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D19: An overall energy balance for energy production taking into account energy inputs associated with farming

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PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
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D19: An overall energy balance for energy production taking into account energy inputs associated with farming

Introduction

Fossil fuels are considered as non-renewable energy sources due the extremely extended periods over which the fuels are produced. They also act as sources of CO_2, releasing gas which has been stored over these long periods. 'Renewable' energy sources provide alternatives to the use of fossil fuels. All forms of energy require some form of production and conversion, either in terms of the material which is used as the source of the energy or energy used in the conversion processes. For a 'renewable' energy source to be sustainable the energy required in production must be less than the energy produced.

An outline of the method for determining energy requirements, deficits and surpluses, is given in deliverable **D18**. This deliverable presents the results of application of this method to a range of crop based anaerobic digestion processes and energy production. It also contains information from a case study conducted by IFA-Tulln at the Rohkraft biogas plant in Austria. A further case study involving a full scale plant is contained in deliverable **D22** 'Energy balance optimisation for an integrated arable/livestock farm unit'.

An example of the energy flows for energy production via combined heat and power (CHP) using the digestate as bio-fertiliser, derived in deliverable **D18**, is shown in Figure 1.

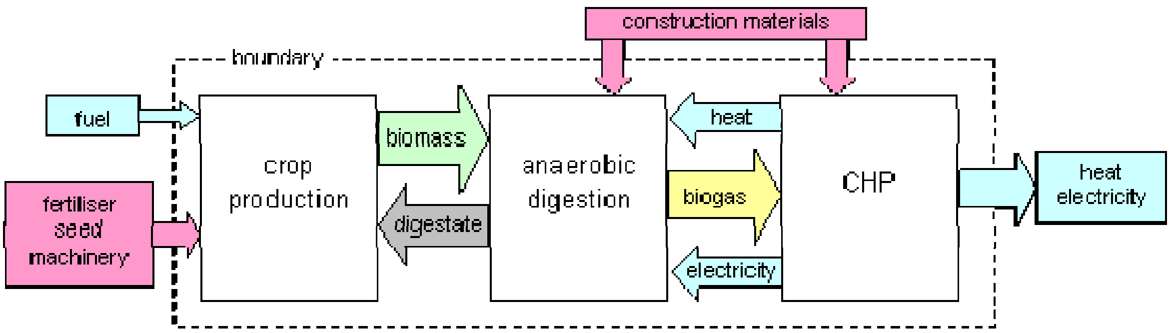


Figure 1: Outline of energy flows for an energy production route using crop based anaerobic digestion

There is no definitive energy balance, the energy deficits and surpluses will vary according to crop yield, climate, digester design and operation, type and efficiency of CHP unit etc. The figures given here will therefore be based on a number of stated assumptions but can be used to compare strategies for energy production and use.

1. Digester is based on a two stage fermenter system using concrete tanks. Total capacity = 3,800 m^3. Embodied energy = 33,753 GJ
2. Life expectancy of the digester = 20 years
3. UK climate
4. CH_4 calorific value = 35.7 MJ/m^3
5. For perennial crops, crop production requirement is averaged over number of years of crop.
6. Digester loading is assumed to be 3kg $VS/m^3/day$
7. Feedstock is assumed to be single substrate, energy crop
8. For crop transport it is assumed that the crop is grown in a circular area around the digester but 30% of this area is unsuitable for energy crop production.

The six scenarios outlined in deliverable **D18** were:

1. crop production using mineral fertiliser, all energy for AD unit imported, biogas exported.
2. crop production using mineral fertiliser, biogas used in CHP, heat and electricity from CHP used for AD plant, electricity exported.
3. crop production using mineral fertiliser, biogas used in CHP, heat and electricity from CHP used for AD plant, biogas exported as vehicle fuel.
4. as scenario 1 but digestate used as fertiliser.
5. as scenario 2 but digestate used as fertiliser.
6. as scenario 3 but digestate used as fertiliser.

