RYE-GRASS AS AN ENERGY CROP USING BIOGAS TECHNOLOGY

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1. TECHNICAL BACKGROUND TO THE PROJECT

This project investigates ryegrass as a wet energy crop and is believed to be the first of its kind in the UK. It is hoped that this research will help towards the Governments target to produce 20% of our energy through renewable sources by 2020 in a move towards a carbon neutral economy. The growing of energy crops creates a diversification opportunity for UK farmers with the reform of the Common Agricultural Policy moving away from subsidised farming. Most energy crop development to date has been directed towards the production of low moisture content biomass which is transformed into useful energy by thermal processes. In contrast this project examines the harvesting of rye-grass as a high moisture energy crop to be transformed into useful energy by anaerobic digestion.

The key features of such a concept are:

- the UK has one of the best climates in the world for growing rye-grass;
- the high moisture content of the grass is not a draw-back since anaerobic digestion is a wet process;
- the primary constituents of the biogas are only carbon, hydrogen and oxygen;
- the wet digestate, containing the nutrients, can be returned to the grassland to enhance future crop growth;
- carbon not transformed to biogas may be sequestered into the soil;
- the process presents a new opportunity for farm diversification without the need to plant new crops.

Grass as an energy crop is being investigated in Germany, Switzerland and Austria in particular, but this project concentrates on the potential within the UK context.

In summary, the process has the potential of creating a sustainable cycle, as summarised in the simple flow diagram below Figure 1, where the biogas plant includes a boiler or CHP unit, which produces energy and an exhaust gas.

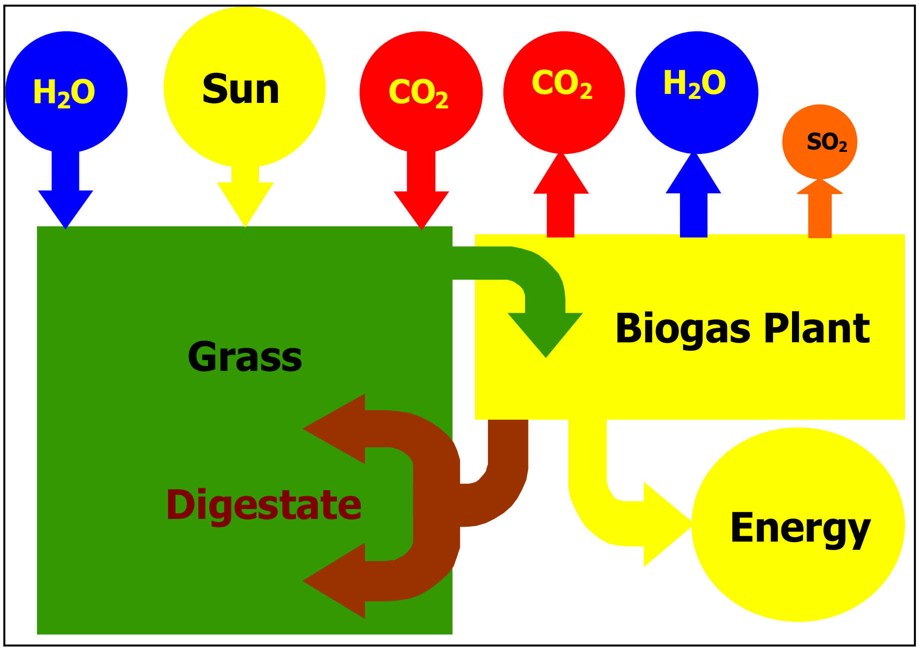

Figure 1: The sustainable cycle

2. AIMS AND OBJECTIVES

2.1. Overall Aim

- To prove that ryegrass in the UK is a potential energy crop for conversion to biogas.

2.2. Specific Objectives

- To achieve a minimum yield of $4060m^3_{CH4}.ha^{-1}.y^{-1}$ which, when converted to electricity on a commercial scale would generate $14MW_e.h.ha^{-1}.y^{-1}$.
- To establish the relationship between the biogas yield and the harvesting cycle.
- To confirm that through storage of the grass it is possible to achieve a constant yield of biogas throughout the year.
- To assess the mass balance and energy balance for the whole process.
- To estimate the economics of a commercial grass to biogas plant.

3. TRIAL PLOTS

3.1. Objectives

The source of the material used for the anaerobic digestion investigated in these experiments was rye grass grown in a number of experimental plots. The grass would be cut at a number of different heights and at different frequencies. Fertiliser would be applied in the form of digestate. The objectives of the work utilising this material were:

- To establish which cut produces the most suitable feedstock for anaerobic digestion.
- To determine which height and frequency of cut produces the highest dry matter yield.
- To achieve a self-sufficient and sustainable system by applying the digestate onto the grass lay as a bio-fertiliser and soil conditioner.

3.2. Experimental Design

The layout of the plots was designed by Greenfinch with guidance from the Institute of Grassland and Environmental Research (IGER). In October 2002 an area approximately a hectare in size was seeded with the intermediate perennial ryegrass (Lolium perenne) variety AberDart at Barrett's Mill, South Shropshire. In May 2003 thirty-six 10m^2 plots were established on this area each measuring 10m x 1m; in 2004 three 100m^2 plots each measuring 10m x 10m were added to the trials. The divisions between the plots measured 0.5m. Figure 2 illustrates the layout of the plots.

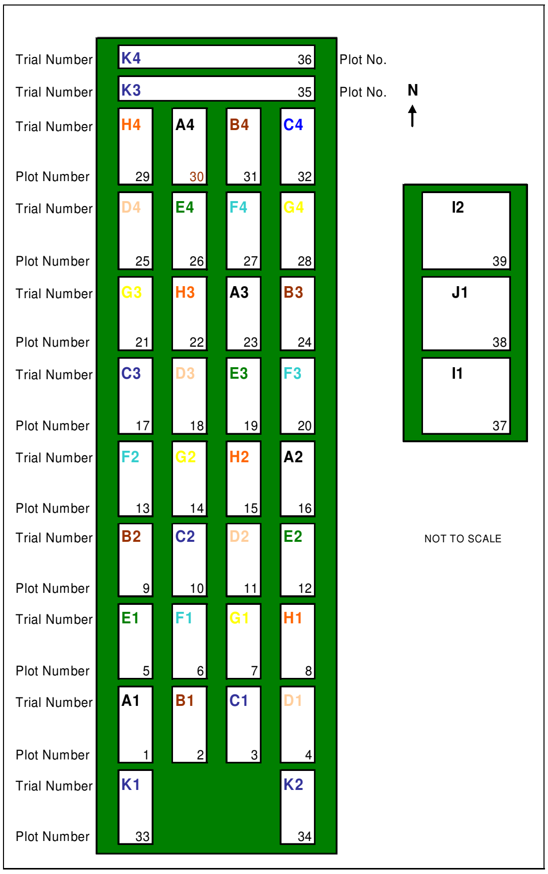

Figure 2: Layout of the grass plots

Several experimental treatments were undertaken on the plots, with each treatment having four plots randomly dispersed amongst the whole area in order to ensure that any differences arising from soil quality in particular were taken into account. The variables were as follows:

- Two residual sward heights (50mm and 100mm),
- Four mowing regimes, cutting at two, four, six and eight week cycles,
- Two sets of plots dedicated to each cutting cycle (except 6 week), each one cut at a different sward height,
- Two sets of plots cut on a four week cycle, which did not receive any digestate,
- Three 100m^2 plots cut at 50mm, two applied with digestate, one without.

Rainfall and soil temperature were also measured daily.

The treatments identified by each individual plot reference are outlined in Table 1.

Table 1: Plot treatments

Plot Reference	Height of Cut (mm)	Frequency of Cut (weeks)	Digestate Application
A	100	4	No
B	100	4	Yes
C	50	4	Yes
D	100	2	Yes
E	50	2	Yes
F	100	6	Yes
G	100	8	Yes
H	50	8	Yes
I	50	4	Yes
J	50	4	No
K	50	4	No

Plots I, J and K were added to the experiment in the second year; K plots were introduced to enhance the findings of the A plots, the only difference being that K plots are cut at 50mm rather than 100mm. The 100m^2 plots were added to confirm that the small plots really are a suitable size on which to collect reliable data. Plots I and J received identical treatment to C and K. The large plots had an extra 1m border around the perimeter that was cut prior to mowing the 100m^2; this was designed to eliminate any edge effect that may have occurred, distorting the yields.

3.3. Description of the Work

Mowing

Each plot was harvested separately at the desired height setting using a Haytor mower with a collection box. The grass was left to wilt on the occasions that it had a high water content early on in the spring when the ground was still wet, or after a heavy dew; it was then collected later in the day using the mower and collection box.

Storage

The grass was put into black bin liners, weighed and ensiled. To ensile the grass as much air as possible was removed from the bag which was then sealed by simply tying a secure knot in the top of the bag. The bag was labelled with the plot identification number, weight and date of harvest. All grass was then stored in a shed at Barrett's Mill for at least 6 weeks before being used as ensiled feedstock.

Digestate

After each harvest, digestate was carefully applied to all plots that had been cut. This was done using a watering can with a spoon attached to the end of the spout allowing for more accurate coverage. In the first year digestate was applied at a rate of 1 litre per $1m^2$ after each cut. Digestate application was altered for the 2004 season. It was decided that the amount of grass taken off the plots should be returned with the corresponding amount of digestate to mimic a self sustaining system. The average plot yield from 2003 was calculated to be 41.1 kg per $10m^2$, which equates to 32.8 litres of digestate after digestion. A comparison the digestate levels applied between 2003 and 2004 is shown in Table 2.

Table 2: Digestate levels applied to the plots in 2003 and 2004

Plot Reference	Digestate Applied per Plot 2003 (litres)	Digestate Applied per Plot 2004 (litres)
A	None	None
B	60	32.8
C	60	32.8
D	120	32.8
E	120	32.8
F	40	32.8
G	30	32.8
H	30	32.8
I	Not monitored	328
J	Not monitored	None
K	None	None

The application of the digestate to the plots was split to allow for application throughout the growing period, this provides for the availability of nutrients when the grass is growing fastest – the period after each cut.. Ten litres was applied to every plot in week 0 (excluding plots A, K and J); the remaining 22.8 litres was split into the number of cuts a plot would receive throughout the year i.e. the plots cut every eight weeks would be cut four times during the growing season, therefore receiving only four digestate applications of 5.7 litres per plot.

Chemical Analysis

Two sets of chemical analysis were conducted, at Greenfinch and IGER. Those conducted in the Greenfinch laboratory included: the percentage of dry matter (DM) within the grass which gives the DM yield for each plot, and the amount of DM being fed to the digester within the feedstock; and the percentage of organic dry matter (ODM) which gives the quantity of matter that has the potential to produce biogas.

Grass plot samples were also sent to IGER for detailed analysis including: %DM, %ODM, pH, total carbon (C), total nitrogen (N), and other parameters as appropriate. These tests were also carried out on the digestate and digester feedstock. From these tests it was possible to establish the quality of the grass as a digester feedstock noting any changes during the ensiling process, with particular reference to the C and N content. It was also possible to look closely at the inputs (digestate) and outputs (grass) of the soil, looking in particular at the N balance.

Soil pH

It is important that soils in grass production maintain a pH of 5.5-6.5. An alkaline soil can limit the availability of nutrients, and an acidic soil can produce an excess of toxic ions, (aluminium and manganese) which will both lead to a reduction in the plant production.[1]

Soil samples were taken from the plots at the beginning of the growing season in 2003, 2004, and 2005. These were analysed by IGER and Lancrop Laboratories. Table 2 shows the mean soil pH for the three tests.

Table 3: Plot pH values

Year	Mean Average pH $10m^2$ Plots	Mean Average pH $100m^2$ Plots
2003	5.2	N/A
2004	6.0	5.3
2005	5.5	5.8

In 2003 it was decided that the soil would not be limed because the pH of the digestate ranges between pH 7.5 – 8 (see Table 8) and may therefore raise the pH level of the soil.

As shown in Table 3 the soil tests in 2004 indicate that the pH of the small plots had risen, the small plots were not limed at this time based on the assumption that once again the digestate would raise the level of the pH. In contrast, the pH values of the larger plots were at a low level so these plots were limed in order to bring them up to a comparable pH level to the small plots.

In 2005 the pH of the large plots increased while the small plots pH decreased; this could have been due to the reduction in the amount of digestate applied to the plots in 2004 compared to that in 2003, previously explained. Table 2 shows the digestate applied to each set of plots for 2003 and 2004. It is clear that there were dramatic reductions in litres of digestate applied from 2003-2004, which may explain the most recent changes in pH levels. Chemical analysis of the digestate is shown in Table 10.

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[1] Hopkins, A (2000), Grass It's Production and Utilization, Blackwell Science, Oxford.

3.4. Results

Rainfall, Temperature and Light

Rainfall, temperature and light are all crucial to herbage growth. Rainfall and soil temperature were measured at Barrett's Mill in 2004. The soil temperature was measured using a soil thermometer. Figure 3 shows the average weekly soil temperature and the average dry matter yield harvested throughout the growing season from March to October 2004. Grass will make little growth below 6°C with optimum growth at 20°C[2]. From the middle of March onwards the soil temperature was above 6°C but failed to reach 20°C or above. It is clear from this graph that dry matter yield rises with increases in temperature.

