Biogas from Energy Crop Digestion

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Task 37 – Energy from Biogas and Landfill Gas

IEA Bioenergy aims to accelerate the use of environmental sound and cost-competitive bioenergy on a sustainable basis, and thereby achieve a substantial contribution to future energy demands.

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The world‘s energy supply – A future challenge

Currently some 80 % of the world‘s overall energy supply of about 400 EJ per year is derived from fossil fuels. Nevertheless roughly 10 – 15 % of this demand is covered by biomass resources, making biomass by far the most important renewable energy source used to date.

On average, in the industrialised countries biomass contributes by some 3 – 13 % to the total energy supplies, but in developing countries this proportion is much higher. In quite a number of countries biomass covers even over 50 to 90 % of the total energy demand.

Biomass combustion is responsible for over 90 % of the current production of secondary energy carriers from biomass. Liquid biofuels cover only a small part and the most used are ethanol and biodiesel. Ethanol is produced from sugar- or starch crops, while biodiesel is derived from vegetable oils or animal fats.

Currently biogas plays a smaller, but steadily growing role. Traditionally applied for sewage sludge treatment- and stabilisation purposes, energy recovery from biogas was a welcome by-product. However, biogas has become a well established energy resource, especially through the use of renewable biomass i.e. “energy crops”. Since about 1950, biogas production from manure and / or energy crops, continued to develop as an important new farm enterprise.

Development of energy crop digestion

The idea to use dedicated plant biomass, the so called “energy crops” for methane production (biomethanation) is not new. Early investigations on the biomethanation potential of different crops and plant materials have been carried out in the 1930s by Buswell in the USA and later on in the 1950s by Reinhold and Noack in Germany. In 1980, Stewart described the potential use of oats, grass and straw in New Zealand, resulting in methane yields of 170–280 $m^3.t^{-1}$ TS. Even water hyacinths and fresh water algae were shown to result in medium methane yields between 150–240 $m^3.t^{-1}$ TS. In the USA a large project on microalgae and kelp for aquatic raw material production was started.

Although the digestion of crop material was demonstrated, the process was hardly applied in practice. Crop digestion was commonly not considered to be economically feasible. Crops, plants, plant by-products and -waste materials were just added occasionally to stabilise anaerobic waste digesters.

With steadily increasing oil prices and improved legal framework conditions, “energy crop”-research and development was again stimulated in the 1990s. In Germany for example, the number of digesters using energy crops has increased from about 100 in 1990 to nearly 4,000 in 2008 (Figure 1).

The steady increase in energy crop digester applications in Germany and similarly in Austria, can be directly attributed to the favourable supportive European and National legal frameworks of eco-tariffs, paid for renewable energy. Depending on the electrical power capacity of the digestion plants, staggered feed in tariffs are guaranteed for the whole depreciation period of the investment. Similar subsidising systems exist for instance in Switzerland and France. Other European countries apply tax exemptions (e.g. Sweden) or certificates (e.g. UK) for renewable energies.

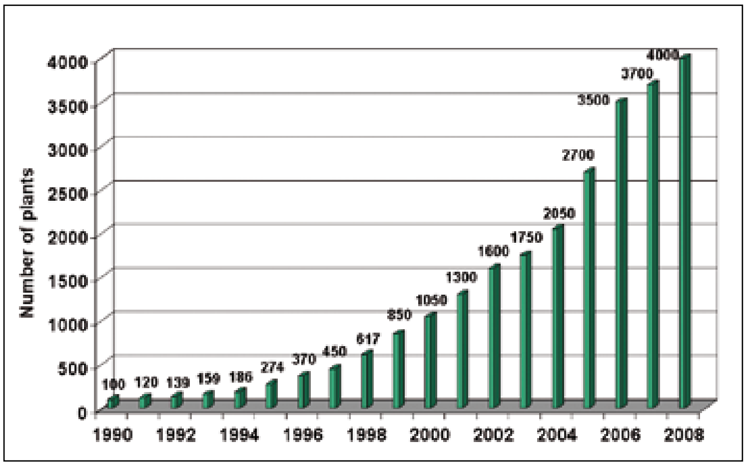

Figure: 1: Number of Biogas Plants in Germany.
Development between 1990 and 2008 (Weiland, 2009)

Energy crops used in anaerobic digestion

Numerous plants and plant materials have been tested for their methane formation potential. In principal many varieties of grass, clover, cereals and maize including whole plants, as well as rape or sunflower proved feasible for methane production. Even hemp, flax, nettle, miscanthus or potatoes, beets, kale, turnip, rhubarb and artichoke were tested successfully. Some practically used "energy crops" are shown in photos 1 to 4. Depending on numerous conditions, a fairly wide range of methane yields, between 120–658 $m^3.t^{-1}$VS, was reported in literature from anaerobic digestion of different crops (Table 1).

Tab. 1: Exemplary methane yields from digestion of various plants and plant materials as reported in literature (Data compilation after Braun, 2007)

Methane yield (m^3 per t volatile solids)

Maize (whole crop)	205 – 450	Barley	353 – 658
Wheat (grain)	384 – 426	Triticale	337 – 555
Oats (grain)	250 – 295	Sorghum	295 – 372
Rye (grain)	283 – 492		
Grass	298 – 467	Alfalfa	340 – 500
Clover grass	290 – 390	Sudan grass	213 – 303
Red clover	300 – 350	Reed Canary Grass	340 – 430
Clover	345 – 350	Ryegrass	390 – 410
Hemp	355 – 409	Nettle	120 – 420
Flax	212	Miscanthus	179 – 218
Sunflower	154 – 400	Rhubarb	320 – 490
Oilseed rape	240 – 340	Turnip	314
Jerusalem artichoke	300 – 370	Kale	240 – 334
Peas	390		
Potatoes	276 – 400	Chaff	270 – 316
Sugar beet	236 – 381	Straw	242 – 324
Fodder beet	420 – 500	Leaves	417 – 453

Recent German practical experience showed mean methane yields of 348 m^3/t VS for maize and 380 m^3/t VS for barley (KTBL, 2009).

