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D30b: Assessment of the potential for crop-derived biogas as an energy source in the EU, taking into account technical and environmental issues and socio-economic impact

1. Introduction

In 2004 the EU25 had a final energy consumption equivalent to 1,140,880 thousand tonnes oil equivalent including 488,069 thousand toe of petroleum products and 268,067 thousand toe of natural gas. The consumption of this energy led to the release of 4063 million tonnes of CO₂ and 19,257 thousand tonnes of CH₄ (European Commission, 2006). Recent moves to reduce the amount of fossil fuels used and thereby mitigate the amount of CO₂ released into the atmosphere through the use of 'renewable' energy have included 'technical' processes - for example wind and wave turbines, photovoltaics and nuclear; and 'green' processes based on the use of plant materials. These plant based processes have included the development of woods and grasses for combustion and increased use of crops for the production of liquid fuels such as bio-ethanol and bio-diesel. Anaerobic digestion can also be used to provide energy in the form of biogas which contains a substantial amount of methane. Whereas anaerobic digestion has previously been seen as a method of waste processing for human and animal wastes and municipal solids waste (MSW) it can also be used to process organic materials directly.

Feedstock for the digester can be in the form of plant material and the remains of processed plant materials that form agricultural wastes, therefore providing an alternative way of producing energy from crops. The advantages of anaerobic digestion are many and relate both to the wide range of materials that can be used as feedstocks and the flexibility of use of the products. The anaerobic digestion process results in two products: the biogas – consisting mainly of CH₄ and CO₂, and the digestate which contains the remainder of the material not converted into biogas. The digestate can be returned to the soil as a form of organic fertiliser providing an enhanced source of nutrients for plant growth and carbon capture as the organic remains are incorporated into soil and plants. Finally, the AD process is highly efficient in converting the plant material into energy and it is possible to operate the digester so that no fossil fuels are required, thereby achieving a condition in which any CO₂ generated comes only from the plant material used in the digester.

This report considers the potential for crop-derived biogas to act as an energy source and how it compares to other crop based bio-fuels. It examines the range of crops that can be used as feedstocks and how the amount of energy produced which is produced per hectare of crop grown is affected by the yield of that crop and the biochemical methane potential (BMP) of the digested material. A renewable energy source can only be effective if the energy value of the fuel produced is greater than the energy required to produce it. This report therefore examines the energy balances for anaerobic digestion using crop materials and shows that it is an energy efficient process and is up to six times more efficient than the currently utilised solvent extraction method for production of bio-diesel (Elsayed *et al.*, 2003). The report examines the potential of anaerobic digestion to supply energy for the EU member states and its potential to fulfil the various energy markets: road fuel, electricity, and heat by providing an alternative source of this energy which could replace oil, coal and natural gas.

2. Potential crop production

The amount of biogas that can be produced from any area of crop is dependent on two factors:

1. The yield of the crop.
2. The potential biogas yield per kg of volatile solids.

The amount of a crop which can be harvested from a hectare of land is dependent on a number of factors including type of crop, growth stage at time of harvest, and environmental factors which affect how well the crop grows.

The type of crop that can be grown and the potential yield varies considerably according to climate. Some crops have a maximum northerly location beyond which they grow only poorly and as locations progress towards the south there is an increase in the requirement for irrigation to make up the required water examples of variations in crop yields are shown in Table 1 and Figure 1. There are also changes in the length of the growing season so that in countries such as Finland crops must be chosen which have a short growing season and can be planted in late spring or have a good tolerance to snow cover and low temperatures. Climate changes are already having an effect on crop selection as Southern countries become drier and Northern countries warmer, the growing season in Finland is now 2 weeks longer than 15 years ago (Rintala, J 2007, pers comm., 12 April).

Table 1: Example crop yields for various EU states

country	winter wheat seed	sugar beet	field beans	Lucerne	green maize fodder
Finland	3.38	35.5	0.3		
Austria	5.32	62.4	3.49	7.2	42.1
United Kingdom	7.8	47	3.54	14	35
Spain	2.3	63.2	1.44	13.4	47.5
Italy	4.46	44.5	1.55	7.9	53.8

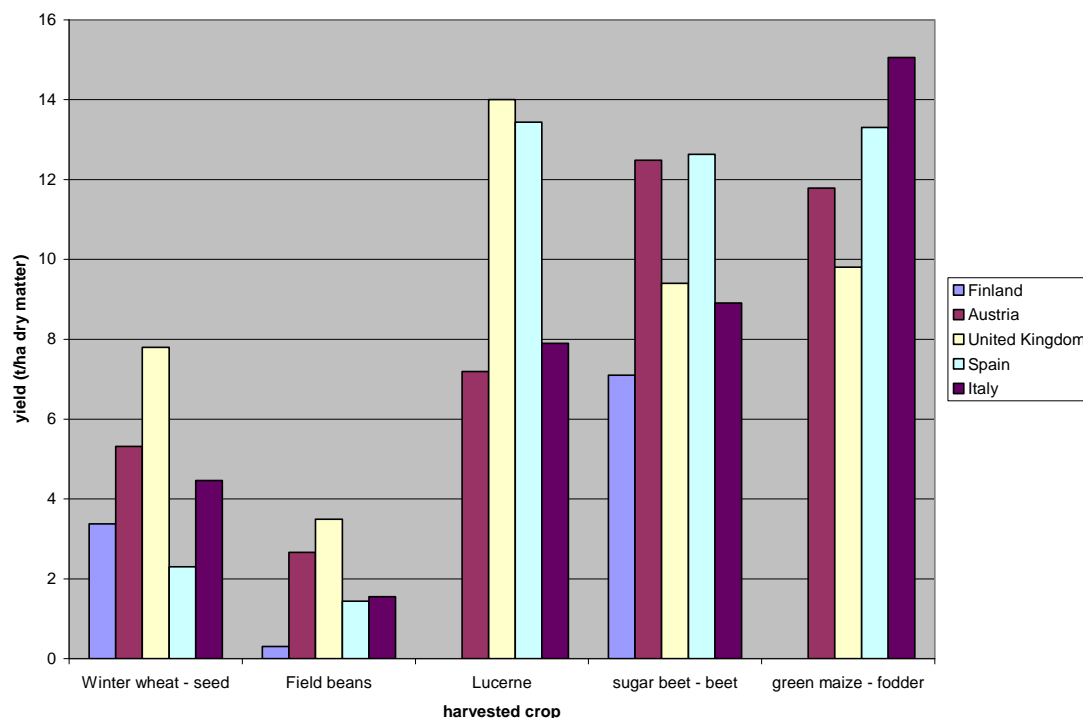


Figure 1: Reported crop yields in various EU states (FAO, 2007)

Growth stage at time of harvest has an effect through the moisture content of the material and chemical composition. As most crops develop they pass through a stage of maximum biomass and then dry out towards grain development. As this occurs the composition of materials in the plant changes, usually towards increase in lignin content as the stems of the plant become more 'woody' and a change in the grain content from sugars towards starch. In some crops such as oil seeds and some cereals such as oats there is an increase in oil content of the material. As the material becomes drier there is likely to be a decrease in biomass as leaves and stem material become dry and lost. At full maturity many plants will start to loose grains and seed. Crops which are usually grown as seed crops can also provide material for AD but would be harvested at the maximum biomass stage rather than the usual harvest.

Compared to other bio-fuels, for example bio-ethanol and bio-diesel which require a limited range of crop species there is, therefore, no single choice of crop which will provide the best source of material throughout the EU. Farmers can choose the crops which grow best in their climate on their particular soil type and fit in with their type of farming.

The crops which have so far been selected for use in the production of energy from AD are mainly those which have been used for animal production – the forage crops. These are crops which have been grown and bred to produce high yields with good digestibility in animals and include maize, grasses, and whole crop cereals. The crops can be harvested during the periods of maximum growth and stored using existing techniques often in the form of ensiling. The effects of storing the materials in this way using different additives and techniques on gas production have been investigated in Cropgen work package 3.

There are a number of advantages in the use of existing forage crops:

- Good breeding programmes exist to increase yield.
- Farmers already have experience in growing these crops.
- Existing machinery and storage facilities can be used.
- There is no major change to the appearance of the environment.
- Crops can be included in current farming practices including rotations.

The potential biogas yield of the crop can be determined using laboratory testing, as reported in WP2. A wide variety of plant materials have been tested for their potential biogas and methane production and the range of potential methane production values reported in the literature are shown in Figure 2. The bar indicates the average of the values reported, the error bars give the range. The range of values results from the wide range of techniques and growth stages used in the various analyses.

The figure shows a wide range of the reported values, even for the same crop and this is due to variations in the testing and reporting methods and also due to the nature of the material harvested. As crops grow and mature the composition of the material changes as does the effect on potential biogas production. The effects of harvest time and changes in crop composition on specific methane potential and overall biogas yields have been reported by Heiermann *et al.* (2002) and Amon *et al.* (2006). The specific methane yield depends on the growth stage at which the crop is harvested, which in turn affects the potential yield of the crop. Some crops which are grown for energy production e.g. short rotation coppice (SRC) usually Willow or Poplar cannot be used for AD due to their high lignin contents when harvested at the usual growth stages.

