherlands, for example, the self-consumed electricity from renewable energies is free of tax	In Sweden, used as alternative to feed in tariffs
Investment	Grants and loans	Some governments offer up-front payments, e.g. in Sweden up to 45%; France 38% for demonstration plants; England and Wales, up to £30,000 for feasibility studies and loan for up to 50% capital cost (England only) capital grant for demonstration plants in UK.	Loans of up to 50% of capital cost for <250 kW mainly manure and slurry based plants (England only)
		Also offered by companies e.g.in Brazil Itaipu Binacional (2009) with emphasis on clean water/manure management.From EU via Common Agricultural Policy Regional Development Funds	Available to schools, colleges and communities
Carbon credits	Agricultural and community development	Widely used e.g. in India, China and other Asian countries; preferential low interest rates, education and health programmes incorporated (see www.snvworld.org); Tradable Certificates awarded per tonne carbon reduced; claimed by governments from the United Nations Convention on Climate Change Clean Development Mechanism for developing countries	Regular payments made to households for quantity of CO_{2e} reduced (approx. 6 tonne/year)
Environment	Manure linked	Package of grants, loans and energy payments to reduce water pollution e.g. Brazil (op. cit.) included with education and sustainable agriculture; Norway manure payment 250 NOK /tonne TS not tied to CHP; See also Development programmes (van Nes, 2006) and http://www.snvworld.org	

Where a crop is used to supplement the slurry in summer it is noticeable that the GHG emissions saving is 17% less than a slurry only option where the slurry can be collected year round. This can be attributed to the energy used to grow and transport the crop. This potential also needs to be viewed in the global context of the conclusions reached by the FAO (2009) and of the EC Joint Research Centre (European Commission, 2010b). These reports show that AD is the most effective process for reducing GHG emissions from livestock manure.

There follows an illustration of the range of support mechanisms which are used and how these may affect the adoption of AD primarily to process animal slurries and manures.

6.1 Incentives offered

Incentives can take a number of forms and are available generally for renewable electricity/CHP generation or aimed at the biofuels sector including the production of biomethane. In contrast, in Brazil for example, the driver for AD is an environmental one, primarily for the improvement of water quality, and initiatives include education programmes on how to build a sustainable future for the farm and/or the community (Bley, 2013).

Where capital costs are high and energy prices low, incentives provide a way to support implementation of the technology as a means of reducing GHG emissions and to support the farmer in bearing the burden of mitigating GHG emissions. As energy costs increase, digester building costs increase (since the costs of steel and other components are directly related to the price of energy), and thus financial support during times of relatively low energy prices is necessary, as illustrated above. Table 19 summaries the examples of the range of incentives which serve to stimulate the adoption of AD and, in particular for the small scale farm plants. Within the tariff systems, some countries add bonus payments to encourage other actions such as landscape conservation or land reclamation which are of social benefit. Inclusion of manure as a feedstock also attracts such a bonus. Table 20 illustrates some of the differences in the manure payments attached to the electricity tariff and also includes the examples of those which 'stand-alone' unrelated to CHP. The German tariff prior to July 2014 is denoted in the table below by the 'strike through', in order to illustrate how incentives can change with, in this case, almost immediate implementation. In contrast, Norway makes a tonnage payment to process manure, the aim of which is to encourage the use of the energy on the farm where it is produced.

Table 20 Examples of incentives which would apply to manure based digesters

	Plant capacity	Rate	Limits
Norway	Not limited	250 NOK/t TS manure	Enshrined in law; annual rate negotiated between Government and farmers
Switzerland	< 50 kW	0.18 CHF/kWh	Linked to electricity
England and Wales	< 250 kW < 200th kW	0.075 £/kWh 0.075£/kWh	Use of heat from CHPHeat only non CHP
Ireland (non CHP)	< 500 kW	0.11 €/kWh	Not specifically for manure
Germany	< 75 kW ~~< 150 kW~~ ~~All plants~~	~~0.20~~ 0.2373 €/kWh ~~0.04~~ Post July 2014 0.0 € ~~0.04~~ Post July 2014 0.0€	Linked to electricity Must include fresh weight manure: > 80% ~~> 60% manure~~ ~~> 60% manure~~
Austria	< 250 kW	0.1950 €/kWh basic tariff	Must include minimum 30% manure
Denmark		0.056 €/kWh basic tariff	Must include minimum 50% manure

Source: derived from Persson and Baxter, 2015

The increase in the numbers of plants in operation in each Task Member country has been reported in the biennial Country Reports (2015) for the IEA Bioenergy Task 37 member countries.

