INTERIM TECHNICAL REPORT

27 MONTHS PERFORMANCE SUMMARY FOR ANAEROBIC DIGESTION OF DAIRY COW SLURRY AT AFBI HILLSBOROUGH

Figure 1: Photograph of AD plant at AFBI (digester tank centre)

Peter Frost and Stephen Gilkinson
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AFBI Hillsborough

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SUMMARY of AFBI DIGESTER PERFORMANCE

Following intensive monitoring of the on-farm anaerobic slurry digester at AFBI, Hillsborough during 27 months of operation with dairy cow slurry as the main input, AFBI has observed that, on average:-

1. 1 tonne of dairy cow slurry at 69g/kg dry matter produced 15.2 cubic meters of biogas containing 85 kWh of energy
2. 1 tonne of organic matter in slurry produced 280 cubic meters of biogas (0.28 m^3/kg organic matter)
3. 32 kWh energy (as heat) per tonne of input slurry was required to maintain mean digester temperature at 37.1^0C (39% of gross energy produced)
4. The available nitrogen concentration in digestate was 19% greater than in raw slurry
5. Digestate did not require mixing before land spreading and did not crust
6. The average H_2S concentration of the biogas was 1,670 ppm.
7. The dry matter concentration of digestate was 20% lower than the raw slurry
8. The COD of digestate was 28% less than that of raw slurry
9. Digester operation required an average of approximately 1.3 person hours per day

INTRODUCTION

Anaerobic digestion of animal slurries on farms involves bacteriological breakdown of organic matter to produce biogas and digested effluent (digestate). Digestate is lower in pollution potential, has less odour, contains fewer viable weed seeds, has fewer pathogens than the input slurry and is an excellent biofertiliser. Biogas is a mixture of gases: methane (50–75%); carbon dioxide (25–50%); nitrogen (0–10%); hydrogen (0–1%); hydrogen sulphide (0–1%); and oxygen[1] (0–2%).

The calorific value of biogas is variable (depending on methane content) at 20-26 MJ/m^3 (5.6-7.2 kWh/m^3). The heating oil equivalent is approximately 0.5 – 0.7 litres oil /m^3 biogas. Biogas is thus an excellent source of renewable energy.

Anaerobic digestion requires a gastight tank with draw-off points for biogas in the headspace, a heating system to maintain optimum digester temperature (35^0C-40^0C for mesophilic digesters), a method of loading inputs and unloading digestate. Mixing of digester contents is necessary to prevent settling of solids and crust formation, as well as to ensure an even temperature within the digester. Typically, mixing is carried out by mechanical stirrers or by biogas recirculation.

To be viable, farm digesters require a regular supply of slurry with greater than 6 % total solids (TS) content, which should produce a biogas yield of about 16 - 20 m^3 biogas per tonne of slurry. Therefore, excessive dilution of slurry should be avoided. On many farms preventing dilution of slurry could involve capital expenditure and/or civil works on site. At the other extreme, a high TS content of slurry (> 12 %) makes for poor flow characteristics and for difficult pumping.

Digester heating is normally carried out by circulating hot water through a heat exchanger located inside or outside the digester. Hot water can be produced by utilising some of the biogas produced through a biogas boiler (75-90% efficient), or through a combined heat and power unit. Alternatively, heat can be provided by electrical heating, by an oil boiler or from some other source of energy. Insulation of the digester is important to minimise heat loss. It is estimated that, depending on climate and temperature of slurry inputted, 20-70 % of the gross energy available in the biogas produced through anaerobic digestion of cattle slurry is required to maintain digester temperature.

DETAILS OF THE AFBI ANAEROBIC DIGESTER

The anaerobic digester at AFBI-Hillsborough was designed to AFBI specifications, supplied and constructed by Greenfinch Ltd (now BiogenGreenfinch), Ludlow, Shropshire. Construction took place between September 2007 and March 2008.

[1] Air may be added to biogas in the digester to reduce the hydrogen sulphide concentration, otherwise there should be no oxygen present.