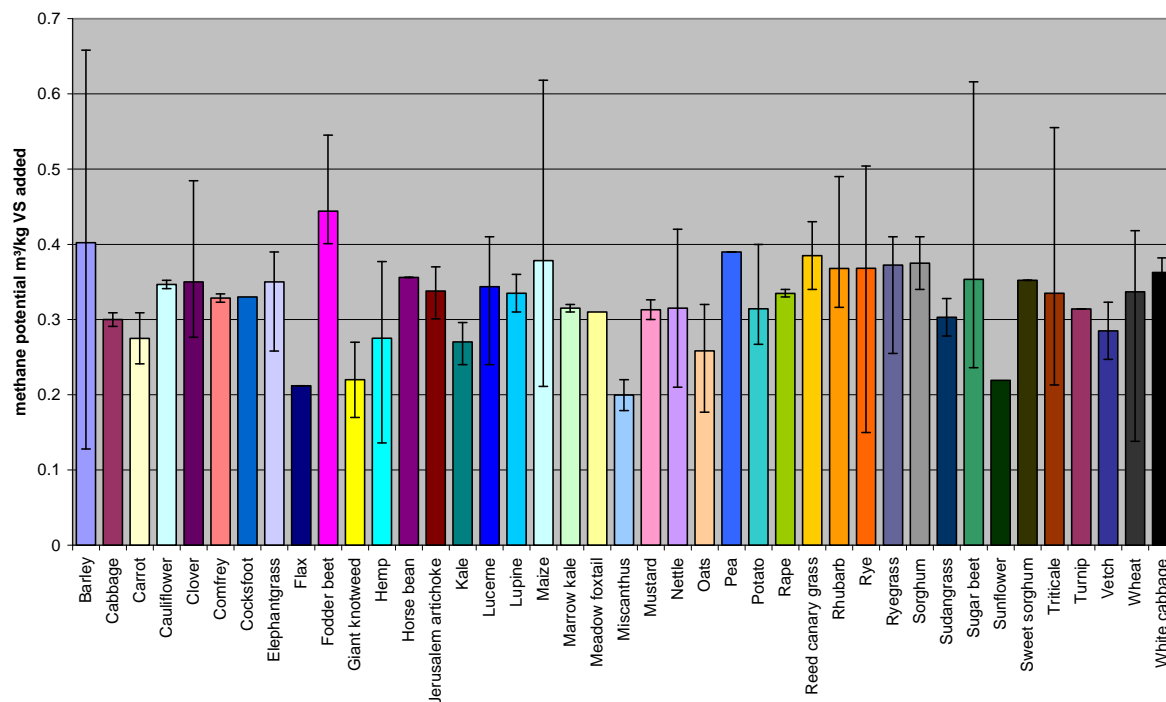


Figure 2: Comparison of reported values for potential methane production from different crops

3. Technical issues

Renewable energy fuels, that is those produced using renewable resources only have value if the energy value of the fuel produced is greater than the energy required. A number of studies have been conducted which examine the energy requirements for bio-fuels including bio-diesel, bio-ethanol and wood fuels (Richards, 2000, Mortimer *et al.*, 2003, Kim and Dale, 2005, Kallivroussis *et al.*, 2002, Janulis, 2004, Hill *et al.*, 2006).

In order to determine an energy balance it is necessary to conduct a life cycle assessment (Russell *et al.*, 2005). This enables the various energy inputs and outputs to the production of the bio-fuel to be examined and an overall energy efficiency can be determined once the boundaries for the assessment are set. The energy requirements for production and processing of the biomass crop can be divided into two types: the direct use of fuels (direct energy), and the use of materials that required energy in their construction or manufacture (indirect energy). Examples of direct fuel usage include tractor fuel, process heat and power. Examples of indirect energy requirements include fertilisers and equipment used in cultivation and processing.

In keeping with previous research on energy balances for agricultural systems, the solar energy input is ignored as the purpose is to consider a comparison of the fossil fuel requirement for production of different bio-fuel types.

The stages involved in an energy from crop system, with the associated energy inputs, are shown in Fig. 1, adapted from Jones (1989). This model is applicable to any of the bio-fuel production systems which use crops as input.

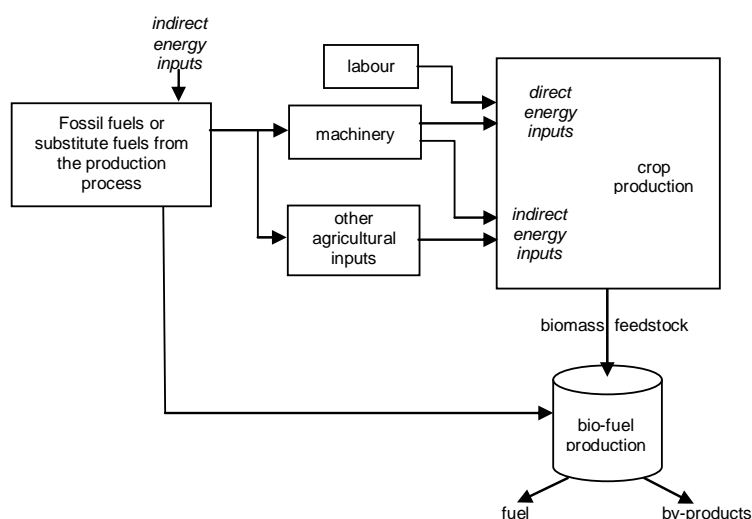


Figure 3: Energy flows in a crop based bio-fuel production system

It is also possible, knowing the energy requirements for each stage of the process, to determine the CO₂ production associated with the fuel production. Production of CO₂ from the consumption of various fossil fuels have been determined as have those for the production of electricity for example Howard *et al.* (1999). The amount of energy used in the extraction, production and processing of various materials has been determined e.g. Alcorn (1996), Buchanan and Honey (1994), Venkatarama Reddy and Jagadish (2003). From these, the CO₂ requirement can be determined.

Thus for a biogas production system based on crops an energy balance can be determined from four stages:

1. Energy required for crop production.
2. Energy for the anaerobic digestion process.
3. Energy for transport of the crop to the digester and of the digestate from the digester.
4. Energy for further fuel processing.

3.1 Energy required for crop production

Using data reported in the literature (Bowers, 1993, Dalgaard et al., 2001, Hülsbergen et al., 2001, Hülsbergen and Kalk, 2001, Leach, 1976, KTBL, 2002, Richards, 2000, Tzilivakis et al., 2005) and a known set of operations for the production of a crop, it is possible to determine an average energy requirement for the production of that crop. Examples of the calculation of these energy balances were developed in deliverable **D25**. Some examples of the energy balances for annual crops are shown in Table 2.

Table 2: Energy balances for annual crops

crop	sowing period	operations per year	energy requirement (GJ/ha)			total	yield (tFM/ha)
			indirect	fuel (l/ha)	fertiliser & sprays		
maize	spring	a,b,e,g,2h,j,k,l	1.92	2.78 (71)	11.8	16.7	40
wheat	winter	b,e,f,g,2h,j,k,l	1.84	2.26 (57)	12.7	17.0	36.5
fodder beet	spring	b,2c,g,d,2h,j,k,l,m,k	3.76	3.38 (86)	14.4	21.8	80
triticale	winter	b,e,f,g,2h,j,k,l	1.84	2.26 (57)	11.6	16.0	38

a:subsoiler, b:plough, c:seedbed cultivations, d:drill, e:drill/harrow, f:roll, g:fertiliser application, h:pesticide application, j:forage harvester, k:cart, l:ensile

The energy balance is derived from the direct energy required - diesel fuel and labour, and the indirect energy. Indirect energy is calculated for the equipment used and for production of the fertilisers and sprays applied to the crop. For the equipment this includes construction (which includes extraction and processing of the raw materials), maintenance, repair and delivery which can be calculated based on weight of equipment and number of hours or hectare over which it is used (Bowers, 1993). The energy value for labour requirement can also be calculated (Leach, 1976) although in the mechanistic environment of European farming this now makes up a very small percentage of the energy requirement.

Forage maize is an example of an annual crop, it is sown and harvested within a 12 month period. Annual crops are subdivided into winter varieties- sown in the autumn and allowed to grow through the winter before being harvested usually in late summer, and spring varieties- sown in the spring and harvested before the winter. Winter sown varieties tend to have a higher yield potential than spring varieties due to the longer growing period but also require a vernalisation period, a period of cold weather which stimulates growth and flowering in the spring. Annual species of crops include wheat, barley, triticale, sugar and fodder beets, beans, soya and oilseed rape. The alternative to annual species are the perennial species of plant. These plants can be sown one year and then harvested over a number of years without re-sowing. The advantage of this is that energy input is reduced as ploughing and seedbed preparation are not required. It also leads to improved soil sequestration of CO₂. Examples of perennial species include many of the grasses, for example perennial, Italian or hybrid ryegrasses, clovers and Lucerne.

3.2 Energy requirement for anaerobic digester construction and operation

A theoretical energy balance for digester operation can be established based on the size, composition and throughput of the digester. Most anaerobic digesters are run at mesophilic temperatures (30 - 42 °C) which is higher than the ambient air temperature so heat is lost through the walls of the digester. Heat is also required to raise the temperature of the feedstock to that of the operating temperature of the digester.

