Project no. **SES6-CT-2004-502824**

Project acronym: **CROPGEN**

Project title: **Renewable energy from crops and agrowastes**

Instrument: Specific Targeted Research Project

Thematic Priority: SUSTDEV: Sustainable Energy Systems

Publishable Final Activity Report

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Revision [0]

Publishable Final Activity Report

1 Project execution

Project name: Renewable energy from crops and agrowastes
Project acronym: CROPGEN
Contract number: SES6-CT-2004-502824

Project logo: cropgen

Website: **www.cropgen.soton.ac.uk**

Summary description of project objectives
The overall objective of the research is to produce from biomass a sustainable fuel source that can be integrated into the existing energy infrastructure in the medium term, and in the longer term will also provide a safe and economical means of supplying the needs of a developing hydrogen fuel economy. The work is based on the use of anaerobic digestion (AD) as a means of producing methane from biomass, including energy crops and agricultural residues. The technology for methane generation by biochemical means is well established: the breakthrough to a cost-effective and competitive energy supply will come from engineering and technical improvements that can be made to increase biomass conversion efficiencies, and from reductions in the cost of biomass. In addition to developing process technology aspects of AD, the research will determine how the technology can best be applied to provide a versatile, low-cost, carbon-neutral gaseous biofuel within an environmentally sound and sustainable agricultural framework.

Participants
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Greenfinch Ltd, UK (Greenfinch)
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1.1 Key findings of the research

1.1.1 Evaluation of potential energy crops and agro-wastes for anaerobic digestion

An extensive review was undertaken of the available literature on potential crops, including non-food crops, energy crops and other plant species not currently grown as crops. Data collection concentrated on those species suitable for growing in European locations and included some that are currently regarded as energy crops, for example as identified in the reviews of [1 and 2]; and natural vegetation that could be used for energy production, as identified by [3]. It was concluded that a number of criteria were useful in assessing the value of crops as feedstock for anaerobic digestion. These included biomass/biogas yield; input energy requirements; alternative/secondary crop uses; land use/availability; and ecological and environmental factors. It is, however, difficult to determine an ideal feedstock species based only on biomass yield as this is affected by many factors including geographical location, fertiliser input, previous cropping and climate. The amount of material harvested also depends on the reason the crop was produced and which part of it is being harvested. For example, winter wheat (*Triticum aestivum*) grown in the UK will yield 6.9 tonnes of dry matter (tDM) ha^{-1} of grain. The same crop harvested earlier as 'whole crop' and stored as forage may yield 12 tDM ha^{-1}. Similarly, yields of different crops vary across the European region and in the extremes certain crops will not grow or will require irrigation to achieve acceptable yields. Different species, and even cultivars, therefore need to be identified to select the one best adapted for the local climatic and soil conditions.

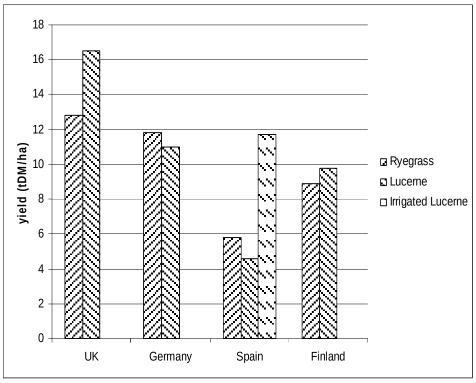


Figure 1. Typical yields (dry tonnes ha^{-1}) of 2 forage grasses in 4 EU locations

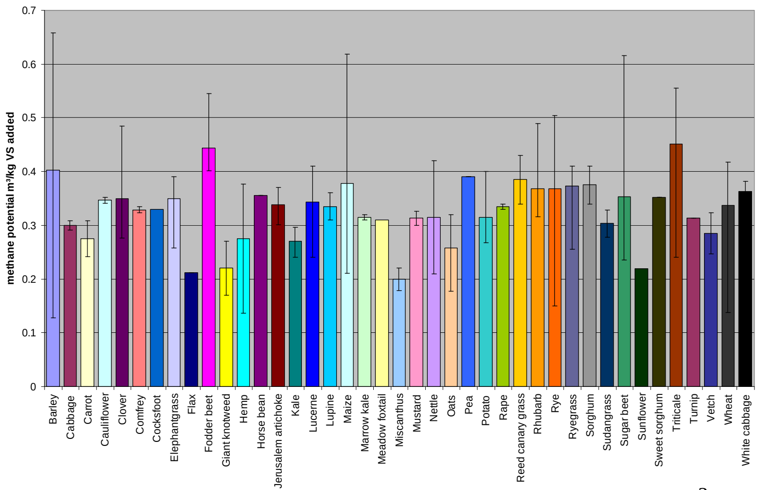


Figure 2. Literature values of the methane potential (m^3 kg^{-1} VS) of a range of crop species grown in the EU

Figure 1 gives an example illustrating the differences in yield for two forage grass species grown in four geographical regions. Figure 2 shows reported average values of the methane potential of a number of crops, with error bars showing the range in these values.

Even high yielding crops with a good methane potential may not be the ideal ones to grow as the net energy production has to take into account the whole life energy requirements in growing and processing the crop through to methane. The energy required in crop production can be divided into two types: direct energy – fuel used in field operations and labour; and indirect energy – energy required to produce equipment and materials used in the production of the crop. Indirect energy includes that required for fertilisers and pesticides, and the manufacture, delivery and maintenance of agricultural equipment. Information on crop yields (where known) climate and fertiliser requirements, potential methane yields, cultivation operations was included in a crop production database (Microsoft Access format) using average values reported in the literature [e.g. 4, 5, 6, 7, 8, 9, 10]. Information in the database can be used to calculate a potential energy balance for digestion based on a unit of land area. Two factors that strongly influence this energy balance are the fertiliser and irrigation requirements for different crops. Reducing fertiliser inputs, for example by planting leguminous crops, species which have a symbiotic relationship with bacteria that fix nitrogen, can significantly impact on the energy ratio of the crop as shown in table 3 where whole crop wheat and red clover are compared.

Table 3. Methane energy production ratios for a leguminous and non leguminous crop

Crop	Yield tDM ha^{-1}	Input energy GJ ha^{-1}	Output fuel energy GJ ha^{-1}	Energy ratio
Whole crop wheat	12.1	25.1	88.8	3.53
Red Clover	15	6.6	103.8	15.7

Other crops, for example white mustard (*Sinapis alba*) and stubble turnips (*Brassica rapa*), can be used as 'catch' crops and provide nutrient capture, an energy source and soil cover at times when land might otherwise be fallow, thus increasing overall biomass yield per hectare within the agricultural year. Mixed cropping, crop rotation, double cropping and intercropping are all possible ways of incorporating energy crops into more effective production cycles to maximise net energy gain per unit of land area. Crop residues left on the land also form another important source of biomass and include cereal straws and vegetative biomass from root crops.

1.1.2 Determination of biochemical methane potentials and kinetic studies

The biochemical methane potential (BMP) test has been widely used to assess the digestibility of organic matter, including plant material. The project has established a database of more than 700 BMP values from both laboratory determinations and the literature. Due to its non-invasive characteristics, ^{13}C CPMAS NMR was tested at Wageningen University as a possible method to replace traditional Van Soest analysis for plant fibre analysis and attempts made directly to link fibre composition measured using these techniques, to laboratory-determined BMP values. The strongest correlation (Figure 3) was found between the content of (lignin + cellulose) and could be used to estimate the CH_4 production (or BMP).

Additional experiments were undertaken by other partners to assess factors that could influence the BMP value, in an effort to standardise the procedure and facilitate interpretation. These included the method of preparation of the material, particle size, source of inoculum; substrate to inoculum ratio, and the use of buffers. Although the work has gone some way to provide an understanding of the factors that influence the test there is still no agreed standardised procedure. Both simple and pseudo-parallel first order kinetic models were used to help evaluate the results.

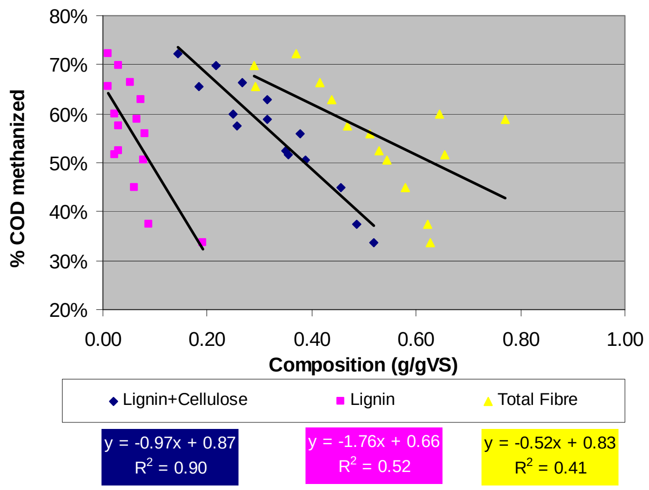


Figure 3. Dependence of methanisation on lignin, cellulose, and total fibre content in 15 plants

1.1.3 Pre-treatments to enhance methane production from energy crops

The aim of this part of the research was to assess processes that take place between harvest and anaerobic digestion of energy crops. From an economic viewpoint it is important identify and minimise any energy losses during storage. Experiments were conducted with grasses (mixtures of timothy and meadow fescue, timothy and clover and ryegrass) and sugar beet tops by partners at JyU and for maize (whole crop and grains) at BOKU.

1.1.3.1 Substrate pre-treatments

Different pre-treatment methods including size reduction, alkaline treatment and thermal pre-treatment (steam explosion) were evaluated. No significant effects on methane production were observed by reducing particle sizes of maize from a distribution typical of forage feeds down to 1 mm. Thermal pre-treatment at varying temperatures and reaction times was used on grass and whole crop maize silage and showed a considerable difference in effect between the two crops in terms of making sugars available. Values for overall methane production in batch fermentation tests (Table 4) showed that thermal pre-treatment significantly improves yields from grass silage, with the best results obtained at 140 °C.