The time from commencement of feeding the digester with slurry until steady state production of biogas was approximately 6 months (end of April 2008 until October 2008). Initially the digester was half filled with dairy cow slurry, which was then heated up to 37^0C using gas cylinders of propane burnt in a gas (biogas) boiler. After approximately 6 weeks there was sufficient biogas volume and quality to convert the boiler over to biogas. Digester feeding then commenced at approximately 6 tonnes per day, slowly building up to 20 tonnes per day over the next 3 months. The cost of propane consumed was approximately £1,500. A steady state could probably have been reached more quickly if the digester has been completely filled with slurry, but twice the amount of propane would have been required. Before appreciable amounts of methane could be produced, the headspace air in the digester had to be purged of oxygen with slurry gas (mainly carbon dioxide) produced by microbes in the slurry.

The AD plant at Hillsborough is detailed in Table 1 and as a photograph in Figure 1 (see front cover).

Table 1: Details of AD plant at AFBI

Digester tank	660 m^3 above ground sealed epoxy coated steel tank with 100 mm mineral wool insulation and 1mm plastic coated steel outer protection. Continuously stirred tank reactor (CSTR) operating at mesophilic temperature (37^0C).
Secondary digester tank	660m^3 above ground epoxy coated sealed steel tank, continuously stirred, but not insulated
Feedstock tank	200 m^3 above ground epoxy coated open top steel tank
Digestate stores	2 of 1,500 m^3 above ground open top steel tanks (1 glass coated and 1 epoxy coated)
Digester feed	Fed hourly with a positive displacement lobe pump
Digester and secondary digester discharge	Discharged hourly with positive displacement lobe pumps
Digester mixing	Biogas recirculation 3 x 5 minutes per hour
Digester heating	External 100kW heat exchanger with circulation of digestate by positive displacement lobe pump. Hot water supplied by district heating system
Digester feed macerator	All digester inputs macerated to a nominal particle size of 12mm
Biogas boiler	Hoval 100kW nominal heat output
CHP	Tedom 23kW nominal electrical output
System control	Programmable logic controller (PLC)
Design and construction	Greenfinch Ltd (now BiogenGreenfinch), Ludlow, Shropshire to AFBI specifications

PERFORMANCE OF THE AFBI ON-FARM DIGESTER

Over the time period (24 January 2009 - 22 April 2011 inclusive) the digester was fed with 16,400 tonnes of mainly dairy cow slurry and produced 247,775 cubic meters (m^3) biogas with a gross energy value of 1,387 megawatt hours (MWh), equivalent to 129,670 litres of heating oil.

Performance figures for the digester were at the low end of commonly quoted ranges, which are often based on laboratory studies using small scale digesters.

Table 2 gives a summary of the AFBI digester performance. On average over the 27 month time period, 1 m^3 (1 tonne) of slurry at 69 g/kg dry matter fed to the digester produced 0.989 m^3 (0.989 tonne) of digestate containing 55 g/kg dry matter, plus 15.2$m^3$of biogas with a gross energy value of 85 kWh. Digestion required 32 kWh of heat per tonne of slurry fed to maintain average digester temperature at 37.1 ^{0}C (equivalent to 39 % of the total biogas energy produced), plus an average demand of 5.4 kWh of electricity per tonne of slurry input for pumps, mixing etc. The mean monthly biogas production per tonne organic matter fed is presented in Figure 2. There is considerable variation within and between years, with no clear seasonal pattern evident. Comparing year 2010 to 2009, there was a 19% increase in biogas production per tonne organic matter fed. The reason(s) for this are undetermined.

