INTERIM TECHNICAL REPORT

PERFORMANCE SUMMARY FOR
ANAEROBIC DIGESTION OF
DAIRY COW SLURRY AND GRASS SILAGE
AT AFBI, HILLSBOUGH
August 2011 – January 2012

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

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Feb 2012

AFBI
Hillsborough

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SUMMARY OF RESULTS

Following intensive monitoring of the on-farm anaerobic slurry digester at AFBI, Hillsborough during 6 months of co-digestion with dairy cow slurry and grass silage (organic matter ratio 1.0 slurry: 0.14 silage), AFBI has observed that, on average:-

1. One tonne of fresh grass silage at 207 g/kg dry matter produced 63 m^3 of methane containing 630 kWh of energy
2. One tonne of grass silage organic matter produced 336 $m^3$of methane (0.336 m^3/kg organic matter)
3. 33 kWh energy (as heat) per tonne of feedstock was required to maintain mean digester temperature at 37^0C (33 % of gross energy produced)
4. The total nitrogen content in the digestate was equal to the total nitrogen content in the combined feedstock
5. The available nitrogen concentration in digestate was 22 % greater than that of the feedstock mix
6. Average hydrogen sulphide concentration of biogas was 1733 ppm.
7. The dry matter concentration of digestate was 24 % lower than the that of the feedstock mix

PERFORMANCE OF THE AFBI ON-FARM DIGESTER

Over a 6 month period from August 2011 to January 2012, the digester was fed with on average 0.75 tonne of grass silage per day at 21% dry matter, along with 19.8 tonnes cattle slurry per day, with a mean dry matter of 6.5%. The total amount of organic matter fed was on average 5% more than that fed during slurry only feeding, but energy production was increased by 20%, reflecting the higher digestibility and consequently higher methane yield from grass silage organic matter, compared to that from slurry organic matter.

Table 1 presents a summary of the AFBI digester performance for the co-digestion period, alongside that from the previous 30 months using slurry only. The main points to note are that during co-digestion:

- Biogas production increased by 32%
- Methane (energy production) increased by 20%
- Methane content decreased by 9% (from 55.7% to 50.5%)
- Slightly lower digestate dry matter content – (due to lower slurry dry matter content)
- The concentration of available N in digestate after co-digestion with grass silage was 19% more than in the raw slurry
- Grass silage produced twice as much methane per tonne organic matter (336 m^3 *cf.* 158 m^3), equivalent to 1176 kWh electricity, assuming CHP electrical efficiency of 35 %

Table 1: Performance over 6 months of the AFBI anaerobic digester, co-digesting cattle slurry and grass silage, compared to slurry only digestion over 30 months

	Slurry only[1]	**Slurry + grass silage**[2]	**% Difference**
Inputs			
Slurry (tonnes/day)	19.9	19.8	-0.6
Grass silage (tonnes/day)	-	0.75	
Dry matter (total solids) (tonnes/day)	1.41	1.45	2.3
Organic matter (tonnes/day)	1.10	1.22	10.9
Organic matter (kg/m^3 digester per day)	2.06	2.08	1.0
Retention time (days)	26.8	27.1	1.1
Temperature (^{0}C)	37.1	37.0	0.0
Outputs			
Digestate	19.7	20.1	1.9
Biogas (m^3/day)	312	414	32.5
Methane (m^3/day)	174	208	19.6
Methane content of biogas (%)	55.7	50.5	-9.4
Hydrogen sulphide content of biogas (ppm)	1670	1733	3.8
Efficiency measures			
m^3 biogas/tonne fed	15.7	20.2	28.7
m^3 biogas/m^3 digester/day	0.59	0.75	26.7
m^3 biogas/tonne dry matter (total solids)	223	285	28.0
m^3 biogas/tonne organic matter	285	358	25.6
m^3 methane/tonne organic matter	158	181	14.3
Digester heating (kWh/tonne slurry input)	32	33	3.1
Energy required for digester heating (% gross energy produced)	37	33	3.1
Slurry			
Dry matter (kg/tonne fresh)	71.1	65.4	-8.0
Organic matter (kg/tonne fresh)	55.5	51.0	-8.1
Nitrogen (kg/tonne fresh)	3.33	3.03	-8.9
Ammonia nitrogen (kg/tonne fresh)	1.78	1.50	-15.8
pH	7.23	7.34	1.5
Digestate			
Dry matter (kg/tonne fresh)	55.3	53.4	-3.4
Organic matter (kg/tonne fresh)	41.3	39.1	-5.2
Nitrogen (kg/tonne fresh)	3.36	3.09	-8.2
Ammonia nitrogen (kg/tonne fresh)	2.10	1.78	-15.4
Ammonia nitrogen /Total nitrogen	0.63	0.58	-8.6
pH	7.92	7.95	0.4
Dry matter digested (%)	24	28	18.5
Organic matter digested (%)	31	36	15.1