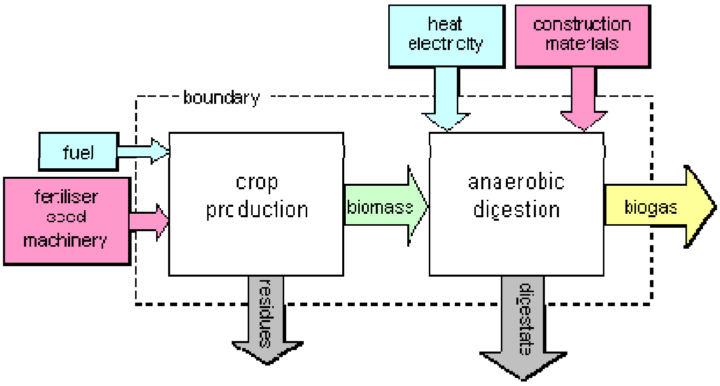
The overall energy balance is given as the total amount of surplus energy from the system and is also expressed as an energy ratio. These are expressed in terms of the assumptions listed above.
energy balance = $E_{out} – E_{in}$
energy ratio = E_{out} / E_{in}

Energy going into the system will vary according to the scenario but will include as a minimum:
$E_{in} = E_{crop\ production} + E_{crop\ transport} + E_{digester\ embodied} + E_{digestate\ disposal}$

E_{out} is the energy value of the fuel produced.

Scenario 1.

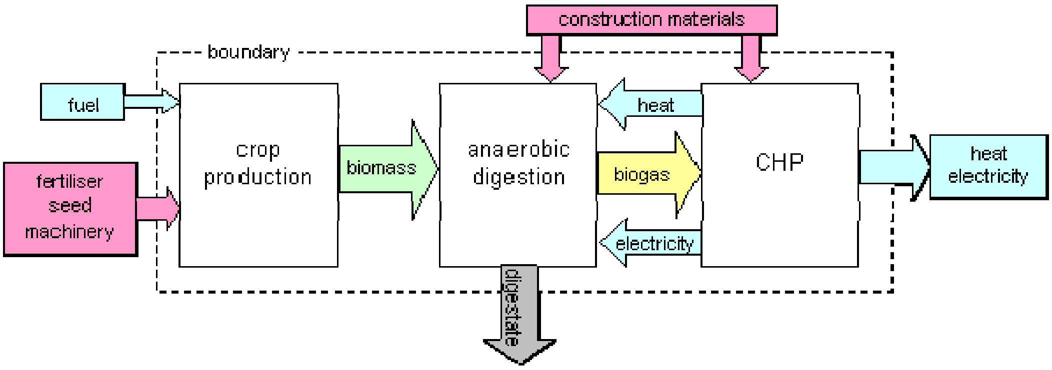
Crop production using mineral fertiliser, all energy imported, biogas exported, digestate transported off site. Note for imported energy electricity is assumed to have a primary:delivered ratio of 3.08 (Howard *et al.*, 1999). Heat is assumed to be supplied by burning natural gas in a boiler. (Primary:delivered 1.11 at 85% efficiency).
The energy output is assumed to be the net calorific value (low heat value) of the biogas.



crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
fertiliser	kg N/ha	160	180	180	140	0	170	220	60
area of crop required	ha	492	518	522	530	1417	827	720	717
crop production	GJ/yr	7429	8133	8874	7950	11619	15878	12600	8963
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester parasitic energy	GJ/yr	7314	7314	12702	7040	12881	10381	9668	10118
digester embodied energy	GJ/yr	1687	1687	1687	1687	1687	1687	1687	1687
digestate disposal	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**GJ/yr**	**17.8**	**18.5**	**25.5**	**18.0**	**29.7**	**30.3**	**26.1**	**22.8**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
total surplus	**TJ/yr**	**69.3**	**69.3**	**63.4**	**59.4**	**63.4**	**69.3**	**67.3**	**67.3**
energy balance	**TJ/yr**	**51.5**	**50.8**	**37.9**	**41.4**	**33.7**	**39.0**	**41.3**	**44.6**
energy ratio (out/in)		**3.9**	**3.7**	**2.5**	**3.3**	**2.1**	**2.3**	**2.6**	**3.0**