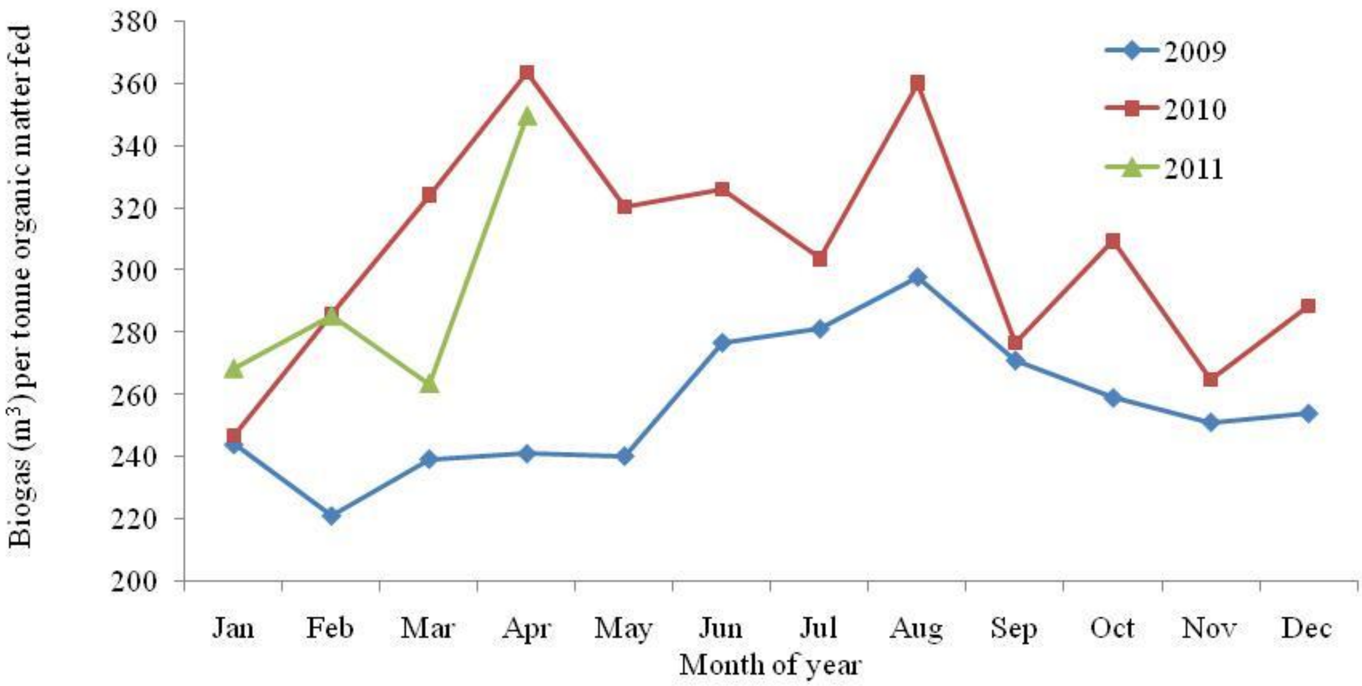


Figure 2: Monthly mean biogas production (m^3) per tonne organic matter fed.

The performance of the combined heat and power unit (CHP) over 10,266 hours of operation from August 2009 (date of commissioning) to April 2011 is summarised in Table 3. Figure 3 summarises the biogas energy output from the digester as utilised either through a CHP or through a biogas boiler. The overall energy efficiency was 87% for the biogas boiler and 78% for the CHP (27% electrical efficiency). Ignoring the energy requirements for digester construction (and all ancillary components), transportation of slurry to the digester and spreading of digestate, the average net renewable energy gain from biogas utilised through the CHP was 28.6 kWh/t of slurry input, with zero use of fossil fuel energy. Use of a biogas boiler gave an average net renewable energy gain of 43 kWh/t of slurry input for a 5.4 kWh/t input of fossil fuel energy (fossil fuel: renewable energy of 1:8). Note that higher biogas yields per tonne of fresh input would be obtained from using higher dry matter slurry or from co-digestion with, for example, grass silage. Work to determine the biogas yield from dairy cow slurry co-digested with grass silage is currently due to commence at AFBI in a DARD funded project.