6.2 The impact of incentives

The effect of the various fiscal supports needs to be set in the context of policies on climate change, energy, waste and agriculture. The impact of waste policy and especially the redirection of food waste from landfill have particular importance for larger commercial scale biogas plants where a pasteuriser is an integral component. For small manure based farm plants of <100 kWe, food waste usually has to be excluded due to additional capital cost of pasteurization. However, it should be noted that, with appropriate regulatory support, the Hub and PoD model of anaerobic digestion is an excellent way to minimise 'waste miles' and effectively recycle nutrients from organic materials such as food waste back to land. A Hub and PoD is where farms act as a Point of Digestion (PoD) and the farm feedstocks are supplemented with centrally pasteurised local food waste and similar organic feedstocks which have been processed at a Hub (Banks *et al.*, 2011, Cropgen, 2011) in line with the Animal By-product Regulation (2009) (see also Defra, 2015).

The intention here is to show examples of how incentives have been used and their direct or indirect effect. Three aspects are considered:

- The quantity of renewable electricity produced from biogas to replace that derived from fossil fuels
- The capacity and numbers of AD plants constructed
- The tonnes of CO_{2e} removed from circulation

Attention in this Section is focussed on the practical role of the incentives on the reduction of GHG emissions. However, the success by which the policy objective is achieved depends on the capacity of individual farms or any other businesses to build an AD plant. Incentives designed to encourage AD for renewable energy, and particularly electricity/CHP is illustrated first, and thereafter those which are independent of electricity.

6.2.1 Electricity/CHP related

It lies beyond the scope of this brochure to carry out any detailed analysis of the contribution of AD in the context of climate change or the total amount of energy from fossil fuel which is replaced. However, the twice yearly publications of the IEA Bioenergy Task 37 (Country Reports, 2015) track the number of plants installed and the growth in the output of electricity measured either as energy (GJ) or in the output of MWh. The situation in Germany is used below as a case study to illustrate:

- Effect of the incentives on the development of the biogas industry,
- Consequences related to land use
- Redirection to favour small manure based plants

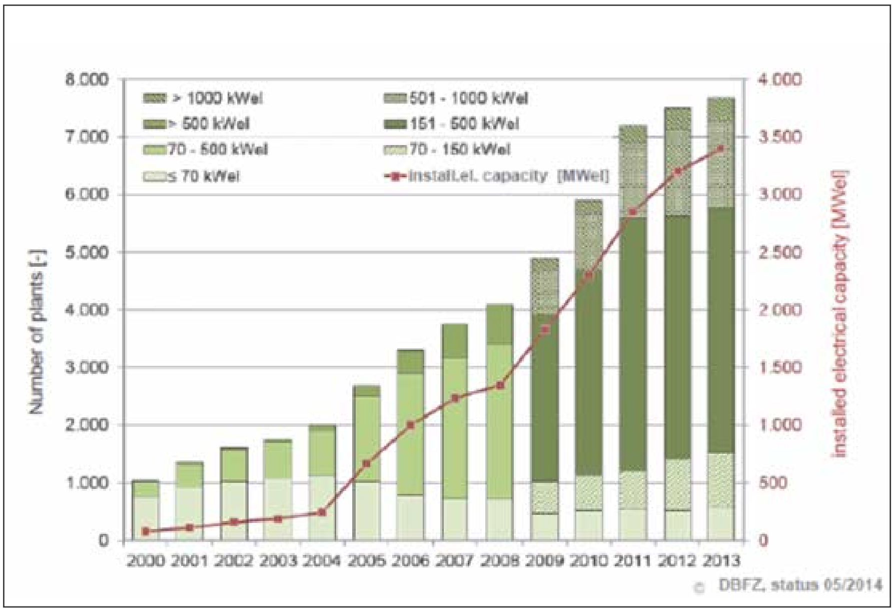

Figure 11: Installed capacity and number of plants in relation to incentives. Source: Scheftelowitz *et al.*, 2014

Figure 11 shows the dramatic increase in plant capacity associated the tariff changes made under the 2004 *Amendment of the Renewable Energy Sources Act* (EEG).

There is also a slow increase in the number of plants in the 70-150 kWe range, but a general decline in the number of plants where 80% of the feedstock by fresh weight is animal manure. Analysis of the raw data for 63 farms (FNR, 2009) revealed that only one of those farms installed a <150 kWe digester/CHP even when the tariff including bonuses increased from £0.10 to £0.16 per kWh. It would be safe to conclude that even a £0.20 tariff is not sufficient to encourage the construction of these small plants in Germany. In July 2014, this tariff, the only surviving incentive for on-farm biogas, was reduced to £0.15.

The increase in the number and size of plants is just part of the impact. Maize, with its high yields and biogas potential is often the feedstock of choice. This can lead in turn to side effects:

- The feedstock required needs more land than a farm has available
- If imported, the plant owner no longer has control of feedstock supply and its price.
- Further adverse effects are reported such as land use change. Where demand for maize destined for AD is intense, it has led to a shortage of affordable land to grow forage crops for the livestock farms.