[1] January 2009 to July 2011; [2] August 2011 to January 2012, organic matter content of slurry and silage provisional and to be confirmed

Table 2: Grass silage properties

Dry matter (kg/t fresh)	Nitrogen (kg/t fresh)	Ammonia nitrogen (kg/t fresh)	D value	Proportion of silage organic matter to slurry organic matter	Methane yield/tonne organic matter (m^3)	Methane yield/tonne fresh silage (m^3)
206	3.89	0.38	61	0.14	336[1]	63[1]

[1] Calculated by subtracting the assumed methane production from slurry – based on previous slurry only results

Practical issues

Additional labour was needed to add silage to the feed hopper (45 minutes/week approximately). Digester mixing times via biogas recirculation were increased, to ensure that a layer of fibre did not accumulate on top on the digester contents (initially this was happening). The above ground digestate store number 2 (5 m high) that received the first co-digested material pumped from the digester developed a fibre crust approximately 0.5 m deep. When digestate store number 2 was full, the digestate discharge from the digester was diverted to digestate store number 1. Initially, digestate store 1 did not develop a floating layer. However, when the quantity of grass silage fed was increased to 2t per d a floating layer developed. Hence it is likely that with silage co-digestion, some mixing will be required so as to avoid a build-up of fibre in the store.

Grass silage was fed 5 days/week (1 tonne per day Monday to Friday) and not at the weekends. This enabled staff to monitor progress during feeding and could address quickly any issues arising. The feeding system operates automatically once started (usually programmed to 4 feeds per day at hourly intervals during daytime, with each feed sequenced to take place after the main feed of slurry). The feeding system has been deliberately programmed for a manual start, to ensure an operator is present to check that the feeder is working correctly. The hardware (Trioliet feeder and Vogelsang QuickMix) have performed very well with grass silage. Contaminants in the silage e.g. stones, should be minimised to avoid damage to mechanical components. The Vogelsang QuickMix has a stone trap which was cleaned out on 3 occasions during the 6 months of silage feeding.

Comments

Biogas quality was reduced following the addition of grass silage (the concentration of CH_4 was lowered by 9.4%). Some reduction was expected (based on lab-scale work at AFBI, Hillsborough), but the magnitude of reduction was likely due in part to higher than required levels of oxygen introduced to the digester during mixing of the digester contents *via* recirculation of biogas. This issue arose as a result of a faulty biogas analyser. H_2S levels were slightly higher with co-digestion *cf.* digestion of slurry only. The opposite was expected (from lab-scale work at AFBI, Hillsborough) and may reflect more on the composition of slurry digested (or diets fed), than any effect of grass silage co-digestion.

Biogas production over the trial period was quite variable, but no more so than during the slurry only feeding period. It is anticipated that as the grass silage fraction is increased, production variability will decrease due to the likely consistent quality within a clamp of grass silage as opposed to the variability in composition of slurry sourced from different tanks which have contents excreted over the course of winter. Using the AFBI data which gave a methane yield from grass silage at 21% DM of 63 m^3/t fresh (table 2) and assuming a yield of available silage for digestion of 48t FW/ha (10t DM/ha) suggests that approximately 30 MWh/ha/y of gross energy could be produced from grass. Net electricity produced from this gross energy will depend on CHP efficiency and process demand for electrical energy. Note that the value for energy production from silage measured at AFBI is provisional and will change depending upon silage dry matter yield, digestibility and CHP electrical efficiency (see tables 3, 4 and 5 below).