The potential heat loss can be calculated using the formula:

$$hl = UA\Delta T$$

where hl = heat loss, (kJ s⁻¹)

U = overall coefficient of heat transfer, (W m⁻².°C)

A = cross-sectional area through which heat loss is occurring, (m²)

ΔT = temperature drop across surface in question, (°C).

Energy is also required to heat the feedstock from ambient to operating temperature. This can be calculated based on the specific heat of the feedstock C , the volume to be added Q , and the temperature difference ΔT :

$$q = CQ\Delta T$$

where C = specific heat of the feedstock (MJ t⁻¹ °C)

Q = amount of feedstock added (m³)

ΔT = temperature difference between digester and feedstock, (°C).

Thus for the 500 m³ digester operating at 35°C in an ambient air temperature of 5°C and ground temperature of 5°C the heat loss hl per day = 1.18 GJ/day

At a 30 day retention time: the amount of feedstock added per day (Q) = $500 / 30 = 16.7 \text{ m}^3$ If the feedstock has a low solids concentration then the specific heat can be assumed to be similar to that of water $C = 4.2 \text{ MJ t}^{-1} \text{ }^\circ\text{C}$. If the incoming feedstock has an initial temperature of $10 \text{ }^\circ\text{C}$ then the heat required:

$$q = 4.2 * 16.7 * (35 - 10) = 1.75 \text{ GJ/day}$$

Heat energy requirement will vary during the year and according to location. A comparison of daily energy requirements for the above digester, sited in Birmingham in the UK and Jyväskylä in Finland at different times of the year is given in Table 3.

Table 3: Average daily heating requirements (GJ d⁻¹)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual requirement (GJ)
Finland	3.52	3.35	3.27	3.18	2.76	2.37	2.16	2.06	2.42	3.03	3.22	3.33	1053
UK	3.07	3.07	2.88	2.59	2.31	2.02	1.83	1.83	2.11	2.10	2.79	2.88	895

The electrical requirement for operating the digester is harder to calculate as it depends on the configuration and ancillary equipment used. One estimate given is 33MJ/tonne processed (Berglund and Börjesson, 2006) which, for the digester above gives a requirement of $16.7 * 33 = 0.55\text{GJ/day}$. This will remain constant throughout the year so the annual electrical energy requirement for the digester = 200GJ.

Energy is also required in the construction and maintenance of the anaerobic digester and plant. Energy and CO₂ requirements for the extraction, processing and manufacture of materials have been reported in the literature (Alcorn, 1996, Hetherington, 1996, Venkatarama Reddy and Jagadish, 2003). Some examples are shown in Table 4.

Table 4: Examples of energy and CO₂ requirement for production of materials

material	energy requirement (GJ/tonne)	carbon released
concrete	4.9	76 kg CO ₂ /t
construction steel	35	1070 kg CO ₂ /t
plastics	87	13 kg CO ₂ /GJ

Using values for the amount of materials used in the construction of an AD the embodied energy and CO₂ requirement can be calculated, an example for a typical Austrian digester plant site (Laaber, M 2006, pers comm., 12 December) are given in Table 5.

Table 5: Embodied energy in an Austrian AD plant

materials	tonnes	energy (GJ)	carbon released (t CO ₂)
concrete (e.g. digester, buildings, silos, etc.)	5060	24794	384.6
bricks	36	34.9	0.5
plaster	18	81	1.1
roof tiles	10	25	0.3
wood	12	81.6	1.1
high-grade steel (e.g. gas pipe)	5	175	5.4
construction steel	90	3150	96.3
steel plate (e.g. digester covering)	4	128	4.3
plastics (e.g. gas pipe, gas membrane, etc.)	2	174	2.3
gravel	4300 m ³	430	36.8
asphalt	1103	3570	46.4
embodied total		32644	579
construction		1110	14
plant total		33753	993

Note – energy for construction taken as 3.4% of total energy (Elsayed et al., 2003)

This embodied energy requirement and release of CO₂ can be divided by the expected life of the plant (usually taken as 25 years) to determine an annual energy and CO₂ requirement.

3.3 Transport of crop and digestate

One of the advantages of anaerobic digestion is that the process is scaleable, the digesters have no minimum size. It is therefore possible to locate the digesters on the farms that supply the crops to be digested. In this case the energy requirement for transporting the crops to the digester is that included in the ensiling process in crop production. Where crops are transported over greater distances there incurs further transport costs. These have been reported by Berglund and Börjesson (2006) as shown in Table 6. The digestate produced as part of the AD process also has to be returned to land. This can be transported and spread either as it has been stored direct from the digester or as separated liquid and solid fractions which can be applied at different times.

Table 6: Primary energy for transport of crops and digestate (Berglund and Börjesson, 2006)

vehicle	load (tonne)	energy input (MJ/tonne km)		material
		incl empty return	excl empty return	
truck	30	1.1 (1.0-1.2)	0.7 (0.6-0.8)	ley crops, tops and leaves of sugar beet
tractor	8	3.5		solid digestate
tractor	15	2.5		liquid digestate
truck	16	1.6 (1.5-2.3)	1.0 (0.8-1.3)	digestate

3.4 Fuel processing

There are a number of uses to which the produced biogas can be put. These include direct combustion to provide heat, use in a combined heat and power (CHP) plant to generate electricity and heat, addition to gas grids as a replacement for natural (fossil) gas, or use as a vehicle fuel. For combustion in a boiler for heat or when used in a CHP unit, provided the produced biogas has a suitable methane content it can be used directly. For use as a vehicle fuel or addition to the gas grid, the biogas needs to be upgraded including removal of impurities such as H₂S and NH₃. There are various technologies to achieve this which require the use of electricity. Figures quoted for upgrading include 0.495 kWh m⁻³ enriched biogas (Weiland and Ahrens, 2006) and 0.75 kWh m⁻³ enriched methane (Murphy et al., 2004).

3.5 An energy balance

Having derived the energies required at the various stages of the production of crops and operation of the anaerobic digester, it is possible to determine an energy balance. In order to do this it is necessary to identify the location of the digester, the feedstock and the use to which the produced biogas is to be used.

For this example we will use a digester based in the UK, using forage maize as the feedstock and using all of the biogas as fuel for a CHP unit to produce a continuous 500kW of electricity when running. All of the feedstock material is produced on the farm surrounding the digester. The CHP unit is assumed to operate 95% of the time (allowing for maintenance and repair) and has an efficiency of 30% in producing electricity. The maize has a dry matter of 30% and a volatile to total solids ratio of 0.94. 1 kg of volatile solids added to the digester produces 0.65 m³ of biogas which is 60% CH₄. Over the period of one year the CHP unit will require 1,398,655 m³ of CH₄ equivalent to 12,717 tonnes fresh weight of maize. At a hydraulic retention time (HRT) of 50 days this requires a digester with a 2000m³ capacity and 318 ha of land on which to grow the maize. The energy balance is shown in Table 7.

Table 7: Energy balance for AD production of electricity

	value	unit
digester capacity	2000	m ³
daily load	34.8	t/day
crop area	318	ha
crop energy requirement	5310.6	GJ/year
crop transport	93	GJ/year
parasitic heat requirement	2133	GJ/year
parasitic electricity requirement	420	GJ/year
digester embodied energy	1350	GJ/year
digestate disposal energy	259.5	GJ/year
total energy requirement	9566	GJ/year
	30	GJ/ha
electricity produced	14980	GJ/year
	4161	MWh/year
heat generated	24966	GJ/year
	6935	MWh/year
ratio of electricity produced/energy required	1.56	

The relative proportions of the energy requirements are shown in Figure 4.

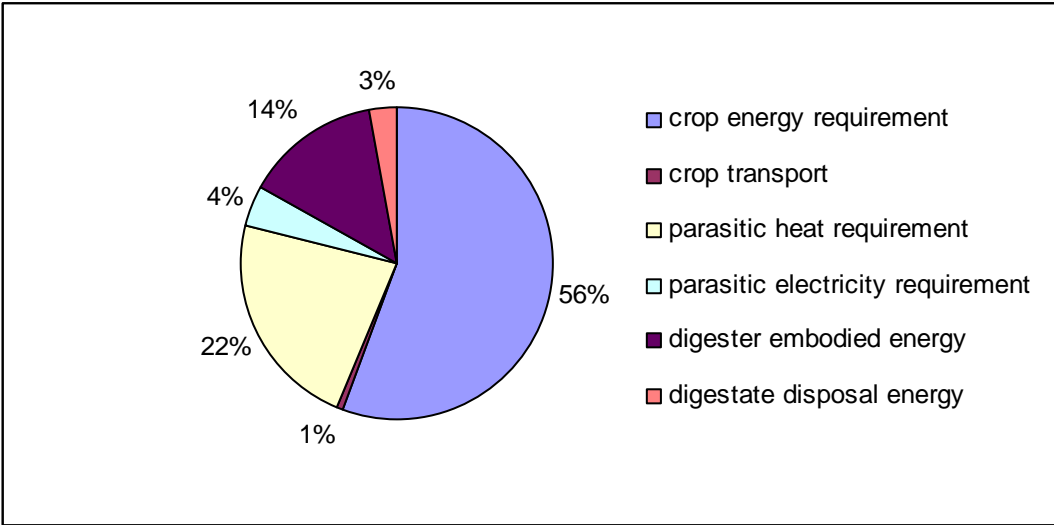


Figure 4: The relative proportions of energy requirements for production and digestion of Maize

The ratio of electricity produced/energy required for fossil fuels is 0.33 (Howard et al., 1999) which is equivalent to the conversion rate of the CHP unit, but no fossil fuels are required.