When compared with the volume of slurry fed, the volume of digestate recovered was almost the same (99%), whilst chemical oxygen demand (COD) and dry matter of the digestate were lowered by 28% and 20% respectively. The total quantities of nutrients (N, P and K) in the digestate were almost identical as those in the input raw slurry. However, due to the process of digestion, the plant available N (ammonia-N) content of the digestate was 19% greater than in the raw slurry (Table 2). Field trials within AFBI are planned under a DARD funded project to determine the effect of this enhanced available nitrogen content on crop yields and nitrogen use efficiency. It is possible that greenhouse gas emissions (methane and nitrous oxide) during digestion, post digestion storage and after land spreading of digestate could be less than from conventional storing and spreading raw slurry. Trials are planned within AFBI with DARD funding to measure emissions of these gases.

Table 2: Performance of AFBI anaerobic digester over 117 weeks (24 January 2009 – 22 April 2011)

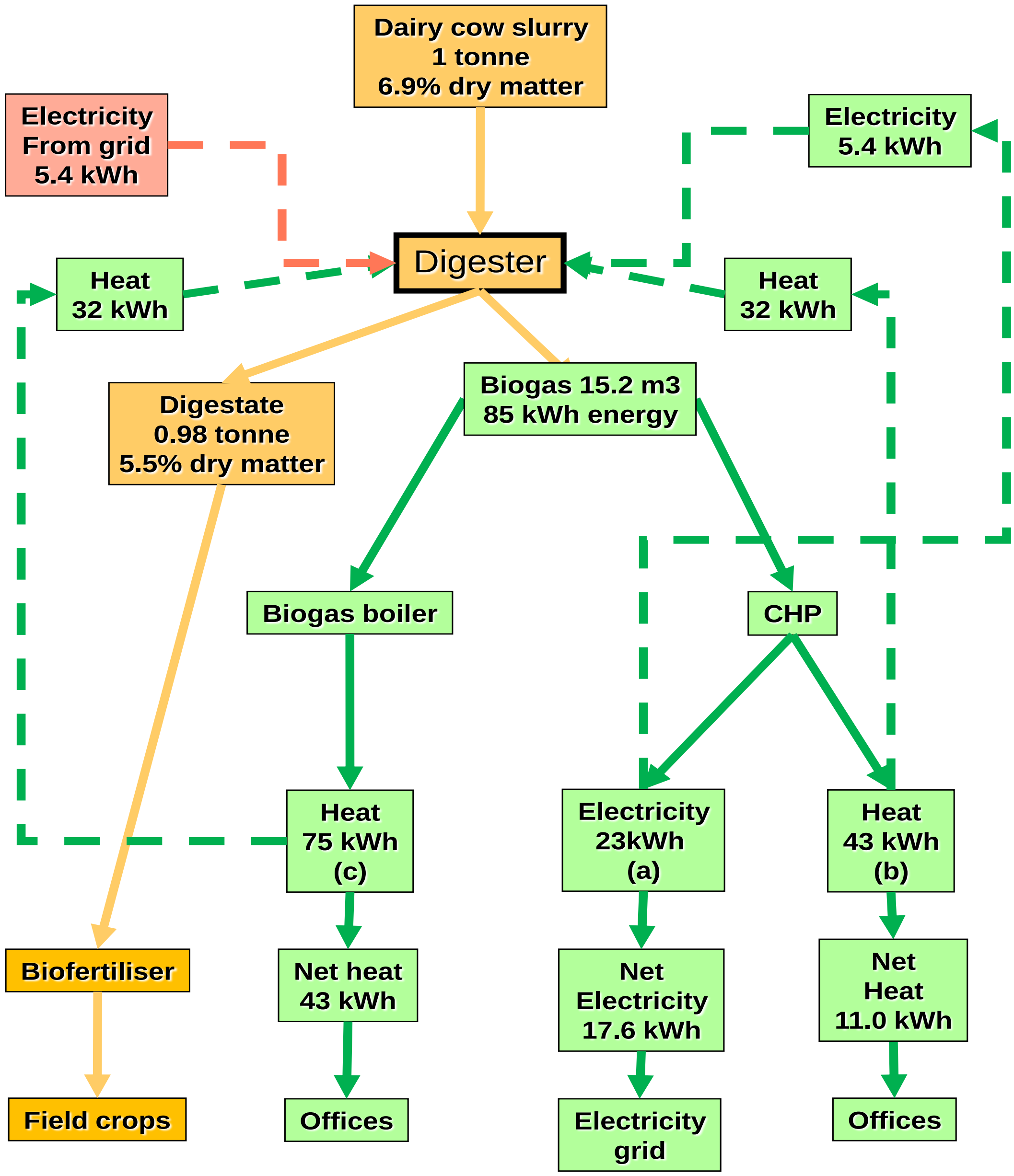
Inputs	**Mean**	**Minimum**	**Maximum**	**Standard deviation**
Slurry (tonnes/day)	20.0	17.6	24.4	1.06
Dry matter (total solids) (tonnes/day)	1.38	0.83	1.79	0.19
Organic matter (tonnes/day)	1.07	0.65	1.40	0.15
Organic matter (kg/m^3 digester per day)	2.02	1.19	2.49	0.29
Retention time (days)	27	23	30	1.29
Temperature (^{0}C)	37.1	36.3	42.0	0.30
Outputs				
Digestate	19.8	17.0	25.4	1.17
Biogas (m^3/day)	303	158	455	50.6
Methane (m^3/day)	169	90	266	27.6
Methane content of biogas (%)	56	52	61	1.6
Hydrogen sulphide content of biogas (ppm)	1670	496	2959	523
Gross biogas energy/tonne slurry (kWh)	85	45	132	14.9
Efficiency measures				
m^3 biogas/tonne slurry	15.2	8.0	22.6	2.73
m^3 biogas/m^3 digester/day	0.57	0.30	0.81	0.09
m^3 biogas/kg dry matter (total solids)	0.22	0.14	0.31	0.034