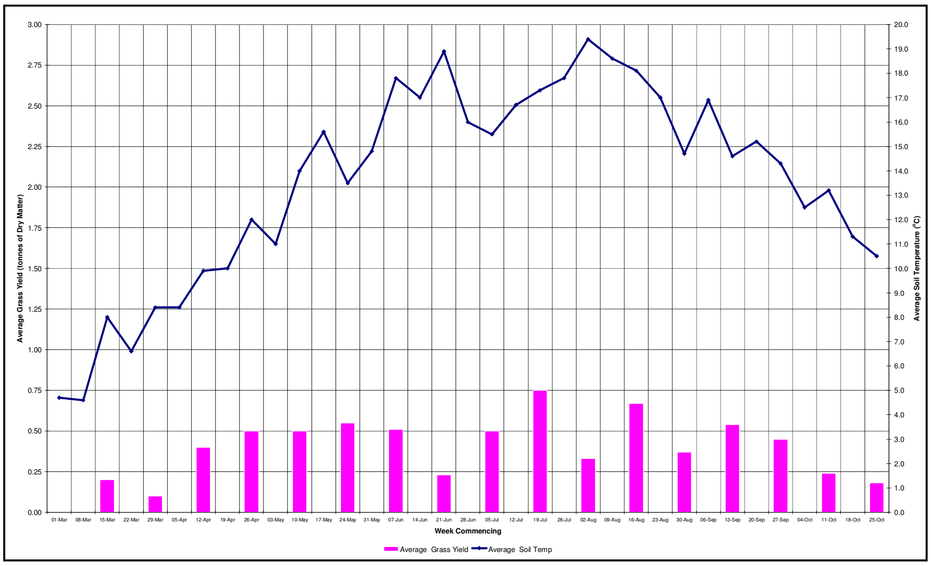

Figure 3: Graph of dry matter yield and soil temperature

During the harvest period (March 2004 – October 2004) the total rainfall at Barrett's Mill was 686mm. The average annual rainfall for Shropshire[3] is 655mm.yr-1, which indicates that water was not a limiting factor in 2004.

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[2] Hopkins, A (2000), Grass It's Production and Utilization, Blackwell Science, Oxford.

[3] Met Office, (2004), 1971-2000 averages, www.met-office.gov.uk/climate/uk/averages/19712000/sites/shawbury.html , Accessed 22nd March 2004.

Table 4 shows the breakdown of rainfall for each month.

Table 4: Monthly Rainfall (2004)

Month (2004)	Rainfall (mm)
March	46.5
April	121
May	72.5
June	41.5
July	72.5
August	125.5
September	80
October	126.5
Total	686 mm

There were noticeable differences in the climate conditions of the first two years of the trials. Figure 4: England and Wales rainfall, 2003 and 2004 to Figure 6 shows the England & Wales mean temperature, rainfall and sunshine hours for 2003 and 2004; these help to illustrate the difference in the climatic conditions between the two years. (The figures used have allowed for topographic, coastal and urban effects where relationships are found to exist.)[4]

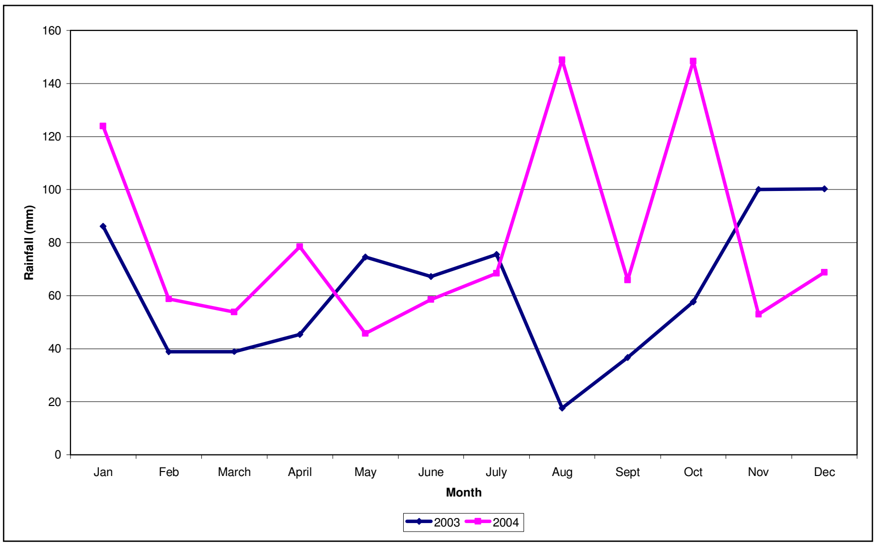

Figure 4: England and Wales rainfall, 2003 and 2004

The largest evidence of difference between the two years is shown in Figure 4: England and Wales rainfall, 2003 and 2004 which indicates how wet the summer of 2004 was in comparison to the summer of 2003.

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[4] The Met Office, (2004) England & Wales Mean Temperature, Rainfall and Sunshine, http://www.met-office.gov.uk/climate/uk/seriesstatistics/ewtempt.txt, accessed 22nd February 2005

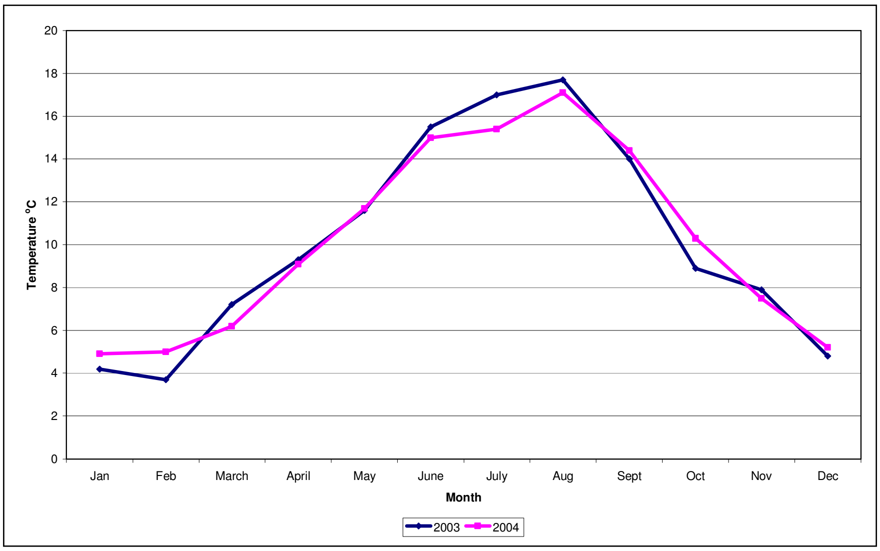

Figure 5: England and Wales temperatures, 2003 and 2004

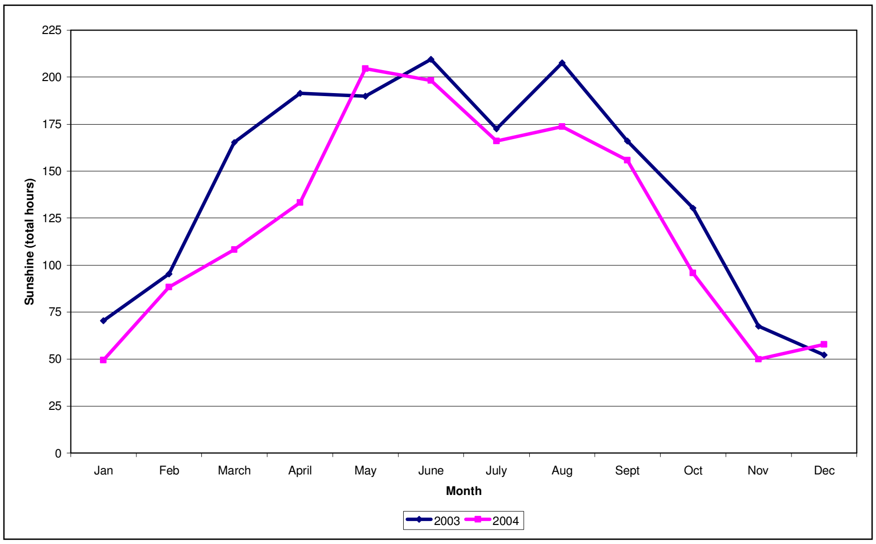

Figure 6: England and Wales sunshine, 2003 and 2004

These graphs show that 2003 was a warmer, dryer and brighter year than 2004. 2004 was much wetter during the summer with less sunshine than 2003. The slightly lower temperatures recorded in the summer of 2004 may have contributed to the reduction in grass yields for 2004. The higher the temperature the quicker the leaves extend with an increase in the number of tillers producing leaves at a faster rate[5]. It is hard to put a figure on the effect the different weather conditions had on each of the year's yields; the weather is just one factor that should be considered alongside soil pH, and nutrient inputs and outputs.

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[5] Hopkins, A (2000), Grass It's Production and Utilization, Blackwell Science, Oxford.

Trial Plots 2003

Table 5: Grass Yields 2003 (Tonnes of Dry Matter per Hectare)

Trial Ref	Harvest Cycle	Ht of Cut mm	Digestate	**1** Plot Yield $t_{DM}.ha^{-1}$	**2** Plot Yield $t_{DM}.ha^{-1}$	**3** Plot Yield $t_{DM}.ha^{-1}$	**4** Plot Yield $t_{DM}.ha^{-1}$	Average Yield $t_{DM}.ha^{-1}$
A	4wks	100	No	3.3	7.2	6.0	5.4	5.5
B	4wks	100	Yes	5.1	10	6.9	5.9	7.0
C	4wks	50	Yes	5.8	11.1	9.8	6.1	8.2
D	2wks	100	Yes	4.9	9.4	10.2	7.1	7.9
E	2wks	50	Yes	10.7	8.8	8.8	8.5	9.2
F	6wks	100	Yes	10.0	8.1	8.0	6.7	8.2
G	8wks	100	Yes	6.0	7.4	5.1	4.2	5.7
H	8wks	50	Yes	8.1	10.1	8.4	5.7	8.1

- In terms of dry matter yield there does not appear to be a major advantage in harvesting more frequently than every 8 weeks. (see Appendix 1 Table 5)
- In terms of dry matter yield there appears to be an advantage in cutting the grass with a close crop, as defined as 50mm. (see Appendix 1 Table 6)
  - Average mean yield for plots cut at 50mm is $8.6t_{DM}.ha^{-1}.y^{-1}$
  - Average mean yield for plots cut at 100mm is $6.8t_{DM}.ha^{-1}.y^{-1}$
- The maximum yield was $11.1t_{DM}.ha^{-1}.y^{-1}$ harvested from plot C2.

Trial Plots 2004

Table 6: Grass Yields 2004 (Tonnes Dry Matter per Hectare)

Trial Ref	Harvest Cycle	Ht of Cut mm	Digestate	**1** Plot Yield $t_{DM}.ha^{-1}$	**2** Plot Yield $t_{DM}.ha^{-1}$	**3** Plot Yield $t_{DM}.ha^{-1}$	**4** Plot Yield $t_{DM}.ha^{-1}$	Average Yield $t_{DM}.ha^{-1}$
A	4wks	100	No	3.0	3.9	4.6	3.3	3.7
B	4wks	100	Yes	5.1	6.8	3.8	4.6	5.1
C	4wks	50	Yes	6.0	9.4	9.2	5.3	7.5
D	2wks	100	Yes	2.9	6.7	6.7	5.8	5.5
E	2wks	50	Yes	8.8	6.6	7.5	6.8	7.5
F	6wks	100	Yes	6.1	5.3	6.2	5.3	5.7
G	8wks	100	Yes	5.3	7.4	5.5	5.1	5.8
H	8wks	50	Yes	8.0	12.7	7.6	7.4	8.9
K	4wks	50	No	5.7	7.0	5.9	6.5	6.3
I	4wks	50	Yes	7.5	7.1	N/A	N/A	7.3
J	4wks	50	No	5.8	N/A	N/A	N/A	5.8

- In terms of dry matter yield there once again does not appear to be a major advantage in harvesting more frequently than every 8 weeks. (see Appendix 2 Table 4)
- Overall dry matter yields are less than 2003 yields (this is illustrated by Graph 5); the maximum yield is $12.7\ t_{DM}.ha^{-1}.y^{-1}$ harvested from plot H2.

- The reduction in overall yield for 2004 is highlighted by the mean average yield for plots cut at 50mm and 100mm (see Appendix 2 Table 5)
  - Average mean yield for plots cut at 50mm is 7.6 $t_{DM}.ha^{-1}.y^{-1}$.(Excluding I and J)
  - Average mean yield for plots cut at 100mm is 5.1 $t_{DM}.ha^{-1}.y^{-1}$.

  These figures also show that for a second year in terms of dry matter yield there appears to be an advantage in cutting the grass with a close crop as defined as 50mm.
- Table 5 and Table 6 show that for both years there is significant variance in the individual plot yields harvested in identical cycles.
- It should be noted that the grass yields show a lot of variability between within the treatments. For example, plot D1 had very low yields in both 2003 and 2004 in comparison to the other replicates. If D1 were to be removed from the data, then treatment D would become the second highest yield treatment in 2003 with a mean yield of 8.9 $t_{DM}.ha^{-1}.y^{-1}$ and fourth highest in 2004 with 6.1$t_{DM}.ha^{-1}.y^{-1}$.

The grass cut on an 8 week cycle contains a lot of stem with a high ligneous content, compared to grass cut on a 2 week cycle that is very leafy with more cellulose. The ligneous material is denser than cellulose therefore giving it a larger weight volume for volume. This could explain the high dry matter yields recorded by the treatments cut on 8 week cycles.

The yields compare well against NIAB trials with Aberdart[6] ryegrass. NIAB's simulated grazing trials are a good comparison to the treatments A, B, C, D, E, K, I, and J as they have a total of 8 to 9 cuts per year with a nitrogen application of 340 $kg.ha^{-1}.y^{-1}$. The NIAB trials yielded 7.21 $t_{DM}.ha^{-1}.y^{-1}$ in the first year and 10.5$t_{DM}.ha^{-1}.y^{-1}$ in the second year. The first year compare well with the relative treatments in this project but the second year yields for NIAB are much higher. An explanation for this could be the large amounts of nitrogen that were applied to the NIAB plots with much less nitrogen applied to the plots within this project.

The NIAB conservation management trials involve 4 to 5 cuts with a nitrogen application of 350 $kg.ha^{-1}.y^{-1}$. This is a good comparison to treatments F, G and H. The yields recorded by NIAB were 16.7$t_{DM}.ha^{-1}.y^{-1}$ in the first year and 13.2$t_{DM}.ha^{-1}.y^{-1}$ in the second year. Treatments F, G, and H yielded much lower than this with a mean average of less than 10 $t_{DM}.ha^{-1}.y^{-1}$. Once again an explanation for this could be the high amount of nitrogen applied to the NIAB trials.