Scenario 2

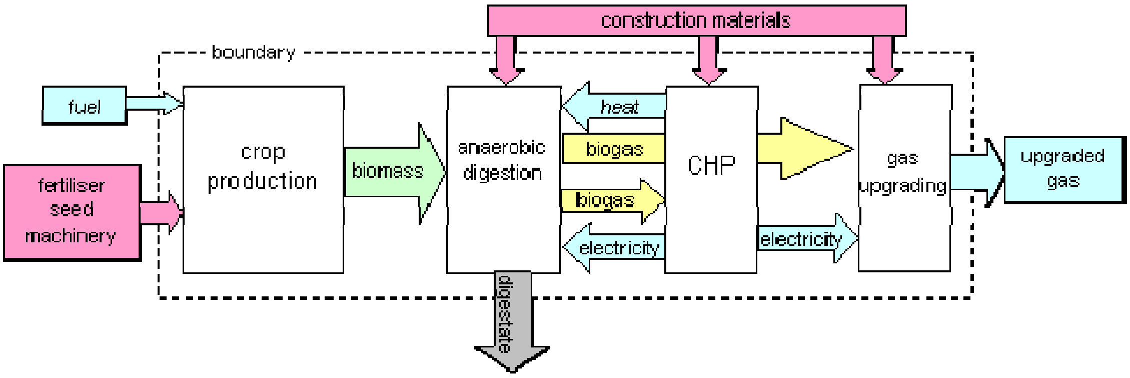
This scenario is the same as scenario except that the biogas is used in a CHP unit on site to generate heat and electricity. The unit is assumed to be 30% efficient at generating electricity and 50% efficient for heat. All parasitic demands are met by the CHP unit. Note that in some cases the energy ratio for electricity exported is less than one. This should be compared to the value for primary energy ratio for electricity, which was 0.32 for the UK in 1996 (Howard *et al.*, 1999).



crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
fertiliser	kg N/ha	160	180	180	140	0	170	220	60
area of crop required	ha	492	518	522	530	1417	827	720	717
crop production	GJ/yr	7429	8133	8874	7950	11619	15878	12600	8963
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester embodied energy	GJ/yr	2109	2109	2109	2109	2109	2109	2109	2109
digestate disposal	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**TJ/yr**	**10.9**	**11.7**	**13.2**	**11.4**	**17.2**	**20.3**	**16.8**	**13.1**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
CHP generated									
Electricity	TJ/yr	20.8	20.8	19.0	17.8	19.0	20.8	20.2	20.2
Heat	TJ/yr	34.7	34.7	31.7	29.7	31.7	34.7	33.7	33.7
digester parasitic energy	TJ/yr	4.7	4.7	7.8	4.5	7.9	6.5	6.1	6.3
surplus									
electricity	TJ/yr	20.1	20.1	17.6	17.2	17.6	19.7	19.2	19.2
	MWh/yr	5597	5597	4899	4782	4892	5481	5343	5326
heat	TJ/yr	30.6	30.6	25.2	25.8	25.2	29.2	28.6	28.4
	MWh/yr	8501	8501	7011	7160	6989	8123	7936	7880
energy balance	**TJ/yr**	**39.9**	**39.1**	**29.7**	**31.6**	**25.5**	**28.7**	**31.0**	**34.5**
energy ratio (out/in)		**4.7**	**4.4**	**3.2**	**3.8**	**2.5**	**2.4**	**2.8**	**3.6**
energy ratio electricity only		1.8	1.7	1.3	1.5	1.0	1.0	1.1	1.5

Scenario 3

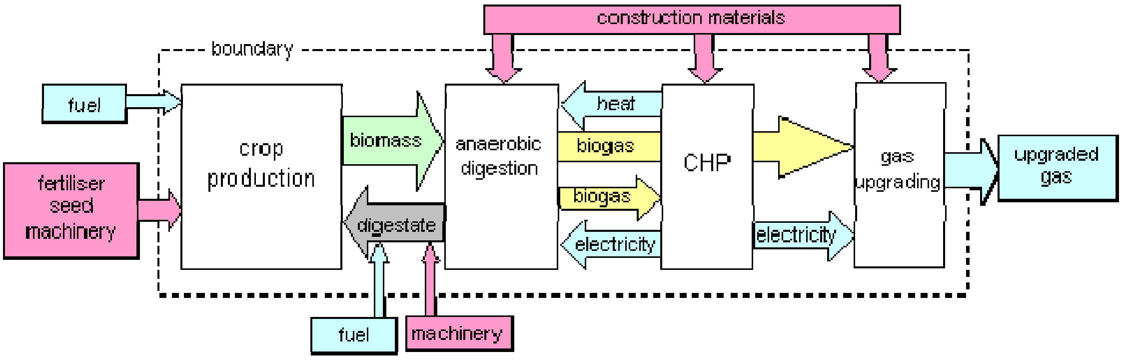
In this scenario energy is exported as CH_4 enriched biogas suitable for vehicle fuel (including compression). All electrical and heat energy required is produced using an on-site CHP unit. Energy required for upgrading and compression is assumed to be 1.8MJ/m^3 upgraded biogas.



crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
crop production	GJ/yr	7429	8133	8874	7950	11619	15878	12600	8963
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester embodied energy	GJ/yr	2109	2109	2109	2109	2109	2109	2109	2109
digestate disposal	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**TJ/yr**	**11.5**	**12.5**	**15.4**	**11.4**	**17.2**	**20.3**	**16.8**	**13.1**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
CH_4 required for CHP	10^6 m^3/yr	0.38	0.38	0.41	0.33	0.41	0.41	0.39	0.40
surplus									
CH_4 in upgraded biogas	10^6 m^3/yr	1.57	1.57	1.37	1.34	1.37	1.53	1.49	1.49
energy value	TJ/yr	55.9	55.9	48.9	47.7	48.8	54.7	53.3	53.2
energy balance	**TJ/yr**	**44.3**	**43.3**	**33.5**	**36.3**	**31.7**	**34.4**	**36.5**	**40.1**
energy ratio (out/in)		**4.8**	**4.5**	**3.2**	**4.2**	**2.8**	**2.7**	**3.2**	**4.1**
energy in diesel equivalent	10^6 l/yr	1.56	1.56	1.37	1.33	1.36	1.53	1.49	1.49

Scenarios 4, 5 and 6 repeat those of 1,2 and 3 with the difference that the digestate is used to replace some of the mineral fertiliser. The digestate will be assumed to have a nitrogen content of 3.5 kg/tonne. Further details of nutrient content of digestate can be found in the report for Cropgen work package **WP4**. In most cases the nitrogen contained in the digestate will be insufficient to replace all of that required by the crop so some mineral fertiliser will also be required. The amount required is determined by assuming that all of the digestate is returned to the crop and only the mineral fertiliser required to make up the difference in nitrogen is applied.

Scenario 4



crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
digestate	t/ha	34	32.3	74.8	30.2	28.1	35.4	36.8	39.5
area of crop required	ha	492	518	522	530	1417	827	720	717
crop production	GJ/yr	4231	4662	5377	4664	9636	9841	7128	5808
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester parasitic energy	GJ/yr	7314	7314	12702	7040	12881	10381	9668	10118
digester embodied energy	GJ/yr	1687	1687	1687	1687	1687	1687	1687	1687
digestate transport & spreading	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**GJ/yr**	**14.4**	**14.9**	**21.8**	**14.6**	**27.7**	**24.1**	**20.4**	**19.6**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
total surplus	**TJ/yr**	**69.3**	**69.3**	**63.4**	**59.4**	**63.4**	**69.3**	**67.3**	**67.3**
energy balance	**TJ/yr**	**54.9**	**54.4**	**41.6**	**44.8**	**35.7**	**45.2**	**47.0**	**47.8**
energy ratio (out/in)		**4.8**	**4.7**	**2.9**	**4.1**	**2.3**	**2.9**	**3.3**	**3.4**

Scenario 5

crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
digestate	t/ha	34	32.3	74.8	30.2	28.1	35.4	36.8	39.5
area of crop required	ha	492	518	522	530	1417	827	720	717
crop production	GJ/yr	4231	4662	5377	4664	9636	9841	7128	5808
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester embodied energy	GJ/yr	2109	2109	2109	2109	2109	2109	2109	2109
digestate transport & spreading	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**TJ/yr**	**7.5**	**8.0**	**9.5**	**8.0**	**15.2**	**14.1**	**11.1**	**9.9**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
CHP generated									
Electricity	TJ/yr	20.8	20.8	19.0	17.8	19.0	20.8	20.2	20.2
Heat	TJ/yr	34.7	34.7	31.7	29.7	31.7	34.7	33.7	33.7
digester parasitic energy	TJ/yr	4.7	4.7	7.8	4.5	7.9	6.5	6.1	6.3
surplus									
electricity	TJ/yr	20.1	20.1	17.6	17.2	17.6	19.7	19.2	19.2
	MWh/yr	5597	5597	4899	4782	4892	5481	5343	5326
heat	TJ/yr	30.6	30.6	25.2	25.8	25.2	29.2	28.6	28.4
	MWh/yr	8501	8501	7011	7160	6989	8123	7936	7880
energy balance	**TJ/yr**	**43.2**	**42.8**	**33.3**	**35.0**	**27.5**	**34.9**	**36.7**	**37.7**
energy ratio (out/in)		**6.7**	**6.3**	**4.5**	**5.4**	**2.8**	**3.5**	**4.3**	**4.8**
energy ratio electricity only		2.7	2.5	1.8	2.2	1.2	1.4	1.7	1.9