m^3 biogas/kg organic matter	0.28	0.18	0.40	0.045
m^3 methane/kg organic matter	0.16	0.10	0.23	0.025
Digester heating (kWh/tonne slurry input)	32	22	41	5.1
Energy required for digester heating (% gross biogas energy)	39	21	68	9.9
Slurry				
Dry matter (g/kg fresh)	69.0	35.3	86.5	9.69
Organic matter (g/kg fresh)	53.9	27.5	67.5	7.75
Organic matter (% of dry matter)	78.0	74.0	80.1	1.2
Nitrogen (g/kg fresh)	3.33	1.84	4.37	0.50
Ammonia nitrogen (g/kg fresh)	1.78	1.26	3.11	0.32
pH	7.23	5.90	8.63	0.50
Volatile fatty acids (g/kg fresh)	5.79	1.30	8.74	1.62
Chemical oxygen demand (g/l)[b]	81	47	103	10.8
Digestate				
Dry matter (g/kg fresh)	54.8	38.8	66.3	6.00
Organic matter (g/kg fresh)	40.0	28.4	50.0	4.64
Organic matter % of dry matter)	73.3	70.7	76.5	0.90
Nitrogen (g/kg fresh)	3.36	2.28	4.29	0.487
Ammonia nitrogen (g/kg fresh)	2.10	1.59	2.91	0.319
pH	7.92	7.15	8.93	0.381
Volatile fatty acids (g/kg fresh) [a]	1.16	0.08	3.35	0.811
Chemical oxygen demand (g/l) [b]	58	47	70	5.2
Dry matter digested (%)	24	15	34	3.8
Organic matter digested (%)	31	19	43	4.9
Chemical oxygen demand digested (%)	29	11	46	7.9
Volatile fatty acids digested (%)	76	23	99	16.7

[a] January 2009 to January 2010; [b] May 2009 to April 2010

Table 3: AFBI Combined Heat and Power outputs over 10,266 hours between August 2009[a] and April 2011.

CHP per m^3 biogas[a]	mean	minimum	maximum	Standard deviation
Electricity (gross kWh/m^3 biogas)	1.51	1.41	1.63	0.06
Heat (gross kWh/m^3 biogas)	2.83	2.62	3.05	0.10
Overall energy efficiency of engine (%)	78	74	84	3.0

[a] CHP was commissioned in August 2009



(a) 27% of gross biogas energy converted to electricity; (b) 51% of gross biogas energy converted to useable heat
(c) 87% of gross biogas energy converted to useable heat

Figure 2: Flow process chart of inputs and outputs following anaerobic digestion of 1 tonne of dairy cow slurry.