While this kind of treatment appears suitable for fibrous material like grasses, it cannot be recommended for substrates with high starch content like maize. In the case of whole crop maize silage, methane yields after pre-treatment are generally lower than the untreated control (Table 5) due to the rapid degradation of starch into compounds that cannot be anaerobically digested and may have inhibitory effects. Alkaline pre-treatments using NaOH and $Ca(OH)_2$ + Na_2CO_3 increased the methane potential from sugar beet tops and grass by 10 and 17% respectively. Acid pre-treatments using 20% peracetic acid (PA) increased the methane yield of grass by 9 % and oat straw by 4 % When the organic matter losses due to treatment were taken into account, however, there was no net increase in methane yield.

Table 4. Total solids (TS), volatile solids (VS) and methane potential after pre-treatment of grass silage (GS) and whole crop maize silage (WCMS)

	TS %		VS %		CH_4 production $Nm^3\ t^{-1}$ VS	
	GS	WCMS	GS	WCMS	GS	WCMS
untreated control	37.4	32.3	32.8	31.1	353.2	486.2
185 °C, 5 min	13.1	14.6	11.5	14.0	407.6	446.5
140 °C, 5 min	16.7	13.1	15.0	12.7	472.3	440.5
140 °C, 20 min	13.4	14.8	11.9	14.3	480.8	424.3
185 °C, 20 min	13.0	13.4	11.4	12.9	387.6	402.2
162 °C, 12.5 min	14.2	14.0	12.5	13.5	404.4	466.3
162 °C, 12.5 min	14.3	15.8	12.6	15.2	418.1	440.5

1.1.3.2 Effect of different silage additives on whole crop maize silages.

Silage additives based on homo and heterofermentative lactic acid bacteria were compared with untreated silage. The addition of amylase, silage stored under semi-aerobic conditions, and silage spoiled with *Clostridium tyrobutyricum* were also tested. Conventional silage additives did not improve the biogas yield, but the results on storage stability in a full-scale silo indicate that they may reduce silage losses. Spoilage with *C. tyrobutyricum*, however, showed a significant improvement in methane yields as a result of the hydrolysis of starch and the formation of butyric acid; but the addition of *C. tyrobutyricum* was not a pre-requisite as *Clostridium* strains were predominant in the buffered silages, even without pre-inoculation. These were only effective when the ensiling conditions were favourable for their growth, however, and are not applicable in a conventional silo. Because of this and because the metabolites may cause odour emissions it cannot not be recommended to use *Clostridia* as a starter culture.

1.1.3.3 Storage stability and aerobic deterioration of silages.

Losses during ensiling in lab-scale experiments were in the range 1.4-8.0% of TS but higher losses were anticipated in full-scale silos. To measure these, BOKU-IFA monitored a silo filled with whole crop maize part of which was covered with plastic film and part with digestate fibre. The crop was weighed into the silo and bulk density estimated by surveying the height. A mass balance (shown in Figure 4) indicated considerable losses during the storage period with both types of coverage. The use of digestate cover resulted in additional 8.7 % loss of organic matter compared with the film.

Work carried out by JyU and Metener looked at ryegrass and timothy-clover stored in the field in plastic covered bales at ambient temperatures and also stored for 2 - 6 months under controlled conditions in laboratory studies. Effects of additives and moisture content were studied in detail and showed that methane yield in digestion tests was unaffected if timothy-clover was stored without pre-wilting and ryegrass stored after 48 h of pre-wilting, although actual harvest conditions (moisture) may affect pre-wilting requirements. There were slight variations in the methane yield ($m^3\ kg^{-1}$ VS added) as a result of the method of storage but more importantly the mass loss of timothy-clover stored in field conditions was high, and for better overall energy recovery the effluent should be collected and used for biogas production. Pre-wilted ryegrass was very dry and no mass loss occurred during field storage. Biological additives did not improve the methane yield of the crops studied.

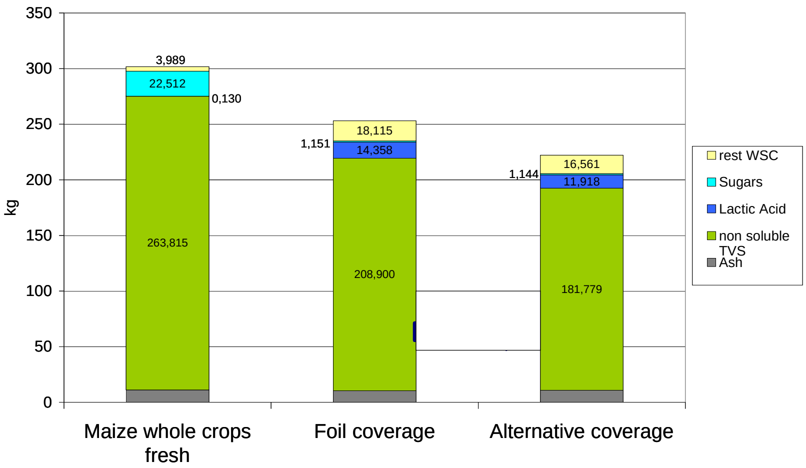


Figure 4. Estimated mass of material from ensiled whole crop maize using plastic film (foil) and digestate fibre (alternative coverage)

1.1.4. Single phase trials, co-digestion and digestate plant nutrient assays

Experiments were carried out in bench, pilot and full-scale digesters on a variety of different substrates as shown in Table 5; some of the parameters are given in Table 6. Trials on sunflower flour at CSIC showed good operational stability up to loadings of 2 kgVS m^{-3} d^{-1} with specific methane yields close to the maximum observed at hydraulic retention time (HRT) > 25days. At a loading of 3 kgVS m^{-3} d^{-1} the specific methane yield decreased considerably although the maximum volumetric yields were reached at this loading with a HRT of 30 days. Digestion at this loading was unstable, however, with high volatile fatty acid (VFA) concentrations and a poor alkalinity ratio.

A full-scale digester with a primary and secondary fermenter each of 1500 m^3 was fed with both a mono-fermentation of maize silage and mixture of maize and grass+clover silage. The digester was monitored for a period of 583 days by BOKU-IFA and a summary of the key digestion parameters, as derived from a mass balance around the primary and secondary digesters, is given in table 5. The maize/grass+clover silage mixture required recirculation of twice the mass of process liquid every day, resulting in a reduction of the HRT for each stage. BOKU-IFA also monitored a two stage digester located in Reidling, Lower Austria which co-digested pig manure with whole crop maize silage, maize grains and smaller amounts of residues from vegetable processing. During the 3-year monitoring period the plant underwent a number of operational and design modifications taking its capacity to 1000 kW nominal electrical power with utilisation of the heat from CHP units for district central heating. Operation was originally as a two stage digester (500 kW_e output) and finally as two main digesters (1 MW_e output) with a covered digestate storage tank. The data given in Table 6 for this plant relate to two stable phases of operation at either end of the transition.

Table 5. Substrates used in continuous and semi-continuous digestion trials

Operation	Substrate	Scale	Temperature	Partner
Semicontinuous	sunflower flour	lab	mesophilic	CSIC
Continuous	maize, grass + clover silage	full	mesophilic	BOKU IFA
Continuous	pig manure, whole crop maize grain silage, vegetable processing waste.	full	mesophilic	BOKU IFA
Semicontinuous	maize	lab	mesophilic	Soton
Semicontinuous	various crops and manure	lab	mesophilic	JyU
Semicontinuous	grass, asparagus and salad crop waste, and turkey manure	pilot	mesophilic	Greenfinch
Semicontinuous	Market waste	pilot	mesophilic & thermophilic	UNIVE-DSA
Semicontinuous	maize	pilot	mesophilic	Metener
Semicontinuous	grass clover mix	pilot	mesophilic	Metener

Laboratory-scale digestion trials were undertaken by Soton using ensiled forage maize as the sole substrate. The digesters were operated following two regimes: the first used a predetermined nominal retention time within the reactor with the addition of tap water to maintain a constant volume; the second simply removed sufficient digestate to keep the reactor at a constant mass after addition of the weight of substrate required for the desired loading, allowing a 'natural' HRT to be established. Digesters in both modes of operation were run over a range of loading rates from 1 - 6 kgVS m^{-3} d^{-1} and maintained for a minimum of 3 retention times at each loading to ensure steady state conditions were achieved. When running for extended periods using maize as the sole substrate it was found necessary to add a trace element supplement to the reactors. The natural retention time reactors showed very good solids destruction (80% VS) and specific methane production in the region of 0.35 m^3 kg^{-1} VS added, but at loading rates above 4 gVS l^{-1} day^{-1} there was a gradual accumulation of propionic acid resulting in reactor failure after less than 2 retention times (140 days).

Co-digestion trials carried out by JyU at laboratory scale gave the best specific methane yields at a 20-day HRT when cattle slurry was mixed with the test crops to provide 30% of the feedstock volatile solids. Both increasing the proportion of crop material and increasing the loading to 4 kgVS m^{-3} d^{-1} decreased the specific methane yield of the mix. Co-digestion trials at full scale (150 m^3 digester) were undertaken by Metener using the same mixes in which the silage was chopped with a diet feeder before mixing with the slurry in a pre-mix tank and feeding to the digester

The work at BOKU-IFA, JyU and Metener highlighted the existence of a residual methane potential in the digestate, which in the case of a short retention time continuously stirred tank reactor (CSTR) used in the JyU study was as much 50% of the methane potential. Greenfinch carried out pilot-scale studies using single crop species of maize, fodder beet and ryegrass in 0.5 m^3 working volume digesters. These were operated without addition of water or recycled liquid to maintain a 'natural' retention time governed simply by the displacement of digestate with fresh substrate. Greenfinch also carried out lab-scale digestion studies using potatoes, carrots, parsnips, Jerusalem artichokes, lucerne, field beans and a mixture of cow slurry, yogurt waste and DAF sludge, the results of which are not presented in this summary. Metener carried out pilot-scale studies in two reactors of 2.3 and 2.7 m^3 using maize silage, corn cob silage, timothy-clover silage, potato silage and a co-digestion mix of silages of potato and timothy with cattle slurry. Both corn cob silage and potato silage when used as single substrates led to digester failure, probably due to an unfavourable C:N ratio.