An alternative use of the biogas produced is as transport fuel which also requires upgrading. For this balance we assume it requires 0.5 kWh/m³ upgraded methane produced (1.8 MJ/m³). The electricity is assumed to be generated by a CHP plant at the digester site using the same operating conditions as above. The digester has a capacity of 2000m³ and produces 2,331,091 m³ of biogas per year. Figures for the energy requirements are shown in Table 8.

Table 8: Energy balance for vehicle fuel production

	value	unit
crop energy requirement	5310.6	GJ/year
crop transport	93	GJ/year
parasitic heat requirement	2133	GJ/year
parasitic electricity requirement	2512	GJ/year
digester embodied energy	1350	GJ/year
digestate disposal energy	259.5	GJ/year
total energy requirement	11658	GJ/year
upgraded CH ₄ produced	1162543	m ³
energy value	41503	GJ
ratio of upgraded methane produced/energy required	3.56	

Digester size has an effect on the energy requirements and energy balance. Larger digesters are more efficient in terms of heat requirement as the reduced surface area to volume ratio means that less heat is lost through the walls of the digester and so less heating is required. There is also evidence from Austria that some digesters produce enough internal heat from the chemical reactions of the digestion process that heat is not required at all and in some cases the digesters are cooled (Lindorfer *et al.*, 2006). Larger digesters, however, have increased

requirement for feedstock plus increased production of digestate and these must be transported over greater distances. Figure 5 shows the effect of increased digester capacity (expressed in terms of the area of crop required as feedstock) on the heat and transport energy requirements. 1000ha of Maize yielding 40 tonnes of fresh matter per hectare (tFM/ha) will supply a digester of approximately 5000m³. These values are based on all of the area surrounding the digester supplying feedstock. If only 50% of the surrounding area produces crops for feedstocks, the rest of the area being used for food, animal forage or buildings etc then the transport energy requirement will be doubled.

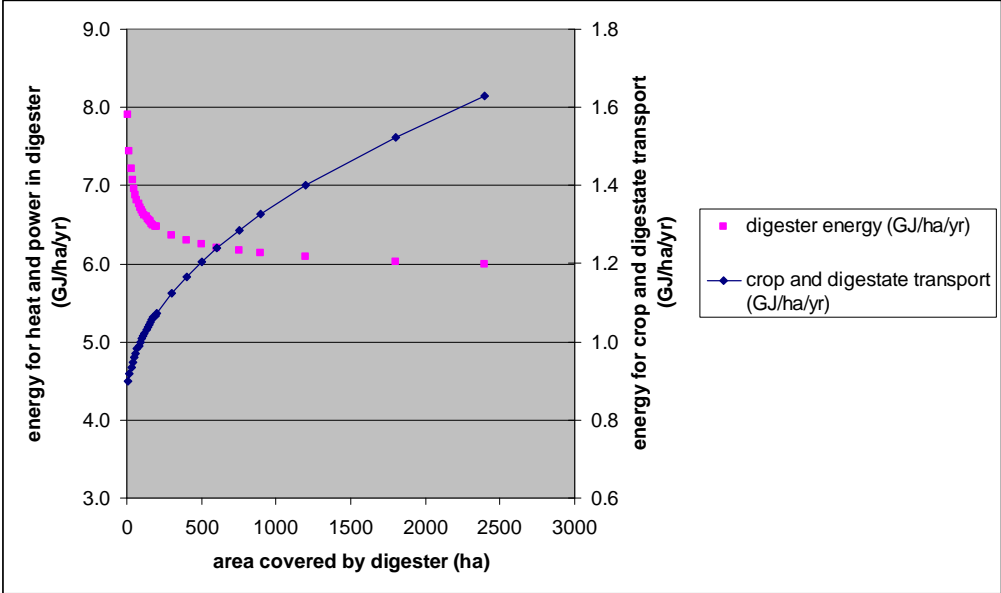


Figure 5: Comparison of energy requirements for different capacity digesters

4. Potential energy production

There is competition for land use between crops for energy production and for food. The amount of land available in the EU is limited (see Table 9), it is therefore important to maximise the energy produced from each hectare.

Table 9: Available land areas in EU (million hectares)

	total area	utilised agricultural area	fallow land without subsidies	set-aside without incentives
EU 25	197.4	156	3.5	6.3

One possibility is to make use of ‘set-aside’ land, land which the EU has declared must not be used for food crop production. This land tends to be of lower agricultural value so is less suited to the highest yielding crops e.g. sugar beet but is suitable for the production of whole crop cereals such as triticale. A ‘whole crop’ is harvested earlier than would be required for grain production while the crop is still ‘green’ and includes almost all of the plant material above ground level. This material can be ensiled and stored in large quantities for use throughout the following year. The potential methane yield from triticale grown on set-aside land in some of the EU 15 states is shown in Table 10. Whole crop harvest figures are not regularly reported but it is possible to calculate a whole crop yield based on the grain yield. Whole crop yield is calculated here from grain yield * 2 (allowing for straw) and converted from 15% moisture content (usual for grain harvest) to 60% moisture content (commonly used in forage harvest). This gives a figure for fresh matter yield per hectare.

Table 10: Potential methane yields from the digestion of whole crop triticale grown on all set-aside

country	set-aside area (ha) (2003)	grain yield (t/ha)	Potential whole crop yield (tFM/ha)	Potential methane yield (m ³)
Belgium	28,470	5.86	46.9	163,912,599
Denmark	230,100	4.86	38.9	1,099,267,752
Germany	1,235,620	6.41	51.3	7,784,658,437
Spain	1,098,560	2.36	18.9	2,549,898,266
France	1,579,960	4.66	37.3	7,237,560,240
Ireland	46,060	4.65	37.2	210,428,297
Netherlands	201,300	5.27	42.2	1,043,262,251
Austria	104,280	5.3	42.4	543,005,398
Portugal	161,910	0.86	6.9	137,201,870
Finland	253,600	4.2	33.7	1,049,582,104
Sweden	297,590	4.41	35.3	1,290,120,590
United Kingdom	701,120	4.65	37.2	3,230,115,238

(European Commission, 2006)

Note: - yields for Ireland are estimates based on those for the UK which has a similar climate.

The energy contained in the potential methane yield may be calculated in terms of tonnes of oil equivalent (toe). One m³ of methane has a net calorific energy value of 35.7 MJ. One tonne of oil equivalent has an energy value of 41.868 GJ (DTI, 2004). If the biogas which could be produced using anaerobic digestion of whole crop triticale was purified to a state in which it could be added to the low pressure gas grid then the amount which could be produced on set-aside land is shown in Table 11. The gas could also be used to replace crude oil and petroleum products, the amount of these used in energy production and the potential for replacement is also shown in Table 11. Values for the energy requirements of the various EU member states contained in Table 11 and the following tables are based on data from EurStat (European Commission, 2006).

Table 11: Potential for natural gas and crude oil for energy production replacement from crops grown on set-aside

country	potential methane yield (1000 toe)	natural gas energy consumption 2004 (1000 toe)	% gas consumption	crude oil for energy production consumption 2005 (1000 toe)	% oil consumption
Belgium	140	9,958	1.4	1,182	11.8
Denmark	937	1,698	55.2	333	281
Germany	6,637	60,297	11.0	7,926	83.7
Spain	2,174	16,372	13.3	4,140	52
France	6,171	32,376	19.1	4,663	132
Ireland	179	1,325	13.5	194	92
Netherlands	889	21,149	4.2	3,886	22.8
Austria	463	4,417	10.5	916	50.5
Portugal	116	1,280	9.1	607	19.1
Finland	894	857	104.4	645	138
Sweden	1,100	480	229.2	731	150
United Kingdom	2,754	50,436	5.4	5,952	46.2

The percentage of gas or crude oil that could be produced varies considerably between EU states and is affected by the potential set-aside area and crop yields. In particular the most Southern countries (which can be very dry) and Northern countries (which are cold) have low yields. An alternative would be to use a larger proportion of the agricultural area to provide crops which could be digested. The area of agricultural land required to fulfil the gas requirement is shown in Table 12. The Netherlands and Belgium would require more land than is available, and for other countries, such as the UK, the requirement would severely compete with the requirement for food production.

Table 12: Area of land required to replace natural gas or crude oil for energy requirement

country	utilised agricultural area (ha)	% utilised agricultural area required	
		for gas	for crude oil
Belgium	1394400	145.4	17.3
Denmark	2658210	15.7	3.1
Germany	16981750	66.1	8.7
Spain	25175260	32.9	8.3
France	27795240	29.8	4.3
Ireland	4271710	8.0	1.2
Netherlands	2007250	238.4	43.8
Austria	3257220	30.5	6.3
Portugal	3725190	47.6	22.6
Finland	2244700	10.8	20.5
Sweden	3126910	4.2	6.3
United Kingdom	16105810	80.4	9.5

An alternative to the production of gas for the replacement of natural gas or crude oil is to use the produced biogas as a fuel source for combined heat and power (CHP) in order to produce electricity. The percentage of electricity consumed which could be produced using crops grown on set-aside land is shown in Table 13.