A comprehensive data bank on crop yields, appropriate climate and growth conditions, based on literature and own investigations, was elaborated in the recent EU funded "CROPGEN" project <http://www.cropgen.soton.ac.uk/>

Crops are frequently used for digestion directly after harvest. The harvest time can influence the bio-degradability and hence the methane yield from plants. Late harvest usually is associated with higher cellulose content in the biomass, causing slower bio-degradation and less methane yield. For a year – round availability of substrates, the crops are most frequently stored in silage clamps. Under favourable circumstances, crops can also be dried, by using for example surplus heat from a CHP.

Technology for anaerobic digestion of energy crops

Numerous technical solutions are offered by the industry, which are all based on the same basic principle. Six steps can be distinguished principally in energy crop digestion processes:

- Harvest and pre-processing of energy crops as a substrate
- Storage of the substrate
- Feed regulation (dosage) and fermentation (digestion)
- Treatment, storage and use of digestate
- Treatment, storage and use of biogas

Photo 1: Maize culture, most frequently used as energy crop, with a wide range of biomass yields per hectare from 9 up to 30 tons DM

Photo 3: Sun flower field in early cultivation stage, used for oil production as well as an energy crop in anaerobic digestion. Hectare yields of 6 – 8 tons DM are possible.

Photo 2: Miscanthus, a perennial plant, producing hectare yields in a wide range of 8 – 25 tons DM

Photo 4: Grass is frequently used as energy plant, enabling 2 – 3 harvests per year under moderate climate conditions. Yields of 12 – 14 tons DM per hectare are obtained.

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Photo 6: Ensiling procedure of whole crop chopped maize, using a front loader

Substrate preparation and dosage

A wide range of annual and perennial plants may be used as energy crops (see Table 1). Nevertheless maize is most widely used by the majority of existing plants. Standard combine harvesters are used, simultaneously chopping the whole maize plant (Photo 5) for the subsequent ensiling.

Ideally the biomass used for ensilage should have TS contents of between 30–40 %. Biomass materials with TS contents below 20 % result in poor silage qualities, high leachate accumulation and subsequently poor biogas yields.

Optimal ensiling results in rapid lactic acid- (5–10 %) and acetic acid fermentation (2–4 %), causing a decrease of the pH to 4–4.5 within several days. Butyric acid formation usually is prevented by the rapid pH decrease. Addition of acid, or of commercially available ensiling additives, can accelerate the lactic acid fermentation and prevent silage failures. Under such conditions, silage may be stored for many months, without major damage or losses.

Usually silage clamps (Photo 6) are used for ensiling the crop material, in order to maintain a year round supply to the digester. Silos must have sufficient storage capacity for a continuous digester operation over the year. In a medium sized installation, typically up to 10,000 tons of silage are prepared during harvest time for continuous use as a substrate (feedstock) over the year. For the storage in silage clamps, shovel loaders feed and compact the material into the silos. The material must be thoroughly compacted and covered with plastic blankets to ensure that the clamp is airtight and to prevent oxygen penetration. An alternative to the clamp is to use bag silos. These could be e.g. 3.5 m diameter and 100 m length. A typical bag silo storage capacity is about 6,000 tons of silage. Bag silos are filled by packing machines, able to load up to 100 t/h, corresponding to 50 ha/d harvest capacity. In smaller energy crop digestion plants, conventional big bale silos are applied for silage preparation and storage. In some cases dry storage of substrates is possible (e.g. maize corn). In some cases available surplus heat from the CHP is used for the drying process.

Fresh energy crops or silage can be used as substrate in most existing digester designs. Precautions have to be taken when fibrous (cellulosic) crop material is going to be used. Cellulosic fibres are rather slowly degradable. Fibres can block pumps, pipes or even the mixing equipment of the digester. When highly contaminated substrates (with sand or soil) are applied (eg. grass, beets), bottom layers can occur and even pipes and pumps can be blocked. Under these circumstances appropriate measures have to be taken, e.g. chopping, homogenisation, sand removal.

Frequently, crops or silage materials that are fed into the digester, have TS contents of at least 20 % up to 40 %. Dry crop materials can have even higher TS contents up to 90 %. Such materials cannot be pumped or homogenised with conventional digester equipment. In this case the substrate needs to be chopped before feeding. In addition dilution may be required to maintain the dry matter content suitable for the use of existing mixing equipments. When required, recycled digestate may be used for the purpose of substrate dilution.

Large scale commercial energy crop digestion plants mainly use solid substrate feeding hoppers or container dosing units (Photo 7). Feed hoppers or containers are periodically filled with shovel loaders (e.g. once daily)

Photo 5: Typical maize harvesting, using a standard combine harvester

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Photo 7: Silage dosing unit (back) with spiral elevator (front). The silage clamps can be seen in the back.

Photo 8: Solid substrate grinder (right) as used for preparation of the dry substrates (maize) in anaerobic digestion of energy crops

Photo 9: General view of a 2-step energy crop digestion plant with digester 1 (right) and combined gas collector and digester 2 (left)

Photo 10: General view of a 2-step energy crop digestion plant with digester 1 and digester 2 combined with membrane gas collector (background). The covered final digestate storage tank can be seen in the right foreground.

and the material is continuously augered through gas tight auger tubes into the digester. Some applications use piston pumps instead of augers.

In digestion plants designed for manure, a small amount of energy crops usually is suspended with digester effluent, or other raw liquid substrates, prior to conventional dosage with piston-, displacement- or rotary pumps. Some installations use more sophisticated liquid suspension feeding, applying continuous automatic substrate dosage and control. Even dry solid substrates are fed (Photo 8) after grinding, either directly into the digesters, or suspended in liquid digestate. Typically semi-continuous substrate dosing is applied, from once a day up to hourly feeding. Only large installations use continuous feeding.

Special care has to be taken in case of substrate changes. Changing composition, fluid dynamics and bio-degradability of some substrate components can severely change the digestion behaviour and can be responsible for digester failures. These can result from overloading, clogging of pipes and pumps, or interference with the mixing system. This in turn reduces the effectiveness of the digestion process and therefore lowers the gas yield and -productivity.