Summer versus winter production

Performance of the digester during summer (June – August) and winter (December – February) was compared. The heat demand in summer was 25 kWh/tonne slurry, while the corresponding figure for winter was 36 kWh/tonne slurry, an increase of 44% compared to summer heat demand. The average temperature of the slurry inputted during the summer period was 16.4^{0}C, while the corresponding figure for the winter period was 6.5^{0}C. Compared to the winter period, biogas production in summer was 3.4% higher per fresh tonne slurry. During the summer the slurry fed contained 6% less dry matter than the slurry fed during the winter. The combined effect was a 10% increase in summer biogas production per tonne slurry dry matter inputted. The reason(s) for this are unknown. However the higher storage temperature in the feedstock tank in summer may have encouraged the first step (hydrolysis) of the digestion process. Some of the summer slurry was sourced from tanks containing slurry deposited during the previous winter from dairy heifers and would have been expected to produce less biogas per tonne dry matter as a result of bacteriological activity during prolonged storage. Based on these figures, summer biogas production resulted in a higher net energy gain per unit of dry matter inputted, compared to winter production, as less energy is required to maintain digester temperature[2]. However if there is no ongoing use for the surplus heat produced from a CHP engine, the difference in net energy output between seasons is solely related to any differences in biogas yield per tonne slurry fed. In winter, up to 100% of the heat from a CHP may be required to maintain digester temperature, where low dry matter slurry is the only feedstock used.

Slurry temperature and thus energy required for heating was found to be highly correlated with ambient temperature, which is to be expected. While there is increased heat loss through the digester walls as ambient temperature decreases, this heat loss is small compared to the heat required to bring colder slurry up to digester operating temperature. Slurry stored in below ground tanks will be much less affected by changes in ambient temperature, compared to slurry stored in above ground tanks.

Biogas scrubbing

The hydrogen sulphide concentration of the biogas was on average approximately 1,670 ppm which was well above the upper limit of 800 ppm stipulated by the manufacturer of the CHP. An activated carbon column was fitted to the biogas line and this lowered hydrogen sulphide concentrations to an acceptable level for CHP operation. In practice the usage rate of activated carbon was approximately 1 kg per 100 m^3

[2] A CHP generator produces approximately 50% of the gross energy in the biogas as heat. Some of this heat (nearly all where only dilute slurries are fed) is required to maintain digester temperature. However, there is usually an excess of heat (particularly when energy crops are fed), which is potentially available for other uses, such as home heating, hot water for milking parlour, etc. Ideally there would be a constant demand for heat near the CHP location, so that an income stream could be obtained from selling heat as hot water. It is much easier and cheaper to move gas than hot water. It may be possible to pipe the biogas to a location remote from the AD site, where electricity and heat are required and thus maximise the use and returns from the combined outputs of a CHP. One option may be to have centralised biogas utilisation from several AD plants, where there is regular demand for electricity and heat.

of biogas scrubbed. Carbon in the column had to be replaced at approximately 14 day intervals. The cost of activated carbon was approximately £1.70/kg, making this method of gas scrubbing expensive. Digester plants with mechanical mixing often add approximately 5% air (1% oxygen) into the headspace of the digester and this allows a particular group of bacteria to sufficiently reduce hydrogen sulphide levels by forming elemental sulphur, which is removed in the digestate. The AFBI digester uses biogas recirculation for mixing digester contents, so the inclusion of air must be strictly controlled, otherwise the whole digester would become aerobic and methane production would cease, as methane producing bacteria are only active in anaerobic conditions.