Table 6. Main findings from single phase trials

Study	**loading rate (kgVS m^{-3} d^{-1})**	**HRT * (days)**	**Volumetric CH_4 prod. m^3CH_4 m^{-3}**	**Specific CH_4 prod. m^3CH_4 $kg^{-1}VS_{added}$**	**% VS removal**
CSIC - sunflower flour	1 - 3	15, 20, 25, 30	0.25 - 0.56	0.13 - 0.26	72 - 92
BOKU - maize primary digester	5.2	34	1.52	0.29	67.5
BOKU - maize secondary digester	1.7	39.4	0.28	0.17	62
BOKU - maize combined digesters	2.6	73.4	1.8	0.35	88
BOKU - maize/grass clover - primary	5.4	24.1	1.28	0.24	53
BOKU - maize/grass clover - secondary	2.5	26.2	0.43	0.17	39
BOKU - maize/grass clover - combined	2.7	50.3	1.71	0.32	81
BOKU -pig manure, maize, veg. waste	2.1	133	1.49	0.39	89.7
BOKU -pig manure, maize, veg. waste	4.2	82	2.83	0.35	87.4
Soton - maize	2-6	20-60	-	0.33	75
Soton - maize	2-8	70-140	-	0.35	80
JyU - cow manure	2	20	0.30-0.32	0.15-0.16	20 - 26
JyU - cow manure/ 30% grass	2	20	0.54	0.27	53
JyU - cow manure/ 30% sugar beet tops	2	20	0.46	0.23	55
JyU - cow manure/30% oat straw	2	20	0.43	0.21	33
Metener - cow manure/ timothy silage	3.1	23.6	0.63	0.21	-
Greenfinch - fodder beet	4	36	-	0.28	77
Greenfinch - maize	4	62	-	0.32	83
Greenfinch - maize	2	123	-	0.39	77
Greenfinch - ryegrass	2	100	-	0.47	-
UNIVE-DSA- market waste (thermophilic)	0.7, 2.2, 4.0, 6.2	20, 18, 16, 14	1.15(OLR 4.0) 2.12(OLR 6.2)	0.42(OLR 4) 0.51(OLR 6.2)	82 - 91
Metener - maize	1- 1.4	142 - 192	0.45	0.37	-
Metener - Timothy	2.9	68	0.62	0.21	-
Metener - potato silage (20%)/ Timothy (45%)/slurry (35%)	1 - 2.8	88	0.35 - 0.95	0.34	-

* including any recycled liquor and assumes a density of slurried feedstock to be 1000 kg m^{-3}
[(a)] Temporary leakage in the gas system

Work by UNIVE-DSA showed that single phase digestion of market wastes could be effective under thermophilic conditions up to loading rates of 6 kgVS m^{-3} d^{-1} whilst maintaining stability of pH (7.5-8), alkalinity (7000 mg $CaCO_3$ l^{-1}), and low VFA (<320 mg l^{-1}).

1.1.5 Process and reactor innovation for optimisation of biogas production

Dealing with relatively novel feedstocks such as energy crops requires consideration of whether better reactor designs and operating regimes are possible. The research has looked at a range of systems from low-cost static bed reactors to complex multi-phase systems with uncoupling of solids and liquid retention times. Trials with static permeating bed systems were carried out at Soton using ensiled whole crop fodder maize as both the substrate and bed medium. The maize showed very rapid acidification reaching low pH values making the use of a single phase batch reactor, with or without liquid recirculation, impractical due to the very low rates of solids destruction. The work therefore focused on two phase systems in which the bed liquors were removed and replaced by clean water or by recycled liquid after treatment in a second stage methanogenic reactor. The research investigated the effects of changing the flush rate, inoculum to substrate ratio in the bed, the effect of introducing buffering, and the interaction between phases. Physical and chemical factors relating to the flush water had some effect on the solids destruction and theoretical methane yield from the hydrolysis and acidification products generated. Major improvements in solids destruction, however, depended not just on replacement of the bed liquor to flush out acid products, but on recycling of the effluent from the second phase reactor to provide a constant source of re-inoculation with microorganisms. This also had the effect of allowing the first stage reactor to become methanogenic, even at fairly short solids retention times, which helped to maintain the pH and buffering of the system leading to improved rates of solid destruction. Work at JyU also showed the necessity of a two phase system when using leach beds for the digestion of crops such as grass silage and sugar beet that contain a proportion of very readily degradable material.

Trials were carried out by Soton with CSTR systems operated in hydraulic flush mode as the hydrolysis/acidification stage of a two phase system. These showed similar levels of solids destruction to those achieved in the leach bed reactors but allowed a much higher VS loading to be applied. This was possible due to the semicontinuous feeding mode which involved separation of the liquid fraction by gravity through a coarse membrane and daily removal of a proportion of the retained solids. These systems were successfully operated at loading rates of up to 20 kgVS m^{-3} day^{-1} with solids retention times (SRT) of 5 days and a flush rate equivalent to 2.85 days, giving VS destruction in the region of 45-50%. Although this value is low in comparison with that achieved by a conventional long retention single pass system, the volumetric solids destruction rate is high at 10 kgVS m^{-3} day^{-1}. The system is therefore high rate but not very efficient in recovering potential energy from the crop as much of this remains in the undigested fibre. Preliminary trials are in progress to examine the potential for a three phase system in which the third stage could be a thermophilic high solids reactor designed to maximise the energy recovery from the residual fibre fraction.

More conventional two-phase systems were investigated by UNIVE-DSA for digestion of post-distribution market wastes. These were tested and shown to operate successfully at a loading rate of up to 77 kgVS m^{-3} day^{-1} on the first stage at a HRT of 1 day, passing forward a load of 10.6 kgVS m^{-3} day^{-1} to the second stage reactor with a 7-day HRT. Both stages were operated at a thermophilic temperature of 55 ^{o}C. The volumetric gas yield of the system was 3.2 m^3 CH_4 m^{-3} reactor day^{-1} with a specific methane production of 0.043 m^3 CH_4 kg^{-1} VS added. The adoption of a two phase system does not appear to lead to a great improvement in terms of gas yield or stability but allowed the system to operate at a higher OLR.

Plug flow systems were investigated using a liquid agro-waste substrate (lactose from cheese production) and ryegrass as an example of an energy crop. For the liquid waste plug flow was simulated through repetitive batch experiments with each batch representing passage of a plug through the reactor. Any plug flow reactor must by definition have a high initial loading when the full load of substrate is introduced to the contents of the plug rather than mixing instantaneously with the whole reactor volume. When using a readily degradable substrate such as lactose this 'shock' loading produced some interesting reactor conditions corresponding to four phases:

1 Hydrogen fermentation phase. This was observed during the first 20 -24 hours after feeding. Up to 50% of total biogas was produced during this period with a hydrogen content of 27-34% by volume.
2 VFA production phase. This was observed between the 2nd and 4th days of each run. The VFA concentration rose very quickly and peaked during this period, gas production slowed down, hydrogen concentrations fell and methane increased. This step can also be considered as a lag phase between hydrogen and methane production.
3 Methanogenic phase. This occurred on 4th - 7th days. Gas production rates rose again and high methane concentrations were observed, accompanied by a steady overall decrease in VFA levels. Up to 35% of the total gas volume can be produced during this stage.
4 Declining phase. This occurred between 7th - 14th days. Gas production slowed down in this period, but the methane percentage was still high. This stage can also be considered as a stabilisation stage: alkalinity was found to improve and the alkalinity ratio decreased. This step is important as it provides enough buffering capacity for the next load of substrate: if this is applied too early the system will fail.

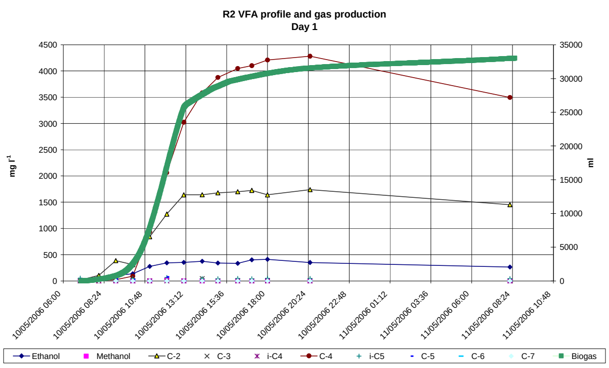


Figure 5. Gas production profile for plug flow digestion of lactose

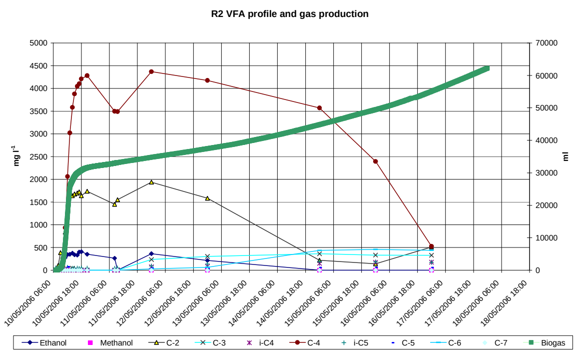


Figure 6. VFA profile for plug flow digestion of lactose

Gas and VFA profiles associated with these phases are shown in Figures 5 and 6. Work by Soton and OPL on plug flow digestion of ryegrass indicated the importance of optimising the recycle ratio by retaining solids. This has the advantage of both providing an inoculum and obtaining any residual energy from the substrate. There are thus similarities between an optimal plug flow approach for high solids substrates and the conditions required for successful operation of a leach bed reactor.

1.1.6 Bio-kinetic data, modelling and digester control

BOKU-IAM developed a software tool for simulation of AD in the form of a virtual laboratory for processing and interpretation of data, formulation of 'fit for purpose' mathematical models, training purposes and dissemination of results. The heart of the software is an adapted version of Anaerobic Digestion Model 1 (ADM1) [11]. Outputs from the model are the gas production, methane content, pH, volatile fatty acid concentration, propionic acid concentration, acetic acid concentration and the COD Reduction. The model has so far been calibrated for 9 substrates (blue, white and yellow lupin, maize, soy, sunflower, rape, rye and wheat), and up to 4 of these can be mixed. An example of the model output is shown in Figures 7 and 8.