Scenario 6

crop		maize	whole crop triticale	fodder beet	sunflower	lupin	perennial ryegrass	timothy grass	lucerne
crop production	GJ/yr	4231	4662	5377	4664	9636	9841	7128	5808
crop transport	GJ/yr	274	282	525	274	952	552	471	493
digester embodied energy	GJ/yr	2109	2109	2109	2109	2109	2109	2109	2109
digestate transport & spreading	GJ/yr	430	432	1009	414	1126	786	701	749
total deficit	**TJ/yr**	**7.0**	**7.5**	**9.0**	**7.5**	**13.8**	**13.3**	**10.4**	**9.2**
CH_4 (in biogas)	10^6 m^3/yr	1.94	1.94	1.78	1.66	1.78	1.94	1.89	1.89
CH_4 required for CHP	10^6 m^3/yr	0.38	0.38	0.41	0.33	0.41	0.41	0.39	0.40
surplus									
CH_4 in upgraded biogas	10^6 m^3/yr	1.57	1.57	1.37	1.34	1.37	1.53	1.49	1.49
energy value	TJ/yr	55.9	55.9	48.9	47.7	48.8	54.7	53.3	53.2
energy balance	**TJ/yr**	**48.8**	**48.4**	**39.9**	**40.3**	**35.0**	**41.4**	**42.9**	**44.0**
energy ratio (out/in)		**7.9**	**7.5**	**5.4**	**6.4**	**3.5**	**4.1**	**5.1**	**5.8**
energy in diesel equivalent	10^6 l/yr	1.56	1.56	1.37	1.33	1.36	1.53	1.49	1.49

A graph of the relative energy ratios is shown in Figure 2.

