INTERIM TECHNICAL REPORT

FIRST 18 MONTH PERFORMANCE SUMMARY FOR ANAEROBIC DIGESTION OF DAIRY COW SLURRY AT AFBI HILLSBOROUGH

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

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August 2010

AD-18-05

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 of operation with dairy cow slurry as the input, AFBI has observed that, on average:-

1. 1 tonne of dairy cow slurry at 72 g/kg dry matter produced 15.5 cubic meters of biogas containing 86 kWh of energy
2. 1 tonne of organic matter in slurry produced 280 cubic meters of biogas (0.28 m^3/kg)
3. 31 kWh energy (as heat) per tonne of input slurry was required to maintain digester temperature at 37^0C (37% of gross energy produced)
4. The available nitrogen concentration in digestate was 20% 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 19% 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 2 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	0–3%
Oxygen[1]	0–2%

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

The calorific value of biogas is variable (depending on methane content) at 20-26 MJ/m^3 (5.6-7.2kWh/m^3; heating oil equivalent is approximately 0.5 – 0.7 l/m^3). 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, dilution of slurry should be avoided. On many farms the removal of dilution water from slurry would involve extensive civil work. 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, 20-60% 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 specified by AFBI and was designed, supplied and constructed by Greenfinch Ltd (now BiogenGreenfinch), Ludlow, Shropshire. Construction took place between September 2007 and March 2008. The time from commencement of feeding the digester with slurry until steady state production of biogas was approximately 6 months (end of March 2008 until the beginning of October 2008). The AD plant at Hillsborough is detailed in Table 1 and as a photograph in Figure 1 on the front cover of this report.

Table 1: Details of AD plant at AFBI

Digester tank	660m^3 above ground epoxy coated sealed steel tank with 100mm mineral wool insulation and 1mm plastic coated steel outer protection. Continuously stirred tank reactor (CSTR) operating at mesophilic temperature (37^{0}C).
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 store	1,500 m^3 above ground epoxy coated open top steel tank
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
Solids feeder	10 m^3 open top hopper complete with mixer, transfer auger and feed augers
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 specification

PERFORMANCE OF THE AFBI ON-FARM DIGESTER

Over the time period (24 January 2009 - 16 July 2010 inclusive) the digester was fed with 10,634 tonnes of mainly dairy cow slurry and produced 164,950 cubic meters (m^3) biogas with a gross energy value of 920.2 megawatt hours (MWh).

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 77 week time period, 1 m^3 (1 tonne) of slurry at 72 g/kg dry matter fed to the digester produced 0.985 m^3 (0.985 tonne) of digestate containing 58 g/kg dry matter, plus 15.5 m^{3}of biogas with a gross energy value of 5.5 kWh/m^3 of biogas. Digestion required 31 kWh of heat per tonne of slurry fed to maintain average digester temperature at 37 ^{0}C (equivalent to 37 % 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 performance of the combined heat and power unit (CHP) over 6,300 hours of operation from August 2009 is summarised in Table 3. Figure 2 summarises the biogas energy output from the digester as utilised either through a CHP or through a biogas boiler. The overall energy efficiency was 88% 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 renewable energy gain from biogas utilised through the CHP was 31 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 44.7 kWh/t of slurry input for a 5.4 kWh/t input of fossil fuel energy (fossil fuel: renewable energy of 1: 8.3). 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 ongoing in AFBI.

When compared with the volume of slurry fed, the volume of digestate recovered was almost the same, whilst chemical oxygen demand (COD) and dry matter of the digestate were lowered by 28% and 19% 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 20% greater than in the raw slurry (Table 2). Field trials are ongoing within AFBI 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 ongoing within AFBI to measure emissions of these gases.

Table 2: Performance of AFBI anaerobic digester over 77 weeks (24 January 2009 – 16 July 2010) (figures are weekly totals/7)