In case of a substrate change, new co-substrate addition or any substantial changes of the dosage, a proper and intensified process control is required. Any substrate change has to be performed carefully, with slowly increasing rates. The resulting methane productivity ($m^3CH_4.m^{-3}.d^{-1}$), the methane yield ($m^3CH_4.kg^{-1}VS$), the course of pH, the volatile solids content and a possible formation of scum layers have to be controlled more frequently.

Co-digestion and only energy crop digestion

The design of the fermenters can differ slightly, depending on the technical solutions applied. Commonly energy crops are fed together with manure or other liquid substrates (co-digestion), in order to keep homogenous fermentation conditions. Similar to “wet digestion”, the TS content of these systems has to remain below 10 % in order to enable proper reactor stirring. In most cases mechanical stirrers are used to mix the digester contents.

Digesters using energy crops only, are applied to a lesser extent. Recirculation of digestate is required in such digesting systems in order to maintain homogenous and well buffered digester conditions.

However some designs of “dry fermentation” systems allow total solids contents much higher than 10 % TS. Without addition of liquid, the TS content can increase above 30 %. A typical practical example of full scale dry fermentation is described later.

Typically two-step, stirred tank, serial reactor designs are applied in most digestion plants (Photos 9 and 10). The second digester is often combined with a membrane type gas holder. One step digesters are rarely used.

Anaerobic digestion of energy crops requires in most cases prolonged hydraulic residence times from several weeks to months. Both mesophilic- and thermophilic fermentation temperatures are commonly applied in anaerobic digestion of energy crops.

Complete biomass degradation with high gas yields and minimised residual gas potential of the digestate is a must in terms of proper economy, as well as ecological soundness of the digestion process. Volatile solids degradation efficiencies of 80 – 90 % should be realised in order to achieve sufficient substrate use and thereby leading to negligible emissions (CH_4, NH_3) from the digestate.

The two products of anaerobic digestion – Biogas and fertilizer (digestate)

In all configurations, the digestate has to be collected in final storage tanks (Photo 11), before land application as fertilizer can be performed. Storage tanks should have gas tight covers in order to prevent unwanted greenhouse gas emissions as methane and ammonia. The additional biogas production, collected from digestate storage tanks, usually pays back the investments for covers within a short period of time. Furthermore covering of the storage tanks prevents emissions of odours around the plant.

Open lagoon storage of digestate (Photo 12) can only be accepted if a nearly complete fermentation (> 90 % VS degradation) can be guaranteed. Complete degradation must be additionally controlled by periodic residual fermentation potential tests with the digestates to be stored.

Finally odour- and ammonia emissions from land application of the digestates as fertiliser must be prevented through the use of proper application technologies. In most cases the digestates can be directly applied after production to the nearby agricultural land. If sufficient land area is not available, digestates have to be pretreated (e.g. sludge separation, NH_3-separation, dewatering) before further use.

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Solid fractions are often separated from the digestate to undergo further composting.

The separated liquid fraction of the digestate is in some cases partly re-circulated for substrate homogenisation. Residual digestate, whenever possible, should be applied on land as crop fertilizer. If continuous use cannot be guaranteed, digestate must be further processed or aerobically purified.

Biogas collected from energy crop digestion is usually used for power production in combined heat and power engines (CHP). Since in CHP units roughly 2/3 of the energy contained in biogas is transformed into heat, continuous heat consumption year round must be assured.

Upgrading of biogas to natural gas quality (pure methane), respectively fuel, allows better use of the biogas energy. Therefore grid injection and / or use of methane as fuel, is increasingly aimed by plant operators.

Practical applications of energy crop digestion

An example of only energy crop digestion

The agricultural plant selected as a typical example (Photo 13), was one of the first, using solely solid energy crop substrates, i.e. maize silage and grass (Figure 2). The plant raw materials are harvested from roughly 300 ha and ensiled for a whole year utilisation. The silage clamp capacity is about 15,000 m^3.

Roughly 25 tons of substrate per day are fed (Figure 3) into the first of two serial digesters. Both digesters are built from concrete, each one with a capacity of 1,500 m^3. The two digesters are operated at 49.5°C. Stirring of the digesters is effected by two horizontally arranged, slow rotating paddles each one with a capacity of 5.5 kW.

The digestate leaving the second digester is separated

Photo 11: Gas tight coverage of a post storage tank for digestate in Sweden. Residual biogas developed from digestate is this way collected for energy use, while greenhouse gas emissions are prevented.

Photo 12: Open lagoon storage for completely digested maize- and grass silage, where there is no longer any methane left in the digestate.

Photo 13: General view of a two-step, 500 $kW_{el.}$ only energy crop digestion plant with digester 1 and dosing unit (center), digester 2 with integrated gas holder (left), silage clamps (background) and storage lagoon for the digestate (foreground right).

by a decanter centrifuge. Part of the liquid fraction is being used for dilution and homogenisation of the substrate, in order to achieve homogenous substrate conditions, respectively TS-contents below 10 %, within the first digester. The solid fraction and the surplus of the liquid digestate are used as valuable phosphate- and nitrogen fertilizer on the nearby fields.

The biogas produced is collected in a 300 m^3 membrane gas holder integrated in digester of step two. The biogas is converted into power and heat and the energy is sold to the public power grid and the local district heating network. Electricity is sold at a rate of 14.5 € cent/kWh.

Tab. 2: Operational parameters of a representative plant, digesting energy crops only. The installed electrical power is 500 kW

Input of maize whole crop silage	5,940 t / year
Input of grass silage	2,181 t / year
Input of clover silage	1,374 t / year
Biogas production	1.88 Mio m^3 / year
Production of electrical energy	4,153 MWh / year
Production of thermal energy	4,220 MWh / year
Own electrical consumption	161 MWh / year
Own thermal consumption	701 MWh / year
Sale of electricity	4,153 MWh / year
Sale of thermal energy	1,697 MWh / year

An example of co-digestion of energy crops

The agricultural plant selected as a typical practical energy crop co-digestion example, was one of the earlier applications, built in 2003. The plant (Photo 14) is located on a pig breeding farm, where the manure (20 m^3/day) is used as a co-substrate (30 % share) to achieve homogenisation of the solid energy crop feedstock. Mainly maize (silage and crushed dry crops) is used, together with minor amounts of residues from vegetable processing. Approximately 11,000 t/year of energy crops are processed together with 7,300 t/year of manure and leachate from the silage clamps. A flow sheet of the installation is shown in Figure 4.