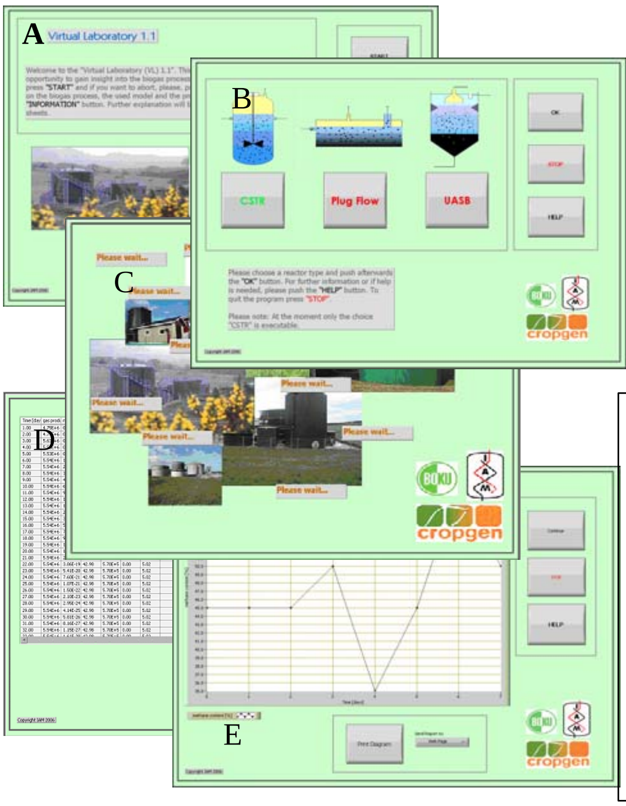


Figure 7. Screenshots from the Virtual Laboratory A) Start of program, B) Reactor types C) Simulation of AD process, D) and E) Output tables and graphs

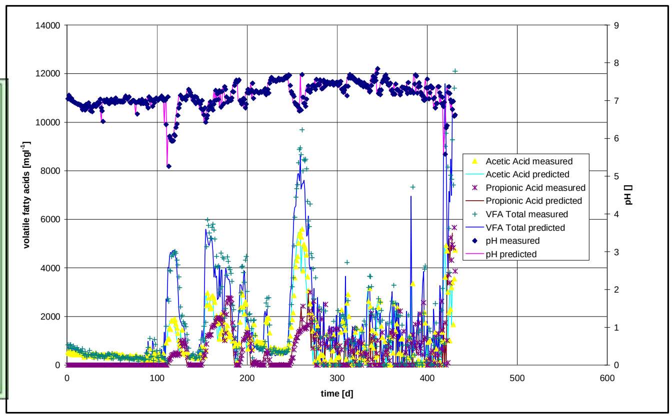


Figure 8. Model results: pH, acetic acid, propionic acid and volatile fatty acid over time

A Fuzzy Logic Control Tool was also developed by BOKU-IAM using as input either the total fatty acid concentration, the pH or the propionic acid concentration, with the methane content and the gas production and organic loading rates. The output gives the organic loading rate to be applied for the following day.

The tool was tested with ADM1 to further refine the program against a number of appraisal factors including gas production, methane content, concentration of acetic, propionic and total volatile fatty acids, COD reduction and pH. The final control tool had the structure given in figure 9. The fuzzy algorithm was then incorporated into a graphical user interface and tested on laboratory reactors. Control by this means showed an improved methane yield and more stable reactor conditions.

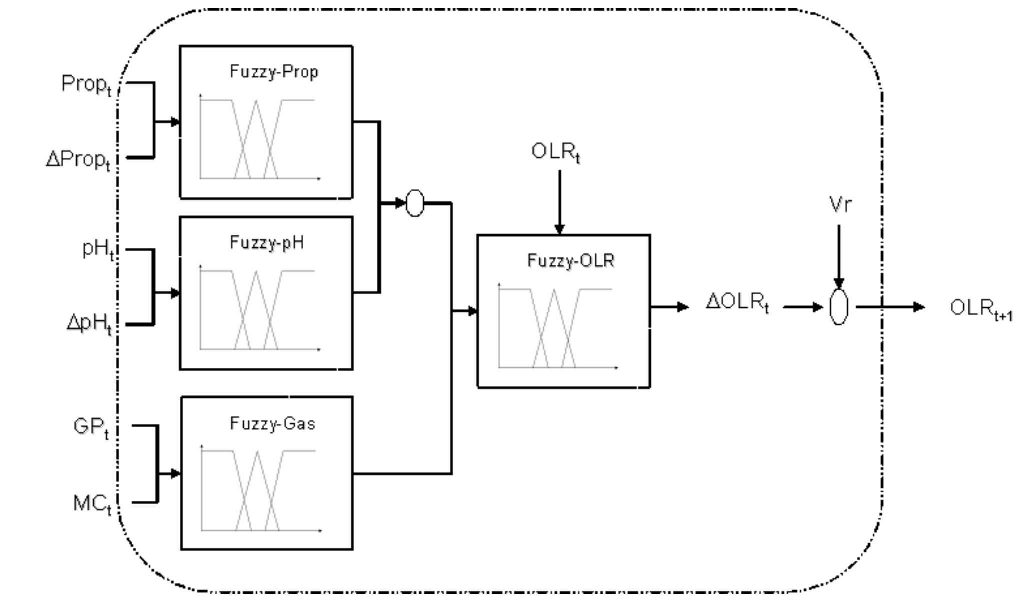


Figure 9. Structure of the fuzzy logic control algorithm.

1.1.7 Large-scale field trials

The cultivation of energy crops requires inputs of time and energy that have to be taken into account when modelling both the net energy productivity of a biomass-to-energy scheme and the economic costs. There are some data available in the literature on fuel consumption and man-hours involved in the cultivation of different crops [12] and the research here was to verify this information. Questionnaires were used to collect data on cultivation, fertilisation, harvest and transport from farmers supplying the biogas plant in Strem, Austria. The required working time and fuel consumption of each step were recorded with the system border defined as the unloading point of the digester feedstock [13]. These data are shown in Table 7.

Detailed information was collected by JyU on the farming inputs used in cultivation of timothy-clover mix at the Kalmari farm near Jyväskylä, Finland, based on a field rotation of four years. Table 8 shows the primary data from which fuel usage and labour time can be calculated knowing that the average fuel consumption of the tractor was 18 l h^{-1} (manufacturer Valtra).

Table 7. Working time and fuel consumption for 4 different crops shown per hectare of cultivation and tonnes dry matter (DM harvested)

Crop	Working time (h t-^{1} DM) farmers	Fuel consumption (l t^{-1} DM) farmers	Working time (h t^{-1} DM) [12]	Fuel consumption (l t^{-1} DM) [12]
Maize silage	0.70	8.9	0.70	7.1
Clover grass (3 cuts)	1.32	9.0	1.16	8.0
Sunflower	0.97	9.0	1.18	8.0
Bean mix*	1.57	30.0	2.06	23.6

* mix of bean, barley, oat, pea, rape, mustard

Table 8. Data for calculation for labour and fuel usage in the cultivation and harvesting of timothy grass.

	Plough	Liquid fertiliser	Solid fertiliser	Harrow	Seedbed cultivation	Roll	Sow and fertilise	Move	Harvest	Lime	Spray
Work width, m	2	15	6	4.5	4	4.5	3	3.2	6.4	12	20
Speed, km h^{-1}	7	8	8	7	7	7	6	7	7	7	8
Procedure times per year	0.25	2	0.25	0.25	0.5	0.5	0.25	2	2	0.25	0.5

Values <1 indicates that procedures have to be carried less frequently than annually.

There is also a potential for energy crop digestion to establish a closed cycle of soil nutrient replenishment by substituting digestate for inorganic fertiliser. This will impact upon the overall net energy production of the scheme. In Finland, for example, the recommended fertilisation for timothy grass is 220 kgN ha^{-1} yr^{-1}, 10 kgP ha^{-1} yr^{-1}, 70 kgK ha^{-1} yr^{-1} and 1750 kg of lime ha^{-1} yr^{-1} and, according to the literature, the energy consumption of fertiliser production is 13.89 kWh kg^{-1}, 2.67 kWh kg^{-1}, 1.86 kWh kg^{-1} and 0.12 kWh kg^{-1} for each component respectively. The need for these inorganic fertilisers can, however, be near zero under optimised conditions when digestate is returned into the fields. The nutrient content of a number of digestates was assayed by Greenfinch who also carried out trials on the use of cattle slurry digestate for fertilising grass leys. An example of the results is shown in table 9 where digestate was applied to a 3-year-old ley at 4 nitrogen loadings (1-4) and compared to the typical application used by the farmer (5) which was supplemented with mineral fertiliser. Typical values for the nutrient content of digestates from different digestion substrates are given in table 13

Table 9. Organic Dry Matter Yield yields (t ODM ha^{-1}) from six replicate trials using a 3 year old grass ley with different fertiliser applications

Treatment Replicate	(1) 327 kg N ha^{-1}	(2) 234 kg N ha^{-1}	(3) 182 kg N ha^{-1}	(4) 0 kg N ha^{-1}	(5) 381 kg N ha^{-1}	(6) 110 kg N ha^{-1}
1	7.2	5.8	5.6	4.9	7.9	6.1
2	8.6	6.5	4.6	3.4	8.7	4.9
3	6.7	7.9	5.2	3.4	8.1	4.9
4	6.6	6.8	5.6	5.9	6.9	3.3
5	6.7	6.2	5.0	3.3	7.6	5.4
6	8.1	5.8	4.5	7.9	8.9	3.5
Average	7.3	6.5	5.1	4.4	8.0	4.7
S.D	0.8	0.8	0.5	1.2	0.7	1.1

Table 10. Nutrient value of digestates from different primary substrates

Feedstock	N (kg tonne^{-1})	P (kg tonne^{-1})	K (kg tonne^{-1})
fodder beet	3.61	0.84	4.43
maize	4.06	0.98	3.38
ryegrass	3.6	0.19	3.71
field beans	4.88	1.94	9.02

1.1.8 Overall assessment for energy production

For a renewable energy source to be viable it must be able to produce more energy from renewable resources than is required from fossil fuels. Energy flows into and out of the system, within defined boundaries, have to be analysed in detail to determine if this is the case. For a crop-based biogas production system this includes crop production, digestion, biogas and digestate utilisation (Figure 10).

Feedstock production: AD can use most organic material as a feedstock and the overall energy balance is influenced by the choice of material. In general the best yields are from whole crop material although these are less easily digested as the lignin content increases. Co-digestion of waste materials, for example animal slurry or agricultural residues with crops can be used to enhance the digestion process and energy balance. The choice of crops may also be based on those that not only give the maximum potential energy but can be grown to enhance crop rotation systems or reduce fertiliser inputs in an integrated farming system for food and energy production.