Because the silage used for co-digestion had a higher total nitrogen concentration than the slurry, the total nitrogen content of the digestate was greater than the raw slurry. Because the proportion of silage on a fresh basis was only 1:26, the effect was relatively modest (+2%). Co-digesting grass silage with dairy cow slurry resulted in a 19% increase in ammonia nitrogen concentration in the digestate compared with the slurry that was co-digested. This increase compares with 18% increase in concentration that occurred in slurry after mono digestion.

In trials at AFBI, Hillsborough using digestate on grassland for herbage production, it was found that the fertiliser replacement value of digestate was on average 0.40 (i.e. 100 kg digestate N applied could replace 40 kg inorganic fertiliser). The value for undigested cattle slurry was 0.35. However there was no difference in the herbage dry matter yield per kilo of ammonia N applied from either undigested or digested slurry. This indicates that the fertiliser replacement value of cattle slurry and digestate are highly correlated with the amount of ammonia N applied. Digestion increased the concentration of ammonia N in digestate relative to that in the mix being fed into the digester and hence, digestion has the potential to reduce the need for inorganic nitrogen.

As AD is a ‘closed system’ (what goes in must come out in the biogas and digestate), and as a result energy, nutrients, water, and volume inputted should be in fully accounted for. The mass of the feedstock inputted to the AFBI digester was fully accounted for in outputs. In addition, over 99% of the nitrogen inputted was accounted for in the digestate, with the rest lost in the biogas as ammonia.

From the values listed in Tables 3 – 5 below, it can be observed that the output of electricity per fresh tonne grass silage is highly dependent on silage dry matter concentration, CHP electrical efficiency and whether electricity is being sold or used to offset the purchase of electricity. Also note that retention times of feedstock in the digester determine biogas production per tonne fed. For example, lab-scale work at AFBI Hillsborough, found that increasing retention time from 25 to 40 days increased energy yield per tonne of grass silage by approximately 13%. The difference in value between selling electricity generated from a CHP to the grid compared to using it to offset consumption from the grid is approximately 9 p/kWh[1]. If surplus heat from the CHP can be effectively utilised, this will further add to income/costs saved. Data in tables 4 and 5 indicate that there is approximately a 70% difference in income/costs saved, between the more likely scenario for the majority of plants (all electricity sold to the grid, no economic use for surplus heat) and the best case scenario (all electricity produced used to offset purchased electricity and all surplus heat used to offset heating oil purchases).

Consideration must be given to the fact that there are losses in the process from ‘field to grid’. In field and in silo losses can be up to 20% of the herbage dry matter produced by the growing crop. The CHP will not run all the time, due to breakdowns, servicing, etc (90% runtime is a good target). Silage quality may be lower than budgeted for, leading to lower biogas yields than predicted. A poor growing season may result in lower yields than anticipated, etc, etc. All these factors impact on the output of electricity/heat and thus affect economic returns from the project.

The data presented in Table 6 give an indication of the impact of dry matter yields and CHP electrical efficiencies on electrical output per hectare of grass silage digested. Both of these parameters have major effects on electrical output per hectare per year and consequently on income obtained. Dividing a cell figure in Table 6 by 8760 (hours in a year) gives the continuous assumed electrical output per hectare. Assuming a utilised yield of 10t DM per hectare, a CHP electrical efficiency of 36% and using the AFBI data presented (Table 2) an annual output of 11,016 kWh electricity/ha/y is achievable (1.26 kW electric continuous). Note the points below Table 6, which may result in actual output being lower.

Table 7 indicates how the dry matter fed/ha and CHP electrical efficiency impact on the land area required for a digester (assuming electrical output of 250 kW).