Two parallel digesters are fed hourly through an automatic dosing unit. The reactors are operated at 39°C and 77 day residence time, corresponding to a volumetric loading rate of 4.4 kg $VS.m^{-3}.d^{-1}$. Reactor mixing is performed by mechanical stirrers. Dilution of the substrate mixture to a TS content of below 10 % is required for sufficient reactor mixing.

About 4,020,000 m^3 biogas are produced annually (Table 3). Hydrogen sulphide is removed by simultaneous addition of air into the head space of the digesters. The biogas is collected in an integrated gas holder inside digester two, as well as in an external dry gas holder. Power and heat are produced in two CHP units with a total capacity of 1 $MW_{el.}$ and 1,034 MW_{th}. The electricity

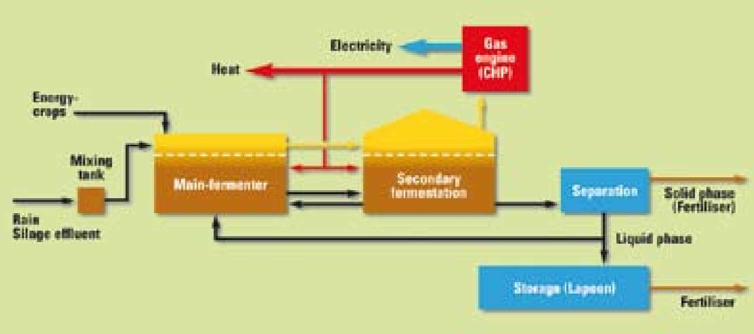

Figure 2: Flow chart of a two – step only energy crop digestion plant with 500 kW electrical capacity. Solid energy crops (maize, grass) are used as the only substrate. Dilution of the substrate to less than 10 % TS is achieved through recycling of liquid digestate and addition of leachate from the silage clamp.

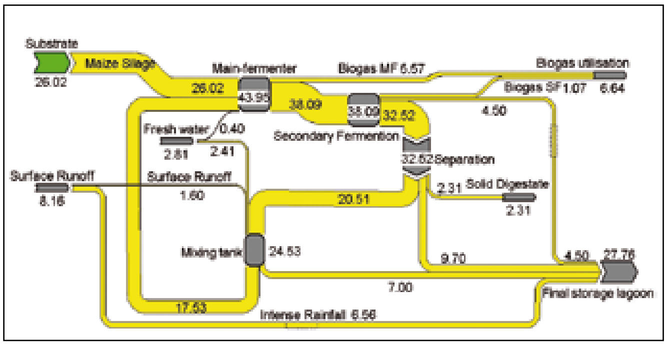

Figure 3: Mass flow diagram from a two-step only energy crop digestion plant of 500 kW electrical capacity. The plant is using liquid / solid separation of digestate and recycles the liquid digestate for substrate dilution. All data is given in tons / day.

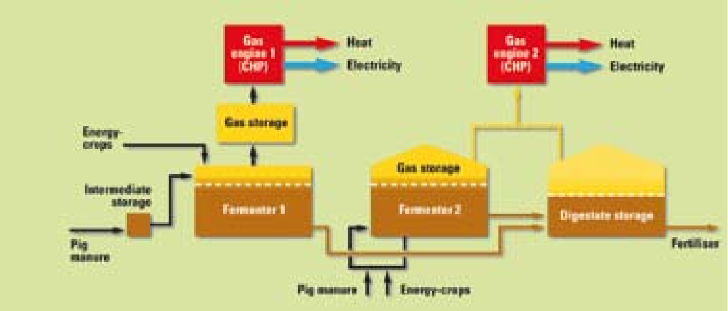

Figure 4: Flow chart of an energy crop co-digestion plant using two parallel fermenters. Solid energy crops (maize) and vegetable processing by-products are used as substrates. Dilution of the substrates to less than 10 % TS is achieved by adding liquid pig manure and leachate from the silage clamp.

Tab. 3: Operational parameters of a representative energy crop co-digestion plant of 1 MW electrical capacity, using 2 parallel fermenters

Silage clamp capacity	9,000 m^3
Volume digester 1	2,000 m^3
Volume digester 2	1,850 m^3
Volume digestate storage tank covered	2,000 m^3
Volume digestate storage tank uncovered	3,800 m^3
Input energy crops	11,000 t / year
Input manure + leachate from silage	7,300 t/year
Substrate dosage / day - Digester 1 / 2	25 m^3 / 20 m^3
Biogas production	4.02 Mio m^3 / year
Production of electrical energy	8,030 MWh / year
Production of thermal energy	8,223 MWh / year
Own electrical energy consumption	562 MWh / year
Own thermal energy consumption	50 MWh / year
Thermal consumption pig breeding	1,000 MWh / year
Sale of electrical energy	8,030 MWh / year
Sale of thermal energy	1,600 MWh / year

is fed to the national power grid and the heat is used in a local district heating network.

The digestate is collected in a gas tight covered final storage tank, before use as fertiliser in the neigbourhood of the farm. Additionally the biogas collected from the final digestate storage tank is used in the two CHP units.

As an annual mean value, it is possible to achieve 98 % of the theoretical capacity of the CHP. The costs of energy production were estimated to 6 – 8 € Cent/kWh, resulting in a net income of 6 – 7 € Cent/kWh produced.

The substrate mass flow and the achieved energy efficiency of the biogas plant are shown in figure 5. While 37 % of the substrate can be used as electricity, 50.9 % is lost as heat. Just 7.8 % of the substrate energy can be used as heat. Methane loss in the CHP is 1.8 %. Own electricity demand is 2.5 %.

Photo 14: General view of a 1 MW_{el}. energy crop co-digestion plant using two parallel digesters (left background) and a covered final digestate storage tank (center foreground). Gas storage is integrated in digester 2 (background) and in the final storage tank (foreground), further storage capacity is provided in a dry gas storage tank (background right).