Lease rentals per hectare in parts of Northern Germany have risen by 140% during the period between 2008 and 2012. This is attributed to competition for land to grow maize for energy. As a result, some dairy farms have changed from the use of local silage to imported soya meal from Brazil (Klawitter, 2012). In Austria, Walla and Schneeberger (2005) previously reported this trend towards an increase in plant capacity and similarly a move away from manure-based AD to produce heat for the farm to larger, mainly crop-based facilities. By 2007, about 83% of the Austrian farms also were based predominantly on maize (Braun and Kirchmayr, 2008). However, where the maize is used to extend the crop rotation, especially between cereals and oil seed rape, then it has a positive benefit for the maintenance of soil health and suppression of weed growth, as well as the minimisation of crop pathogens. The use of maize in this context can improve husbandry practice.

For the policy maker:

- Incentives stimulated the growth of the German AD industry and the output of electricity. In Austria, there is a similar response to the feed-in tariff under the Eco-electricity Act 2002 (Braun and Kirchmayr, 2008). The UK, too, has experienced growth in the AD sector since the introduction of incentives over the past 5-7 years.
- AD industry growth with dependence on crop feedstocks such as maize is a high risk strategy. This is exemplified by an 83% increase in maize cost/tonne within the 12 months between October 2006-2007 (Weiland, 2008; Braun and Kirchmayr, 2008). This is attributed to the increase in costs for diesel, synthetic fertiliser and crop protection, together with that for haulage (Delzeit *et al.*, 2012). It is a response to policy, the exploitation of which offered the chance of a profitable new farm enterprise at the feedstock price which prevailed when the plant was built.

Government reaction to the risks to biogas production and therefore to renewable electricity output generally led to an increase in the level of the incentives under the 2009 German EEG law. Overall, tariffs were raised to offset the increase in variable costs of maize and so cushion the biogas plants from the especially high maize prices which were outside the farm control.

Thereafter, the next law, EEG 2012, shifted the tariffs away from maize and used them to encourage the development of <75 kWe farm plants where 60% of the feedstock must be manure (Delzeit *et al.*, 2012) It also provided a manure bonus of either £0.06 or £0.05 for plants of <500 kWe and >500 kWe respectively when manure formed 60% or 80% by weight of the feedstock (Delzeit *et al.*, 2012).

There is also evidence that incentives influence equipment suppliers. For example, R&D in some construction companies focus on the production of a range of low cost small plants <100 kWe. However, for example, this focus turned to 75 kWe designs (Schmack GmbH, pers. comm., 2012), to be in line with the new tariff band introduced in 2012. Similarly, one German supplier of <50 kWe dual-fuelled biogas engines has ceased to offer those at the smaller end of the scale in order to concentrate on marketing a 75 kWe model and larger systems up to 500 kWe capacity (Schnell Motoren, pers. communication, 2013).

The new 2014 German EEG law is regarded as the start of an energy shift by the Minstry for Economy and Energy but, more dramatically, it is a severe blow to their biogas industry.

6.2.2 Non electricity/CHP related

There are other fiscal incentives which have particular application to the very small scale manure based plants. Examples of other financial support in IEA Task 37 member countries for biogas upgrading for vehicle use and gas grid injection are given in Persson and Baxter (2015). However, of greater relevance for present purposes is the Swedish approach to give tangible 'public good' incentives which are felt in the pokket of biomethane users. This includes, for example, reduced vehicle taxation, as well as free parking places. If applied to the small scale farm AD plants, the range of very small upgrading systems of <10 Nm^3/hour have the potential to reduce dependence on diesel fuel, not only for use on the farm, but also for vehicles engaged in the farm business. Such incentives also support rural areas where small local vehicle refuelling stations have been closed, necessitating vehicle owners to travel further to refuel. Such plants already operate in parts of India, Sri Lanka and Brazil.

6.3 Contribution of incentives to GHG abatement

Up to this point, the discussion has hinged on the use of incentives as a policy mechanism to support renewable energy production including that from AD. Even before any potential GHG emissions from compounds of nitrogen are taken in account (see Section 4), there is a clear consensus at the global level that AD is an effective, indeed recommended means by which to reduce GHGs from livestock manure:

- Through emissions from storage
- By replacement of fossil fuel based fertiliser
- Through the production of renewable energy to replace that from fossil fuels

This is quite apart from its contribution to the maintenance of a sustainable system of agricultural and environmental management. However, the incentives above recognise only the emissions which arise from the direct replacement of fossil fuel based energy. Another aspect to the evaluation of the GHG emissions reduction involves the cost of CO_{2e} emissions and this cost needs to be taken into account when assessing value for

Table 21 Marginal Abatement Cost (MAC) examples (Profit/cost per tonne CO_{2e} mitigated)