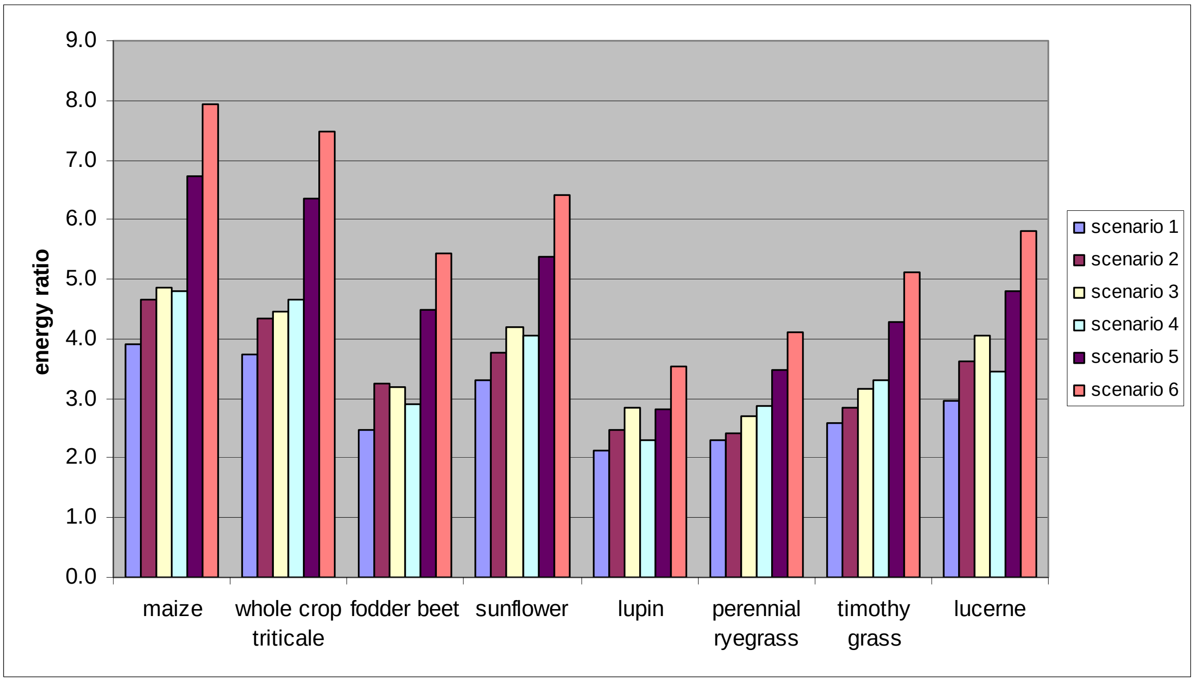


Figure 2: Energy ratios for different crops and scenarios

A chart of the surplus energy produced per hectare is shown in Figure 3. In this representation the best scenarios are 1 and 4 but it should be remembered these are for biogas only; some form of post production processing will be required to use the energy in the biogas.