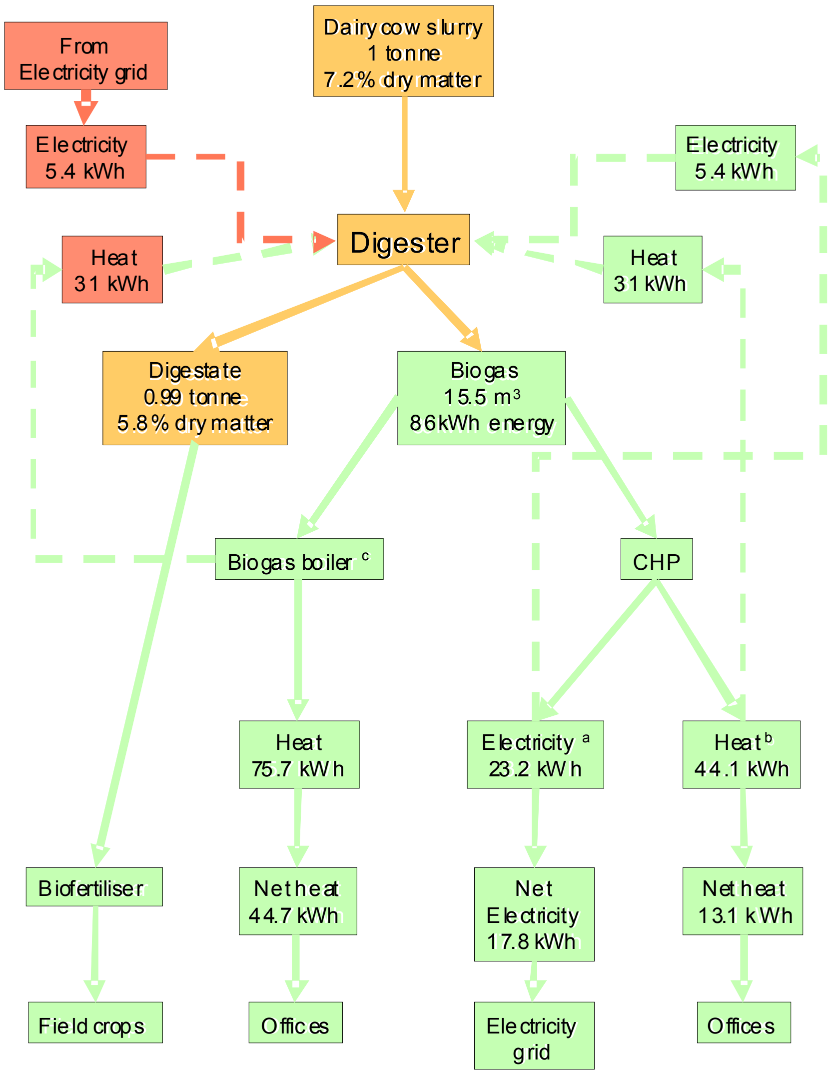
Inputs	**Mean**	**Minimum**	**Maximum**	**Standard deviation**
Slurry (tonnes/day)	19.7	17.6	20.7	0.64
Dry matter (total solids) (tonnes/day)	1.49	0.93	1.67	0.15
Organic matter (tonnes/day)	1.10	0.70	1.31	0.12
Organic matter (kg/m^3 digester per day)	2.09	1.34	2.48	0.23
Retention time (days)	27	25	30	0.91
Temperature (^{0}C)	37.1	36.3	39.5	0.30
Outputs				
Digestate	19.6	17.0	21.4	0.82
Biogas (m^3/day)	306	158	410	48.4
Methane (m^3/day)	171	90	227	26.4
Methane content of biogas (%)	56	52	60	1.4
Hydrogen sulphide content of biogas (ppm)	1671	628	2959	523
Gross biogas energy/tonne slurry (kWh)	86	45	116	14.5
Efficiency measures				
m^3 biogas/tonne slurry	15.5	8.0	21.0	2.60
m^3 biogas/m^3 digester/day	0.58	0.30	0.78	0.09
m^3 biogas/kg dry matter (total solids)	0.22	0.17	0.32	0.035
m^3 biogas/kg organic matter	0.28	0.21	0.41	0.046
m^3 methane/kg organic matter	0.16	0.10	0.22	0.025
Digester heating (kWh/tonne slurry input)	31	22	39	4.8
Energy required for digester heating (% gross biogas energy)	37	21	66	9.2
Slurry				
Dry matter (g/kg fresh)	71.8	46.7	82.7	7.26
Organic matter (g/kg fresh)	55.8	36.0	64.9	5.87
Organic matter (% of dry matter)[a]	77.7	74.0	80.1	1.6
Nitrogen (g/kg fresh)	3.49	2.44	4.37	0.43
Ammonia nitrogen (g/kg fresh)	1.87	1.33	3.11	0.32
pH	7.31	6.04	7.98	0.37
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)	57.9	47.5	66.4	4.38
Organic matter (g/kg fresh)[a]	42.2	34.7	50.0	3.50
Organic matter % of dry matter)	73.4	70.7	76.5	1.3
Nitrogen (g/kg fresh)	3.56	2.76	4.29	0.425
Ammonia nitrogen (g/kg fresh)	2.24	1.76	4.56	0.406
pH	7.92	7.15	8.93	0.379
Volatile fatty acids (g/kg fresh)[b]	1.16	0.08	3.35	0.811
Chemical oxygen demand (g/l)[c]	58	47	70	5.2
Dry matter digested (%)	21	11	33	5.0
Organic matter digested (%)	26	15	37	4.7
Chemical oxygen demand digested (%)	29	11	46	7.9
Volatile fatty acids digested (%)	76	23	99	16.7

[a] January 2009 to December 2009
[b] January 2009 to January 2010
[c] May 2009 to April 2009

Table 3: AFBI Combined Heat and Power outputs over 6,300 hours between August 2009 and July 2010.

CHP [a]	**mean**	**minimum**	**maximum**	**Standard deviation**
Electricity (gross kWh/m^3 biogas)	1.49	1.41	1.57	0.05
Heat (gross kWh/m^3 biogas)	2.83	2.62	3.05	0.11
Overall energy efficiency of engine (%)	78	74	84	2.8

[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] 88% of gross biogas energy converted to useable heat

Figure 2: Flow process chart of energy inputs and outputs during anaerobic digestion of 1 tonne of dairy cow slurry (all values are per tonne of fresh slurry input).