	Scenario	1	2	3	4
Example	Capital cost	Slurry, 185 days housing, boiler, incentive on total heat	Slurry, 365 days housing, boiler, incentive on excess	Slurry, 365 days housing, CHP & heat	Slurry, 185 housing, CHP & heat, top up with crop in summer
	Tonnes CO_{2e} /year	76	119	151	125
MAC cost with no incentives – Energy: electricity (£0.11) & oil (£0.42) at October 2014 price					
(a)	£100K digester	-111	-58	33	6
	£150K digester	-187	-106	-6	-41
	£200K digester	-263	-155	-44	-97
MAC cost with electricity incentive @ £0.1013/heat @ £0.076 – Energy at October 2014 prices (see Table 17)					
(b)	£100K digester	38	22	73	72
	£150K digester	-38	-26	34	26
	£200K digester	-114	-59	-4	-20

money which AD can offer. This is known as the marginal abatement cost (MAC) where:

$$\frac{\textit{The farm's profit or loss}}{\textit{kg or tonnes of } CO_{2e} \textit{ abated}}$$

An illustration of MACs based on the experience of one country (UK) is shown in Table 21. This concept is transferable to other countries that have different energy prices and incentives. In simple terms, where there is no incentive the cost of GHG abatement has to be covered by the farmer, in which case the farmer can only justify the installation of a digester if it offers a significant improvement in the productivity of the slurry.

The MAC figures shown in red in unshaded cells (Table 21) predict losses associated with installation of an AD plant, and thus a farmer would be unlikely to make an investment in AD. However, for plants up to £150,000 even without incentive there can be a win-win situation for the farmer and the policy maker with just an 11 kWe CHP if slurry only or slurry supplemented with other feedstock is available year round. In this situation the farmer still carries the costs of GHG reduction policy.

If there is an incentive, as for example at the levels used for illustration in Table 21, an AD plant, even with a capital cost up to £200,000 could be financially attractive. An incentive can change the position dramatically from loss to profit, but the farmer still carries part of the costs for CO_2 abatement. If the AD system can bring financial benefit to the farmer, even with a small incentive, this gives good value for money to the policy maker. Based on a Life Cycle Assessment, Styles *et al.* (2014) reached the same conclusion using an example of a 133 cow herd from which the slurry is stored in an open lagoon. In the latter case, a £0.20 incentive for electricity would cost the tax payer £60 per tonne CO_{2e} saved. When this is compared with off shore wind energy with an incentive of £0.9 /kWh, the cost of GHG abatement is £182 per tonne. Independent of the approach taken, it is contended that small scale farm AD offers good value for money. An incentive which recognises the whole process for managing the reduction of GHGs from livestock manure, and not tied to electricity or CHP, can create the demand to stimulate production, bring down capital cost and ultimately have the potential to remove the need for incentives for energy in isolation.

Agri-environment schemes were first introduced into EU agricultural policy during the late 1980s as an option to be applied by Member States. Since 1992, the application of agri-environment programmes has been compulsory for Member States in the framework of their rural development plans. The United States has also recently issued a 'Biogas Opportunities Roadmap' (USDA, 2014) as part of a larger strategy to reduce emissions of greenhouse gases.

7. Concluding remarks and the way ahead

Extensive investigations at the international level all reach the same conclusion that AD is the most effective, indeed recommended technology for the removal of methane emissions from storage of livestock manure. There is also a cautionary note that the AD process could potentially increase the amount of ammonia which can be released from the digestate into the atmosphere. This, however, is a matter for best practice management and therefore not an insuperable problem. It can be resolved in the main by the gas tight storage of the digestate, as well as by the timing and method of application of the digestate to land. The cost calculations in the preceding section assume best practice in the plant design and management. These approaches are taken as standard practice in the foregoing pages.

There is no technical limitation on the scale of AD, as demonstrated by the millions of digesters in China and the Indian sub-continent which serve both the energy needs of families or small rural communities and are equally important for their social and economic development. Livestock manure is a key element in such schemes and is reinforced by its scope to add value to both human waste and crop residues. AD is a multi-purpose process. It reduces the GHG emissions from the storage of the livestock manure, the recovered biogas replaces oil, kerosene or wood as fuels and so reduces the release of particulates and toxins into the atmosphere. As a consequence, their detrimental effects on human health are reduced, while the reduction or elimination of pathogens during the process can lead to improved human health as well as animal health and productivity. These small scale plants wherever they are located can usually be integrated into a wholly sustainable farming system for the reduction of pollution to land, air and water.

The evidence presented in this report considers the potential financial implications for the adoption of AD for the reduction of GHGs which arise from the storage and handling of livestock manure on small scale dairy farms.

The approach to adoption of AD at small scale differs from when it is installed as an alternative farm energy enterprise or as a commercial plant. There is a different attitude and psychology to the use of AD when it is used as a basic farm process to enhance the productivity and monetary value of slurry. On such a dairy farm, the slurry tank, or other storage system, is a major cost without any income. Dairy farmers generally need a simple, efficient and minimal cost system for dealing with slurry, and preferably one that reduces net cost to the farm. The investigations in these pages show that, in appropriate circumstances, a small AD system can meet this need. For the farmer, the avoided costs and a predictable level of expenditure on energy, for example, are as important as any additional income from outside sources. This factor must not be overlooked in any evaluation of these very small plants. Nevertheless, there is still the underlying dependence on the relationship between capital cost, energy prices and incentives, quite apart from any extra costs incurred to meet national regulations.