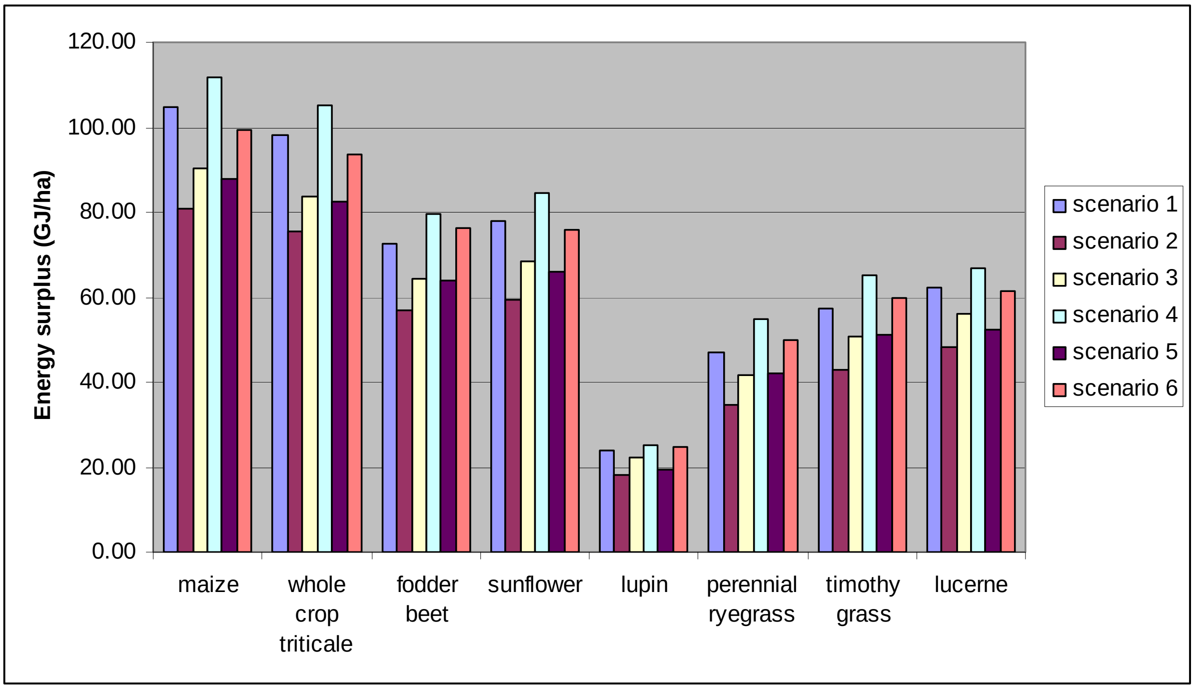


Figure 3: Energy surplus per hectare of crop for various scenarios and crops

Case study: Rohkraft Biogas Plant

The Rohkraft biogas plant is situated in an agricultural area in Lower Austria next to a small village called Reidling. It was started in December 2003 as a two stage continuous stirred tank reactor system with a main digester volume of 2000 m^3, a second digester step of 1850 m^3 and open storage tanks with a volume of 3800 m^3. All digesters are built from concrete. The storage of the solid substrates is realised in four open storage silos from concrete with a total capacity of 15000 m^3. All leachates of the silages are collected and discharged into the manure storage tank (135 m^3). The substrates applied are pig manure (30 %) and solid energy crops (70 %) like maize and residues from vegetable processing. Except for the pig manure, which is supplied by the own pig breeding, all substrates are acquired from farmers from the region. The same farmers collect the digestate of the plant to use it as fertilizer on their agricultural areas. The feed dosage is executed automatically 24 times per day. All input weights are recorded. The average process temperature is 39 °C. The removal of H_2S out of the biogas is achieved by air dosage into the digester headroom, the removal of the steam water by using a fixed bed. Biogas quantity and quality are analysed online, based on infrared (flow rate, CH_4 and CO_2) and electrochemical cells (O_2 and H_2S). Biogas is used to generate electrical current and heat in two combined heat and power units (CHP) with an electrical capacity of 500 kW and a thermal capacity of 517 kW each (GE Jenbacher, Austria). Electricity is fed into the national grid and heat is mainly used for a local heat supply in the neighbouring village of Reidling. After one year of operation, a second process line was set up, characterised by the dosage of substrates directly into the second digester and a second combined heat and power unit with the same capacity as the first one. These modifications resulted after two months of adaptation in a total electrical capacity of 1 MW and a thermal capacity of 1034 kW. The hydraulic retention time reduced from 132 days to 77,2 days due to the upgrading. The mean organic loading increased to 4,4 kg VS/m^3 reactor per day.

The Reidling biogas plant shows that the co-digestion of manure, residuals of food processing and energy crops in continuous stirred reactor systems is an effective and robust way for the production of biogas. Especially in agricultural areas this systems are very attractive, since the local production of energy is an promising source of income for the farmers and the whole region as alternative to the price decline of agricultural products in Europe. However, in plants like this, that are working with a high percentage of energy crops, the energy generation costs strongly depend on the market prices for the agricultural substrates. The experiences of the first years show, that it is possible to achieve a degree of efficiency, due to a good process control which is comparable to industrial processing. Still it is important to use both, electricity and heat as it is shown in the present plant.

Table 1: Energy balance for the Rohkraft biogas plant

	12/2005
Input energy crops:	11000 t/year
Input manure + leachates:	7300 t/year
Biogas production:	4.02 Mio m^3/year
Production of electrical energy:	8030 MWh/year
Production of thermal energy:	8223 MWh/year
Own electrical consumption:	562 MWh/year
Own thermal consumption:	50 MWh/year
Thermal consumption pig breeding:	1000 MWh/year

Conclusion

The energy balances shown here are indicators. Specific energy balances will be dependent on many variables and each digester set up will be different. Energy balance will be affected by digester design which affects heat loss and electrical requirement. Crop yield affects the amount of energy available per hectare of land used and is itself affected by climate, soil conditions and growth stage of the crop at harvest. For example, using the criteria for scenario 6 using whole crop triticale, change in the methane potential will affect the energy ratio as shown in Table 2. This effect is also reported in deliverable **D22** where the ratio varied from 5.5 to 6.3 according to growth stage at time of harvest.

Table 2: Effect of methane potential on energy ratio

methane potential m^3/kg VS added	energy ratio
0.32	6.9
0.34	7.4
0.36	7.8
0.38	8.3

Where the biogas is used in CHP (scenarios 2 and 5) the energy ratio is considerably enhanced through use of the heat produced both for heating the digester where required and exported to local industry or domestic dwellings.

High yield of fresh matter of a crop is not necessarily an indicator of high biogas yield or energy ratio. For example fodder beet has twice the fresh matter yield of most other crops but has a low total solids content so produces proportionally less biogas per tonne of fresh matter. Leguminous crops have lower energy requirements for fertiliser as part of the crop production but in the case of lupins have low total solids yield and Lucerne requires multiple harvests per year which leads to higher energy requirement than single harvest crops such as maize. Using digestate as fertiliser improves the efficiency of the system for all the crops.

In all cases shown here the energy ratio is greater than one so the process is sustainable and can lead to a reduction in the use of fossil fuels.

References

Howard, N., Edwards, S. & Anderson, J. (1999) BRE Methodology for Environmental Profiles of Construction Materials, Components and Buildings. London, DETR.