Digester design: There is a wide range of digester types available. The majority of energy required, however, is needed for heating feedstock to digester temperature, maintaining the temperature of the digester and keeping the contents mixed. These energy requirements can be estimated on engineering principles although there is still some uncertainty as to the contribution to digester heating made through metabolic heat generation, the so called 'self-heating effect'

Post treatment/use of digester products: The AD process produces two outputs (digestate and biogas), which must be considered in terms of value both from economic and energy points of view. The digestate can be a valuable source of bio-fertiliser and contains the majority of the nutrients that were in the original feedstock: examples of nutrient values measured as part of the project are shown in table 10. If there is a requirement for heat the biogas can be used directly, without any form of processing as long as the methane content is high enough to burn, and recovery of the energy may be >90%. More typically biogas is used for CHP and the conversion to electricity may be only 30-35% efficient with a further 45-55% recoverable as heat. To use biogas as an 'approved' vehicle fuel energy is required to first to remove CO_2 and other impurities and then to compress the purified gas.

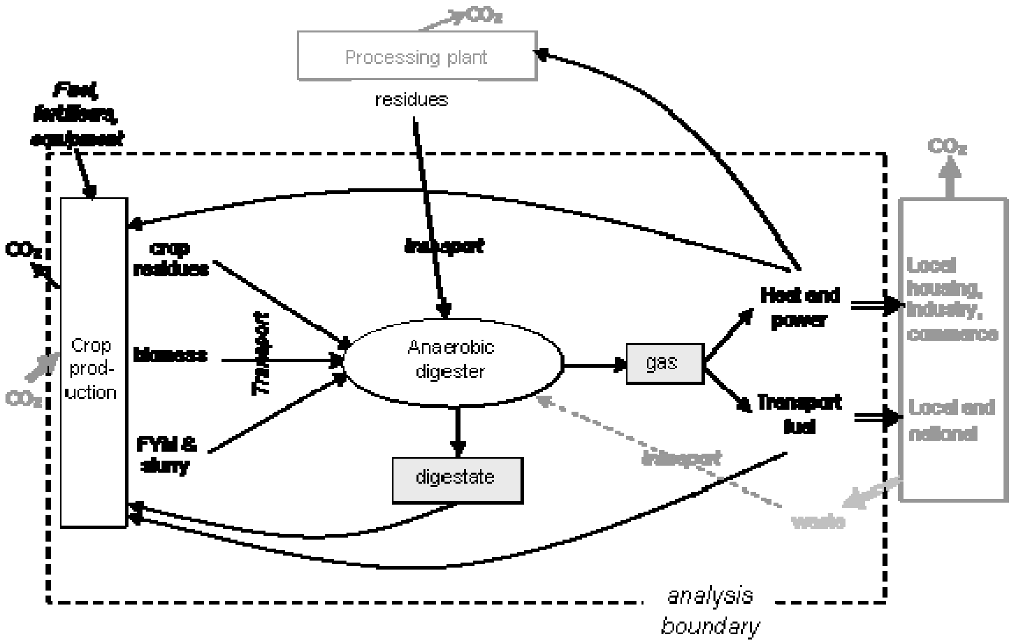


Figure 10. Main components and analysis boundary for crop-based anaerobic digestion system

1.1.8.1 Overall energetic assessment of bio-energy production

The research has produced a number of case studies for crop-based AD energy systems, and typical values of energy inputs into a commercial scale energy crop digester are given in table 11 with the probable biogas yield and thermal energy value. Thus the net crop energy yield is 127 GJ ha^{-1}. The real energy gain depends on how the methane is used, for example, conversion to electricity without heat recovery would only give a net gain of 17 GJ ha^{-1} (4722 kWh ha^{-1}) whereas conversion to vehicle fuel yields a net gain of 77 GJ ha^{-1} (equivalent to 2150 l of diesel).

The efficiency can be improved, for example by replacing fossil fuel based fertilisers with digestate; increasing the efficiency of electricity generation; reducing heat loss from the digester (or using self heating materials). The energy yield per hectare of crop used can also be improved by, for example: increasing the crop yield per hectare; reducing fertiliser inputs (e.g. by using legumes); reducing the number of crop operations; supplementing the crop based feedstock with animal slurries and agrowastes.

Table 11: An example of the energy requirement for a 2000m³ crop-based anaerobic digester

item	value	unit
digester capacity	2000	m^3
daily load	34.8	t day^{-1}
crop area	318	ha
crop energy requirement	5311	GJ $year^{-1}$
crop transport	93	GJ $year^{-1}$
parasitic heat requirement	2133	GJ $year^{-1}$
parasitic electricity requirement	420	GJ $year^{-1}$
digester embodied energy	1350	GJ $year^{-1}$
digestate disposal energy	260	GJ $year^{-1}$
total energy requirement (E_{in})	**9,566**	**GJ $year^{-1}$**
	30	**GJ ha^{-1}**
biogas produced	2,331,026	m^3
energy value (60% CH_4) (E_{out})	**49,930**	**GJ $year^{-1}$**
	157	**GJ ha^{-1}**

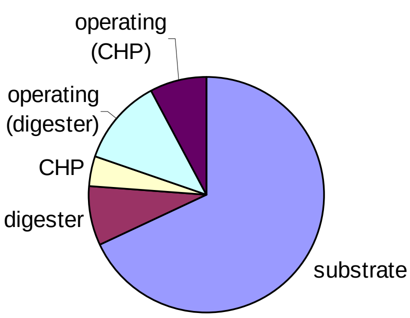
Table 12: Cost analysis for electricity generated from CHP

item	value	unit
substrate	11,000	tonnes
substrate cost	302,500	€ $year^{-1}$
digester capital	880,000	€
CHP size	420	$kW_{electricity}$
CHP cost	475,000	€
annual repayments	54,200	€ $year^{-1}$
operating costs (€4.8/tonne)	52,800	€ $year^{-1}$
operating cost CHP (0.01ct/kWh)	34,455	€ $year^{-1}$
total	**444,000**	**€ $year^{-1}$**
electricity generated	3,445,564	kWh $year^{-1}$
life cycle cost of electricity production	**0.13**	**€ kWh^{-1}**

1.1.9 Economic assessment

The economics of crop based anaerobic digesters are difficult to assess because of the number of site-specific variables including the type and construction of the digester, type of substrate/s used, source of substrates, and value of products (electricity, heat, transport fuel, upgraded biogas, digestate etc).

The research has gathered information concerning each of these factors which has been incorporated into an economic model by CUC. The elements in this model are: crop production costs; capital cost of digester and fuel utilisation equipment; operating costs; and capital depreciation including interest. An example of the results is given in table 12. These relate to an 11,000 tonne per annum plant with an operating life of 25 years, fed on maize with a methane potential of 0.35 m^3 kgVS $added^{-1}$. The major influence on costs is that of the substrate, as shown in Figure 11, and in the example used this will be the major influence on the profitability of the plant as shown in Figure 12. A feedstock cost greater than €36 per tonne of fresh matter takes the plant to a zero profit. The costs given are indicative rather than absolute and will vary from country to country and situation to situation. Anaerobic digestion is an efficient process for the production of energy and provides a good return for energy invested. In terms of economic life-cycles the impact is less positive for crop-based digesters due to the high cost of substrate production.



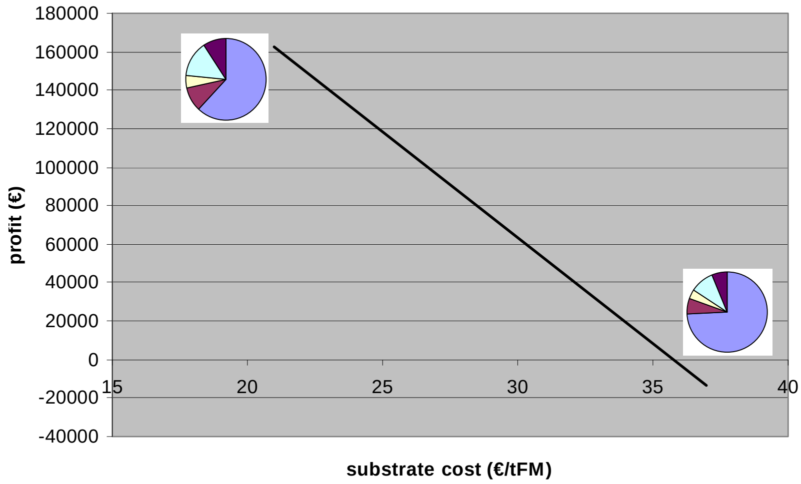


Figure 11. Cost proportions   *Figure 12. Effect of substrate cost on profit*

There are also less obvious benefits from on farm digestion as an energy source. The treatment of agrowastes will reduce the emission of greenhouse gases, and can make use of land which is less suitable for other crops or provide farmers with alternatives for diversification where traditional land uses for dairy or meat production may be in decline.

1.2 OVERALL TARGETS AND CONCLUSIONS

At the beginning of the CROPGEN project seven typical summary targets were identified, covering different aspects of the project as a whole. These are shown in Table 13.

Parameter		Target
1	Digester volatile solids loading rates for pilot-scale plant per unit of reactor capacity	10 kg VS m^{-3}
2	Digester volatile solids loading rates in innovative lab-scale two-phase systems, per unit of reactor capacity	20 kg VS m^{-3}
3	Biochemical methane potential of crops identified in research as suitable for energy production	0.35 m^3 kg^{-1}
4	Net crop energy yield after inputs into cultivation and harvesting	48%
5	Life cycle cost for conversion of biomass energy into methane	35 MJ/€
6	Full life cycle cost of energy production in the form of electricity	0.05 € kWh^{-1}
7	Full life cycle cost of energy production in the form of biofuel	0.036 € kWh^{-1}

Targets 1 and 2 have been achieved, in two-phase pilot-scale systems operated by UNIVE-DSA for co-digestion of market wastes and at laboratory scale in hydraulic flush systems at Soton. In the process of the research, however, a great deal more has been learned concerning the applicability of these systems. In terms of energy production, sophisticated systems with high volumetric yields may be less applicable than those with higher specific methane yields that are capable of maximising MJ per hectare. Target 3 has also been met, in a range of crops identified in the literature or grown and tested by Soton and WU: once again the lesson from integration between different parts of the research is that while the BMP of individual crop materials is an important factor, for optimum energy production it cannot be considered in isolation from yield in tonnes per hectare or from the other energy inputs needed for production. Targets 4 and 5 which embody some of the above principles have been met and exceeded, with examples of net crop energy yields of over 400% and life cycle costs for conversion of biomass energy into methane of 91 MJ $€^{-1}$. The two targets that have not been met are 6 and 7, with life cycle costs of electricity production currently coming in at around 0.13 € kWh^{-1} in an example based on maize. There are a number of reasons for this: the cost of substrate is a major factor, as is uncertainty about the actual costs of digester construction. This latter point is especially important as, being a new sector, plant investment costs are high and operating scales are still low. Perhaps most importantly, the work has demonstrated that the outcome of economic assessment is sensitive both to the choice of system boundaries and to factors which are themselves subject to considerable variation. This lends further support to the importance of energy as a fundamental accounting unit, but more work is clearly needed to clarify the influence of the main economic drivers and inhibitors to allow appropriate framing of policy and regulation.