All mechanical components of the digester (pumps etc.) operated reliably throughout the time period. The digester feedstock tank was filled weekly (140 tonnes) and this took approximately 5 hours with a tractor and transfer vacuum slurry tanker. The total time required to manage the digester (including daily, weekly, monthly and quarterly checks) was approximately 486 person hours per annum (Table 3). Servicing of the digester plant (including biogas boiler) required an additional 10 person days per year (2 services per year). CHP servicing was at 500 hour intervals and required approximately 3 person hours per service (approximately 45 person hours per year). Daily checks of the plant could be done in 15 minutes, assuming no other tasks are involved.

Table 3: Labour requirements for AFBI AD plant (excluding CHP and plant servicing)

Operation	Number of people	Time (hours)	Annual time (approximate person hours per year)
Daily management/checking	1	0.25	91
Weekly management/checking	1	+0.5	+26
Monthly management/checking	1	+0.5	+6
Quarterly management/checking	1	+1.0	+4
Weekly - transfer of raw slurry to digester	1	5	260
Occasional (e.g. clear blockage below ground tank submersible pump)	2	1	26
Every 10 days - change activated carbon	2	1	73
Total	-	-	**486**

COMMENTS

Anaerobic digestion can play a major role in production of renewable energy as well as helping to manage and recycle organic nutrients as fertiliser. Furthermore, anaerobic digestion is very effective at lowering the pathogen load in digestate. A Quality Protocol has been developed for digestate[3] that aims to provide

[3] Quality Protocol – Anaerobic Digestate – end of waste criteria for the production and use of quality outputs from anaerobic digestion of source-segregated biodegradable waste. July 2010. Developed by Waste & Resources Action Programme (WRAP) and the Northern Ireland Environment Agency in consultation with industry and other regulatory stakeholders. It is applicable in England, Wales and Northern Ireland.

increased market confidence in the quality of end products from materials that are classified as '*waste*' and so encourage greater recovery and recycling. Most farm based AD plants will not need to comply with this Quality Protocol, as feedstocks (manures and crops) produced on the home farm are not considered as 'waste' under current waste management legislation.

Digestate can be mechanically separated, in the same manner as whole slurry, to create a 'solid' fibrous fraction with a higher dry matter concentration and a liquid fraction with a lower dry matter concentration than the inputted material. Note that these two outputs need to be stored and handled separately. The advantages of mechanical separation include:

- Lowering the volume of liquid requiring storage
- Creating potential to export plant nutrients contained in the separated fibre off farm
- Improving the efficiency in nitrogen uptake from the liquid fraction
- Providing a greater window of opportunity for application of the liquid fraction
- Lowering the requirement for mixing of the liquid fraction prior to spreading.

Mechanical separators commonly used on farms include rotary screens, belt presses, and screw presses. Chemicals can be used to improve separator efficiency and to help differentially partition plant nutrients (particularly phosphorous) to the separated fibrous fraction. However chemical addition is not likely to be financially or practically feasible for most farm situations. The separated fibre fraction has a potential market value that may be further enhanced by composting to produce a "peat substitute" containing N, P and K that could be used as combined soil conditioner and fertiliser for horticultural use. It is likely that thorough aerobic composting of the separated fibre provide further pasteurisation of the digestate.

Anaerobic digestion, either on its own or when followed by mechanical separation, has thus a significant potential in helping nutrient management at farm level.

The digestate from the AFBI digester was 28% lower in chemical oxygen demand than the raw input slurry (Table 2) and therefore it is concluded that AD partly reduced the pollution potential of digested slurry. However, the digestate was still highly polluting and not suitable for direct discharge to water-courses. Experience at Hillsborough suggests that the smell of digestate produced from dairy cow slurry was similar to that from whole slurry, though the smell was less intense and did not persist as long after land spreading. In addition, the digestate at Hillsborough did not require in-store mixing, was free flowing and was easily spread by trailing-shoe tanker. It should be stressed that digestion to reduce pollution potential is an incomplete process and that other processes such as aeration may be used to further reduce odour and COD. A comparative study would be required to assess the relative costs and benefits from the various options available.