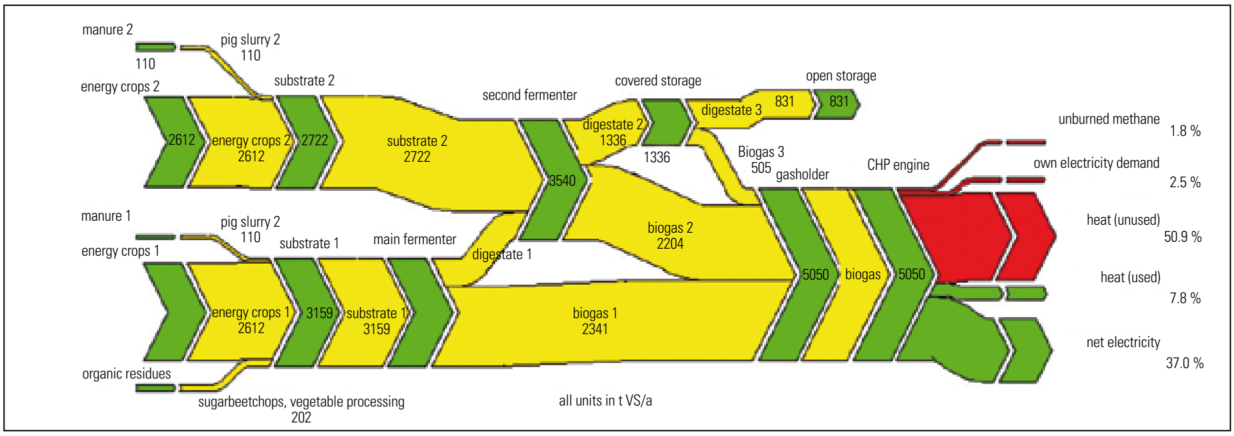

Figure 5: Mass flow and energy efficiency of an energy crop co-digestion plant, showing a net electrical efficiency of 37 % and a high proportion of unused heat (50.9 %). Just 7.8 % of the overall energy can be used as heat. Methane loss in the CHP is 1.8 %. Own electricity demand is 2.5 %.

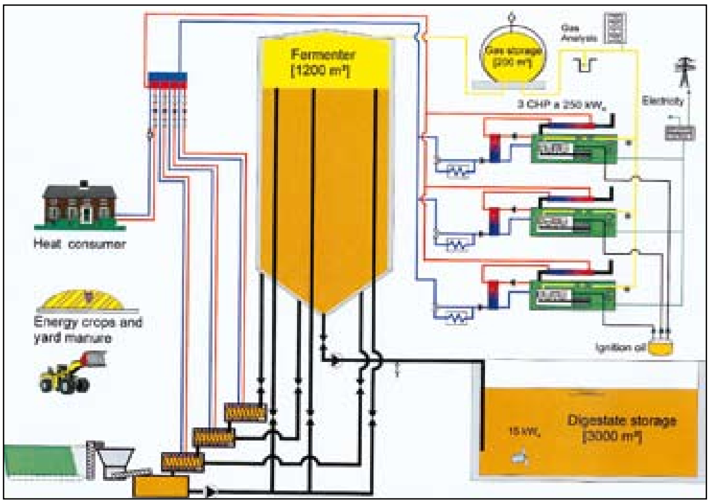

Figure 6: Flow chart of the dry-digestion process of energy crops

An example of dry-fermentation of energy crops

The agricultural plant selected as a typical example (Photo 15), was one of the first continuously operated dry-fermentation plants, treating solid energy crop substrates with high solids concentration in the digester. The plant is operated by four farmers who own together 355 ha arable land and 25 ha pasture land for raw material production.

The process is carried out in a vertical plug-flow digester without substrate stirring inside the reactor. The ensiled energy crops are mixed with digestate and the mixture is pumped to the top of the digester (Figure 6). The digester consists of two zones: An upper zone where an intensive fermentation takes place by constantly recycling the digestate and a second zone for post-fermentation, where digestate is allowed to ferment without an extra feeding. The digesting material flows from the top of the digester to the conical bottom by gravity only. The biogas is captured at the top of the fermenter and flows to an external dry gas holder. The reactor is operated at 54 °C and 29 day residence time, corresponding to a volumetric loading rate of 9.7 kg VS.m^{-3}d^{-1}. The substrate mixture has a total solids content of around 30 %, while the digestate has a total solids content of approximately 16 %. The specific biogas productivity is 5.8 m^3 per m^3 reactor volume and day.

The digester has a volume of 1,200 m^3 with a height of 25 m and a diameter of 8.5 m. For power and heat production three CHP units with a total capacity of 750 kW$_{el}$ and 780 kW$_{th}$ are installed. Due to higher feed-in tariffs at below 500 kW$_{el.}$, the electrical output is limited today to a maximum of 500 kW$_{el}$. Therefore only 60 % of the total digester volume is used and only two CHP units are regularly running. Electricity is fed to the regional power grid and heat is used in a district heating network for heating houses and for drying pig ears.

The plant was taken into operation at the end of 2006 and treats 11,500 tons substrate per year (Table 4). As an annual mean value, 97 % of the theoretical capacity of two CHP units is achieved. The electricity is sold to the public grid at a fixed rate of 17.9 € cent/kWh, according the German Renewable Energy Act (EEG).

The vertical design makes high solids concentrations feasible without the need of mixing. The downflow operation avoids phase separation and prevents the formation of a scum layer. The vertical design minimizes the surface area requirement and makes the integration of the plant on the farm site easier.