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[6] NIAB 2004, 2004/2005 Varieties of Grasses & Herbage Legumes Participants Handbook, NIAB

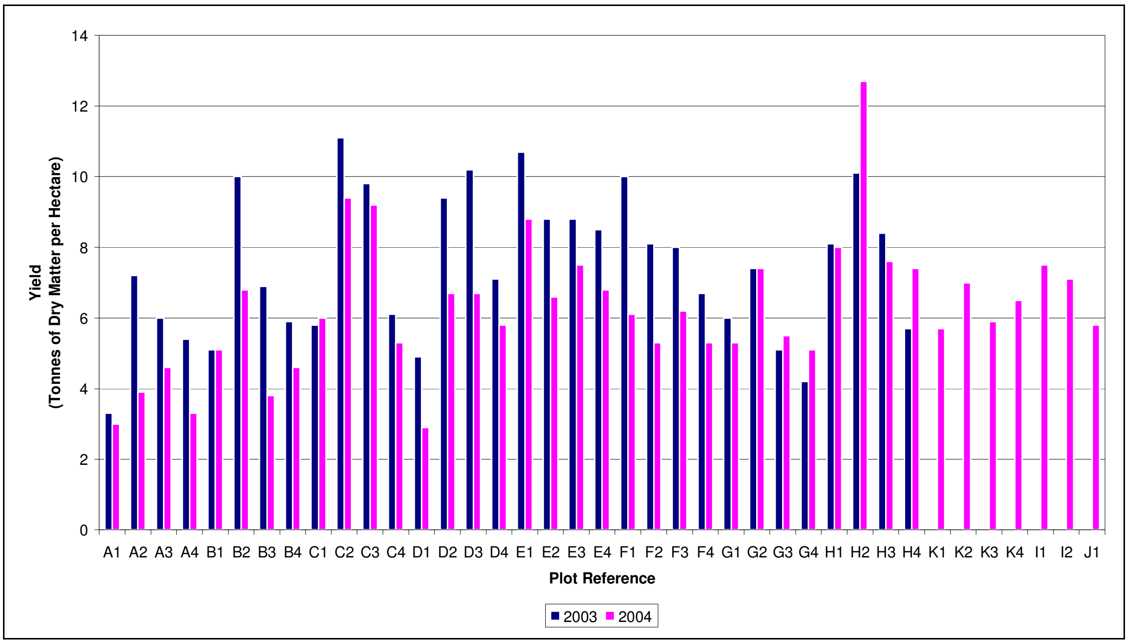

Figure 7: Grass Yields for 2003 and 2004

Figure 7 shows the grass yields for each individual plot for 2003 and 2004. The lower yields experienced by all plots in 2004 except plots C1, G2, G3, G4, H2 & H4, could be as a result of the reduction in digestate applied to each plot. The only plots to receive more digestate in 2004 than 2003 are treatments G and H which received 30 litres in 2003 and 32.8 litres in 2004. This could partly explain the higher yields recorded by these plots in 2004.

Table 7 shows the average yields for each treatment in 2003 and 2004, the digestate applied in each year and the yield difference in percentage terms.

Table 7: Digestate applications and average yields

Trial Plot Reference	Average Plot Yield 2003 ($t_{DM.}ha^{-1}.y^{-1}$)	Average Plot Yield 2004 ($t_{DM.}ha^{-1}.y^{-1}$)	Yield Average Difference %	Digestate Application per plot 2003	Digestate Application per plot 2004 (3.28 litres per m^2)
A	5.5	3.7	-33%	None	None
B	7.0	5.1	-28%	60	32.8
C	8.2	7.5	-9%	60	32.8
D	7.9	5.4	-32%	120	32.8
E	9.2	7.2	-22%	120	32.8
F	8.2	5.7	-31%	40	32.8
G	5.7	5.8	+1%	30	32.8
H	8.1	8.9	+10%	30	32.8
K	-	6.3	-	None	None
I	-	7.3	-	Not monitored	328
J	-	5.8	-	Not monitored	328

IGER Results & Statistics

Table 8 shows the herbage yield, N input, offtake and surplus, total C offtake, N efficiency and C:N ratio for each of the small plot treatments. Mean data tables can be referred to in Appendix 2 tables 14 – 16.

With reference to herbage dry matter yield Table 8 shows:

- There is significantly more herbage yielded from plots that are cut every 8 weeks compared with plots cut every 4 and 6 weeks. (see also Appendix 2, Table 4)
- There is significantly more herbage yielded from plots cut at 50mm compared to those cut at 100mm; 7.6 and 5.1 $t_{DM}.ha^{-1}$. (see also Appendix 2, Table 5)
- There is significantly more herbage harvested from plots that receive digestate than those without; 6.5 and 5.2 $t_{DM}.ha^{-1}$ (see also Appendix 2, Table 6)

With reference to herbage N offtake Table 8 shows;

- Significantly more N is removed from plots cut every 2 weeks compared to those every 4, 6, and 8 weeks.
- Significantly more N is removed from plots cut at 50mm compared to those cut at 100mm; 192 and 141 $kg.ha^{-1}$.
- Significantly more N is removed from plots that receive digestate than those without; 172 and 133 $kg.ha^{-1}$.

With reference to herbage C offtake Table 8 shows;

- Significantly more C is removed from plots cut every 2 and 4 weeks compared to those cut every 6 and 8 weeks.
- Significantly more C is removed from plots cut at 50mm compared to those cut at 100mm; 2358 and 1978 $kg.ha^{-1}$.
- Significantly more C is removed from plots that receive digestate than those without; 2215 and 1908 $kg.ha^{-1}$.

Table 8: Herbage yields and elemental analysis

Herbage yield, N input, total N offtake and N surplus (N input minus N offtake), total C offtake, N efficiency and C:N ratio for each treatment (small plots only).

Treatment	D	E	B	C	A	K	F	G	H		Significance			
											Cut			
	tonnes/ha									s.e.d*	Frequency §	Height †	Digestate #	Height x digestate $
Herbage DM yield	5.36	7.25	5.07	7.47	3.72	5.86	5.72	5.83	8.91	0.890	0.019	<0.001	0.027	NS
	kg/ha													
N supplied in digestate	115.9	115.9	70.0	70.0	0	0	65.3	79.3	79.3	-	-	-	-	-
Herbage N offtake	179.6	235	139.2	200	106.5	158.6	140.3	137.6	173.3	26.03	0.008	0.006	0.055	NS
N surplus	-63.7	-119.1	-69.2	-130	-106.5	-158.6	-75	-58.3	-94	29.43	-	-	-	-
Herbage C offtake	3561	1923	2456	3762	1527	2288	1043	1303	1458	147.3	<0.001	<0.001	<0.001	0.015
	kg DM/kg N input													
N efficiency	46.2	62.6	72.5	106.7			87.6	73.5	112.3	12.18	<0.001	<0.001	-	-
C:N ratio	23:01	09:01	18:01	20:01	14:01	14:01	08:01	10:01	08:01	23:01	0.002	0.006	NS	NS

*, for treatment means ; §, 2, 4, 6 and 8 week frequencies; †, 2, 4 and 8 week frequencies only; #, only within 4 week frequency; $, interaction between height and digestate, 4 week frequency only; NS, not significant

N efficiency is reported as herbage removed (kg) per kilogram of N applied via digestate application.

Table 8 shows:

- N efficiency is significantly greater on plots that are cut every 4, 6, and 8 weeks compared to those every 2 weeks.
- N efficiency is significantly greater on plots that are cut at 50mm than those cut at 100mm; 94 and 70 $kg_{DM}.kg^{-1}{}_{N}$.

With reference to the C:N ratio Table 8 shows that;

- The C:N ratio is significantly higher in plots cut at 2 and 4 weeks, compared to those cut at 6 and 8 weeks.
- The C:N ratio is significantly higher in plots cut at 100mm compared to those cut at 50mm; 14:1 and 13:1.

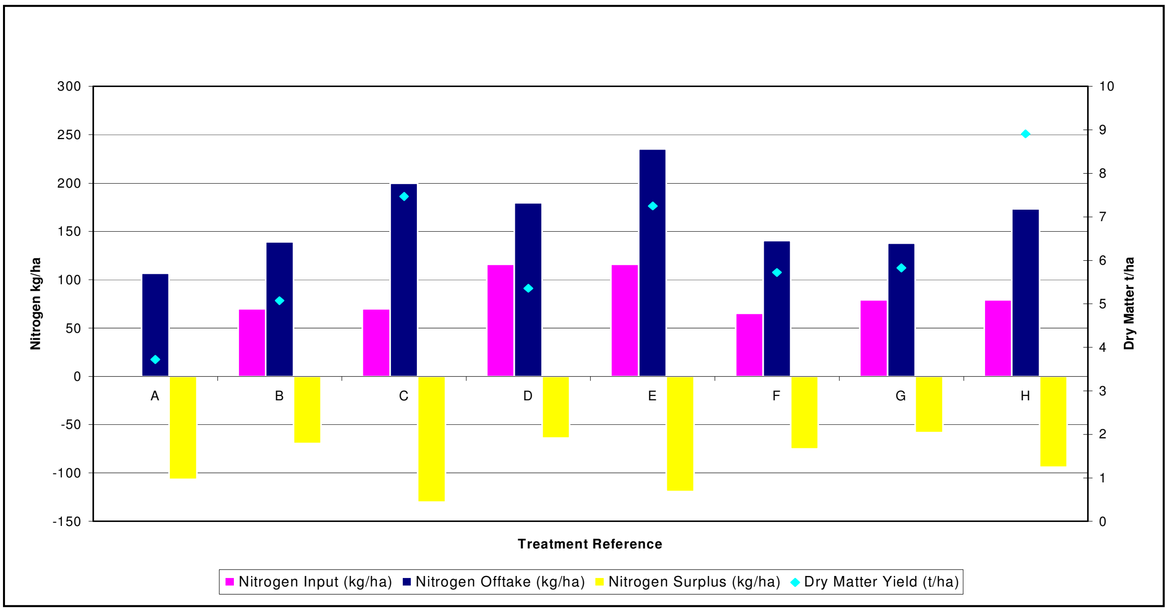

Figure 8: Nitrogen input, offtake and surplus, against herbage yield

Figure 8 shows the N surplus after N input and offtake are considered, marked alongside the herbage dry matter yield. (See Table 9). It is clear from Figure 8 that N offtake is greater than N input. If growing conditions are not limiting, i.e. good water and nutrient availability then herbage growth will react to inputs of N. There is a large amount of non-available N in the soil organic matter but only a small amount of this is mineralised enabling the soil to use it beneficially. Table 9 shows the nutrient contents of the soil in March 2004; the total available N is shown to be very low. Treatments B, D, F and G have lower negative surplus N than the other plots; B, D, F and G are all cut at 100mm and as previously stated there is a significantly higher amount of N offtake from plots cut at 50mm.

Table 9: Soil Analysis March 2004

Treatment	Total N $kg.t^{-1}$	P $kg.t^{-1}$	Index	K $kg.t^{-1}$	Index	Mg $kg.t^{-1}$	Index
A	3.3	14	1	53	0	97	2
B	3.1	18	2	80	1	100	2
C	3.5	16	2	64	1	96	2
D	3.3	17	2	101	1	100	2
E	3.3	15	1	78	1	92	2
F	3.4	14	1	59	0	99	2
G	3.4	17	2	50	0	105	3
H	3	11	1	49	0	95	2

Table 9 also contains values for the soil index, which indicates the nutrient content available within the soil. There is no index for N because this is very rarely tested, N being stated as the quantity required by a crop rather than the N required within the soil. For P and K, the index scale ranges from 0 (low), 1 (moderately low), 2 (adequate), etc. An index of 2 is the target level.

Soil nutrient status is likely to be at its lowest at this time of year following rainfall over winter when crop uptake is minimal and nutrient leaching from the soil is highest. It is important, therefore, to apply N, and to a lesser extent phosphorus (usually in the form of P_2O_5) and potassium (in the form of K_2O) to soils, especially in spring and also to areas after cutting where relatively large amounts of N are removed in herbage. Grazing systems are slightly different due to the return of N to the soil through dung and urine[7]. There should always be a surplus of organic N within the soil allowing it to become mineralised ready for the crop to use. In these trials N, P and K were returned to the soil in the form of digestate. Table 10 shows the chemical analyses of liquid digestate for each date of application.

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[7] Hopkins, A (2000), Grass It's Production and Utilization, Blackwell Science, Oxford

Table 11 shows the total nutrients that each treatment received from the digestate.