Summer versus winter production

Performances of the digester during summer (June – August) and winter (December – February) were compared. The average heat demand in winter was 36 kWh/tonne slurry, while the corresponding figure for the summer period was 25 kWh/tonne slurry. The average temperature of the slurry inputted during the summer period was 16.6^{0}C, while the corresponding figure for the winter period was 6.2^{0}C. Compared to the winter period, biogas production in summer was 11% higher per fresh tonne slurry. In summer, the slurry feedstock contained 8% less dry matter than in the winter. The combined effect of greater biogas yield per tonne of fresh slurry and more dilute slurry in summer resulted in an 18% increase in biogas production per tonne slurry dry matter inputted during the summer. The reason for this is 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 feedstock slurry for the summer was sourced from slurry produced by dairy heifers during the previous winter. It might have been expected that this slurry would have produced less biogas per tonne dry matter as a result of bacteriological activity during prolonged storage.

Biogas scrubbing

The hydrogen sulphide concentration of the biogas was on average approximately 1,700 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 of biogas scrubbed (cost approximately £1.60 per kg). Carbon in the column had to be replaced at approximately 14 day intervals, depending on amount of biogas produced and concentration of hydrogen sulphide in the biogas. Digester plants that are fitted with mechanical mixers often add approximately 5% air (1% oxygen) into the headspace of the digester to encourage growth of bacteria that will lower hydrogen sulphide levels through formation of elemental sulphur, which is removed in the digestate. The AFBI digester uses biogas recirculation for mixing digester contents, thus the inclusion of air must be strictly controlled to prevent the digester becoming aerobic.

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 3 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 754 person hours per annum (Table 3). Servicing of the digester plant (including biogas boiler) required an additional 5 person days per year (2 services per year). CHP servicing was at 750 hour intervals and required approximately 3 person hours per service (approximately 30 person hours per year). Daily checks of the plant could be completed in 15 minutes, assuming no other tasks are involved.

Table 3: Labour requirements for AFBI AD plant

Operation	Number of people	Time (hours)	Annual time (approximate person hours per year)
Management/checking			
Daily	1	1	365
Weekly	1	+0.5	+26
Monthly	1	+0.5	+6.0
Quarterly	1	+1.0	+4.0
Weekly - transfer of raw slurry to digester	1	4	208
Occasional (e.g. once per 2 weeks below ground tank submersible pump clear blockage)	3	1	72
Every 10 days - change activated carbon	2	1	73
Total	**-**	**-**	**754**

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, though there is incomplete kill of some bacterial pathogens such as salmonella, listeria, E coli and campylobacter. Work will be untaken in this area to quantify the extent of these reductions. However, digestate can be pasteurised to eliminate pathogens and help break any excreta related disease cycle on a farm. In addition, digestate can be mechanically separated, in the same manner as whole slurry, to create a fibrous fraction with a higher dry matter concentration and a liquid fraction with a lower dry matter concentration than the inputted material. It is likely that thorough aerobic composting of the separated fibre would kill many of the pathogens originally in the fibre. 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. The separated fibre 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 horticulture. Note that separation creates two outputs, a liquid and a fibrous material, that need to be stored and handled separately.

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 COD 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 was 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 last 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. Under some conditions these positive environmental benefits from anaerobic digestion could be very important. 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.

One tonne of dairy cow slurry at AFBI (7.2 % dry matter concentration) produced approximately 15.5 m^3 biogas, equivalent to approximately 8 1itres of diesel oil (4.2 to 10.8 1itres depending on hydraulic retention time, temperature and exact calorific value of biogas)[1]. When this biogas was utilised by a biogas boiler or by a CHP it produced:

- Biogas boiler – Net 4.2 litres oil equivalent after digester heating with an additional requirement for 5.4 kWh of electricity for digester plant operation
- CHP – Net 17.8 kWh electricity plus 1.2 litres oil equivalent as net heat after digester heating and operation

The net energy produced by digesting one tonne of dairy cow slurry (7.2% dry matter) is worth approximately £1 when the biogas is combusted in a biogas boiler, or approximately £3.50 when the biogas is utilised through a CHP unit (electricity with double ROC's plus heat)[2]. Should the current proposal to issue quadruple ROCs go ahead, the net energy value of the electricity and heat produced from biogas utilised through a CHP would increase to approximately £5.50 per tonne of slurry digested. These values are over and above the value of digestate as a biofertiliser.

[1] Assumes the energy value for diesel oil is 10.7 kWh/litre
[2] Assumes cost of heating oil 40p/litre; cost of electricity 13p/kWh; revenue from electricity sale of 13.5p/kWh (4.5p/kWh + 2x4.5p/kWh double ROCs; performance data listed in this publication

Co-digesting other organic materials along with slurry can greatly increase biogas yield. 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.