Conclusions to this effect have been reached by a number of studies made over the last three decades. There has been considerable progress in understanding process management and plant design since many of these studies were undertaken. It is, however, an over-simplification to assert that the high levels of incentives are needed to offset the high capital costs of such plants. The previous pages have shown what constitute the capital costs and where the operating costs lie. The farmer needs an awareness of how best to match the feedstock, in this case slurry, with the choice of plant design. In Europe and Brazil for example, many companies are working to bring down these costs and match their digesters to meet the needs of the small farms.

The driving force behind the incentive systems adopted by national governments is to encourage renewable energy production as for example in Europe to replace the use of fossil fuels and so remove the sources of the GHG emissions. These incentives have and still are fulfilling that purpose. However, they have not been favourable to the development of anaerobic digestion on a small scale and especially manure based plants, simply because these have been geared to electricity production which involves further complexity and investment in generation capacity. To tackle the issues of agricultural GHG emissions, the approach used in these pages gives a lead as to how AD, as the acknowledged best available technology for the reduction of GHGs from manure, can be achieved through the non CHP option where it fulfils the needs for heating or cooling within the buildings of the farmstead as a whole rather than the dairy in isolation.

Widespread adoption can drive the cost of small scale AD plants down through innovation, development and production and, where incentives are present, can allow support so that such plants can fit into the existing farming system, rather than having to alter the farming system in order to accommodate the digester and the incentive scheme.

The incentive schemes in place in Europe have led to the development of a biogas industry which has allowed farms to become energy enterprises, primarily with the use of purpose-grown biomass. The focus has certainly shifted from the use of AD as a technology to derive resource and environmental benefit from the management of manures. Even in the UK, which now offers incentives for heat use, the competing incentives which make 'energy farming' so financially attractive are unlikely to shift the current trend away from larger and financially more lucrative schemes. In practice, there are some co-digestion plants which were constructed as mainly slurry AD systems but have excluded slurry from the current operation and converted the plants to operate on food waste and crops.

Slurry is a huge undervalued resource which is present on very large numbers of widely dispersed farms. Countries such as Denmark, Austria, Switzerland and Germany already offer an extra incentive to encourage the inclusion of manure. Alternatively, a set percentage of manure can be included in the feedstock mix to qualify for the bonus. This is progress. However, there are thousands upon thousands of dairy, pig and poultry farms, all of which contribute to the estimated 87Mt of CO_{2e} emissions from livestock manure in Europe. These explorations have highlighted a wide policy gap for which the installation of small scale AD plants to reduce GHG emissions from slurry storage has the potential to make in aggregate a considerable contribution to the reduction of GHG emissions from livestock manure and at the same time improve the efficiency of the farm. The attraction for the farm is that the AD process adds value to the slurry so that it can generate income to offset some of the overheads of the dairy herd or to reduce those costs when compared with the *status quo*.

Given the stimulus of a favourable combination of capital cost, energy price and incentive at the outset, there is a win for the policy maker and a win felt in the pocket of the farmer. Agri-environment schemes were first introduced into EU agricultural policy during the late 1980s as an option to be applied by Member States. Since 1992, the application of agri-environment programmes has been compulsory for Member States in the framework of their rural development plans. The structures are in place to capitalise on the use of small AD plants so they become standard pieces of farm equipment which turns slurry into a resource.

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9. Further reading

AGRICULTURE GLOBAL METHANE INITIATIVE. Regular reports on the livestock and other agriculture activities relevant to AD from 41 countries worldwide
Available at: www.globalmethane.org/agriculture/index.aspx

BAUER, F., HULTEBERG, C., PERSSON, T., TAMM, D. (2012) Biogas upgrading – Overview and assessment of commercial technologies. Swedish Gas Technology Centre, Malmö.
Available at: http://www.sgc.se/en/?pg=1445649&c=

Appendix A – Currency Conversions

Currency conversions from 1 GB Pound Sterling (£) (reference date: 27th October 2014)

Australian Dollar (AUD)	nd	
Brazilian Real (BRL)	4.08	
Danish Kroner (DKK)	9.46	
Euro (€)	1.27	Applies to Austria, Finland, France, Germany, Ireland, Netherlands,
Norwegian Krone (NOK)	10.67	
South Korean Won (KRW)	1,695.20	
Swedish Krona (SEK)	11.06	
Swiss Franc (CHF)	1.53	
US Dollar (USD)	1.61	

Appendix B – Livestock Unit Coefficients

A Livestock Unit is usually defined in terms of feed requirements. The ratios in the table below are based on metabolisable energy requirements, with one livestock unit being considered as the maintenance of a mature black and white dairy cow yielding an average annual milk yield.