Table 13: Potential electricity generation from AD using crops grown on set-aside

country	Electricity consumed 2004 (MWh)	potential generation from set-aside (MWh)	potential consumed electricity generated from set-aside (%)
Belgium	80613979	568959	0.71
Denmark	32973688	3815680	11.57
Germany	513366006	27021414	5.26
Spain	230687874	8850980	3.84
France	415910440	25122375	6.04
Ireland	23029242	730420	3.17
Netherlands	103131460	3621279	3.51
Austria	56375120	1884832	3.34
Portugal	44674404	476243	1.07
Finland	83137890	1448638	1.74
Sweden	130371099	4478152	3.43
United Kingdom	340065143	11212089	3.30

A further possibility, as stated earlier is the use of the biogas produced as vehicle fuel. This provides an alternative to the production of bio-ethanol and bio-diesel as liquid bio-fuels.

Analysis of the energy balances for bio-ethanol and bio-diesel have been conducted, for example Kaltschmitt *et al.* (1997), Richards (2000), Kim and Dale (2005), Hill *et al.* (2006) and a number of reports have been summarised and evaluated in Elsayed *et al.* (2003). A comparison of relative efficiencies and energy balances of the three fuel sources is shown in Table 14. To enable relative comparison, the net amounts of fuel which could be produced per hectare have been converted into litres of diesel equivalent. To produce a road usable fuel the biogas must be processed including scrubbing to remove impurities and in some cases compression. The energy requirements for this have been calculated and subtracted from the energy produced per hectare before conversion to litres of diesel. The figures for crop production and fuel processing for the bio-ethanol and bio-diesel are adapted from Elsayed *et al.* (2003).

A comparison of the annual consumption of road fuel and the various bio-fuels produced using set-aside land is shown in

Table 15. The proposal of the EU is that 5.75% of fossil fuels used for vehicles is replaced by bio-fuels by the year 2010. Using only set-aside this cannot be achieved from bio-ethanol and bio-diesel in any of the EU states and would require the use of land currently used for crop production. In contrast the target could be achieved through the use of biogas in most of the countries shown.

Table 14: Comparison of energy efficiencies in production of transport fuels

fuel crop	bio-diesel	bio-ethanol		methane			methane	methane whole crop triticale (a)
	OSR seed	sugar beet	wheat grain	sugar beet	wheat grain	maize	whole crop triticale	
fertiliser (N kg/ha)	195	147	150	147	150	150	160	80
crop yield (fresh yield t/ha)	3	56	8	56	8	40	38	38
crop yield (t DM/ha)	3	11.5	6.9	11.5	6.9	12.6	15	15
energy for crop production (GJ/ha)	12.7	11.9	12.8	11.9	15.5	16.7	16	11.6
energy for processing (GJ/ha)	9.2	41.4	13.2	10.8	8	8	8.3	8.3
energy of fuel produced (GJ/ha)	40.4	117	61.1	124.8	89	157.1	166	166
energy ratio (output/input)	1.84	2.20	2.35	5.50	3.79	6.36	6.83	8.34
net energy produced (GJ/ha)	18.5	63.7	35.1	102.1	65.5	132.4	141.7	146.1
potential electricity generated MWh/ha				9.4	6.1	12.2	13.1	13.5
energy to convert to vehicle fuel (GJ/ha)				5.3	3.7	6.6	7	7
energy of vehicle fuel produced (GJ/ha)				96.8	61.8	125.8	134.7	139.1
equivalent litres of diesel.	517	1779	980	2704	1726	3514	3763	3885

Note a) Assumes the use of digestate to replace 50% of the mineral fertiliser used to provide nitrogen.

Table 15: Potential production of road fuel from set-aside land

country	road fuel consumption (2003)	potential biogas (from whole crop triticale)		potential bio-diesel (from oilseed rape seed)			potential bio-ethanol (from winter wheat grain)		
	(1000 toe)	(1000 toe)	%	yield (t/ha)	(1000 toe)	%	yield (t/ha)	(1000 toe)	%
Belgium	8488	139.8	1.6	3.64	32.5	0.4	8.2	42.4	0.5
Denmark	4027	937.3	23.3	2.8	201.9	5.0	7.4	310.1	7.7
Germany	53187	6637.8	12.5	3.68	1425.3	2.7	7.9	1784.9	3.4
Spain	30817	2174.2	7.1	1.29	444.2	1.4	2.3	460.9	1.5
France	42273	6171.3	14.6	2.66	1317.3	3.1	6.8	1950.9	4.6
Ireland	3811	179.4	4.7	3	43.3	1.1	9.8	82.3	2.2
Netherlands	11004	889.6	8.1	3.39	213.9	1.9	8.3	304.7	2.8
Austria	6779	463.0	6.8	2.62	85.6	1.3	5.3	100.8	1.5
Portugal	6343	117.0	1.8	1.3(a)	66	1.0	1.2	35.4	0.6
Finland	3936	355.9	9.0	1.38	109.7	2.8	3.4	156.3	4.0
Sweden	6950	1100.1	15.8	3.1	289.2	4.2	3.4	184.5	2.7
United Kingdom	39304	2754.3	7.0	2.57	564.8	1.4	7.8	997.5	2.5

notes: (a) estimate

5. Digestate and the effect on energy balance

The second product of anaerobic digestion is the digestate and in many cases until recently this was the primary output of the process. Thus sewage works had anaerobic digesters installed in order to process the sewage sludge and produce material with reduced odour and increased homogenisation which was fit to be returned to land. Seven of digesters have been installed recently in the UK by Greenfinch Ltd. in order to process cattle slurry in order to reduce contamination of local rivers and beaches.

The digestate contains the majority of the nutrients which were in the original feedstocks fed to the digester but in a form in which they are more available for uptake by plants. The digestate as it comes out the digester has a moisture content around of 90% which is similar to cattle slurry. The material can therefore be returned to land using existing slurry spreading technology. Alternatively the digestate can be separated into solid and liquid fractions which can be spread at separate times. Thus in the case of maize, the solid fraction can be applied to land before ploughing and the liquid fraction later in the plants development.

Where mineral fertilisers are applied to crops, the energy required for fertiliser production can make up over 50% of the energy requirement for crop production. Some examples of recommended nitrogen applications and the resulting energy requirements are shown in Table 16. In the examples for grass, the recommended nitrogen application is up to 340 kg/ha but legislation on Nitrogen Vulnerable Zones (NVZs) restricts the application of nitrogen to 170 kg/ha. This leads to a reduction in the energy requirement for crop production but will also lead to a reduction of yield.

Table 16: Energy requirements form the use of mineral nitrogen

crop	wheat	maize	fodder beet	grass	grass (NVZ)
recommended nitrogen input (kg/ha)	180	150	180	340	170
energy of nitrogen MJ/ha	7.25	6.05	7.25	13.7	6.85
total energy of crop production MJ/ha	17	16.7	21.8	28.4	21.1
% energy in nitrogen	42.6	36.2	33.2	48.2	32.5

Replacement of the mineral fertiliser with digestate reduces the energy requirement. Due to some losses the mineral fertilisers cannot be completely replaced by the digestate. There is little reported in the literature of the nitrogen content of digestate, which will vary according to the feedstock of the digester. Examples have been given of 4.8 kg N/tonne (Rodhe *et al.*, 2006), 3.5 kg N/tonne (Lewis, L 2006 pers comm, 12, November) and 2.5 kg/tonne (Sealey, 2006). Assuming a value of 3.5 kg/tonne, an application rate of 160kg N/ha will require the application of 46tonnes of digestate per ha. The energy requirement for loading and spreading the digestate can be calculated using the figures of Berglund and Börjesson (2006) of 5 MJ/tonne loading, 3.5 MJ/tonne/km transport to the field and 17MJ/tonne spreading. If the fields are assumed to be 1km from the digester then the energy requirement for loading and spreading the digestate is 25.5 MJ/tonne. At 46 tonnes per ha this gives an energy requirement of 1.17 GJ of energy for loading and spreading the digestate. Table 17 shows the change in energy for crop production resulting from the use of digestate. Three scenarios are given: i) using only mineral fertiliser, ii) replacing 50% of the mineral nitrogen with digestate, and iii) replacing all of the mineral based nitrogen with digestate. Note that because of the losses in the system, 100% replacement of the mineral nitrogen with digestate could only be achieved through the use of mineral fertiliser or legumes in order to fix atmospheric nitrogen some where else in the farms production. If the application rate is calculated based on the nitrogen content of the digestate then amount of phosphate and potassium applied may be insufficient and have to be supplemented by other sources including mineral fertilisers.

Table 17: Energy requirements using digestate on whole crop triticale

scenario	i) mineral nitrogen		ii) 50% digestate		iii) 100% digestate	
	amount (kg/ha)	energy (MJ/ha)	amount (kg/ha)	energy (MJ/ha)	amount (kg/ha)	energy (MJ/ha)
mineral N	160	6448	80	3224	0	0
mineral P ₂ O ₅	60	204	50	170	42	143
mineral K ₂ O	200	1460	101	737	2	15
digestate tonne/ha	0		23		46	
digestate N	0		80	0	160	0
digestate P ₂ O ₅	0	0	9	0	18	0
digestate K ₂ O	0	0	99	0	198	0
energy to spread mineral fertiliser		118		118		118
energy to spread digestate		0		586		1173
energy for fertiliser application (GJ/ha)		8.23		4.84		1.45

Table 17 shows the energy requirements for different combinations of mineral fertilisers and digestate. It is assumed that the digestate contains 3.5 kg N/tonne, 0.4 kg P₂O₅ /tonne, 4.3 K₂O /tonne and the amount of mineral supplement for P₂O₅ and K₂O required for addition to the digestate is calculated accordingly.