Overall, the project has shown that biogas production on farms is technically feasible using conventional technology and can be applied to a wide range of feedstocks ranging from dedicated energy crops to agricultural residues. When using energy crops for methane production the net energy gain per hectare of land is very favourable compared to first generation liquid biofuels, the chief advantages being the ability to use whole crop material either as the main substrate or as a co-digestate, and the possibility of retaining nutrients and returning these to the land. Despite the high energy returns the economics of using only cultivated energy crops remain marginal due to the costs associated with crop cultivation.

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Section 2 Dissemination and use

2.1 Publishable results

The publishable results to date consist of the documents and presentations described below. Because of the number of documents, and the large size of many of the files involved, these have not been included in the text of this report but are presented in an appendix in CD format. The majority of these materials and a number of others are also available on the Publications page of the CROPGEN website www.cropgen.soton.ac.uk.

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
BMP assay development	Presentation to 10th IWA Specialist Conference on AD, Montreal (Oth_01)	1 Agriculture 2 Bio-energy	No further collaboration required. Work ongoing with IWA Specialist group	Available through CROPGEN website	**WU** and other partners involved
Influence on AD of flocculants	Presentation to 1st Int. Meeting on Environmental Biotechnology and Engineering, Mexico City (Oth_02)	1 Wastewater 2 Agriculture 3 Bio-energy	No further collaboration required. Work ongoing.	Being disseminated through publications etc	**UNIVE-DSA** and **UNIVR-DST**
Presentation on CROPGEN project and concepts	Presented to EU-Russia FP6 Bioenergy Workshop, Moscow (CG_05)	1 Bio-energy	No further collaboration required.	Available through CROPGEN website	**Soton** and all other partners
Examples of presentation materials from other workshops	CROPGEN workshops in e.g. BioExcell and UK AD (CG_03)	1 Agriculture 2 Bio-energy	No further collaboration required.	Available through CROPGEN website	**Soton** and all other partners
Poster for EPSRC international visit Southampton	EPSRC International Review visit (CG_04)	1 Bio-energy 2 Agriculture 3 Engineering	No further collaboration required.	Available through CROPGEN website	**Soton** and other partners involved
Presentation on OPL digesters	Example of talk by C Maltin (Oth_03)	1 Bio-energy 2 Agriculture 3 Engineering	No further collaboration required.	Available through CROPGEN website	**OPL**
Pilot scale 2-phase AD for energy crops	Presentation, Finnish Environmental Science conference (Oth_04)	1 Agriculture 2 Bioenergy 3 Engineering	No further collaboration required, work on-going.	Available through CROPGEN website	**JyU** and **Metener**
AD of energy crops	Seminar on agricultural biogas production, Kuopio, Finland (Oth_05)	1 Agriculture 2 Bioenergy 3 Engineering	No further collaboration required, work on-going.	Available through CROPGEN website	**JyU** and **Metener**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
Microbial fuel cells using AD	Poster, International conference on space microbiology, Belgium (Oth_07)	1 Bioenergy 2 Engineering	No further collaboration required.	Available through CROPGEN website	**BOKU-IAM**
Small-scale biogas comes of age	Presentation on small-scale digesters (Oth_09)	1 Bioenergy 2 Engineering	No further collaboration required.	Available through CROPGEN website	**Greenfinch**
Ensiling and biogas	Presentations to XIV International Silage Conference Dublin, Ireland (Oth_10 and 11)	1 Bioenergy 2 Agriculture	No further collaboration required, work on-going.	Being disseminated through publications etc	**BOKU-IFA**
Materials of Jyvaskyla University Summer School 2005	Summer school on renewable energy in biogas from crops and agro-wastes (JSS05_01 to 18)	1 Agriculture 2 Bioenergy 3 Engineering	No further collaboration required.	Available through CROPGEN website	**JyU, Soton, BOKU-IFA, Metener, Greenfinch**
ADSW 2005 workshop	Special workshop presentations to 4th IWA ADSW Conference (ADSWw_01 to 05)	1 Agriculture 2 Bioenergy	No further collaboration required.	Being disseminated through publications etc	**Soton, JyU, UNIVR-DST, UNIVE-DSA, Greenfinch,** plus Biotroll
ADSW 2005 conference papers	Presentations in the main sessions of the 4th IWA ADSW conference (Oth_Copenhagen_1 to 3)	1 Bioenergy 2 Engineering	No further collaboration required, research continuing.	Possible copyright	**BOKU, JyU** and other partners involved
Presentation and paper on ADM1 and CROPGEN results	Presented to 1st ADM1 Workshop (Oth_13 and 14)	1 Engineering 2 Bioenergy	No further collaboration required.	Possible copyright	**BOKU-IAM**
ICUC CROPGEN activities	Presentation, International Conference on Industrial Crops and Rural Development, Murcia, Spain (Oth_15)	1 Agriculture 2 Bioenergy	No further collaboration required. Work ongoing.	Available through CROPGEN website	**Soton** and other partners involved
Joint CROPGEN/ IEA meeting	Materials from special session with invited experts (CIEA_01 to 19)	1 Agriculture 2 Bioenergy	No further collaboration required.	Available through CROPGEN website	**BOKU-IFA** and other partners involved
Latin American Workshop on AD, Uruguay	Presentations to IWA Specialist workshop (Oth_Urguay_1 to 4)	1 Bioenergy	No further collaboration required.	Possible copyright	**JyU, BOKU, WU**
14th European Biomass Conference and Exhibition	Presentations and papers (Oth_Paris_1 to 3)	1 Agriculture 2 Bioenergy	No further collaboration required.	Possible copyright	**Soton, BOKU, Greenfinch**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
Biovakka plant presentation	Presentation to farmers (oth_16)	1 Agriculture 2 Bioenergy	No further collaboration required.	Available through CROPGEN website	**JyU**
Presentation on Greenhouse gas emissions	EC DG Environment working group (Oth_17)	1 Agriculture 2 Bioenergy	Work continuing on data collection and interpretation.	Available through CROPGEN website	**Soton**
Efficiency evaluation of energy crop digestion plants	FAO workshop (Oth_18)	1 Agriculture 2 Bioenergy	No further collaboration required, research ongoing.	Available through CROPGEN website	**BOKU-IFA**
Mini-symposium	Materials presented to Austrian biogas industry (VMS_1 to 8)	1 Bioenergy 2 Agriculture 3 Engineering	No further collaboration required.	Available through CROPGEN website	**BOKU-IFA** and other partners involved
Status of biogas production and application	Presentation to joint CROPGEN-IEA workshop at 15th European Biomass conference (Berlin_01)	1 Bioenergy 2 Engineering	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Workpackage summary report	Final CROPGEN meeting Berlin (Berlin_02)	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Addition of Clostridium tyrobutyricam and buffer to whole crop maize silage and its effects on chemical composition and biogas formation	Poster from 15th European Biomass conference (Berlin_03)	1 Agriculture 2 Biotechnology	No further collaboration required.	Being disseminated through publications	**BOKU-IFA**
Quantifying mass and energy losses of two different silo coverages for energy crops - full scale investigations of silage quality at an AD plant	Poster from 15th European Biomass conference (Berlin_04)	1 Agriculture 2 Bioenergy	No further collaboration required.	Being disseminated through publications	**BOKU-IFA**
CROPGEN presentation	Presentation, FP6 Biomass contractors' meeting, Jonkoping (CG_19)	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Critical remarks on monitoring and control of technical scale biogas plants	Presentation to 1st ADM1 workshop, Copenhagen 2005 (Oth_13 and 14)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**BOKU-IAM**