Table 10: Digestate chemical analysis

Date	pH	Total N	Total P	Total K	NH4-N	Total Mg	Total S	Total solids
		kg.m^{-3}	kg.m^{-3}	kg.m^{-3}	kg.m^{-3}	kg.m^{-3}	kg.m^{-3}	%
21-Oct	7.5	4.5	0.27	4.41	2.89	NA	NA	NA
03-Mar	7.9	3.8	0.15	3.99	2.92	NA	NA	NA
31-Mar	8.1	4.0	0.08	3.68	2.45	0.05	0.11	2.5
14-Apr	8.0	3.8	0.09	3.42	2.63	0.05	0.11	2.4
28-Apr	No sample							
12-May	8.0	4.3	0.41	2.73	2.08	0.38	0.24	4.0
26-May	7.7	3.8	0.13	4.01	2.47	0.06	0.14	3.4
09-Jun	7.7	4.2	0.32	4.00	2.42	0.25	0.21	4.7
23-Jun	7.8	3.4	0.14	3.44	2.21	0.08	0.13	2.9
07-Jul	8.1	3.6	0.17	3.36	2.35	0.09	0.14	2.9
21-Jul	8.1	3.5	0.14	3.12	1.96	0.06	0.12	2.6
04-Aug	No sample							
18-Aug	7.1	3.5	0.14	3.98	1.85	0.06	trace	3.7
01-Sep	8.1	4.1	0.50	4.14	1.20	0.40	0.25	5.1
15-Sep	8.3	3.0	0.11	3.10	1.36	0.08	0.11	2.1
29-Sep	7.6	2.7	0.12	4.13	1.48	0.05	0.12	3.3
13-Oct	7.7	2.9	0.14	3.91	1.75	0.06	0.13	3.3
27-Oct	7.6	2.6	0.13	3.94	1.12	0.05	0.12	5.5

Table 11: Nutrients in the digestate

Treatment	Total N	Total P	Total K	NH4-N	Total Mg	Total S
			(kg.ha^{-1})			
D	115.9	5.5	117.9	72.7	3.0	4.0
E	115.9	5.5	117.9	72.7	3.0	4.0
B	70.0	1.4	36.0	20.8	0.8	1.2
C	70.0	2.8	70.2	40.7	1.6	2.3
A	0	0	0	0	0	0
K	0	0	0	0	0	0
F	65.3	2.5	70.9	40.5	1.2	1.9
G	79.3	3.8	82.4	46.7	2.4	2.5
H	79.3	3.8	82.4	46.7	2.4	2.5
I	76.6	4.7	74.1	42.5	3.4	3.3
J	0	0	0	0	0	0

Table 12: N,P,K requirements for ryegrass

Nutrient	Ryegrass requirement[8] kg.ha^{-1}	Digestate required to satisfy nutrient requirements m^3	Actual nutrient input 2004 kg.ha^{-1}
N	284-380	79-105	65-116
P_2O_5	93-160	93-160	1.4-5.5
K_2O	176-463	36-118	36-118
MgO	49	401	1.2-3.4

These results show that the amount of digestate applied has not supplied sufficient nutrients to the soil for optimal herbage growth. Clearly, it is not possible to sustain a grass lay that is producing herbage for energy production through an anaerobic digester because the nutrients required by the soil cannot be returned through the digested material due to the small quantity of digestate available. This is illustrated by Table 12 and the calculation below showing the amount of digestate produced from herbage offtake.

$13t_{DM}.ha^{-1}$ @ 20% DM = 65t fresh matter.ha^{-1} (Herbage offtake)

= 52m^3 bio fertiliser (Digested herbage)

To satisfy the nutrient requirement of the soil, it is suggested that farm yard manure (FYM) and animal slurry is imported onto the land (see Table 13 for pig FYM & slurry nutrient values[9]). An application of up to 40m^3.ha^{-1} of pig FYM in the autumn would help to boost the P_2O_5 input through the winter; the FYM also includes a large amount of K_2O and organic matter that will benefit soil condition, water holding capacity and earth worm populations. The 52m^3 of digestate would need to be supplemented by up to 80.5m^3 of pig slurry to

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[9] ANON (2000). *Fertiliser Recommendation for Agricultural and Horticultural Crops.* Ministry of Agriculture Fisheries and Food, Reference Book 209. 7th Edition. London: The Stationery Office.

ensure enough N is applied. The availability of N in pig slurry in spring is 50-60% compared with 35% for cattle slurry[8]. Table 14 shows the nutrient content for each fertiliser application. Importing animal slurry and FYM helps to avoid applying artificial fertilisers which are expensive and require a large amount of energy for their production.

Table 13: Pig FYM, slurry, and digestate nutrient values

Fertiliser	N	P_2O_5	K_2O
Pig FYM in autumn ($kg.t^{-1}$)	0.7	4.2	4.5
Pig Slurry in Spring ($kg.m^{-3}$)	2.0	1.0	2.2
Pig Slurry in Summer ($kg.m^{-3}$)	1.2	1.0	2.2
Avg. Digestate ($kg.m^{-3}$)	3.6	0.19	3.71

Table 14: Total nutrient input for each fertiliser

Fertiliser	N ($kg.m^{-3}$)	P_2O_5 ($kg.m^{-3}$)	K_2O ($kg.m^{-3}$)
Pig FYM Autumn ($40m^3$)	28($kg.t^{-1}$)	168($kg.t^{-1}$)	180($kg.t^{-1}$)
Digestate ($52m^3$)	109.2	20.8	234
Pig Slurry Spring ($73.4m^3$)	146.8	73.4	161.48
Total	284	262.2	575.48

Table 14 shows that the total P_2O_5 and K_2O levels are much higher than the ryegrass levels required (see Table 12). If these were made as a single application, some of the N, P_2O_5 and K_2O will leach into the soil water and aquifers. If K_2O does enter into water and aquifers it is not polluting, but the N and P_2O_5 is harmful to aquatic life and causes algae blooms. In order to prevent this, the applications of fertiliser are staggered, with the FYM applied in the autumn and the digestate and slurry applied throughout the spring and summer. This will give the grass a chance to use up these smaller doses of nutrients rather than one large deposit which may not be used as efficiently with greater levels of leaching.

High levels of K_2O in the soil will lock up MgO. While the grass is being used as a feedstock for anaerobic digestion this is not a problem but if the ground were to be turned back to a livestock system then this could have a huge effect on the animals due to their MgO requirement. This is a long term factor that needs to be considered. A solution to this could be to balance the P_2O_5 and K_2O levels using the organic manures and use artificial N fertiliser to balance the N requirement. This would obviously be a large cost economically and environmentally so a cost-benefit analysis would need to be carried out specifically looking at the use of the land over a given period of time.

Table 15 shows the percentage of N and C contents in the grass immediately after being harvested, and in grass that has been ensiled and is ready to be digester feedstock. There is very little change in the N and C contents within the grass. The slight drop in N is expected through the release of ammonia during the ensiling process.

Table 15: Nitrogen (N) and carbon (C) values

	% N	% C
Fresh Harvested Grass	3.03	40.70
Digester Feedstock	2.65	40.61

Table 16 shows the mean figures for herbage yield, N and C offtake comparing the large and small plots. As explained beneath Table 8, the treatments used for the figures in are all cut every 4 weeks; identical treatments to the large plots. The large plot figures are a very close comparison to the small plot figures indicating that the small plots were a good size for carrying out this research and provide realistic data.

Table 16: Herbage yields, N and C takeoff

	Digestate – Small Plots		Digestate – Large Plots	
	With	Without	With	Without
Herbage yield ($t_{DM}.ha^{-1}.y^{-1}$)	6.5	4.8	6.4	4.9
N Offtake ($kg.ha^{-1}.y^{-1}$)	172	133	152	117
C offtake ($kg.ha^{-1}.y^{-1}$)	2215	1908	2423	1944
C:N Ratio	14:1	-	15:1	16:1

3.5. Conclusion

Herbage Yields

The results show that plots cut at 50mm yield higher than those at 100mm and plots cut on an eight week cycle yield more than plots cut on 2, 4, and 6 week cycle. Treatment H is the best harvest combination for highest dry matter yield, cutting at 50mm on an eight week cycle. Table 6 shows that in 2004 H2 produced the maximum yield with 12.7 $t_{DM}.ha^{-1}.y^{-1}$, in 2003 it was also high yielding with 10.1 $t_{DM}.ha^{-1}.y^{-1}$.

Overall yields were better in 2003 than 2004. This is due to a variety of factors including;

- a difference in weather conditions, shown in graphs 2, 3, and 4. There were less sunlight hours in 2004, including lower temperatures in the summer months, and an unusually high amount of rain in August, September and October, and
- a lower N input as a direct result of a reduction in the amount of digestate applied and depletion of soil N reserves (discussed below).

Suitable Feedstock

Statistical analysis shows that the C:N ratio of the herbage is higher for the 2 and 4 week cutting cycles than for 6 and 8 week cutting cycles. The C:N ratio is also higher for plots cut at 100mm than those cut at 50mm. Anaerobic digestion requires a C:N ratio of between 15-30:1. Treatments B (4 week cycle, cut at 100mm) & D (2 week cycle, cut at 100mm) are therefore the best cutting regime suited to produce good feedstock for anaerobic digestion.

Digestate as a Bio-fertiliser

Statistical analysis shows a significant increase in herbage yield for plots receiving digestate compared with those without digestate applied. This can be seen by looking at the difference in yields on Table 5 and Table 6 and is illustrated by Figure 7. Changes to the amounts of digestate applied in 2004 affected herbage yields with the majority of treatments receiving less digestate and, consequently, yielding less herbage as a result. The exception to this was for treatments G & H that received a slight increase in the amount of digestate applied in 2004 and recorded higher dry matter herbage yields. Clearly, the amount of digestate applied greatly impacts on the amount of herbage dry matter harvested.

Soil N supply is dependent upon soil N reserves, the amount of digestate applied to the plot and the N offtake in the herbage. Figure 8 shows the N balance between offtake and input. However, soil N reserves were not measured in this experiment and so N surplus should be viewed with some caution. As previously stated ryegrass typically requires 284 – 380kg $_N$.ha^{-1}. The actual N input from digestate alone was between 65 – 116 kg$_N$.ha^{-1}. This shows that the grass production was not sustainable with N supplied solely by the return of digestate following anaerobic digestion of the herbage removed. It is possible that the N requirement for optimal nutrient supply could be met through the application of an increased amount of digestate, imported animal slurry/FYM or mineral fertiliser. Given this scenario, pig slurry has a high total N and available N content and, being readily available, was considered as the most suitable organic amendment for grass production. For these reasons, pig slurry/FYM were considered in the examples shown in Table 13 and Table 14. It is clear from Table 7: Digestate applications and average yields and Figure 8 that the soil was N deficient, especially in 2004; an increased amount of digestate or additional slurry/FYM applied would increase the N input and in turn increase the herbage yield and create a positive N surplus. In addition to the pig slurry being used as a fertiliser it could also be fed to the digester increasing the quantity of feedstock and biogas production.

Storage

Table 15 shows that the N and C within the feedstock changes very little through the ensiling process. This enables the grass to be stored and makes it possible to feed the digester with grass throughout the year.

The highest yielding treatment (Treatment H) and the best treatments for digester feedstock in terms of C:N ratio (Treatments B and D) do not coincide. If the digester was fed purely on grass on a farm that only produced energy crops, then perhaps the grass would be harvested on a four week cycle. This would help to ensure the long-term health of the digester but the annual grass yields would be lower. A more likely scenario is that the digester will be fed grass as part of a farming system that includes livestock (dairy and/or beef cattle) so that both grass and slurry would be available for use as a feedstock. However, in this situation, grass is more likely to be used as animal feed rather than digester feed and, therefore, would be cut on a longer cycle e.g. every 6 – 8 weeks producing a high yielding crop with a lower C:N ratio. Slurry from housed livestock would be used as feedstock during the winter months with grass and waste silage being fed to the digester in summer months when there is less slurry available.

4. SMALL SCALE DIGESTION TRIALS

4.1. Objectives

- To anaerobically digest ryegrass using a single stage continuously stirred tank reactor (CSTR).
- To establish the methane yield for ryegrass with a target of 410 $m^3_{CH4}.t^{-1}_{ODM}$ which is quoted by Professor Weiland[10] as being the maximum yield for ryegrass.
- To examine any differences in the digestibility and methane yields of ensiled and fresh grass.

4.2. Experimental Design


Photo 1: 0.3m³ digester

Two different small scale anaerobic digesters have been used for this part of the project. The first digester was built specifically for these trials. It was a 0.3 m^3 digester with a single pump that was used to re-circulate digestate, heat, and mix the digester. It was fed by auguring the grass into the vessel, through a pipe in the side of the digester with another pipe for discharge, see Photo 1. Although the digester produced biogas, there were a number of problems which reduced the efficiency of the process. The pump continually blocked which meant that the contents of the digester would lose temperature and remained still making the unmixed digestion process unstable. This digester ran for nine months before it was replaced in December 2004 by a 1.5m^3 digester, a previously tried and tested design. There were no pumps used in this second digester. The digester was mixed by compressing gas and re-circulating it up through the digester. The digester was heated using an internal heating system in the base of the tank. The digester vessel was had no internal parts reducing the chance of scum formation. The grass was augured in through the top of the digester with an overflow weir for discharge. Photo 2 shows the 1.5m^3 digester. Both


Photo 2: 1500 litre digester

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[10] Weiland, P, Rieger, C, and Ehrmann, T,2002, Evaluation of the Newest Biogas Plants in Germany with Respect to Renewable Energy Production, Greenhouse Gas Reduction and Nutrient Management, Federal Agricultural Research Centre (FAL), Germany.

digesters were run continuously and fed daily. The main goal throughout these trials, highlighted in section 4.1, was to establish the quantity of methane produced from 1kg of organic dry matter. The digesters were both fed 5kg of fresh grass or silage everyday. Daily readings ensured that the digesters were continually monitored. The gas was collected in the same way on both models using a bell over water gas holder, this meant that the gas production analysis were consistent throughout the trials.

4.3. Description of the work

Daily Readings

The monitoring, feeding and analysis of the digester were all part of the daily routine.

The daily readings helped to control and understand what is or has been going on inside the digester. The readings included recording the temperature and the hours run by either the pump or the gas mixing.

The gas holder height was measured and recorded which gave the amount of gas produced from the previous days feed; the gas was then analysed using an infra red gas analyser. Finally the gas holder was lowered by opening the gas valve and the new starting height then recorded.

The discharge pipe or the overflow weir would then be rodded with a plunger. This encouraged any digestate above the digester overflow weir to discharge before the new feed was fed preventing any fresh feedstock from immediately discharging.

Five kilograms of feedstock were measured out into buckets for each day at the beginning of each week. By the end of the week the fresh grass or silage was often spoilt compared to that at the beginning of the week; it was therefore decided that the feed would be made up on a Monday and on a Thursday allowing the feedstock less time to spoil before being fed to the digester, giving a consistent quality of feedstock. Where necessary the grass was shredded to reduce the particle size allowing it to be pumped and to enhance the digestion process with an increase in surface area for the bacteria to access.