6. Socio-economics

When considering the development of any renewable energy production there are a number of factors regarding the effect of production of that fuel on the environment which should be taken into account. These include the local economy, environmental impacts and diversity of flora and fauna. Most forms of production of renewable energy involve some change in land use. If biomass is used as the supply source for fuel production what effects will changing the crops grown have on the appearance of the countryside, the condition of soil and use of the land, either for farming or pleasure use? Issues relating to environmental impacts of changing land use were addressed in deliverable **D30a**. It is difficult to get an overall economic balance for farm based anaerobic digestion as each EU state has a different policy towards purchase and pricing of the produced energy. The economics of fuel production can be partially related to energy requirements – energy into crop production has to be purchased in the form of fuel, fertilisers sprays and equipment. From a development perspective, the increase in numbers of constructed plants in countries such as Germany and Austria has led to more standardised designs and improved construction efficiencies which are reflected in the economics of digester use. This section of the report will consider some of the economic implications of the use of anaerobic digestion for fuel production in a farming environment and compare some alternative farm strategies. Other socio-economic effects of the use of AD which are considered include CO₂ production and energy self sufficiency, distributed energy production and the environmental effects of crop based energy production using AD.

6.1 Economic assessments

Developing an economic model for biogas production is difficult due to a combination of variation in costs and relative values of the products produced between different EU states and a lack of documented information regarding the costs of anaerobic digesters – partly the result of the commercial nature of the information. The costs of digesters, both construction and operating, also vary with each individual digester according to its location, design, feedstocks and usage of products. Cropgen has focused on the production of biogas and the resulting use of the biogas from crops and agro wastes, effectively a farm based energy production system. Each farm will have its own circumstances which dictate the materials produced and the costs of these materials and the size and nature of the digester used.

A simplified model for determining the capital costs for a digester system is shown in Figure 6. The chart compares values for a ‘simple’ farm digester – a mesophilic system with no pre or post treatment, and a model for Danish centralised anaerobic digester (CAD) systems presented by Murphy and McCarthy (2005). The Danish CAD systems are mostly thermophilic and have pasteurisation units which make them more expensive to build and operate.

The cost of the digester is determined by the amount of substrate to be processed which will affect the size of the digester. The amount of substrate can be calculated from either the capacity of the farm to produce material (according to its area) or in the case of CHP by the required electrical output from the CHP. For this example we will take a required output of 500kW_{electricity}. The CHP unit is assumed to run for 95% of the time (allowing for maintenance and repair) and is 30% efficient in the production of electricity. The generator produces 4,161

MWh of electricity per annum requiring 1,398,655 m³ of CH₄. Production of methane is determined by the substrates added to the digester and the amount of methane which can be generated per kg of volatile solids added. The capital cost for a CHP unit supplying 500 kW_{electricity} is assumed to be €546840 (Murphy and McCarthy, 2005). If maize is selected as the substrate for digestion and the methane potential is taken to be 335m³ CH₄ per tonne of VS added, 11,389 tonnes of substrate are required. From Figure 6 the capital cost of the digester can be calculated as €1.006 million giving a total installation cost of €1.55 million. Annual repayments can be calculated based on the estimated life of the plant, in this case 20 years, and a simplified calculation of the annual interest can be conducted assuming all of the capital investment is borrowed. Thus for this example, the annual repayments are equivalent to €7,689 and the annual interest €2,151. Operating costs vary considerably according to the design and operation of the digester, we shall assume here an annual figure of 5% of the capital costs, equivalent to €0.347 per year. Operating costs for the CHP are taken as €0.01/kWh (Murphy and McCarthy, 2005), equal to €41,610 per year. The total annual expenditure for this digester can therefore be calculated as €231,797 per year.

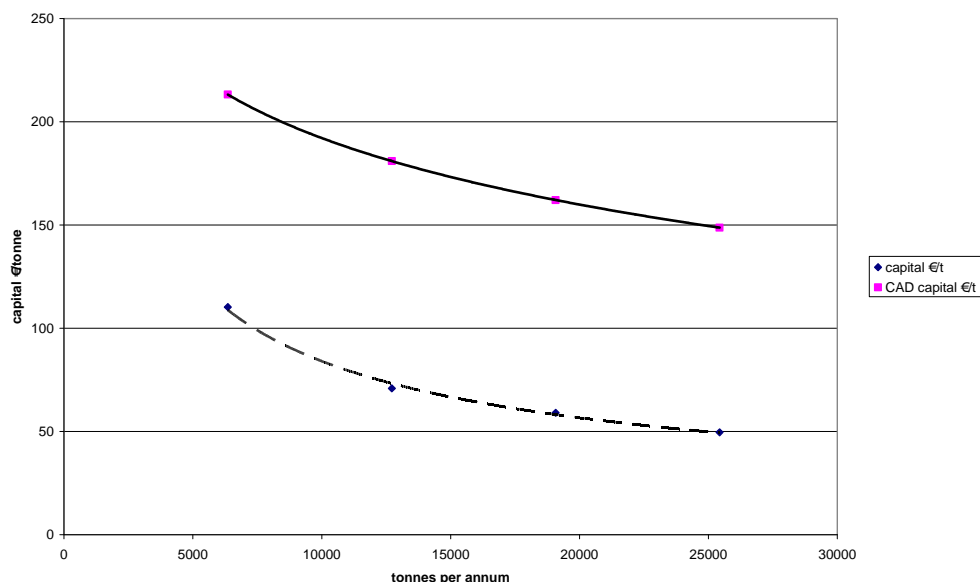


Figure 6: Models for digester capital costs

This costing model is based on the assumption that the biogas produced will be used in a combined heat and power unit to generate electricity, which is the principal use mode of operation of farm based anaerobic digesters in Austria and Germany. The value of the electricity produced varies considerably according to which EU state the digester is operating in. Thus Austria and Germany have established ‘feed in’ tariffs which guarantee the producer a fixed price for the electricity produced over the next 13 years (Walla and Schneeberger, 2005). This rate is determined according to the size of the CHP unit, use of heat and input substrate as shown in Table 18. Thus a farmer in Germany producing electricity with a 500 kW_{elec} generator from energy crops and utilising the heat from the CHP unit (by selling to local industry, heating the local village etc) can expect to receive 17.9 €/kWh. The equivalent farmer in Austria would receive 14.5 €/kWh although there is a 25% reduction for including organic waste.

In the UK, the value of the electricity is determined in two parts, the value of the electricity produced and sold to the energy companies and Renewable Obligation Certificates (ROCs) which have a variable value and can be traded. Finland has no fixed price for electricity

generated from biogas and sold to the grid and although there are tax incentives these have been difficult to collect. The market price for electricity has been around 3-4 cent/kWh. As reported in deliverable **D15** and briefly in section 3.5 a certain amount of the electricity generated is required for use in the plant, to operate pumps, mixers, macerators etc. The amount of this ‘parasitic’ electricity can be subtracted from the amount produced to determine the amount available for sale. For the 500 kW_{elec} unit specified 4,161 MWh are generated, 104.8 MWh are required for use around the plant therefore 4,056 MWh are available for sale. At a price of 14.5 Cent.kWh for crop based production without sale of the heat this gives an income of €588,152.

Table 18: Electricity prices in Austria and Germany (€/kWh)

Austria		up to 100kW _e	up to 500kW _e	up to 1MW _e	over 1MW _e
tariff		16.5	14.5	12.5	10.3
including organic waste		12.4	10.9	9.4	7.7
Germany		up to 150kW _e	up to 500kW _e	up to 5MW _e	over 5MW _e
basic		11.5	9.9	8.9	8.4
bonus for crops		6	6	4	
CHP bonus		2	2	2	2
technology bonus		2	2	2	

The final cost in a crop based energy production system is the cost of the crop itself. This will also vary according to whether the crop is produced on the farm or imported, if the farm is tenanted or owner occupied, how much of the work is contracted and various variable costs which change each year including the price of fuel and fertiliser. The most expensive ‘worst case’ scenario for crop production can be calculated based on rented land, use of mineral fertilisers and all operations conducted by contractors. In the case of maize the cost of crop production can therefore be estimated as €68 per hectare per year.

At a yield of 38 tonnes fresh weight per hectare, 300 hectare of maize will be required equivalent to an annual cost of €326,684 per year. This assumes production of the maize is local and no extra haulage is required. The costs and income for the crop based digester generating 500kW_{elec} are shown in Table 19.

Table 19: Digester costs and income for generation of 500kW_{elec}

item	value	
Total capital	1,554,000	€
annual repayments	78,000	€/year
interest repayments (8%)	62,000	€/year
operating costs	92,000	€/year
feedstock costs	296,000	€/year
revenue from electricity	588,000	€/year
profit	60,000	€/year

The production of the biogas and conversion into saleable electricity is subject to a number of variables. The above example is based on a methane potential of 335m³ per tonne of volatile solids added. If this rate is lower then more material will be required. This increases the area of land and corresponding digester size leading to increased capital, interest and operating

costs. Similarly if the crop yield cannot be maintained an increased area of land and associated costs will be required to provide the substrate.