1. To calculate the stocking density of grazing livestock, allowances should strictly be made for variation in output e.g. yield per cow or live weight gain per head, and also for quantities of non-forage feed consumed by each category of stock.
2. To calculate the total Livestock Units on a farm, the appropriate Livestock Units should be multiplied by the monthly average livestock numbers, except in the case of lambs and purchased stores where throughput should be used.
3. Because of the range in breed and type of animal in any one category (e.g. Friesian/Holstein and Channel Island dairy cows) the results obtained from the use of these figures must be interpreted with care.

These are ratios for converting numbers of animals into Livestock Units

Type of Stock	Livestock Units
Cattle	
Dairy cows	1.00
Dairy Bulls	0.65
Beef Cows	0.75
Beef Bulls	0.65
Heifers in calf	0.80
Other Cattle (excluding intensive beef systems)	
0 – 12 months	0.34
12 – 24 months	0.65
over 24 months[(a)]	0.80
Barley Beef	0.47
Poultry	
Cocks, hens, pullets in lay	0.0017
Pullets one week to point of lay	0.0030
Broilers	0.0017
Other table chicken	0.004
Turkeys	0.005
Ducks, geese, other poultry	0.003
Sheep	0.08
Rams	
Lowland ewes	0.11
Upland ewes	0.08
Hill ewes	0.06
Store lambs, under 1 year	0.04
Breeding ewe hogs, 6 to 12 months	0.06
Other sheep over 1 year	0.08
Pigs	
Boars	0.35
Breeding sows	0.44
Gilts in pig	0.20
Maiden gilts	0.18
Other pigs	0.17
Other Livestock	
Horses	0.80
Breeding female goats	0.16
Other goats	0.11

Source: Defra (2010) Definitions used in farm business management.

archive.defra.gov.uk/foodfarm/farmmanage/advice / See also FAO (nd) Tropical Livestock Units - Food and Agriculture Organization http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/Mixed1/

Appendix C– The Kalmari farm experience

Introduction

This case study of Kalmari Farm in Finland illustrates how an enterprising farmer used his initiative and practical skills to lower the costs of building a biogas plant and a biogas upgrading system to produce vehicle fuel. The information for this case study is provided by Metener Ltd, the commercial company founded by the farmer in 2002. Metener Ltd delivers process and construction planning, automation, biogas and biomass treatment equipment and pipe systems, as well as biogas utilisation equipment (www.metener.fi).

The Kalmari experience

Mr Erkki Kalmari is the 11th generation of his family to farm this land since 1666. The farm is situated in the small village of Laukä in Central Finland about 15 kilometres to the north of Jyväskylä. The farm is mainly dairy and includes 70 ha of fodder and other crops.

Mr Kalmari built the first digester in 1998 when the farm had about 100 LSU (40 cows and about 60 herd replacements, as well as a beef herd). The reasons Mr Kalmari decided to build a digester were:

- To replace expensive electricity purchased from the national grid
- To avoid the labour intensive tasks required to harvest and chip the wood from the estate which was required as fuel for the boiler to provide heating and hot water
- To improve the hygiene standards associated with manure management

The digester was constructed using equipment and materials which were already on the farm or could be found locally at little or no cost. Table C1 summarises details and performance of the digester as built in 1998. It is impossible to establish the full cost of the plant, as all the time used to find the components and the labour for the construction were absorbed into the daily running of the farm. However, anecdotal evidence suggests that it cost about 9,000 Euro to acquire the various components.

Table C1 Details and performance of the Kalmari plant in 1998

Feedstock: 6 tonnes slurry/day,
Digester tank: 150 m^3, including 20 m^3 for gas storage
Operating temperature: Mesophilic 35°C
Retention time: 20-22 days
Biogas output: 25 m^3/t of slurry
Methane content: 60-65%
Equipment included:
80 kW gas boiler,
15 kWe CHP unit
Activated carbon to reduce H_2S from 300-500ppm to 10-30ppm for the CHP engine only

The original digester installed in 1998 (Photo: Metener Oy)

Between 1998 and 2002, it is estimated that the digester saved the farm between 27,000 and 31,000 Euro (Table C 2).

Measurements of Faecal Streptococci and Coliform bacteria populations showed digestion to reduce these by 98% and 99% respectively compared with those in the feedstock slurry (residence time in the digester was 22 days at 35°C). These data are summarised in Figure C1 below which also illustrates that there was no regrowth of pathogens after six months of covered storage before the digestate was applied to land.