The 300 litre digester had plunges in the inlet and outlet pipes ensuring that everything remained inside the digester until they were removed during the daily readings.

Analysis

The readings were entered daily into a spreadsheet calculating gas production and quantities of feed and discharge. Feedstock and digestate were analysed weekly for the total solids and the volatile solids (organic dry matter). See appendix 3 for this test method.

Photo 3: 1.5m^3 digester contents

4.4. Results

The 0.3m^3 digester ran for two periods. The first was from September 2003 to November 2003 and was fed on ensiled grass harvested during the 2003 growing season. The second was from March 2004 to July 2004 and was fed on freshly harvested grass. The 1.5m^3 digester ran from January 2005 to May 2005 and was fed on ensiled grass harvested during the 2004 growing season. The ryegrass was successfully anaerobically digested producing biogas and digestate (bio-fertiliser). Photo 3 shows the contents of the 1.5m^3 digester when the lid was removed for alterations to the auger system.

The gas produced throughout the trials was a good enough quality to burn with average methane content of approximately 53%.

The mean monthly methane yields are as follows:

Table 17: 0.3m^3 Digester September 2003 – November 2003 (Silage)

Month	$m^3_{CH4}.t^{-1}_{ODM}$
September	375
October	310
November	304

Table 18: 0.3m^3 Digester March 2004 – July 2004 (Fresh Grass)

Month	$m^3_{CH4}.t^{-1}_{ODM}$
March	203
April	295
May	252
June	196
July	134

Table 19: 1.5m^3 Digester January 2005 – May 2005 (Silage)

Month	$m^3_{CH4}.t^{-1}_{ODM}$
January	265
February	347
March	347
April	429
May	383

Table 17 and Table 18 show that the 0.3m^3 digester produced reasonable methane yields in the early stages of both trials before declining towards the end. The fresh grass failed to reach 0.3m$^3_{CH4}$.t$^{-1}_{ODM}$in comparison to the silage which reached a mean monthly average of 375 m$^3_{CH4}$.t$^{-1}_{ODM}$. The 1.5m^3 digester methane yield figures shown in Table 19 are high and consistent during February and March, increasing in April and falling in May. The overall mean methane yield figures for each of the three trials are;

Table 20: Average methane yield figures

Date	$m^3_{CH4}.t^{-1}_{ODM}$
Sept. '03 – Nov '03	325
March '04 – July '04	229
Jan. '05 – May '05	357

There is a clear difference between the methane yields of the fresh grass and the silage shown by Table 20; the overall methane yield of the silage is 342 $m^3_{CH4}.t^{-1}_{ODM}$, and 229 $m^3_{CH4}.t^{-1}_{ODM}$ for fresh grass. These results will have been affected by the two different digester designs. The conditions within the 1.5m^3 digester were more stable than those in the 0.3m^{3}digester, which is indicated by the higher methane yield and consistent gas quality. The overall average mean methane yield for the three trials is 288 $m^3_{CH4}.t^{-1}_{ODM}$. The range of daily methane production for 1tonne of ryegrass ODM was very variable for all of the trials; these figures are shown in Figure 9 to Figure 11.

The figures below show the daily methane yield for ryegrass.

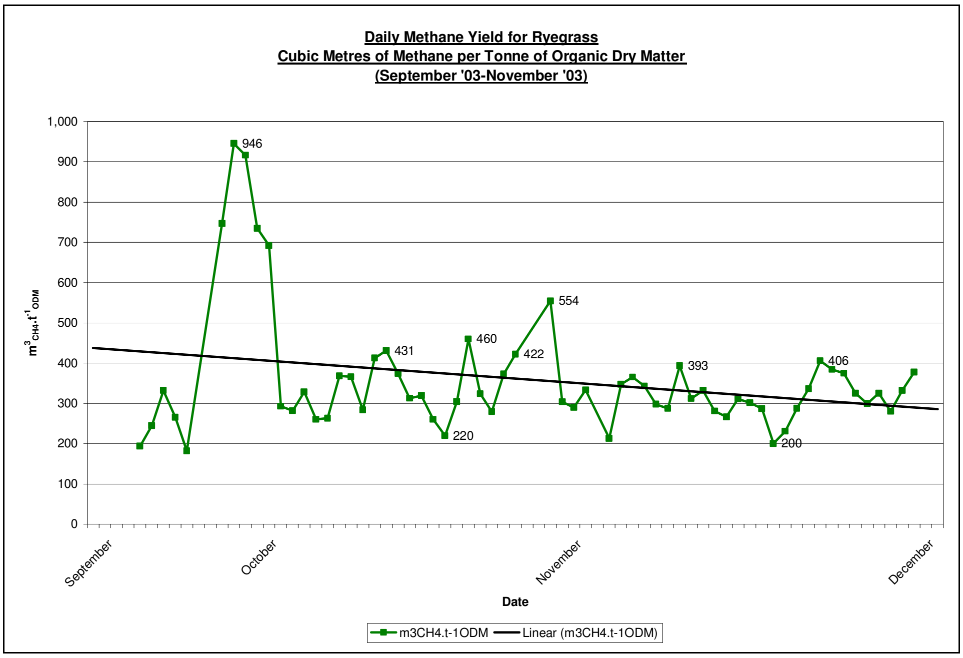

Figure 9: Methane yield - September '03 to November '03

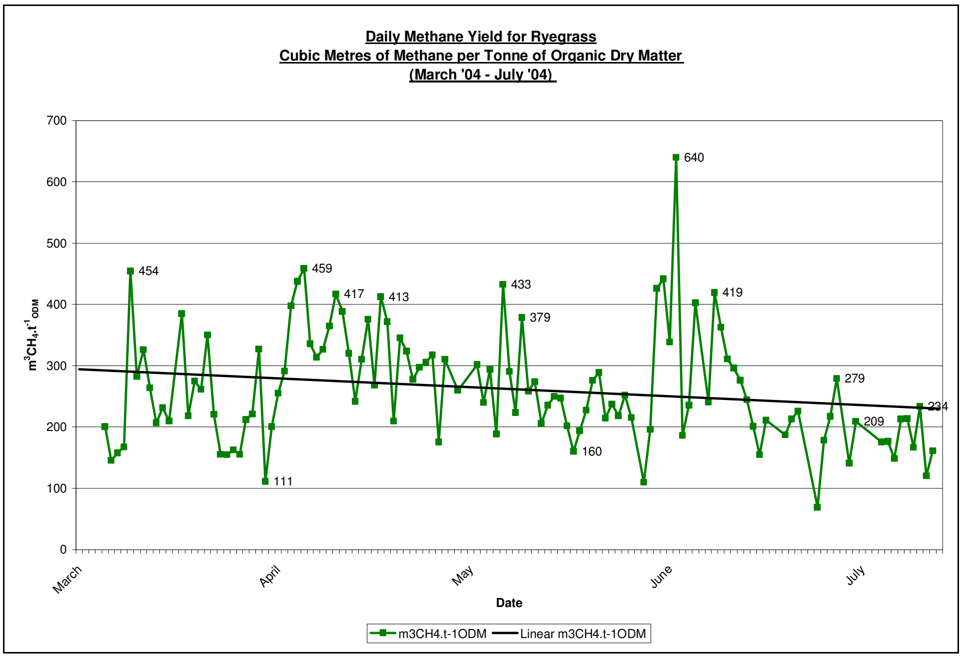

Figure 10: Methane yield - March '04 to July '04

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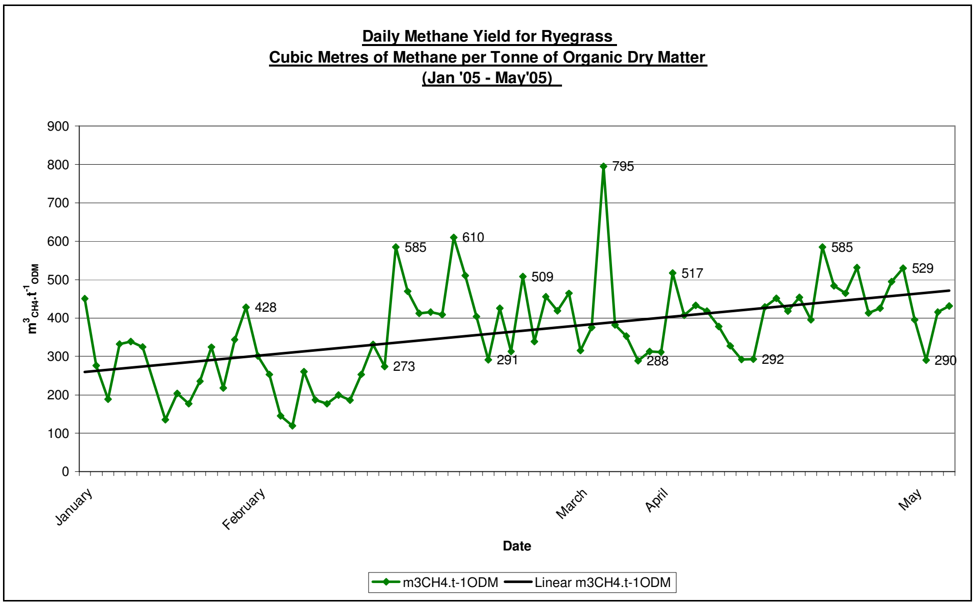

Figure 11: Methane yield - Jan '05 to May '05

Figure 9 shows the daily methane production for the 0.3m^3 digester fed on silage. The production was fairly consistent from October to the end of November shown by the horizontal trend line; on average methane yields of between 200-460 m$^3_{CH4}$.t$^{-1}_{ODM}$ were recorded. A mechanical failure with the pump shut the plant down at the beginning of December; it was re-commissioned in February the following year.

From February the daily methane yield (illustrated by Figure 10) was very inconsistent with figures of between 100 and 600 m$^3_{CH4}$.t$^{-1}_{ODM}$. The digester became biologically unstable several times indicated by methane contents of less than 50%. This may have been caused by the quality of the feedstock, (e.g. differences between 2 & 8 week cut grass, or spoilt grass or silage), or the re-occurring mechanical problems associated with the pump which impacted on the mixing and temperature of the digester causing frequent scum formation; in turn this disturbed the micro-organisms and therefore the digestion process. Problems with the pump also caused frequent scum formation. The sloping trend line emphasises this decline in digester health.

Figure 11 shows the daily methane yield from the 1.5m^3 digester for the final set of trials with a silage feedstock. Once the digester had stabilised (consistent gas quality of 50% methane or above) the average methane yield ranged between 270 and 600 m$^3_{CH4}$.t$^{-1}_{ODM}$, never dropping below 270 m$^3_{CH4}$.t$^{-1}_{ODM}$. The trend line shows a steady increase in methane production as the digester became more acclimatised to the grass. The methane quality remained at a consistent level during this final trial, dropping below 50% only once or twice. If the gas quality on either of the digesters dropped below 50% methane contents then the digester would not be fed until it improved to a minimum of 50%.

It should be noted that the retention time of the 0.3m^3 digester was 60 days and 300 days for the 1.5 m^3 digester. A feed rate of 5kg of wet matter was fed throughout the trials equal to approximately 1kg of dry solids per day. The retention time relates to the quantity of feed and the size of the digester which results in the length of time that the material remains inside the digester; the retention time of grass is hard to establish due to its specific gravity which will vary from 0.8-1.2 depending on the state of the grass. This means that 5kg of grass may be 4-6 litres when in the digester. Most gas is given off between 1 and 14 days[11]; once the digestion process has stabilised, and the feed is constant, the gas production should also stabilise. When taking daily readings it was assumed that the gas produced that day is a direct result of the previous days feed. One of the aims of this project is to establish the methane yield for ryegrass therefore these long retention times were not a critical issue within this research, measurable gas production and digester health were of key importance.

The figure set by Weiland of 410 m$^3_{CH4}$.t$^{-1}_{ODM}$ was reached and exceeded throughout the trials but the mean averages are significantly lower. In correspondence with Weiland, he stated that this figure is based on batch trials in 25 litre fermenters at 37°C therefore this figure cannot be reached in a CSTR. Batch reactors are maintained until all of the available gas in the material has been collected, even though the rate of production drops to very low levels. For constant production, the digesters are supplied with regular feed, collecting the majority of the available methane but never achieving the full potential of the feedstock. The grass length was cut at only few mm and ensiled before digestion as their experiments have shown that ensiling increases the gas yield. Gas yields of between 220 – 380 m$^3_{CH4}$.t$^{-1}_{ODM}$ were also recorded. See appendix 4 for the correspondence.

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[11] Fulford, D, (1988), Running a Biogas Programme: A handbook, Intermediate Technology Publications, London

4.5. Conclusion

Ryegrass can be anaerobically digested to produce biogas and bio-fertiliser. This was proved through the use of two different digesters.

The mean average methane yield from this experiment was 288 $m^3_{CH4}.t^{-1}_{ODM}$. This figure includes all data from both digesters, using fresh grass and silage. The range of gas yields varied greatly, shown by graphs 7-9, from 200-600 $m^3_{CH4}.t^{-1}_{ODM}$.

There is a definite difference in the quantity of methane produced from fresh grass to that produced from silage. This is clearly seen by the 3 trials, Table 21 highlights these figures.

Table 21: Feedstock and methane production

Date	Digester	Feedstock	$m^3_{CH4}.t^{-1}_{ODM}$
Sept. '03 – Nov '03	$0.3m^3$	Silage	325
March '04 – July '04	$0.3m^3$	Fresh Grass	229
Jan. '05 – May '05	$1.5m^3$	Silage	357

It must be noted that the fresh grass was only digested for one trial using the $0.3m^3$digester which had mechanical problems throughout the trials impacting on the digestion process and the end results. Fresh grass should be digested in the $1.5m^3$ digester to enhance this data, but unfortunately there was not time within this project. The 1500 litre digester was more stable than the $0.3m^3$ digester with an average gas production of 357 $m^3_{CH4}.t^{-1}_{ODM}$.