Table 20 presents a sensitivity analysis resulting from changes in the methane production from the substrate. Note that the revenue from the electricity declines as the digester size increases as more pumping etc is required for the increase in amount of feedstock. One way to reduce the costs would be to increase the loading rate of the digester although the crop area, and associated costs, will still increase.

Table 20: Effect of change in methane production from substrate (fixed loading rate, 38 tFM/ha)

CH ₄ (m ³ /tVSadded)	crop area (ha)	crop cost (€)	annual costs (€)	operating costs (€)	total cost (€)	revenue from electricity (€)	profit (€)
0.335	300	295,000	140,000	92,000	527,000	588,000	61,000
0.3	335	323,000	144,000	94,000	561,000	586,000	25,000
0.275	365	360,000	147,000	96,000	603,000	585,000	-18,000
0.25	402	396,000	151,000	98,000	645,000	583,000	-62,000

The above calculations have been made assuming that the digester is farm based, the farmer uses crops grown on the farm and that crop production costs €968/ha for a 38t/ha yield (€ 25.5 / tonne). Many farms have less than the area required to produce enough crop material to supply the digester and so would need to ‘buy in’ crop material from other farms. The effect of substrate cost on profit is shown in Figure 7. If the input substrate costs €30 / tonne the digester operator will require a price for the electricity of at least 14.2 €/kWh to break even without the sale of heat or other outputs.

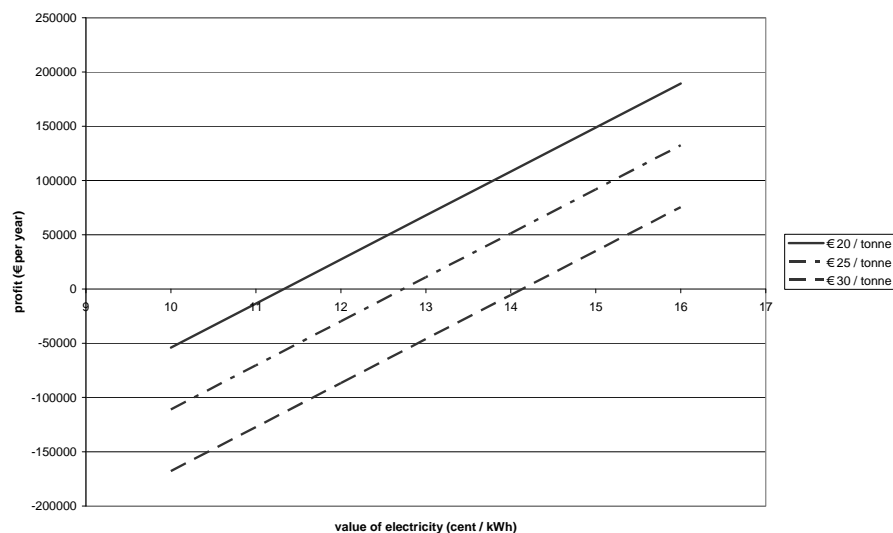


Figure 7: Effect of change of substrate cost and value of electricity sold

An alternative to generating electricity by using the biogas in a CHP unit is to use it as vehicle fuel. The biogas can be burned directly in vehicle engines but as it contains up to 50% CO₂ the range of the vehicle is limited. In order to extend this the biogas can be scrubbed of the CO₂ and other impurities. The capital cost of a biogas scrubber can be estimated as €7,860/Nm³ CH₄ enriched biogas/hour with an operating cost of €0.03/Nm³ CH₄ enriched biogas (Murphy and McCarthy, 2005). If it is assumed that the power required for the scrubber comes from an on-site CHP unit (which also provides the heat for the digester) the digestion unit above would produce 1,328,722 m³ of CH₄ enriched biogas. The capital cost of the scrubber is therefore €1,192,362 but requires a smaller CHP unit as it is only producing

electricity for the plant, not for export. A graph of potential profit against revenue for the CH₄ enriched biogas is shown in Figure 8.

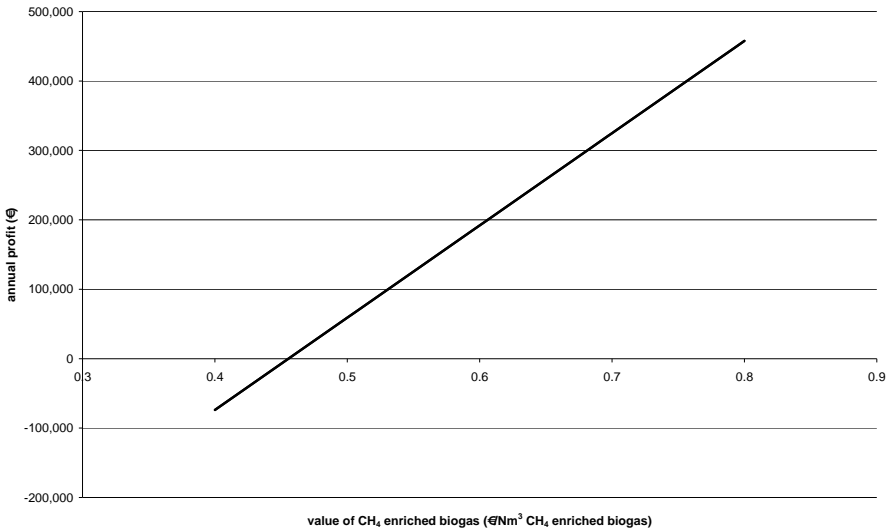


Figure 8: profit from export of CH₄ enriched biogas

Capital costs for a plant producing vehicle fuel are higher due to the extra processing equipment required but the potential revenue is also higher. At a price of €0.67 /Nm³ CH₄ enriched biogas the profit would be €284,190 which is greater than the profit from selling electricity. The use of biogas as vehicle fuel is increasing, in 2006 Sweden had 68 public filling stations and 10,400 vehicles running on gas by 2010 it intends to have 500 gas filling stations and 70,000 vehicles running on gas. Vehicles manufacturers already producing vehicles which run on biogas include Volvo, Mercedes, Volkswagen, General Motors and Renault. The effectiveness of a vehicle fuel strategy has been shown by Metener Oy in Finland who are part of the Cropgen project.

When considering the economics of energy production in a farm environment the potential revenue can be compared with that relating to more traditional farming activities - such as dairy production and arable crops - such as wheat and maize. Farm economics are complex and vary according to the size and nature of the farm, products, variable market prices and subsidies. There is also considerable legislation regarding agriculture including the storage and application of fertilisers (mineral, slurries and digestates), areas of set-aside, requirements for diversity and land management.

Table 21 provides a comparison of four simplified farm strategies based on a 300ha farm in the UK. The four scenarios are: 1) a dairy farm with 600 milking cows, most of the forage provided on farm; 2) an arable farm with mono-crop wheat which could be sold for food or energy production; 3) a mixed arable farm growing oilseed rape, the farm is sown 1/3 to each of three crops (oilseed rape cannot be grown on the same field in successive years so cannot be used for the entire farm); 4) a farm system producing biogas from on farm grown forage crops as used in previous examples. Farm product prices are based on values as of March 2007 (FWI, 2007). The calculations are based only on primary products and do not include the sale of items such as straw from cereal crops and heat from the CHP unit.

Table 21: economic comparisons

	Dairy farm	Cereal production	mixed arable (OSR, wheat & barley)	Biogas
	2 cows/ha	mono crop wheat	rotation cropping 1/3 OSR 1/3 wheat, 1/3 barley	forage crops
	7000l milk/cow	8t grain/ha	OSR 3t seed/ha 300 t seed	38 t FM /ha
	4,200,000 l milk	2,400 t grain	€239 / tonne	11,400 t forage
	€0.23 / l	€145 / tonne	wheat 8t/ha 800 t grain	electricity
	calves €348 / cow		€145 / tonne	€558,000
			barley 5t/ha 500t grain	
			€130 / tonne	
single payment subsidy	3.8 cent/l	€266/ha	€266/ha	€266/ha
income	€1,334,400	€427,800	€332,500	€637,800
costs	€0.3 / l			
	€1,260,000	€378,450	€361,340	€527,000
profit	€74,400	€49,350	-€28,840	€110,000

From Table 21 it can be seen that production of biogas from forage crops and using it in a CHP unit to produce electricity yields the greatest profit in this simplified model. It is also the only system in this example that can yield a profit without the use of the single payment subsidies. However, relatively small changes in the price of grain or milk can have considerable effects on profit. Changes in the farm operation also have effects, the figures used for costs assume the land is rented and all labour is paid. If the farm is owner occupied and labour is provided 'unpaid' in the form of the farmer and their relations than the profit margin is increased. A further way to reduce the cost of crop production would be the use of digestate to replace mineral based fertilisers. For example in the production of maize the fertiliser cost is €109 / ha, replacing half of the fertiliser with digestate would save €1.40 per tonne of feedstock. The prices for farm products are affected by world wide production and demand, as the world's population increases there also becomes greater demand for food crops and competition for land use.