Tab. 4: Operational parameters of a continuously operated dry-digestion plant with an electrical capacity of 500 kW$_{el.}$

Input of whole crop maize silage	5,700 t / year
Input of total plant cereal silage	2,760 t / year
Input of sunflower silage	1,490 t / year
Input of grass silage	720 t / year
Input of yard manure	830 t / year
Production of electrical energy	4,140 MWh / year
Production of thermal energy	4,340 MWh / year
Own electrical consumption	350 MWh / year
Own thermal consumption	275 MWh / year

Photo 15: The dry-digestion installation with the feeding bin from where the digester is fed automatically

Long term biogas plant operational experience

Performance of full-scale energy crop digestion plants

Long term measurements of full scale energy crop digesters give insight in the process performance. In an Austrian project, 41 representative digestion plants were monitored over extended periods of time. A broad variety of substrates was used for biogas production (Figure 7). Energy crop addition varied between 10 – 100 %. The share of manure added was between 5 – 95 %, two plants used no manure at all. Most plants were also adding agricultural residues and by-products in minor amounts (5–10 %), in five digesters 20 – 60 % co-substrates were added and one plant was using agricultural residues exclusively. Bio-waste from source separated collection (mainly kitchen and restaurant waste) was digested in 11 plants (15 – 25 %) and one plant was operated exclusively with bio-waste.

Fresh substrate processing capacity varied in a wide range of about 1 – 59 t/d (Table 5). A mean biogas yield of 0.67 Nm^{3}kg^{-1} VS and a CH$_4$-content of about 55 % was monitored. The VS degradation efficiency varied between 61.5 – 96.8 %, with a median value of 82.8 %. While power generation showed median efficiencies of 31.3 %, the median thermal efficiency, due to missing heat utilisation, was fairly poor (16.5 %). As a result, the overall efficiency of the biogas energetic use was just 30.5 – 73 %.

Tab. 5: Typical long term operational data as derived from 41 full – scale energy crop digestion plants in Austria (Laaber et al., 2005).

Parameter	Unit	Median[1]	Min.	Max.
Substrate processing capacity	t . d^{-1}	13.2	0.8	58.9
Hydraulic retention time[2]	d	133	44	483
Loading rate (VS)	kg . m^{-3}.d^{-1}	3.5	1	8
Amount of VS fed into digester	t . d^{-1}	2.3	0.3	13.8
Amount of biogas produced	Nm^3 . d^{-1}	1,461	232	8,876
Biogas yield referred to VS	Nm^3 . kg^{-1}	0.673	0.423	1.018
Biogas productivity	Nm^3 . m^{-3}.d^{-1}	0.89	0.24	2.30
Methane concentration	% (v/v)	54.8	49.7	67.0
Methane yield referred to VS	Nm^3 . kg^{-1}	0.362	0.267	0.567
Degradation of VS	%	82.8	61.5	96.8
Availability of CHP	%	83.3	35.7	98.2
CHP operational hours per year	hours	7,300	3,100	8,600
Electricity utilization efficiency	%	31.3	20.7	39.2
Thermal utilization efficiency	%	16.5	0.0	42.6
Overall efficiency of biogas energy use[3]	%	47.3	30.5	72.7

A similar, earlier evaluation of German biogas plants (Weiland, 2004) showed comparable results. Most plants were using manure based substrate mixtures, with different share of energy crops (i.e. maize, grass, cerials). Food- and vegetable wastes, potato processing residues, whey and fat trap contents were applied as co-substrates together with manure. Manure was dominating (75 – 100 % share) in nearly 50 % of the plants considered. About 83 % of the new German agricultural biogas plants are operated with a mixture of energy crops and manure, 15 % use only energy crops and just 2 % were operated with manure only.

In the considered Austrian digestion plants, an even distribution between one- and two step digester configurations was observed. In some cases (15 %) three step digesters were used. Nearly 90 % of all plants are operated at mesophilic temperatures between 30 – 42°C, only 10 % of the new plants use thermophilic digestion temperatures between 50 – 55°C.

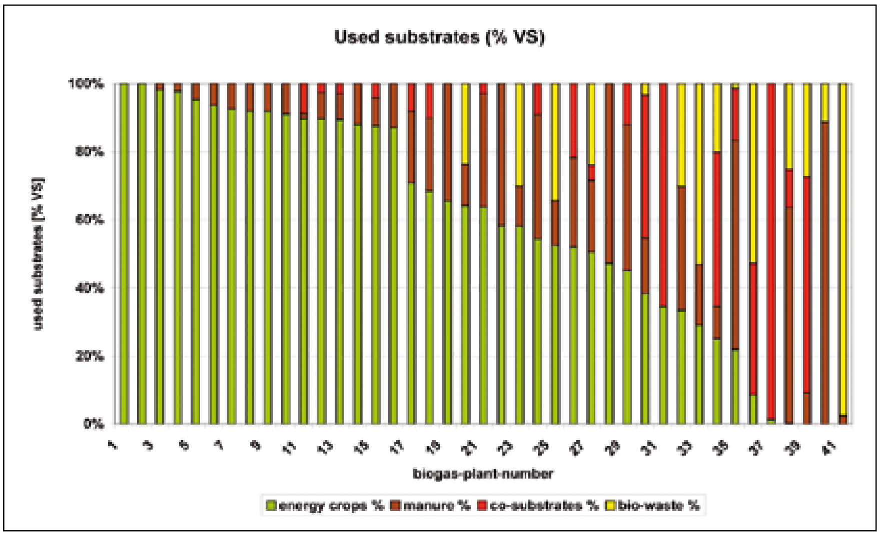

Figure 7: Distribution of energy crops, manure, co-substrates and bio-wastes as used in 41 representative Austrian full scale energy crop digestion plants (Laaber et al, 2005)

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1) Instead of average values the statistic term median is used in calculations (weighted mean value)

2) Mass of substrate (t/d) instead of (m^3/d) is referred to the reactor volume (m^3)

3) Net calorific value

Nearly 90 % of all new German plants are operated with wet-digestion technology while the rest of them use dry-digestion. The total solids content of the substrates used in wet fermentation systems, was between 13 – 30 % TS.

The input TS content in the case of dry-digestion was above 30 %. The final digestate TS content is always below 10 %, allowing proper homogenisation and application of the digestate as fertilizer.

With wet digestion systems, a loading rate of 1.2 – 4.3 $kg.m^{-3}.d^{-1}$ VS was used in most cases. The majority of digesters was operated with a residence time of 50 – 150 days, the remaining used a residence time below 50 days or over 150 days, some 10 % used more than 200 days residence time. Short residence times of below 50 days could only be realised when the share of energy crops was below 20 %. If mono-digestion of only energy crops was applied, the residence time was always above 100 days.