The mean average gas yield for silage is 342 $m^3_{CH4}.t^{-1}_{ODM}$, compared to 229 $m^3_{CH4}.t^{-1}_{ODM}$ for fresh grass. Once again the conditions of the digester for the fresh grass trial were not constant; and the biological stability of the digester contents was less stable than that of silage, indicated by poorer gas quality. This leads us to believe that even with fresh grass trials using the $1.5m^3$digester the overall gas yield would still be lower than that of silage. An explanation for this could be that the silage has started to react and break down biologically prior to being fed to the digester enhancing the digestion process, compared to fresh grass that is placed straight into the digester immediately after being cut. The tests carried out by IGER showed that there is very little difference between the fresh grass and the grass ready to be fed to the digester. This is just comparing C and N quantities. The acids produced during the ensiling process were not analysed with in this project in comparison to those in the fresh grass. This makeup of the feedstock is vital to the digestion process, and more research must be done on silage preparation. Research is being carried out on this at Vienna University as part of Cropgen, a research project funded by the EU.

A closer look at the research carried out by Weiland shows that his experiments were a lot smaller than the trials in this project with the 410 $m^3_{CH4}.t^{-1}_{ODM}$ being a maximum methane yield. His findings relate closely to those found from this project helping to verify this research.

5. THE LARGE PLOT

5.1. Objectives

- To harvest the area on a regular basis, feeding the grass to the 20m^3 digester fresh or ensiling it and storing it for future use.
- To apply the resulting digestate as a bio-fertiliser back onto the land.

5.2. Description of the Work

In the first season the grass was mown every two weeks and either ensiled or fed fresh to the digester as required. This was done using a ride on mower. The ensiled grass was not good quality as it was often mown when wet producing poor silage. It was decided that in the second year the grass would be mown when required by the digester as fresh grass feedstock. In addition this would reduce the cost of storing the grass on a commercial scale. This worked well, cutting the grass at the highest setting as the feedstock was required.

6. 20m^3 BIOGAS PLANT

6.1. Objectives

- To trial the digestion of ryegrass on a larger scale using grass harvested from the large plot to feed the digester all year round using both fresh and ensiled grass.
- To use the digester to experiment with various modifications investigating the best way to design a commercial plant for the digestion of ryegrass.

6.2. Initial Digester Design

The digester capacity is 20m^3 with a reception tank for preparing the feedstock, a storage tank for the digestate and a bell over water gas holder.

Photo 4: Biogas Plant

Photo 5: Reception Tank

See Photo 4 and 5.

The feedstock was prepared as liquid slurry by mixing the grass with re-circulated digestate. This was mixed and chopped in the reception tank using a chopper pump. This pump was also used to feed the digester which was fed manually every day following the preparation of the feed mix. The feed entered the digester through a pipe in the roof. The digester was mixed using biogas that was recirculated up through the digester. The digester was heated using an internal heat exchanger, with the temperature of the digester set at 37°C. The digestate was discharged via an overflow weir which occurred when the contents within the digester vessel became higher than the top of the overflow pipe. The overflow pipe can be seen in photo 4 situated between the digester and the digestate storage tank.

6.3. Problems

This initial design created several problems;

- The digester contents developed a skin on the top as a resulted of grass sticking to the gas recirculation pipes and the internal heat exchanger.
- The grass was chopped when passing through the chopper pump but the particle size reduction was minimal allowing substantial lengths of grass to enter into the digester and stick to the components within the digester.
- The gas mixing would partially break up the scum which would then move and snap the gas recirculation pipes as it fell.

- Every time the digester was fed the feed would fall on top of the skin which would then develop its own skin creating layers of scum within the digester.
- The scum would often build up preventing the gas from passing through the gas takeoff pipe at the top of the digester; this then caused the gas to be released to atmosphere through the pressure relief valve.

6.4. Modifications

- The gas mixing pipes were relocated down the sides of the digester to the floor of the vessel.
- The internal heat exchanger was removed and replaced by an external heat exchanger. This was a pump that drew liquor from the bottom of the digester, up through the heat exchanger and back in at the top of the digester in through the side panel. This uses the same concept adopted by the 0.3m^3 digester.
- The feed mechanism was modified so that it was fed through the inlet pipe of the heat exchanger at the topside of the digester.
- The feed from the mixing tank was redirected through a macerator and mono pump before entering into the digester. The macerator chopped the feedstock which further reduced the particle size of the material entering the digester. This enhanced the digestion process two stage by increasing the surface area available for the bacteria, and preventing the feedstock from clogging in the pipes or in the digester vessel itself.
- The most recent modification is the edition of a discharge pump and a belt press separator. This allows the solids to be separated out leaving a thin digestate liquor. This reduces the amount of solids that are re-circulated within the liquor when making the feed mix.
- A design was prepared for the installation of an auger system that would feed the grass in dry rather than being mixed with a liquid allowing it to be pumped into the digester. Having trialled this on the 0.3m^3 digester and experienced problems with continuous blockages in the mixing pump, it was decided that it would be better to stick with the existing feeding mechanism.

The digester was monitored closely for gas production in the first year. The biogas yield was found to be an average of 9m^3 per day from 100kg of grass per day; this is equivalent to approximately 250 $m^3_{CH4}.t^{-1}_{ODM}$. The monitoring ceased during the engineering modifications but it is expected that the gas yield would now be higher due to the new layout of the digester and the reduced particle size, which both appear to enhance the digestion process.

6.5. Conclusion

The modifications to the digester have been very successful with the digester being fed on grass throughout the alterations. Relocating internal mechanical parts has been crucial, allowing nothing for the grass to get stuck on which would result in a build up of scum. The gas mixing works well and is assisted by the external heat exchanger which recirculates the liquor when the digester calls for heat. The new feeding mechanism is also a good improvement with a noticeable reduction in particle size and less blockages. There are still occasional problems with pumping grass; a thick mix can easily block up the mixing and feeding pumps. As mentioned above the idea of an auger feeding system was dropped in favour of the current method. Having said this, quick mix pumps in Germany combine an auger feeding system with the addition of recirculated digester contents to push the feedstock through into the digester. There would be no particle size reduction using this method therefore it would be important that the size of the material was chopped as small as possible at the point of harvest.

7. COMMERICAL RYEGRASS BIOGAS PLANT

7.1. Objectives

- To design a commercial biogas plant specifically for the digestion of ryegrass for energy production.
- To assess the economics of such a project with particular reference to the capital and operating costs of the plant and the costs of harvesting and transporting the feedstock.
- To analyse the energy input used to produce the feedstock against the energy ouput produced at the end of the process.

7.2. Outline Design

This design is based on a farm with 100 hectares of ryegrass which is to be harvested as feedstock for the digester. The area of 100 hectares was chosen so that a large enough plant could be designed suitable for a combined heat and power (CHP) unit for the production of heat and electricity. It is assumed that all feedstock is silage and figures within the process calculations spread sheet (appendix 5) are based on this assumption. The grass is harvested using a tractor mower followed by a forage harvester which chops the grass to an average of 40mm in length which is suitable to be fed to the digester without further particle size reduction. Once harvested the grass is stored in a silage clamp.

The grass will be transferred daily from the silage clamp into a hopper using a front end loader. At the bottom of the hopper there will be an auger, beneath which digester liquid is pumped through pushing the grass into the digester; this is called a quick mix pump. This system allows both liquid and solid feedstock to be fed to the digester.

The digester will be an above ground insulated cylindrical vessel. It will be mixed using gas mixing as the 1.5m^3 and 20m^3 digesters have demonstrated that this works very well. The digester will be heated using an internal heat exchanger.

Digestate will discharge over a mechanical press which will separate the solids and the liquor. The liquid digestate will be stored in a large storage tank until the farmer is ready to spread it onto the land. The solid digestate will fall into a pile beneath the separator which can be used as a soil conditioner.

This plant will not require a pasteurisation unit as there are no animal by products within the feedstock. The pasteurisation unit has been left in the spreadsheet allowing for future expansion of the plant.

The digestate storage tank will double as a gas holder with a flexible membrane over the top of the store. This design will ensure that all the gas is collected including any from the storage tank, the odours will all be contained and will reduce the footprint of the plant without the need for additional ground space for a separate gas holder.

The gas will be used on site in a CHP unit with a spark ignition engine. In Germany it is common practise for farmers to use duel fuel engines because they are cheaper, however they require diesel as the pilot fuel. CHP units are now designed to take un-scrubbed biogas with hydrogen sulphide levels of up to 500ppm.

A standby gas boiler will also be included to use any excess gas and to back up the CHP unit during maintenance work.

7.3. Economic Analysis

7.3.1. Ryegrass Biogas Plant

Feedstock

The cost of establishing the grass sward is £150 per hectare; this includes ploughing, drilling, rolling and the cost of the seed. The lay will last five years. On the balance sheet this will be included under feedstock production which will include the yearly harvesting costs and the establishment cost of £30 per hectare per year.

The digestate from the biogas plant can be used to fertilise the sward but as mentioned in section 3 it would need to be supplemented by additional fertiliser such as pig FYM and slurry. It is important that muck or slurry is used rather than nitrogen fertiliser which is energy expensive to produce and releases large amounts of carbon dioxide. A figure of £20 per hectare per year should be allowed for the importing of farm manure and slurry and will be included in the cost of feedstock production.

The cost of harvesting ryegrass as silage is £395 per hectare based on four cuts per year. This figure includes, mowing it, collecting and chopping it using a forage harvester, transport from the field to the silage clamp, and the rolling and the sealing of the silage clamp. (This price is based on contracting costs in 2005) It is assumed that the farmer will already have a silage clamp in which to store the grass. The total cost of production is £445 per hectare per year.

The cost of land must be taken into account as a rent whether or not the land is owned by the farmer. The cost of land in this project is £150 per hectare, this will vary depending on each individual situation.

Transport

The cost of transport is not an issue as the silage clamp will be situated on the farm alongside the biogas plant. It is presumed that the farmer will already have a front end loader from previous or continuing farming practises which will be used to load the hopper, but the costs of this operation have been included.

Capital Cost

Project management & design	£38,000
Supply & installation of ryegrass hopper & feed system	£44,000
Supply & installation of digester tank & equipment	£115,000
Supply & installation of press & equipment	£30,000
Supply & installation of digestate and gas storage	£68,000
Supply & installation of CHP unit & gas boiler	£95,000
Supply & installation of control panel, instrumentation & cabling	£32,000
Construction of tank bases and control building	£38,000
Process commissioning, training and manual	£15,000
Contingency	£25,000
	£500,000

Annual Operating Costs

The operating costs include the labour, maintenance and spares, engine oil and other consumables and utilities.

Revenue

The main drive of this project is the production of renewable energy which is where the main income will come from the sale of electricity back to the national grid. There is also a large economic benefit to be had from the surplus heat produced by the CHP unit. For example it could be used in glasshouses to grow fruit and vegetables all year round. In addition CO_2 from the biogas could also be used in a glasshouse enhancing the growing environment for plants. To make this biogas plant economically viable it is essential that the heat energy is used.

Income can be had from the digestate fibre which could be sold locally as a soil enhancer. The liquid digestate also has an economic value to the farmer as it can be recycled back onto the land as a bio-fertiliser replacing the cost of mineral fertilisers.

Expansion of the biogas plant could allow for other feedstock to be brought in for which a gate fee could be charged, e.g. local authority waste, other agricultural waste, or abattoir waste. It should be noted that if animal by-products are to be fed to the digester then a pasteurisation unit must be added to the plant to comply with the Animal By-Product Regulations.

Economic Analysis

The economic analysis can be seen on the spread sheet on the following page. Three scenarios are given each with different incomes. A1 only receives income from the sale of electricity, A2 receives income from the sale of electricity and compost, and A3 receives income from the sale of electricity, compost and heat.

The key figures used are a ryegrass yield of $12.7t_{DM}.ha^{-1}.y^{-1}$, which is equivalent to 11.1t_{ODM}.ha^{-1}.y^{-1}, this is the maximum yield recorded on plot H2. A methane yield of 342m^3_{CH4}.t^{-1}_{ODM} is used as this was the mean average gas yield for ryegrass. The average methane content of the gas is 53%. The availability of the CHP is 95%, with an electrical efficiency of 33% and a heat efficiency of 52%.

The mass and energy balance for this plant is shown in appendix 6.