The data in table 4 indicate the possible range in financial outputs per tonne slurry digested for a range of biogas yields between 8 – 20 m^3 per tonne of fresh slurry and a range of CHP electrical efficiencies between 25 – 37%. Returns also depend on whether surplus heat can be utilised and whether electricity generated is sold or used to offset electricity purchases.

Table 4 Sensitivity analysis of financial output as affected by biogas yield per tonne slurry and electrical efficiency of CHP on financial value of digested slurry.

Biogas / tonne slurry (m^3)	8	12	16	20
Electrical efficiency of CHP (%)	25	29	33	37
Electricity produced (kWh/tonne)	11.0	19.1	29.0	40.7
Heat produced (kWh/tonne)	24.2	33.7	41.4	47.3
Net electricity (kWh)	5.6	13.7	26.6	35.3
Net heat (kWh)	-7.81	1.7	9.4	15.3
Financial output				
Electricity sold, no heat used[a]	£1.99	£3.45	£5.24	£7.34
Purchased electricity offset, plus all heat used on site[b]	£2.72	£5.30	£8.42	£12.10

[a] Assumes 4 ROC's @ 18p per kWh and electricity sold @ 4.5 pence per kWh

[b] Assumes 4 ROC's @ 18p per kWh, electricity bought @ 13.5 kWh, heating oil costs 60 pence/l with a gross energy value of 10.7 kWh/l and oil boiler efficiency of 85%.

Table 5 Sensitivity analysis of financial returns relative to biogas yield from slurry, when biogas burnt in biogas boiler.

Biogas / tonne slurry (m^3)	8	12	16	20
Heat produced (kWh/tonne)	39.0	58.5	78.0	97.4
Net heat (kWh/tonne)	7.0	26.5	46.0	65.4
Oil equivalent	0.8	2.9	5.1	7.2
Financial output[a]	-£0.27	£1.02	£2.30	£3.59

[a] Cost of plant electrical consumption subtracted. Assumes heat is used to offset heating oil purchases.

The financial returns are very dependent on the yield of biogas per tonne of feedstock, how the biogas is utilised (CHP or biogas boiler), whether surplus heat can be used and whether electricity is sold or used to offset purchases. The data in tables 4 & 5 show that financial outputs per tonne slurry digested may range between -£0.27 to £12.10. This is a vast range and shows that detailed physical and financial sensitivity analysis are required to determine viability, before commencement of a biogas project.

A realistic target for CHP runtime is 90-95% of a year. When the CHP stops revenue stops, but biogas is still produced and must be utilised. Most biogas plants have very limited gas storage capacity, as it is not generally economically feasible to store considerable quantities of biogas. Therefore a surplus gas burner must be installed as part of a digester plant, for use when other normal means of biogas consumption are not available. Methane is considered to be a greenhouse gas with a global warming potential 23 times that of carbon dioxide. Therefore biogas should not be released directly into the atmosphere.

Biogas can have a high hydrogen sulphide content (similar to slurry gas released during mixing of slurry tanks). Hence, relevant safety procedures must be adhered to at all times.

Co-digesting other organic materials along with slurry can greatly increase biogas yield per unit volume of digester. For example, by adding 3 tonnes grass silage with the slurry, the AFBI digester could, in theory, more than double biogas production. Work is ongoing within AFBI to determine the benefits from co-digestion with grass silage[4]

[4] Preliminary work at AFBI, Hillsborough with lab-scale anaerobic digesters has found that the yield of biogas from 1 tonne of good quality grass silage (27% dry matter) is approximately 125 m^3. The exact amount depends on silage quality, what other materials are co-digested with the silage, how long the silage is kept in the digester and digester temperature. This biogas yield equates to approximately 8,900 kWh electricity per hectare of land devoted to grass silage production (assuming 10 tonnes of grass silage dry matter is fed and all biogas is consumed in a CHP with 35% electrical efficiency). This is equivalent to 1.02 kW continuous electrical production from a hectare of grassland. No allowance has been made for CHP downtime, or AD plant electrical consumption. Plant electrical consumption is likely to be approximately 6-10 kWh per tonne grass silage fed.