[1] Assuming purchase price from grid 15 p/kWh and sale price to grid 6.0 p/kWh

Table 3: Electrical output (kWh) per fresh tonne grass silage, as affected by dry matter concentration and CHP electrical efficiency[1]

CHP electrical efficiency %	Grass silage dry matter %							
	20	**22**	**24**	**26**	**28**	**30**	**32**	**34**
30	183	202	220	238	257	275	294	312
32	196	215	235	254	274	294	313	333
34	208	229	250	270	291	312	333	353
36	220	242	264	286	308	330	352	374
38	232	256	279	302	325	349	372	395
40	245	269	294	318	342	367	391	416
42	257	283	308	334	360	385	411	437

[1] Assuming 336 m^3 methane/tonne organic matter and 910 kg organic matter/tonne silage dry matter.

Table 4: Income from electricity (£ per fresh tonne grass silage digested) as affected by dry matter concentration and CHP electrical efficiency (likely scenario for many digesters)[2]

CHP electrical efficiency %	Grass silage dry matter %							
	20	**22**	**24**	**26**	**28**	**30**	**32**	**34**
30	43	48	52	57	61	65	67	71
32	46	51	56	60	65	70	72	76
34	49	54	59	64	69	74	76	81
36	52	58	63	68	73	79	81	86
38	55	61	66	72	77	83	85	90
40	58	64	70	76	82	87	90	95
42	61	67	73	80	86	92	94	100

[2] Assumes 4 ROC's @ 18p/kWh, electricity sold @ 6 p/kWh, plant electrical consumption of 10 kWh per tonne of silage and that surplus heat is not used.

Table 5: Income from electricity (£per tonne grass silage digested) as affected by dry matter concentration and CHP electrical efficiency (best case scenario)[3]

CHP electrical efficiency %	**Grass silage dry matter %**							
	20	**22**	**24**	**26**	**28**	**30**	**32**	**34**
30	74	81	89	97	104	112	120	128
32	78	86	94	102	110	118	126	134
34	82	90	99	107	116	124	133	141
36	86	95	104	112	121	130	139	148
38	90	99	108	118	127	136	146	155
40	94	103	113	123	133	142	152	162
42	98	108	118	128	138	148	159	169

[3] Assumes 4 ROC's @ 18p/kWh, electricity purchases offset @ 15p/kWh, plant electrical consumption of 10 kWh per tonne silage, surplus heat from CHP (45% heat efficiency) replacing oil purchases @ 60 p/l.

Table 6: Electrical output from AD of grass silage (kW per hectare per year[4]) at different dry matter yields and CHP electrical efficiencies

CHP electrical efficiency %	Grass silage digested (tonnes dry matter/hectare/year) [5]							
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**
30	7,344	8,262	9,180	10,098	11,016	11,934	12,852	13,770
32	7,834	8,813	9,792	10,771	11,750	12,730	13,709	14,688
34	8,323	9,364	10,404	11,444	12,485	13,525	14,566	15,606
36	8,813	9,914	11,016	12,118	13,219	14,321	15,422	16,524
38	9,302	10,465	11,628	12,791	13,954	15,116	16,279	17,442
40	9,792	11,016	12,240	13,464	14,688	15,912	17,136	18,360
42	10,282	11,567	12,852	14,137	15,422	16,708	17,993	19,278

[4] Assumes 336 m^3 methane per tonne organic matter of grass silage and all biogas consumed in CHP. No account taken of plant electrical consumption (circa 10 kWh/fresh tonne silage). Dividing a cell figure in Table 6 by 8760 (hours in a year) gives the continuous assumed electrical output.

[5] These figures are for quantities of silage dry matter available from the silo. In field and in silo dry matter losses can account for up to 20% of the growing crop.

Table 7: Area of land required (hectares) for 250 kW continuous output for different grass dry matter yields and CHP electrical efficiencies[6]

CHP electrical efficiency %	Grass silage digested (tonnes dry matter/hectare/year)							
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**
30	298	265	239	217	199	184	170	159
32	280	249	224	203	186	172	160	149
34	263	234	210	191	175	162	150	140
36	249	221	199	181	166	153	142	133
38	235	209	188	171	157	145	135	126
40	224	199	179	163	149	138	128	119
42	213	189	170	155	142	131	122	114

[6] Using assumptions in previous tables and ignoring any contribution from slurry that may be fed