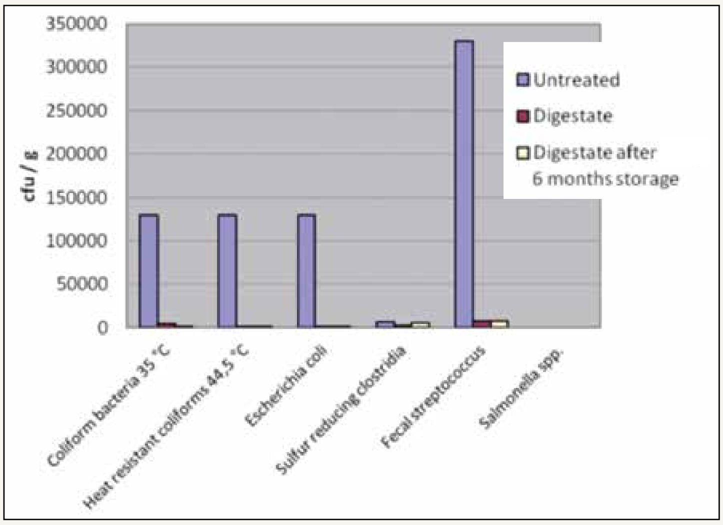
At first, this was a slurry-only digester with a total feedstock of 1680 t/year available from the livestock on the farm during the period of housing. From 2001, the farm secured a supply of 60 t/year of confectionary residues. When required, these residues were delivered by tractor and trailer from the local sweet factory to maintain the biogas output to meet the farm's energy demand. This feed supplement yielded a 35% increase in biogas output at no extra cost for the farm. This laid the foundation in 2002 for the second development stage – the addition of a micro high pressure water scrubber to upgrade the biogas to biomethane and the installation of the first farm biomethane filling station in Finland. The upgrading system served only the farm and was not connected to a gas grid. Additions to the plant made in 2002 are summarised in Table C3.

Mr Kalmari designed and built the biomethane upgrading plant himself and again made use of recycled parts and/or those which could be purchased 'off the shelf' from builders merchants and similar sources. For vehicle use, the biogas was upgraded to 95% methane content and pressurized to 270 bar. In 2002, Mr Kalmari purchased a Volvo V70 car which was already modified to a dual fuel system which operated on biomethane and diesel fuel – the first in Finland. By 2006, biomethane was sold mainly to neighbours who operated an 'honesty box' system.

Table C2 Examples of the benefits achieved from the digester (for 1998–2002 prices)

Self-sufficiency in heat and electricity, even during the coldest winters	Replaced wood chips and logs cut from the farm estate
Reduced cost of fuel bills: a) Labour b) Heat c) Electricity	 Labour cost for harvesting, cutting and feeding wood fuel to meet demand for 300 kWh of heat @ average price 50 – 60 €/MWh 15,000 – 18,000 €/year 7,000 €/year
Reduction in fertiliser bills (includes the addition of sweet factory residues used from 2001)	5,000 – 6000 €
Reduced veterinary bills	Not quantifiable, but better animal health and higher milk yields per cow

Figure C1 Quantity of pathogens in untreated cow slurry, digestate after digestion and digestate after storage for six months



(Source: Luostarinen, J. (2001). Farm-scale biogas production in Northern Europe, available at: www.valorgas.soton.ac.uk/Pub_docs/iit_131213_metener.pdf)

Table C3 2002 additions to the original Kalmari AD plant

Characteristic of the 2002 development The 120 m³ original digester with gas storage remains in use as well as the 15 kWe CHP
Additions: 1 To the digester and CHP 90 m³ Feedstock concrete slab mixing tank 25 kWe self-converted diesel engine for operation with biogas
Addition 2 Biogas upgrading plant and biomethane filling station: High pressure water scrubber to process 8 Nm³/h of biogas Compressors Volvo Bi-fuel V70 private car purchased for personal use Biomethane filling station for the farm car and available for neighbours to use

Figure C2 Patented Metener biogas upgrading technology (J. Läntelä) (left) and Kalmari Farm's new fully commercial biogas filling station (O. Pakarinen) (right)

The year 2008 marked the start of the third development phase which involved an increase both in the quantity of feedstock and its biogas output. Hitherto, the farm had taken as much of the sweet factory residues as it needed to maintain its self-sufficiency for heat and power and for upgrading to biomethane. After 2008, the farm received the entire confectionary residue which the factory produced. This was delivered by tractor and trailer in 7-8 tonne loads to fit with the production level in the factory. The increased annual input of feedstock in 2008 is summarised in Table C4 Inputs and outputs for the Kalmari AD plant (post-2008). This increase resulted in increased biogas output and this made it possible to expand biomethane output. Up to this point, although the biomethane was available for sale to neighbours, few took the opportunity because the Finnish Government imposed a 10,000 Euro tax on biogas cars unless the required written permission for ownership had been secured in advance from the State Treasurer. This tax was rescinded in 2006, after which biogas cars paid the same tax as petrol cars and the demand from neighbours gained momentum.