Biogas production using anaerobic digestion allows for the use of non-food crops and production of material on land unsuitable for food production. Farmer's can therefore optimise the use of land and maximise the production of food or energy leading to increased revenue.

6.2 CO₂ production and energy self-sufficiency in digester operation

The production of energy using anaerobic digestion can be almost completely self-sufficient in its energy requirements, that is no energy is required other than that produced within the process itself. The two energy requirements for an anaerobic digester are heat and electricity. A combined heat and power plant (CHP) can be installed on the site of the digester, operating on the biogas produced. In many cases the biogas can be used directly without further processing. Heat generated in the CHP is often enough to maintain the temperature of the digester and for raising the feedstock from ambient to operating temperature. Where the heat from the CHP is insufficient a simple gas boiler can be installed, also operating on the biogas produced. Production and collection of the crop material used as feedstock requires the use of vehicles (tractors, lorries etc.) which require fuel. These vehicles could use engines running on methane enriched biogas. This fuel can be produced using gas scrubbers to remove

contaminants and the majority of the CO₂. These scrubbers require energy, in the form of electricity, which can be provided by the CHP unit. If the digestate is used as fertiliser then the requirement for mineral fertiliser (based on fossil fuels) is also reduced to a minimum, the fuel production process is almost completely self-contained from an energy point of view. The paths of energy and materials for a crop based AD process are shown in Figure 9.

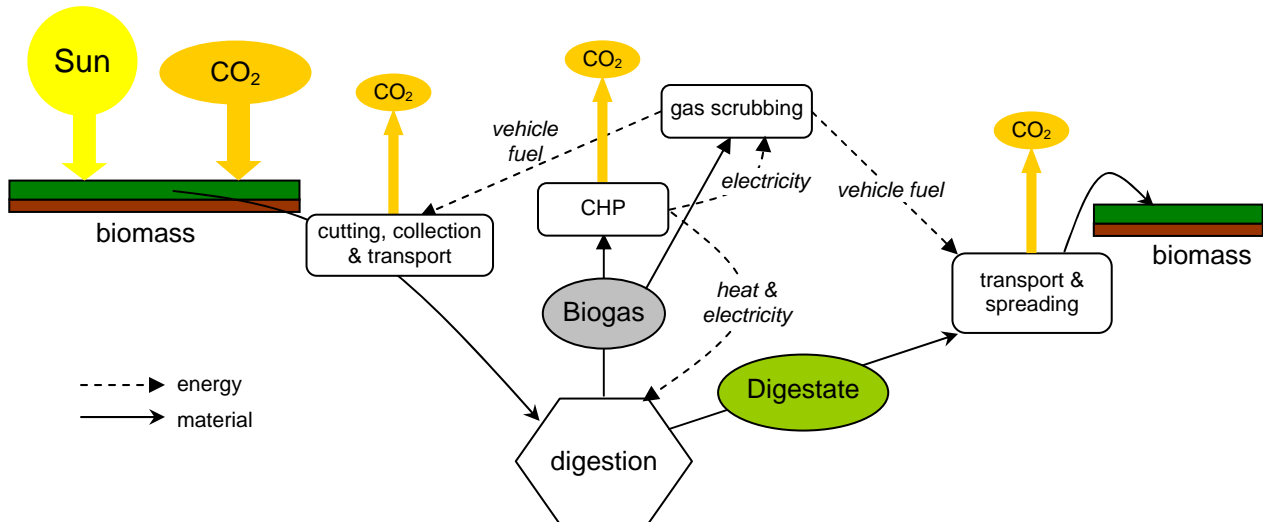


Figure 9: Energy and material movement in a crop based AD system

In terms of CO₂ production the process should be considered as starting from plant growth. CO₂ is absorbed by the plant material during growth, this material is then used in the fuel production process. If no fossil fuels are consumed then the only CO₂ produced is that which was absorbed by the plant material, the process is CO₂ neutral. As the AD process produces more energy than is required than it also contributes to reduction of CO₂ produced in fuel production and use. Use of the digestate as fertiliser reduces the requirement for mineral fertilisers, further reducing the production of CO₂.

Further CO₂ reduction can be achieved through crop selection. Where crops require minimum tillage - for example direct drilling of forage rye after a wheat crop, or are perennial - for example grass and so do not require ploughing every year, there is less disturbance of the soil structure and increased sequestration of CO₂.

6.3 Distributed energy production

One advantage of anaerobic digestion is the scalability of the technology. As the digesters can be built to smaller scales they can be placed on individual farms providing a form of distributed energy system. Economy of scale requires some bio-fuel plants to be built on a large scale. Recent plants proposed, or being built in the UK require around 100,000 tonnes of grain or seed per year. Elsayed *et al.* (2003) report a value of 260km as the average distance grain is transported to a bio-ethanol plant. At 20t of grain per load, the grain required for a modest 40,000 tonne per annum plant travels 520,000 km. By producing a larger number of smaller plants, the transport requirements too and from fields can be reduced, thus reducing the requirement for more traffic on roads and disruption to lives in the regions of the production plants. Where the AD plants are used to generate electricity, distributed systems give an increase in efficiency due to reduced energy losses along power lines. Excess heat generated can be distributed to local villages. Where the biogas is used as transport fuel, the

gas can be cleaned and compressed at the site of the digester, or piped between close digesters to a local distribution point and made available to vehicles. This reduces the requirement for the transport of liquid fuels over large distances from a small number of refineries.

6.4 Environmental effects

There is much concern over the environment and the environmental impact of new technologies, especially those relating to renewable energy. Windmills provide an effective source of electricity generation but many wind farms have been proposed or built in areas of outstanding natural beauty. There has been much opposition to these and their effects on the appearance of the landscape, wildlife and in particular birds. Other fuel sources such as short rotation coppice and *Miscanthus* for combustion fuels require large areas of crops which will remain in place for about 20 years. These crops have considerable impact on the appearance of the landscape and require farmers to commit to a single source of income for this period. Even with grant aid, the uptake of these crops has not been as great as expected. Crops for bio-ethanol and bio-diesel are effectively mono-cultures, large areas of a single crop grown year after year. This is damaging to the soil and requires high inputs of fertilisers and sprays to maintain. Some improvement on this position can be made through the use of crop rotation but the effect is limited if the high yields required are to be achieved. Crop growth for anaerobic digestion allows the possibility of producing energy without major change to the appearance of the landscape. The same crops which are currently grown for fodder for animal production and for grazing of animals can be used. Where high yield crops such as maize are incorporated into the farm they can be grown as part of crop rotation systems. The anaerobic digesters themselves, if farm based, do not require to be very large and have a similar appearance to grain silos already in use in farms. Digestate storage replaces the already existing systems for slurry storage and can use the same tanks, with the addition of covers to capture any final methane emissions. Where animals are kept on farm and the slurry produced is digested there are environmental benefits in terms of odours and reduction of pathogens.

Modern farming has involved the reduction in labour and increased use of mechanical implements in order to improve efficiencies. Globalisation of the transport of agricultural products has also led to cheaper imports of products such as milk. These factors have led to many smaller farms, and those in disadvantaged areas such as uplands going out of business. The requirement for energy sourced from renewable materials such as crops gives new possibilities for these farms. A digester centred within a number of farms could take the crops grown there for input and return the digestate. The energy produced has greater value than the milk and crops currently produced and the digestate assists in reducing the production costs by replacing mineral fertilisers.

AD provides an opportunity to produce energy with minimal visual impact on the environment and with the possibility to increase the diversity of crops grown, whilst maintaining farms and farming traditions which are otherwise being lost.

7. Conclusion

Anaerobic digestion provides an efficient means of producing a flexible form of energy from renewable resources in the form of crops and agricultural wastes. Unlike other forms of crop based fuels it can make use of a wide range of plant species often as whole crop, and materials that would otherwise be discarded for example tops of plants such as sugar beet, vegetable wastes and animal slurries. Currently many of the crops used as feedstocks for anaerobic

digesters are the same as those used for animals, particularly dairy cattle. As the techniques used to produce the relevant crops are the same as those already existing to produce fodder for animals, there is the advantage that there is no need for farmers to change their farming practices or invest in new machinery. This also means that farmers can change the use of the crops produced according to market forces. There is currently a decline in the requirement for milk from some European countries resulting in reduction in the size and number of dairy herds. This land, which will be unused could be used for the production of crops for use in AD. Similarly set-aside land and fallow land which is currently unproductive can be used with suitable crops to maximise land use and efficiency.

The biogas produced in the anaerobic digestion process, is a flexible fuel and can be put to a range of uses including: direct heating, combined heat and power and as transport fuel. The technology for biogas production is scaleable and energy could be produced with minimal impact on the appearance of the environment. The digestate produced as part of the process can be used to improve soils and reduce the requirement for energy hungry mineral fertilisers. The use of digestate could also lead to the improvement of 'marginal' lands in order that they might be improved and economically produce crops, which could be fed to digesters and so on.

Anaerobic digestion provides energy from the same crops as bio-diesel and bio-ethanol but with greater efficiency and in a form which has a wider range of uses. It should not be considered as a replacement for these fuels but has great potential to develop alongside them and can be used to provide energy in areas where the land is not suitable for crops for the liquid bio-fuels. The potential of the biogas produced to replace currently used fossil fuels is promising and will increase as varieties of crops used are bred to give higher yields and improved methane potentials.

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