Publishable result	Description	Sector(s) of application	Stage of development / collaboration	Patents or other IPR protection	Owner & other partners involved
Anaerobic digestion in an integrated farming environment	Presentation, Wales renewable energy conference (Oth_19)	1 Bioenergy 2 Agriculture	No further collaboration required.	Available through CROPGEN website	**Soton**
Effect of different pre-treatments on methane yield from lignocellulosic substrates and pig manure	Abstract from International Conference on Agricultural Waste (Oth_20)	1 Bioenergy 2 Agriculture	No further collaboration required, research ongoing.	Being disseminated through publications	**BOKU-IFA**
Entwicklungen bei der Prozesssteuereng	Presentations to Biogas 06 conference (Oth_21 and 22)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Available through CROPGEN website	**BOKU-IAM**
Modelling the decomposition of energy crops in anaerobic digestion	Poster presentation Biomass 2005 (Oth_23)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Available through CROPGEN website	**BOKU-IAM**
Thermophilic co-digestion in single and separate phases	Presentation to IX Congresso annuale INCA (Oth_24)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**UNIVE-DSA**, UNIVR-DST
Efficiency gains within the anaerobic digestion process fed with energy crops, utilising plug flow.	IWA Young Researchers Conference (Oth_25)	1 Engineering 2 Bioenergy	No further collaboration required, research ongoing.	Being disseminated through publications	**Soton,** OPL
Methane production from reed canary grass	Poster and paper, Finnish conference of Environmental Sciences 2007 (Oth_26 and 27)	1 Bioenergy 2 Agriculture	No further collaboration required.	Being disseminated through publications	**JyU**
CROPGEN workpackage 7	Poster, Festsymposium - 60 Jahre IAM, Vienna (Oth_28)	1 Bioenergy 2 Engineering	No further collaboration required.	Available through CROPGEN website	**BOKU-IAM**
Anaerobic digestion and biogas technology within UK agriculture	Presentation to UK stakeholders and end-users (Oth_29)	1 Agriculture 2 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Greenfinch**
Sustainable energy production in microbial fuel cells	Poster, JSC conference, Vienna (Oth_30)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**BOKU-IAM**
Development of an on-line tool for the simulation of the anaerobic digestion process	Presentation to JSC conference, Vienna (oth_31)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**BOKU-IAM**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
AD of cheese farm waste using continuously-stirred tank reactors under two different feeding regimes	IWA Young Researchers Conference (Oth_32)	1 Bioenergy 2 Engineering 3 Agriculture	No further collaboration required, work ongoing.	Being disseminated through publications	**Soton,** OPL
On-line simulation of anaerobic digestion - an example for modelling and control of complex bio-processes	Poster, Life Science Circle - Industrielle Biotechnologie, Vienna (Oth_33)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**BOKU-IAM**
Single and two-phase thermophilic co-digestion of waste activated sludge and solid agro-waste. Performance comparison on pilot scale.	Presentation, Specialized Conference – Sustainable Sludge Management: State of the Art, Challenges and Perspectives (Oth_34)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**UNIVE-DSA,** UNIVR-DST
Biokaasuprosessi - raaka-ainet, tuottokyky, kasittely processi (in Finnish)	Biogas seminar presentation (Oth_35)	1 Bioenergy 2 Engineering 3 Agriculture	No further collaboration required.	Available through CROPGEN website	**JyU**
Biomethane potential of crops - intrinsic value or test dependent?	Presentation, Biomass for Energy Conference: Challenges for Agriculture (oth_36)	1 Bioenergy	No further collaboration required, research ongoing and to be taken forward by IWA Group.	Being disseminated through publications and future standards	**WU**
Biogas from energy crops and biowastes	Presentation, Helsinki Biorefineries conference (Oth_37)	1 Bioenergy 2 Engineering 3 Agriculture	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Potential of AD for mitigation of GHG emissions and production of renewable energy from agriculture: barriers and incentives to widespread adoption in Europe	IWA Agrowaste conference presentation (Oth_38)	1 Agriculture 2 Bioenergy	No further collaboration required.	Copyright	**Soton**
Optimising anaerobic digestion of agricultural substrates	Presentation, Maastricht meeting (Oth_39)	1 Bioenergy	No further collaboration required, research ongoing and to be taken forward by IWA Group.	Being disseminated through publications	**WU**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
Renewable energy from crops and agrowastes	Rothampstead research centre presentation (Oth_40)	1 Bioenergy 2 Engineering 3 Agriculture	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Agricultural biogas as an alternative to biogas and biodiesel as a renewable energy source	South Somerset presentation (Oth_41)	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Soton,** Greenfinch, OPL
Biogas from energy crops and biowastes	Presentation to Syngenta (Oth_42)	1 Bioenergy 2 Engineering 3 Agriculture	No further collaboration required.	Available through CROPGEN website	**Soton**
Anaerobic co-digestion of sludge with highly biodegradable substrates	Presentation, Energy from Biomass workshop, Venice (Oth_43)	1 Bioenergy 2 Engineering	No further collaboration required, research ongoing.	Being disseminated through publications	**UNIVE-DSA**
Crops for biogas production: yields, suitability and energy balances	Poster presentation, CUC International conference (Oth_44)	1 Agriculture 2 Bioenergy	No further collaboration required.	Being disseminated through publications	**Soton**
EU CROPGEN: Biogas from energy crops and agrowastes	Paper and presentation, Bioenergy 2007 (CG_19 and 20)	1 Bioenergy 2 Agriculture 3 Engineering	No further collaboration required.	Available through CROPGEN website	**Soton,** all partners
Materials of Jyvaskyla University Summer School 2007	Summer school on renewable energy in biogas from crops and agro-wastes (JSS07_01 to 13)	1 Agriculture 2 Bioenergy 3 Engineering	No further collaboration required.	Being disseminated through publications	**JyU,** Soton, BOKU-IFA, Metener
Deliverable D2	Project presentation	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Soton** and all partners
Deliverable D3	Project website	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**Soton** and all partners
Deliverable D5	Standardised test procedures for assessing kinetic constants and evaluating reaction rates	1 Bioenergy	To be taken forward through IWA Specialist group	Available through CROPGEN website	**WU,** UNIVR-DST
Deliverable D6	Comparison of traditional analytical procedure for assessing hydrolysis with advanced NMR techniques	1 Bioenergy	Results promising, funding may be sought for further development	Available through CROPGEN website	**WU**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
Deliverable D7	Kinetic data from a modified BMP test with uncoupling of solids and liquid retention times	1 Bioenergy	No further collaboration required until single phase standardised	Available through CROPGEN website	**Soton**
Deliverable D9	Inputs to the European Energy Crops InterNetwork database	1 Bioenergy 2 Agriculture	EECN database no longer exists. Further collaboration to extend coverage.	Available through CROPGEN website	**Soton**
Deliverable D11	Optimal pre-treatment methods to increase methane yields under various conditions	1 Bioenergy 2 Agriculture	No further collaboration required, research on-going.	Available through CROPGEN website	**BOKU-IFA, JyU**
Deliverable D12	Optimal storage systems for the energy crops for various climatic conditions	1 Agriculture 2 Bioenergy	No further collaboration required.	Available through CROPGEN website	**JyU, BOKU-IFA**
Deliverable D13	Characterisation of optimised silage starter cultures	1 Agriculture 2 Bioenergy	No further collaboration required.	Available through CROPGEN website	**BOKU-IFA**
Deliverable D17	Database on the methane production potential from mixed digestion	1 Bioenergy 2 Agriculture	No further collaboration required.	Available through CROPGEN website	**JyU**
Deliverable D18	Quantification of energy deficits and surpluses for a staged approach to crop energy production	1 Bioenergy 2 Agriculture 3 Engineering	Model established, needs further verification and validation	Available through CROPGEN website	**Soton,** BOKU, JyU
Deliverable D19	An overall energy balance for energy production taking into account energy inputs associated with farming	1 Bioenergy 2 Agriculture	Further research to establish energy requirements for wider range of crops and AD systems. Extend monitoring of biogas plants to give more data.	Available through CROPGEN website	**Soton, BOKU, JyU, Metener**
Deliverable D21	Comparative data on mixed and static bed reactors for inducing high rates of solids hydrolysis	1 Bioenergy 2 Engineering	Further research required on application of results	Available through CROPGEN website	**Soton**

Publishable result	**Description**	**Sector(s)** of application	**Stage of development / collaboration**	Patents or other IPR protection	**Owner** & other partners involved
Deliverable D22	Energy balance optimisation for an integrated arable/livestock farm unit	1 Bioenergy 2 Agriculture 3 Engineering	On-farm research to monitor energy consumption with different crops/cropping systems	Available through CROPGEN website	**Soton, BOKU, JyU, Metener**
Deliverable D23	Cost-benefit analysis to determine whether farm energy production can lead to measurable advantages in the longer-term productivity cycle	1 Bioenergy 2 Agriculture	Collaboration with AD plant producers to get accurate data	Available through CROPGEN website	**Soton, BOKU**
Deliverable D25	Life cycle energy balances on a number of crop species	1 Bioenergy 2 Agriculture	As D22	Available through CROPGEN website	**Soton, BOKU, JyU**
Deliverable D26	Digestion and codigestion mass balance for different operative conditions and process configurations for oily crops and agricultural market wastes	1 Bioenergy	No further collaboration required.	Available through CROPGEN website	**CSIC, UNIVE-DSA**
Deliverable D27	Mathematical description of the AD process with high solids feedstocks for design purposes	1 Bioenergy 2 Engineering	Research ongoing in this area.	Available through CROPGEN website	**WU,** BOKU-IAM
Deliverable D28	A DSS to assist in operational control of plant for optimisation of biogas production and methane content	1 Bioenergy 2 Engineering	Ongoing development to working product.	Available through CROPGEN website	**BOKU-IAM**
Deliverable 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 Bioenergy 2 Agriculture	Further research planned e.g. through UK RELU programme	Available through CROPGEN website	**Soton, BOKU, JyU,** Metener, Greenfinch.

2.2 Journal papers and dissertations

In addition the following academic journal papers have been published, submitted or are in preparation. As publication usually involves transfer of copyright these papers are not reproduced here but can be accessed through the normal system. Authors' copies are expected to become available in the next 12-18 months.

Published:

Banks C. J., Salter A. M., Chesshire M. (2007). Potential of anaerobic digestion for mitigation of green house gas emissions and production of renewable energy from agriculture: barriers and incentives to widespread adoption in Europe. Water Science and Technology, 55(10), 165-171

Lehtomäki, A., Huttunen, S. and Rintala, J. (2007). Laboratory investigations on co-digestion of energy crops, crop residues and cow manure: Effect of crop to manure ratio. Resources, Conservation and Recycling, in press.

Lehtomäki, A. and Björnsson, L. (2005) Methane production from energy crops in two-stage anaerobic digestion. Proceedings of the 7th Finnish Conference of Environmental Sciences, 12-13 May 2005, Jyväskylä, Finland, p. 144-147.

Lehtomäki, A. and Rintala, J. (2005) Biogas from energy crops (in Finnish). FINBIO Publications 33, p. 49-54.

Lehtomäki, A., Ronkainen, O. and Rintala, J. (2005) Developing storage methods for optimised methane production from energy crops in northern conditions. In: Ahring, B. K. and Harmann, H. (Eds.), Proc. of 4th Int. Symp. on Anaerobic Digestion of Solid Waste, August 31- September 2, 2005, Copenhagen, Denmark, vol. 1, pp. 101-108.

Lehtomäki, A., Ronkainen, O., Viinikainen, T., Alen, R. and Rintala, J. (2005) Factors affecting methane production from energy crops and crop residues. In: Borzacconi, L., Castelló, E., Etchebehere, C., Gutiérrez, S. and Lopez, I. (Eds.), Proc. of the 8th Latin American Workshop and Symposium on Anaerobic Digestion, 2.-5.10.2005, Punta del Este, Uruguay, pp. 469-474.

Lehtomäki, A., Vavilin, V.A. and Rintala, J.A. (2005) Kinetic analysis of methane production from energy crops. In: Ahring, B. K. and Harmann, H. (Eds.), Proc. of 4th Int. Symp. on Anaerobic Digestion of Solid Waste, August 31- September 2, 2005, Copenhagen, Denmark, vol. 2, pp. 67-72.