The CH_4 content in the biogas was 50 – 55 % (in 55 % of the plants) and 55 – 65 % in 45 % of the plants considered. A methane productivity of 0.7 – 0.9 $m^3.m^{-3}.d^{-1}$ was typical for 1/3 of all plants. Nevertheless the methane productivity varied in the broad range of 0.5 – 1.1 $m^3.m^{-3}.d^{-1}$, with only few plants achieving a productivity of more than 1.1. The majority of all plants (80 %) achieved a CHP efficiency of 80 – 95 %, while the remaining achieved only 50 – 80 % efficiency.

Significance and potential of energy crop digestion

Energy crops allow a growth of agriculture through increased demand of locally grown feedstocks. Furthermore the cultivation of energy crops promotes rural investments and creates new jobs. Currently most energy crops (as well as most important food crops), are grown as intensive monocultures. Annual monocultures are often associated with high rates of soil erosion. Some crops, like maize, deplete soil nutrients more rapidly than others, and might require significant levels of agrochemicals (fertilizer, pesticides) unless the digestate is carefully recycled. High yield energy crops may also depend on irrigation. The risks of water depletion and of pollution may occur. Nevertheless, if sustainability criteria are followed (Cramer et al., 2006), the use of energy crops will reduce GHG emissions by replacing fossil fuels.

No single crop can cover all specific requirements of the various local conditions. Comprehensive investigations for the selection of optimised plantation systems for different habitats have been started in some countries like Germany, Netherlands or Austria (FNR, 2008). Results so far demonstrate a considerable influence of the soil quality, climate, water availability, crop rotation and last but not least of the harvest time on the biomass yield, the methane production and consequently on the overall economic process viability.

Biogas yield per hectare of crops

All crops have been found to give similar biogas yields per t of VS (Table 1). On the other hand, different crops give different biomass yields per hectare. Under different climate conditions, even the same crop can give considerable different hectare yields.

Consequently, a better measure to compare overall yields, is the energy yield per hectare of cultivated land (Table 6).

Due to its high hectare yields of up to 30 t TS, maize is widely used under moderate climate conditions as a substrate in many energy crop digestion plants.

Beets (up to 34 t) and potatoes (up to 50 t) can also achieve high yields per hectare, but are comparably seldom used for anaerobic digestion, mainly due to operational drawbacks from soil contamination and hence sand accumulation inside the digesters.

Recent date from German practical experience show even higher crop yields, i.e. 40–60 t/ha for maize, 4.4–6.3 t/ha for rye, 40–60 t/ha for sugar beets and 80–100 t/ha for fodder beets (KTBL, 2009).

Grass (up to 14 – 20 t) and clover (up to 19 t) result in medium energy yields per hectare, but are commonly used on account of their wide availability and their modest growth requirements.

There are also other grains that are needed for crop rotation (e.g. rye), but they give less biomass yield per hectare, compared for example to maize or beets.

Low input-, high diversity mixtures of native grassland perennials, may improve soil and water quality. In

Tab. 6: Range of estimated crop- and methane yields, respectively calculated energy yields per hectare, from selected examples of plants

Crop	Crop yield[1] t . ha^{-1}	Measured methane yield[2] m^3. t^{-1} VS	Calculated methane yield m^3 . ha^{-1}
Maize (whole crop)	9–30	397–618	3,573–18,540
Wheat (grain)	3.6–11.75	384–426	1,382–5,005
Oats (grain)	4.1–12.4	250–365	1,025–4,526
Rye (grain)	2.1	283–492	594–1,033
Barley (grain)	3.6–4.1	353–658	1,271–2,698
Triticale (grain)	3.3–11.9	337–555	1,112–6,604
Sorghum	8–25	295–372	2,360–9,300
Grass	12–14	298–467	3,576–6,538
Red clover	5–19	300–350	1,500–6,650
Alfalfa	7.5–16.5	340–500	2,550–8,250
Sudan grass	10–20	213–303	2,130–6,060
Reed Canary Grass	5–11	340–430	1,700–4,730
Hemp	8–16	355–409	2,840–6,544
Flax	5.5–12.5	212	1,166–2,650
Nettle	5.6–10	120–420	672–4,200
Ryegrass	7.4–15	390–410	2,886–6,150
Miscanthus	8–25	179–218	1,432–5,450
Sunflower	6–8	154–400	929–3,200
Oilseed rape	2.5–7.8	240–340	600–2,652
Jerusalem artichoke	9–16	300–370	2,700–5,920
Peas	3.7–4.7	390	1,443–1,833
Rhubarb	2–4	320–490	640–1,960
Turnip	5–7.5	314	1,570–2,355
Kale	6–45	240–334	1,440–15,030
Potatoes	10.7–50	276–400	2,953–20,000
Sugar beet	3–16	236–381	708–6,096
Fodder beet	8–34	401–500	3,208–17,000

the long run, perennials may even outnumber annual monocultures in terms of biomass yield per hectare. Furthermore such cultures are net sequesters of carbon, can be produced on agriculturally degraded lands and do neither displace food production nor cause loss of biodiversity (Tilman et al, 2006).

As a consequence energy crops should be carefully selected, depending on local climate conditions, availability of irrigation water, robustness against diseases and last but not least – based on biomass yield per hectare.

Net energy yield per hectare of crops

High net energy yield per hectare is an indispensable prerequisite for an economic operation of an energy crop digestion plant. This includes high biomass yields and low energy requirement for plant cultivation, harvest and processing.

In crop production, energy is required for ploughing, seedbed cultivation, fertilising, pesticide- and herbicide application, harvest and transport (Table 7). Furthermore considerable energy is required for the production of fertilisers, pesticides and herbicides.

From practical experience, on average, about 50 % of the total energy requirement is spent for fertiliser production, minor amounts are required for machinery (22 %), transport fuel (15 %) and pesticides (13 %).