In 2008, the main change was the construction of the new 1,000 m³ digester. This was retrofitted into an existing concrete slurry lagoon, the sides of which were raised a further two metres in height with the same type of concrete slabs as those used for the original lagoon. A submersible stirrer and heat exchangers were installed and thereafter the whole tank was also closed with a concrete cover. The design capacity of the new digester was planned to allow for further growth in demand for vehicle fuel and therefore for an increase in feedstock from which to produce the biogas (this would have the effect of reducing the retention time given in Table C5). Other components which were added included an extra 1,500 m³ covered gas tight post-storage tank for the digestate and biogas. New equipment for biogas upgrading to biomethane was constructed, together with a larger vehicle fuelling facility. The main changes to the plant in 2008 are summarised in Table C5.

The 120 m³ tank (a converted road tanker used to transport heavy fuel oil) which had previously served as the digester was converted into the pasteuriser. There were no additions to the CHP system or to the boiler. The farm had become entirely self-sufficient for heat and electricity even during the coldest winters. The plant was fully automated and the labour input reduced to an hour or two a day.

In 2011, the Kalmari Farm opened its first metered public biomethane filling station for the commercial sale of the vehicle fuel and a capacity to serve 200 cars (Figure C2). However, by 2013, the number had increased to 300 regular customers, about 80 of whom were from the local area.

By this stage, the feedstock range had been widened to make use of other available residues in order to secure

Table C4 Inputs and outputs for the Kalmari AD plant (post-2008)

Input: Feedstock mix	**Quantity/year**
Cow manure	2,000 m³
Confectionary residues	200 m³
Agri-industrial residues	300 m³
Some silage and grass	50 t
Total annual input/year	2,500 m³ + crop as required
Outputs:	
End products of the mix:	
Electricity	105 MWh
Heat	350 MWh
Biomethane for use as vehicle fuel	1,000 MWh

Table C5 Plant characteristics/modifications, 2008

Plant characteristics	**Capacity:**
Digester volume	1000 m^3
Digester temperature (no change)	Mesophilic: 35°C
Retention time	100-150 days
Digestate storage tank with 6 months space and gas store	1500 m^3
CHP *(no change)*	25 kWe 50 kW_{th}
Gas boiler used for hot water, space heating and grain drying *(no change)*	80 kW_{th}
Pasteuriser (previously used as the 120 m^3 digester tank)	70°C
Biogas upgrading: high pressure batch water scrubber	50 Nm^3 /hour
Steel gas storage bottles and vehicle filling station	

sufficient gas output to meet the demand for the self-sufficiency of the farm and the workshops on site, as well as to develop the growing biomethane market. Under the current licence regulation, the farm is limited to a maximum of 500 m^3 of agri-industrial residues.

The addition of the agri-industrial residues and food waste (Table C6) required alterations to the plant design and additional space for digestate and biogas storage.

Inclusion of non-agricultural residues in the feedstock also required the addition of a pasteuriser for compliance with the EU ABPR Regulation (2009).

It is not possible from available data to calculate the net financial benefit to the farm without details of the operating costs. However, Table C6 shows the importance of the avoided expenditure over the first nine years and the growth of new income thereafter.

The sales income from vehicle fuel increased dramatically with the installation of the larger biogas upgrading system and a filling station for metered sale to the public. Vehicle fuel income has now overtaken that from the livestock which provided the basis for this plant. The whole success of the Kalmari experience is particularly noteworthy in that the avoided expenditure was the principal incentive rather than reliance upon government subsidy.

See IEA success story "Pioneering biogas farming in Central Finland" for further information (http://www.motiva.fi/files/7682/success-story-kalmari2012.pdf)

Table C6 Summary of annual financial benefits 1998 – 2011 (Euro)

Financial benefit	**Stage 1 1998 - 2001**	**Stage 2 2002 - 2007**	**Stage 3 2008 - 2011**	**Comments**
Avoided expenditure:				
Electricity	7,000	10,000	13,000	Combined effect of electricity price increase and increase farm consumption
Heat	15,000 - 18,000	18,000 - 20,000	18,000 - 20,000	Includes heat from the CHP and boiler
Car fuel	2,000	2,000	6,000	
Tractor fuel	0	0	Circa 1,000	
Artificial fertiliser replacement	5,000 - 6,000	5,000 - 6,000	5,000 - 6,000	
Reduced expenditure on veterinary bills	Not quantified	Not quantified	Not quantified	
Sub-total avoided expenditure (a)	*29,000 - 35,000*	*35,000 - 38,000*	*43,000 - 46,000*	
New income sources:				
Electricity export	0	0	0	
Heat	0	0	0	
Biomethane for vehicle fuel	0	12,000	90,000	
Extra litres of milk	Not quantifiable	Not quantifiable	Not quantifiable	
Gate fees	0	0	5,000	
Sub-total new income (b)	*0*	*12,000*	*95,000*	
Total financial benefit (a) + (b)	**29,000 - 35,000**	**47,000 - 50,000**	**138,000 - 141,000**	

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Task 37 - Energy from Biogas

IEA Bioenergy

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of work carried out by IEA Bioenergy Task 37: Energy from Biogas.

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