Paavola, T., Lehtomäki, A., Seppälä, M. and Rintala, J. (2007) Methane production from reed canary grass. Proceedings of the 8th Finnish Conference of Environmental Sciences, 10-11 May 2007, Mikkeli, Finland, p. 234-237.

Pavan P., Bolzonella D., Fatone F., Mata-Alvarez J. (2005). Thermophilic anaerobic co-digestion of agro-waste and waste activated sludge: influence of the organic loading rate. Proceedings 4th ISAD-SW, Copenhagen, Denmark, 28th August - 1st September 2005.

Pavan P., Cavinato C., Bolzonella D., Fatone F., Cecchi F. (2007) Single and two-phase co-digestion of waste activeted sludge and solid agro-wastes. *Water Practice and Technology*. IWA Publishing, London, ISSN Online: 1751-231X

Rintala, J., Paavola, T. and Lehtomäki, A. (2004) Biogas technology in waste disposal (in Finnish). Tekniikka ja Kunta 7:52-54.

Raposo, F., Banks, C.J. Siegert, I. Heaven S. and R. Borja. (2006) Influence of inoculum to substrate ratio on the biochemical methane potential of maize in batch tests. *Process Biochemistry*, 41, 1444-1450.

Raposo, F., Rincón, B. and Borja, R. (2006) Influence of inoculum to substrate ratio on anaerobic digestion of extracted sunflower flour in batch reactors. Proc. of 4th Euro Fed Lipid Congress (Oils, Fats and Lipids for a Healthier Future), 1-4 October 2006, Madrid, Spain, pp. 292.

Accepted:

Cavinato C., Pavan P., Fatone F., Cecchi F. (2007) Bioenergy from waste activated sludge and market-waste: single and two phase thermophilic codigestion**.** The Eighth International Conference on Chemical and Process Engineering, 24-27 June 2007, Ischia, Naples (Itlay).

Pabón Pereira, C.P. van Lier, J.B.Sanders,W. Slingerland, M.A. Rabbinge, R. (2005). The Role of Anaerobic Digestion in Sugarcane Chains in Colombia. Proceedings VIII Latin American Workshop and Symposium on Anaerobic Digestion Punta del Este (Uruguay), October 2-5 2005

Pabón Pereira, C.P. van Lier, J.B.Sanders,W.Slingerland,M.A. Rabbinge, R. (2005). The role of anaerobic digestion in biomass energy chains. Proceedings 4th International Symposium on Anaerobic Digestion of Solid Waste -ADSW. Copenhagen (Denmark), 31 Aug – 2 Sept 2005.

Pavan P., Bolzonella D., Fatone F., Mata-Alvarez J. (2005). Thermophilic anaerobic co-digestion of agro-waste and waste activated sludge: influence of the organic loading rate. Proceedings 4th ISAD-SW, Copenhagen, Denmark, 28th August - 1st September 2005.

Pavan, P., Cavinato, C., Bolzonella D., and F. Cecchi. (2006).Single and two-phase thermophilic co-digestion of waste activated sludge and solid agro-waste. Performance comparison on pilot scale. IWA Specialized Conference 'Sustainable Sludge Management: state of the art, challenges and perspectives', 29-31 May 2006, Moscow, Russia.

Raposo, F., Banks, C.J. Siegert, I. Heaven S. and R. Borja. (2006) Influence of inoculum to substrate ratio on the biochemical methane potential of maize in batch tests. *Process Biochemistry*, 42 in press (accepted on 20 January 2006).

Salter A. M., Delafield M., Heaven S., Gunton Z. (accepted). Closing the CO2 and Energy Cycles by Anaerobic Digestion of Road Verge Material to Provide Transport Fuel. Proceedings of ICE Waste and Resource Management.

Submitted:

Cysneiros, D., Karatzas, K. A. G. , Banks, C.J. and Heaven, S. (in review) Anaerobic digestion of maize for energy production in leach-bed reactors.

Lehtomäki, A., Huttunen, S., Lehtinen, T. and Rintala, J. (in review): Anaerobic digestion of grass silage in batch leach bed processes for methane production.

Lehtomäki, A., Ronkainen, O. and Rintala, J. (in review): Effect of storage on anaerobic digestion of energy crops and crop residues.

Lehtomäki, A., Ronkainen, O., Viinikainen, T., Alen, R. and Rintala, J. (in review): Factors affecting methane production from energy crops and crop residues.

Lehtomäki, A., Viinikainen, T. and Rintala, J. (in review): Screening energy crops and crop residues for methane biofuel production.

Jagadabhi, P., Lehtomäki, A. and Rintala, J. (in review): Co-digestion of grass silage and cow manure in CSTR by re-circulation of alkali treated solids of the digestate

Salter A. M., Banks C. J., Chesshire M. (in review). Calculation of an energy balance for anaerobic digestion of crop biomass including agricultural and processing energy usage, and comparison of net-energy output with other biofuels. Biomass and Bioenergy.

Raposo, F., Borja, R., Rincón, B. and Jiménez, A.M. (in review): Assessment of process control parameters in the biochemical methane potential of sunflower oil cake. Biomass and Bioenergy.

In Preparation:

Banks, C.J. Lapshina, E., and Heaven, S. (in prep.) Hydrogen production in a lactose-fed plug flow reactor.

Cysneiros, D., Karatzas, K. A. G. , Banks, C.J. and Heaven, S. (in prep.). Key parameters in the operation and performance of leach-bed reactors for anaerobic digestion of maize as an energy crop.

Heaven, S and Banks, C.J. (in prep.). Kinetic study of the anaerobic digestion of maize as a single substrate for energy production.

Heaven, S and Banks, C.J. (in prep.). Performance of hydraulic flush reactors in a two-phase system for the anaerobic digestion of maize as an energy crop.

Martin Santos, M.A., Banks, C.J. and Heaven, S. (in prep.). Experimental factors influencing the biochemical methane potential of maize as a typical energy crop.
Neylan, D.J. and Banks, C.J. (in prep.). Innovations in reactor design and operation for energy production from rye grass.
Pabon, C.P., Castanares, G., and van Lier, J. (in prep.). Effect of substrate treatment, inoculum and buffer system on anaerobic biodegradability tests.
Pabon, C.P., and van Lier, J. (in prep.). Optimized oxitop protocol for screening energy crops and agroresidues for anaerobic potential.
Pabon, C.P., Matilla, I., and van Lier, J. (in prep.). Influence of plant composition on methane potential and kinetics of plant material.
Salter A.M. and Banks, C.J. (in prep.). A whole process analysis of crop based energy production from crops and agrowastes using anaerobic digestion including crop storage and fuel conversion.
Seppälä, M., Paavola, T. and Rintala, J. (in prep). Biogas potential of energy crops in Finland.
Viinikainen, T., Lehtomäki, A. and Rintala, J. (in prep.). Chemical characteristics and methane production potential of Finnish energy crops and crop residues.
Viinikainen, T., Lehtomäki, A., Ronkainen, O. and Rintala, J. (in prep.). Effect of chemical pre-treatments on anaerobic digestion of energy crops and crop residues.
Ronkainen, O., Lehtomäki, A., Rissanen, S. and Rintala, J. (in prep.). Storing energy crops for biogas production: effects of TS-concentration and biological additive.
Ronkainen, O., Tähti, H. and Rintala, J. (in prep.). H_2 and CH_4 production from grass silage; effect of alkaline pre-treatment.
Mykkänen, E. Rintala, J. (in prep). Monitoring digester performance in full scale biogas plant digesting energy crops and cow manure.
Luostarinen, J. and Rintala, J. (in prep). Energy balance in Finnish farm-scale biogas plant using energy crops.
Raposo, F. and Borja, R. (in prep.). Kinetic evaluation of anaerobic digestion of sunflower oil cake in batch mode.
Zhang, Y., Walker, M., Banks, C.J. and Heaven, S. (in prep.) Some common errors in the measurement of biogas and methane production in laboratory studies of anaerobic digestion.

PhD and MSc Theses

Completed:

Lehtomäki, A. 2006: Biogas production from Energy Crops and Crop Residues. PhD thesis. Jyväskylä Studies in Biological and Environmental Science 163. University of Jyväskylä, Finland, 91 p.
Lindorfer, H. (2007): Optimised digestion of energy crops and agricultural residues in rural biogas plants. PhD thesis, BOKU.

Cornell, Marie (2006). The impact of different retention times on the hydrolysis of maize. MSc thesis, University of Southampton.

In progress:

Neylan, David: working title "Influence of recycling rates on anaerobic digestion of ryegrass in plug flow systems". (MPhil/PhD, University of Southampton).
Cysneiros, Denise: working title "Anaerobic digestion of maize for energy production in leach-bed reactors". (MPhil/PhD, University of Southampton).
Laaber, Michael: working title "Gütesiegel Biogas - Bewertung von Biogasanlagen mittels technischer, ökonomischer und sozioökonomischer Faktoren" ("Gütesiegel Biogas" - Assessment of biogas plants using technical, economical, and socioeconomical factors). (PhD, BOKU).

Perez Lopez, Carmen: working title "Physikalisch-chemische Vorbehandlung von zellulosehältigen Substraten zur Verbesserung der Biogasausbeute". (Physical-chemical pre-treatment of cellulosic substrates in order to improve biogas yields). (PhD, BOKU).

Resch, Christoph: working title: "Vergleichende Bilanzierung von abfall- und energiepflanzenverwertenden Biogasanlagen" (Comparative balancing of biogas plants using wastes and energy crops). (PhD, BOKU).

dos Santos, Jamile Pereira Teixeira: working title "Mikrobiologische Vorbehandlung von Substraten zur Verbesserung der Biogasausbeute" (Microbiological pre-treatment of substrates in order to improve biogas yields) (PhD, BOKU).

Luostarinen, Juha: Energy balance in Finnish farm-scale biogas plant using energy crops (in Finnish). (MSc, University of Jyvaskyla).

Mykkänen, Eeli: Monitoring digester performance in full scale biogas plant digesting energy crops and cow manure (in Finnish). (MSc, University of Jyvaskyla).

Plattonen, Hanna: Fertilizing value of different composts and digestates in agriculture (in Finnish). (MSc, Jyvaskyla University).

Rissanen, Sanna: Effect of storage on methane production potential and nutrient composition of energy crops and their leachates (in Finnish). (MSc, University of Jyvaskyla).