ON- FARM ANAEROBIC DIGESTER SIMPLE ECONOMIC ASSESSMENT		**Case A1**	**Case A2**	**Case A3**
Annual Energy Crop Production	tonnes per year	6,367	6,367	6,367
Annual Slurry Production	tonnes per year	0	0	0
Total Digester Feedstock	tonnes per year	6,367	6,367	6,367
Biogas Yield from Energy Crop	m3 per day	2,003	2,003	2,003
Biogas Yield from Slurry	m3 per day	0	0	0
Total Biogas Yield	m3 per day	2,003	2,003	2,003
Energy Value of Biogas	kW (fuel)	438	438	438
Potential CHP Electricity Production	kW (electrical)	145	145	145
Potential CHP Heat Production	kW (heat)	228	228	228
Process Heat	kW (heat)	32	32	32
CHP Availability	%	95	95	95
Usage Factor for Surplus Heat	%	0	0	66
Gross Electricity Production	MW.hrs per year	1,203	1,203	1,203
Net Useful Heat Production	MW.hrs per year	0	0	1,174
Oil Equivalence of Useful Heat	litres per year	0	0	138,165
Value of Electricity	£ per MW.hr	75	75	75
Value of Heat	£ per MW.hr	20	20	20
Value of Gross Electricity Production	£ per year	90,227	90,227	90,227
Value of Net Heat Production	£ per year	0	0	23,488
Value of Energy Production	£ per year	90,227	90,227	113,715
Area of Land Required for Energy Crops	hectares	100	100	100
Cost of Production of Energy Crops	£ per year	45,000	45,000	45,000
Cost of Land for Energy Crops	£ per year	15,000	15,000	15,000
Percentage of Biofertiliser as Solid	%	7	7	7
Production of Solid Biofertiliser	tonnes per year	446	446	446
Production of Liquid Biofertiliser	tonnes per year	5,921	5,921	5,921
Value of Solid Biofertiliser	£ per tonne	0.00	5.00	5.00
Value of Solid Biofertiliser	£ per year	0	2,228	2,228
Labour Costs	£ per year	8,000	8,000	8,000
Operating & Maintenance Costs	£ per year	12,000	12,000	12,000
Summary of Economics - £ per year				
Income				
Value of Electricity		90,227	90,227	90,227
Value of Heat		0	0	23,488
Value of Solid Biofertiliser		0	2,228	2,228
Total Income		**90,227**	**92,455**	**115,943**
Expenditure				
Labour Costs		8,000	8,000	8,000
Maintenance & Operating Costs		12,000	12,000	12,000
Cost of Energy Crops		60,000	60,000	60,000
Total Expenditure		**80,000**	**80,000**	**80,000**
Income less Expenditure		**10,227**	**12,455**	**35,943**
Capital Costs				
Capital Cost of Plant	£	500,000	500,000	500,000
Capital Grant	%	0	0	0
Net Capital Cost of Plant	£	500,000	500,000	500,000
Interest Rate	%	7.0	7.0	7.0
Capital Pay-Back Period	years	15	15	15
Average Annual Finance Cost	£ per year	50,833	50,833	50,833
Income less Expenditure less Finance		**-40,607**	**-38,378**	**-14,890**

7.3.2. Ryegrass and Pig Slurry Biogas Plant

The ryegrass economic model shows that the sales of electricity, heat and compost are vital, but even at these optimistic prices the revenue fails to cover the expenditure. To enhance the digestion process and increase energy production pig slurry will become an additional feedstock to the ryegrass from 100 hectares of land. There will be no extra cost in importing this as a feedstock as it is already incorporated into the cost of grass production; the quantity of pig slurry imported for digestion will be equal to the amount of extra nutrients required to fertilise the grass, see page 18 for details. It is thought that there will be no nutrients lost from the pig slurry as a result of the anaerobic digestion process, those going into the digester will be equal to those going out and will be readily available for the plants to use.

The costs of the plant will be higher than the previous model with the addition of two tanks. The first will be a holding tank for a months supply of pig slurry with a single membrane cover to capture any gas which can then be utilised through the main gas holder. The second tank will be an additional digestate storage tank which will also have a single membrane roof to capture any gas. Each digestate storage tank will contain 44 days of digester discharge. Appendix 7 shows the process calculations for a feedstock of pig slurry and ryegrass. There will be an increase in the volume of feedstock however the digester size will remain the same. This will mean that the retention time of the grass will be reduced due to the large volume of pig slurry that will be fed into the digester; co-digestion trials in the 20m^3 digester carried out since the end of this research have indicated that grass digests well with a variety of feedstocks and at a much shorter retention time than those within this project.

Capital Cost

Project management & design	£38,000
Supply & installation of ryegrass hopper & feed system	£44,000
Supply & installation of digester tank & equipment	£115,000
Supply & installation of press & equipment	£30,000
Supply & installation first digestate storage tank and gas storage	£68,000
Supply & installation of second digestate storage tank	£30,000
Supply & installation of pig slurry holding tank	£30,000
Supply & installation of CHP unit & gas boiler	£95,000
Supply & installation of control panel, instrumentation & cabling	£32,000
Construction of tank bases and control building	£38,000
Process commissioning, training and manual	£15,000
Contingency	£25,000
	£560,000

Annual Operating Costs

The operating costs will remain the same as the ryegrass model. There will be no extra handling of the feedstock because the pig slurry is imported anyway and the running costs of the plant will also remain the same.

Revenue

The revenue streams will remain the same as the ryegrass model.

The economic spreadsheet on the following page sets out the same scenarios for the previous model but for a ryegrass and pig slurry biogas plant. The key figures used in addition to those listed for the ryegrass model are a gas quality of 58% methane and a yield of $232\mathrm{m}^3_{\mathrm{CH4}}.\mathrm{t}^{-1}_{\mathrm{ODM}}$.

The mass and energy balance for this plant is shown in appendix 8. The two simple economic spreadsheets for both commercial models can be seen side by side in appendix 9.

ON- FARM ANAEROBIC DIGESTER SIMPLE ECONOMIC ASSESSMENT		**Case B1**	**Case B2**	**Case B3**
Annual Energy Crop Production	tonnes per year	6,367	6,367	6,367
Annual Slurry Production	tonnes per year	7,352	7,352	7,352
Total Digester Feedstock	tonnes per year	13,719	13,719	13,719
Biogas Yield from Energy Crop	m3 per day	2,003	2,003	2,003
Biogas Yield from Slurry	m3 per day	274	274	274
Total Biogas Yield	m3 per day	2,276	2,276	2,276
Energy Value of Biogas	kW (fuel)	545	545	545
Potential CHP Electricity Production	kW (electrical)	180	180	180
Potential CHP Heat Production	kW (heat)	284	284	284
Process Heat	kW (heat)	68	68	68
CHP Availability	%	95	95	95
Usage Factor for Surplus Heat	%	0	0	66
Gross Electricity Production	MW.hrs per year	1,498	1,498	1,498
Net Useful Heat Production	MW.hrs per year	0	0	1,298
Oil Equivalence of Useful Heat	litres per year	0	0	152,733
Value of Electricity	£ per MW.hr	75	75	75
Value of Heat	£ per MW.hr	20	20	20
Value of Gross Electricity Production	£ per year	112,338	112,338	112,338
Value of Net Heat Production	£ per year	0	0	25,965
Value of Energy Production	£ per year	112,338	112,338	138,302
Area of Land Required for Energy Crops	hectares	100	100	100
Cost of Production of Energy Crops	£ per year	45,000	45,000	45,000
Cost of Land for Energy Crops	£ per year	15,000	15,000	15,000
Percentage of Biofertiliser as Solid	%	5	5	5
Production of Solid Biofertiliser	tonnes per year	680	680	680
Production of Liquid Biofertiliser	tonnes per year	12,919	12,919	12,919
Value of Solid Biofertiliser	£ per tonne	0.00	5.00	5.00
Value of Solid Biofertiliser	£ per year	0	3,400	3,400
Labour Costs	£ per year	8,000	8,000	8,000
Operating & Maintenance Costs	£ per year	12,000	12,000	12,000
Summary of Economics - £ per year				
Income				
Value of Electricity		112,338	112,338	112,338
Value of Heat		0	0	25,965
Value of Solid Biofertiliser		0	3,400	3,400
Total Income		**112,338**	**115,737**	**141,702**
Expenditure				
Labour Costs		8,000	8,000	8,000
Maintenance & Operating Costs		12,000	12,000	12,000
Cost of Energy Crops		60,000	60,000	60,000
Total Expenditure		**80,000**	**80,000**	**80,000**
Income less Expenditure		**32,338**	**35,737**	**61,702**
Capital Costs				
Capital Cost of Plant	£	560,000	560,000	560,000
Capital Grant	%	0	0	0
Net Capital Cost of Plant	£	560,000	560,000	560,000
Interest Rate	%	7.0	7.0	7.0
Capital Pay-Back Period	years	15	15	15
Average Annual Finance Cost	£ per year	56,933	56,933	56,933
Income less Expenditure less Finance		**-24,596**	**-21,196**	**4,769**

7.4. Energy Balance

The energy balance for the anaerobic digestion of ryegrass can be seen below. This is based on work carried out by Southampton University as part of Cropgen, a European Union funded research project. The cultivation figures used are based on the work of Leach[12]. In this model the grass will be harvested 4 times a year with digestate added as fertiliser after each harvest. The grass yields are based on plot H2, with a methane yield of 342 m^3CH_4.tODM. Production energy is the energy the biogas plant requires to run itself.

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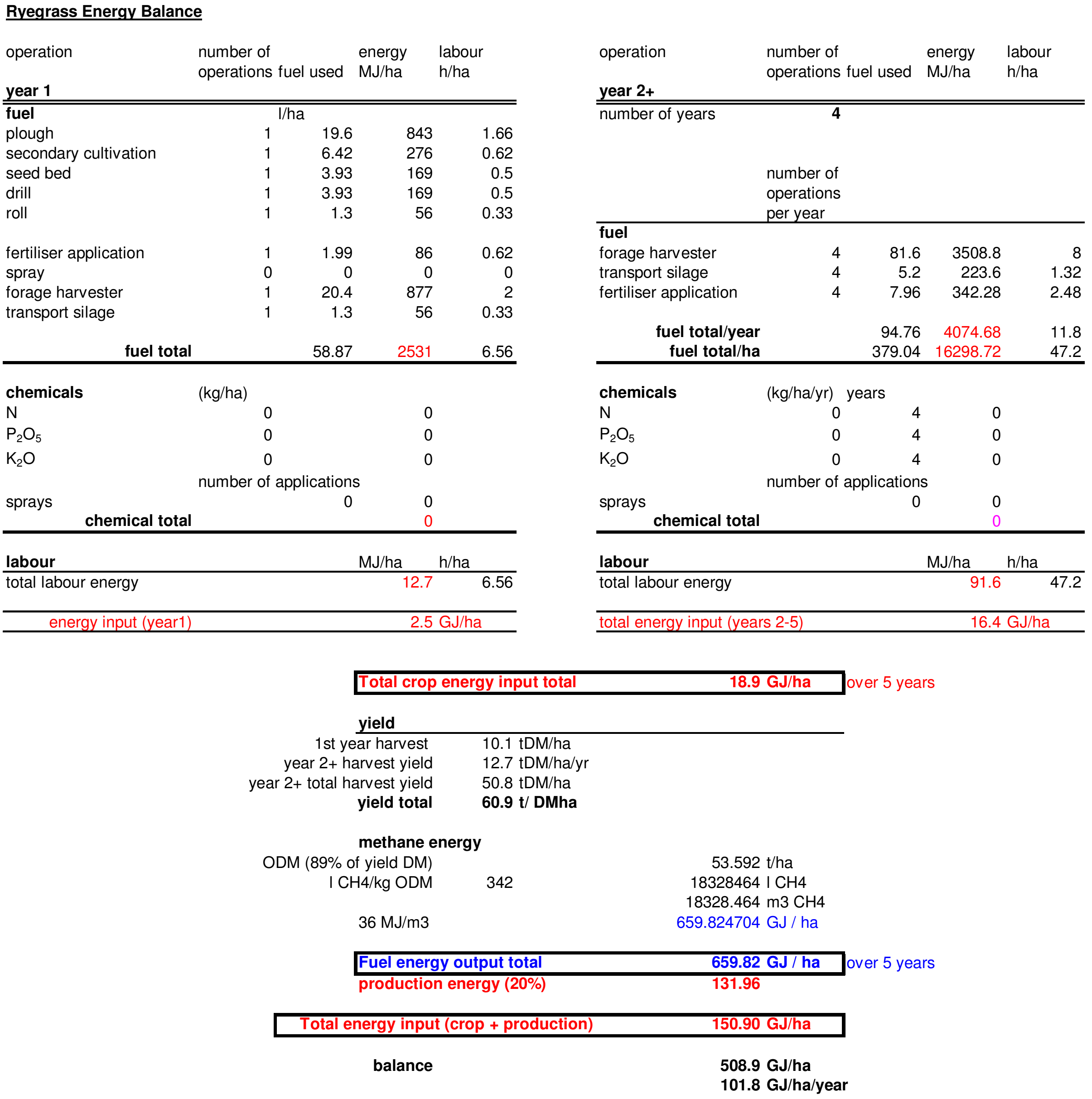
[12] Leach, G. (1976) *Energy and Food Production*, Guildford, IPC Science and Technology Press.



Ryegrass Energy Balance

operation	number of operations	fuel used	energy MJ/ha	labour h/ha
year 1				
fuel		l/ha		
plough	1	19.6	843	1.66
secondary cultivation	1	6.42	276	0.62
seed bed	1	3.93	169	0.5
drill	1	3.93	169	0.5
roll	1	1.3	56	0.33
fertiliser application	1	1.99	86	0.62
spray	0	0	0	0
forage harvester	1	20.4	877	2
transport silage	1	1.3	56	0.33
fuel total		58.87	2531	6.56
chemicals	(kg/ha)			
N	0		0	
P_2O_5	0		0	
K_2O	0		0	
	number of applications			
sprays		0	0	
chemical total			0	
labour			MJ/ha	h/ha
total labour energy			12.7	6.56
energy input (year1)			2.5 GJ/ha	

operation	number of operations	fuel used	energy MJ/ha	labour h/ha
year 2+				
number of years	**4**			
	number of operations per year			
fuel				
forage harvester	4	81.6	3508.8	8
transport silage	4	5.2	223.6	1.32
fertiliser application	4	7.96	342.28	2.48
fuel total/year		94.76	4074.68	11.8
fuel total/ha		379.04	16298.72	47.2
chemicals	(kg/ha/yr)	years		
N	0	4	0	
P_2O_5	0	4	0	
K_2O	0	4	0	
	number of applications			
sprays		0	0	
chemical total			0	
labour			MJ/ha	h/ha
total labour energy			91.6	47.2
total energy input (years 2-5)			16.4 GJ/ha	

Total crop energy input total		**18.9 GJ/ha**	over 5 years
yield			
1st year harvest	10.1 tDM/ha		
year 2+ harvest yield	12.7 tDM/ha/yr		
year 2+ total harvest yield	50.8 tDM/ha		
yield total	**60.9 t/ DMha**		
methane energy			
ODM (89% of yield DM)		53.592 t/ha	
l CH4/kg ODM	342	18328464 l CH4	
		18328.464 m3 CH4	
36 MJ/m3		659.824704 GJ / ha	
Fuel energy output total		**659.82 GJ / ha**	over 5 years
production energy (20%)		**131.96**	
Total energy input (crop + production)		**150.90 GJ/ha**	
balance		**508.9 GJ/ha**	
		101.8 GJ/ha/year	

The energy ratio for ryegrass is 1:4.4 (input energy:output energy), with an energy balance figure of 101.8 $GJ.ha^{-1}.y^{-1}$. (This includes dividing the energy cost of sowing the crop in the first year across the 5 years of the crop life). In comparison, wheat grain grown for biogas production produces 71$GJ.ha^{-1}.y^{-1}$ with an energy ratio of 1:3. Red Clover, which has a higher dry matter yield than ryegrass, produces 107$GJ.ha^{-1}.y^{-1}$ and has an energy ratio of 1:4.5. The breakdown of each energy balance can be seen in appendix 10.

Biogas produced from crops can also be compared with other equivalent biofuels. Biogas produced from crops can also be compared with other equivalent biofuels particularly biodiesel and bioethanol. A number of studies by Mortimer *et al*[13,14] have compared the energy requirements for the production and processing of biofuels using a standard format. In these studies the energy required for cultivation is given as a single figure rather than a breakdown of operations. In order to compare the efficiency of anaerobic digestion with these other biofuels we can consider the use of wheat grain. The cultivation energy required for production of wheat grain is the same for AD and bioethanol so any differences result from the energy required for the production process itself. A comparison of the energy requirements is shown in Table 22. The breakdown of the energy balances can be seen in appendix 11.

Table 22

Crop	Biofuel	Energy Balance $GJ.ha^{-1}.y^{-1}$	Energy Ratio (input:output)
Wheat	Bioethanol	34.67	1:2.3
Wheat	Biogas	68.48	1:3
Oilseed Rape	Biodiesel	18.25	1:1.8

It is important that the energy balance is looked at alongside the ratio; if a crop and fuel combination has a high energy ratio the benefits are limited if the amount of energy returned is small.

7.5. Conclusion

From the pilot scale plant a commercial design has been developed using today's technology to run a digester purely on ryegrass. The capital and operating costs of the plant are calculated with a payback time of 15 years. The plant would struggle to break even, even with revenue maximised through the sale of the electricity, heat and compost. This biogas plant would only be purchased with a major capital grant, or if the farmer had all the feedstock production equipment and an immediate use for the heat energy.

A more likely scenario is presented in the second commercial design which includes an additional feedstock which is the pig slurry already imported for rye-grass fertilisation. This model has a larger capital cost however the energy production is higher. The economic spreadsheet for this second model once again shows the importance of maximising revenue from the electricity, heat and compost with case B3 just breaking even. Appendix 11 shows the two commercial models side by side each with the three income scenarios, from which it is clear that it is more beneficial to co-digest the pig slurry with the ryegrass. The set up of this digester will allow the farmer to

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[13] Mortimer, Elsayed, and Horne, 2004, Energy and Greenhouse Gas Emissions for Bioethanol Production from Wheat Grain and Sugar Beet, Sheffield Hallam University.

[14] Mortimer, Cormack, Elsayed and Horne, 2003, Evaluation of the Comparative Energy, global Warming and Socio-economic Costs and Benefits of Biodiesel, Sheffield Hallam University.

import a variety of feedstocks, both liquid and solid. Co-digestion trials since the end of this research have indicated that grass is much easier to digest with other liquid feedstocks.

The energy balance for rye-grass (and alternative ley crops) to biogas is high, especially in comparison to bioethanol and biodiesel production. To make the most of a farm energy crop biogas plant a farmer should be advised to grow a variety of high yielding biomass crops which complement one another throughout the seasons. For example, maize could be fed to the digester through the autumn with potatoes through the winter months and grasses and grains in the spring and summer. This would reduce the need for storage and enhance the digestion process with a variety of bacteria digesting the different feedstock in turn creating a healthier digester compared to one that is fed a mono crop. Slurries and manures could also be incorporated within the feedstocks. This type of energy crop farming would help with the maintenance of the soil due to the crop rotations which would include nitrogen fixing crops such as red clover reducing the need for additions of nitrogen fertiliser.

The use of the biogas plant can be maximised by building a digester which allows for co-digestion with other materials including animal slurries, shown by the second commercial model. Waste is a huge issue, in particular bio-degradable waste, and biogas technology could play a huge part in reducing this ever increasing problem. Farmers may also gain financially by collecting gate fees for the imported material. Recent rises in oil prices have seen interest shift towards renewable sources of energy; for a biogas plant this could make the financial model look a lot more positive with an increase the demand for green electricity and heat, and a bio-fertiliser with a low energy input, demanding a lower price in comparison to mineral fertiliser which will increases in price in accordance with the cost of oil.

8. Conclusion

Referring back to the original objectives the following conclusions can be drawn;

- The maximum feasible methane yield recorded was $3800 m^3_{CH4}.ha^{-1}.y^{-1}$, (equivalent to $342 m^3_{CH4}.t^{-1}_{ODM}$) which when converted to electricity would produce 11.7MW.h.$ha^{-1}.y^{-1}$. (See appendix 5 for energy production details) These figures are based on the maximum grass ODM yield and the average methane yield for silage. This is lower than the original target yield of $4060\ m^3_{CH4}.ha^{-1}.y^{-1}$ which when converted to electricity would generate 14MWh.$ha^{-1}.y^{-1}$. This target figure was calculated using a ryegrass yield of $9.9 t_{ODM}.ha^{-1}$ with a methane yield of $410 m^3_{CH4}.t^{-1}_{ODM}$. As discussed in section 4 the original methane yield target was taken from a paper by Professor Weiland[15], which on closer inspection turns out to be a maximum figure recorded from 25 litre batch experiments which would not be feasible on a larger scale as they are capital and labour intensive. The digestion of ryegrass could be enhanced by the introduction of another feedstock, e.g. slurry, to co-digest with the ryegrass. This study has been proved that a grass system could be sustained but becomes a delicate biological environment and less versatile than a digester fed a variety of feedstocks.
- Grass harvested on a 2 and 4 week cycle have good C:N ratios for anaerobic digestion (18-23:1) compared to the plots harvested on a less frequent cycle of 6 -8 weeks (8-10:1). The ideal C:N ratio for anaerobic digestion is 15-30:1. Plots cut at a height of 100mm have a better C:N ratio than those cut at 50mm (see appendix 1). Visually it is clear that there is a higher lignin content in grass cut on an 8 week cycle than grass cut on a 2 week cycle. This indicates that biogas will be produced quicker from grass cut every 2 weeks due to the higher content of cellulose and small amount of ligneous material which takes a shorter time to break down than grass cut every 8 weeks.
- As a result of ensiling the grass it is possible to achieve a constant yield of biogas throughout the year. This research has shown that ensiled grass produces a higher average methane yield of $342\ m^3_{CH4}.t^{-1}_{ODM}$ compared to fresh grass with $229\ m^3_{CH4}.t^{-1}_{ODM}$. A possible explanation for this is that during the ensiling process the breakdown commences with the production of acids beneficial to the anaerobic digestion process.
- The energy and mass balance calculations can be seen in appendix 5 and are mapped out in diagrammatic form in appendix 6. The figures are based on the design of a commercial scale plant. The input is ryegrass from 100 hectares which it is assumed will yield $11.1\ t_{ODM}.ha^{-1}.y^{-1}$ based on this research. These process calculations also assume that the grass will yield $342\ m^3_{CH4}.t^{-1}_{ODM}$ also based on results from this research. The inputs

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[15] Weiland, P, Rieger, C, and Ehrmann, T,2002, Evaluation of the Newest Biogas Plants in Germany with Respect to Renewable Energy Production, Greenhouse Gas Reduction and Nutrient Management, Federal Agricultural Research Centre (FAL), Germany.

and outputs for this commercial scale plant based on the assumptions above are shown in

- The energy balance shown on page 39 shows the production of biogas using ryegrass to have a positive balance of 101.8GJ.ha^{-1}.y^{-1} with an energy ratio of 1:4.4. This compares well against the use of other crops to produce biogas, e.g red clover which has an energy balance of 107.8GJ.ha^{-1}.y^{-1} and an energy ratio of 1:4.5. A slightly different model based on the work of Mortimer et al, 2003 and 2004 was used to compare the use of winter wheat for biogas and bio-ethanol production and oilseed rape for the production of biodiesel. Table 22, page 40, shows the direct comparison of these technologies indicating that winter wheat for biogas production has both a high energy production of 68.48GJ.ha^{-1}.y^{-1} and a good energy ratio of 1:3. Both winter wheat used for the production of bioethanol and oilseed rape for the production of biodeisel show lower energy balances and ratios.

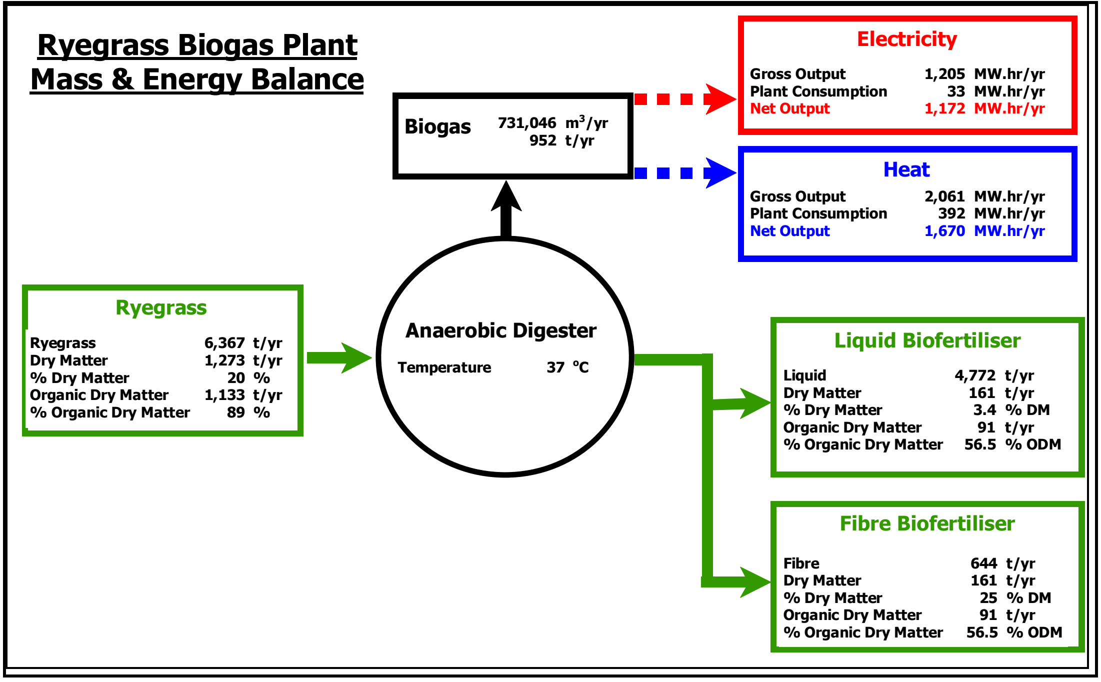

Figure 12: Ryegrass biogas plant mass & energy balance

- The design of a commercial biogas plant run on ryegrass and the inputs & outputs look attractive, however, the financial model shows that unless there is a large initial capital investment or the farmer already has all the major equipment for the feedstock production then it is unlikely that this investment would be made. The economic spreadsheet for a commercial ryegrass plant shows that the plant would struggle to break even, even with the sale of electricity, heat and compost. The second commercial scale model includes grass and pig slurry as co-digesting feedstock. The pig slurry is primarily imported as an additional fertiliser for the ryegrass production. The economic spreadsheet for this model is much more positive but it is still clear that the sales of electricity, heat and compost are vital to the financial stability of the plant. There will be an increase in the capital cost of this second plant; this will make it equipped to take in a variety of feedstock, both liquid and solid. If other waste is imported a gate fee could be commanded creating another income for the plant. The commercial digester design can easily accommodate a wide range of feedstock including animal by products with the addition of a pasteurisation unit.

- This project has provided very firm grounding for Greenfinch's current research within Cropgen, a European consortium investigating the production of biogas using agri wastes and energy crops. In Germany, at the time of writing, there are 3,000 farm biogas plants being run on crops and agri wastes proving that biogas technology is viable. The reform of the Common Agricultural Policy forcing farmers to grow crops that have real monitory value, combined with the continuing rise in the price of oil, will make anaerobic digestion a real option for energy production.

Glossery

DM	dry matter
ODM	organic dry matter
CH_4	Methane
CO_2	Carbon Dioxide
H_2S	Hydrogen Sulphide
N	Nitrogen
C	Carbon
P	Phosphorous
K	Potassium
P_2O_5	Phosphate
K_2O	Potash
MgO	Magnesium Oxide
CHP	Combined Heat & Power
TS	total solids
VS	volatile solids
$kg.ha^{-1}.y^{-1}$	kilograms per hectare per year
$kg.t^{-1}$	kilogram per tonne
$kg.m^{-3}$	kilogram per cubic metre
$kg.ha^{-1}$	kilogram per hectare
$kg_{DM}.kg^{-1}{}_{N}$	kilograms of dry matter per kilogram of nitrogen
$t_{DM}.ha^{-1}$	tonnes of dry matter per hectare
$t_{DM}.ha^{-1}.y^{-1}$	tonnes of dry matter per hectare per year
$t_{ODM}.ha^{-1}.y^{-1}$	tonnes of organic dry matter per hectare per year
$m^3{}_{CH4}.t^{-1}{}_{ODM}$	cubic metres of methane per tonne of organic dry matter
$m^3{}_{CH4}.ha^{-1}.y^{-1}$	cubic metres of methane per hectare per year
MW.h	megawatt hours
$MW_e.h$	megawatt (electricity) hours
$MW_{th}.h$	megawatt (thermal) hours
$kW_e.h$	kilowatt (electricity) hours
$kW_{th}.h$	kilowatt (thermal) hours
$MW_e.h.ha^{-1}.y^{-1}$	megawatt (electricity) hours per hectare per year
$GJ.ha^{-1}.y^{-1}$	giga joules per hectare per year