Besides crop production, further energy is required as process energy in the digestion process, for digestate post-treatment, -transport or -upgrading, and eventually for biogas upgrading.

As a very simplified, rough estimation, a 15 % electricity process energy demand for the digestion process is commonly calculated. Additionally energy transfer losses occur during utilisation of the biogas in engines, boilers, or during upgrading of biogas. A further process heat demand of 20 to 35 % is required, depending on the design and the insulation of the plant.

For a rough calculation of the net energy yield in energy crop digestion, the mean values for potatoes, maize, fodder beet, oilseed rape and rye can be taken as examples (Table 8). These crops cover the whole range of highest (about 10,000 m^3.ha^{-1} methane) to lowest (below 1,000 m^3.ha^{-1} methane) calculable yields.

As an exemplary assumption a comparably low overall process energy demand of 15% for the digestion process is calculated. If the process energy demand and the energy requirement for crop production (16,800–24,200 MJ.m^{-3}) are subtracted from the primary methane yields, the respective net energy produced per hectare is obtained.

As it can be seen (Table 8) the obtainable net energy production varies in a broad range of 8–288 GJ per hectare.

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[1] Statistics Handbook Austria 2005. Statistik Austria, Vienna Austria. "CROPGEN" data bank (see below)

[2] For data source of the range given, see "CROPGEN" data bank at http://www.cropgen.soton.ac.uk

Tab. 7: Commonly estimated range of required energy input per hectare, for the cultivation of different plants

Crop	Energy requirement (GJ / ha)
Potatoes	24.2
Beets	16.8–23.9
Wheat, barley, maize	14.5–19.1

The respective energy output / input ratios vary between 1.4 (rye) in the worst case and 5.1 (maize) in the best case.

With the assumptions chosen, a positive net energy production can be achieved, even in the worst case of poor crop yields (e.g. rye). But the overall economy and feasibility of a technical process application depends on numerous further influential parameters. Consequently the economic viability of energy crop digestion is indispensable dependent on a high return on energy sales.

Profitability of energy crop digestion

From practical experience, an economic operation of energy crop digestion can only be achieved, if high crop- and biogas yields can be realised at reasonable low investment-, raw material- and production costs. Additional benefits, i.e. gate fees for co-substrates, on farm local crop production, subsidised feed in power tariffs, improve the overall economics substantially and have to be considered carefully for the economic process evaluation.

A recent profitability evaluation of energy crop digestion (Weiland, 2008), shows an break even point at a raw material price of € 30/ton (maize) and biogas plant investment costs of € 4,000/$kW_{el.}$ (Table 9). Depending on local production conditions this exemplary calculation can change substantially and can therefore only be considered as a rough guidance.

Tab. 8: Rough calculation of net energy yield and output / input ratios, for a wide range of calculable methane yields per ha, respectively selected examples of crops

	Maize	Potatoes	Fodder beet	Oilseed rape	Rye
Methane yield $m^3 . ha^{-1}$	9,886	10,258	9,450	1,442	814
$MJ . ha^{-1}$	353,919	367,236	338,310	51,623	29,141
Process energy demand for digestion	- 53,088	- 55,085	-50,746	- 7,745	- 4,371
Energy requirement in cropping	- 16,800	- 24,200	- 20,350	- 16,800	- 16,800
Total energy requirement	- 69,888	- 79,285	- 71,096	- 24,545	- 21,171
Net energy yield $MJ.ha^{-1}$	284,031	287,951	267,214	27,078	7,970
Output / Input ratio	5.1	4.6	4.8	2.1	1.4

Future significance of biogas from biomass

The traditional role of agriculture in energy supply was lost in the more recent past, when petrol / diesel driven vehicles replaced horses. Biomass used to be the main source of energy up to the early 20th century. Most of other things needed daily, e.g. food, fodder, fertiliser, fibres etc., have also been derived from biomass.

With the progressive depletion of fossil raw materials, biomass again will become an important raw material, both for material- and energy production.

Microbial energy conversion processes, e.g. biogas production, offer several substantial advantages. While thermal energy generation (combustion, gasification) destroys the structure of the organic substance, finally resulting in inorganic ash, bioconversions protect valuable organic structures and the remaining by-products can be advantageously recycled as fertiliser or soil conditioner.

Closed nutrient cycles will become increasingly important. Therefore finding processes and crops yielding the best "value" in terms of energy production, while causing the least environmental drawbacks, is still a major challenge of bio-energy generation.

As a matter of fact, the available worldwide land for crop production is limited. The surface of the earth is mostly covered by oceans (361 . 10^6 km^2). From the remaining area of 149 . 10^6 km^2 about 55.7 % are covered by forests, 16.1 % (or 24 . 10^6 km^2) is pastureland and only about 9.4 % (or 14 . 10^6 km^2) is arable land. Europe has a total area of 2.3 . 10^6 km^2, of which 41 % consist of forests, 13 % of arable land and 8 % of pasture land.

A steadily increasing population needs more food and the demand of biomass for industrial use is strongly increasing as well. As a consequence, a growing competition for the different applications occurs. Advantageously, biogas can be produced from plants not being competitive with food production. Even soils, not suitable for food production, can be used for the cultivation of energy crops. Furthermore numerous organic industrial- and agricultural by-products, residues and bio-wastes can be valuable substrates for anaerobic digestion.

Tab. 9: Economical approch of energy crop digestion in function maize silage prices and biogas plant investment costs of a medium size digestion plant (500 kW_{el}). After Weiland, (2008).

Silage maize [€ / ton]	Biogas plant investment costs [€ / kW_{el}]		
	3,000	3,500	4,000
	Profitability [€ year]		
18	155,500	129,800	104,000
20	135,800	110,000	84,300
22	116,00	90,300	64,600
24	96,200	70,500	44,800
26	76,500	50,700	25,000
28	56,700	31,000	5,300
30	36,900	22,200	-14,500

Assumptions: 7,750 operational hours/year; Electrical power efficiency 37 %; No heat use

Theoretical potential of biogas from energy crops

Many estimations of the potential and availability of biomass have been published in the last years. A recently published study (EEA Technical Report No 12, 2007) estimates the environmentally compatible overall bio-energy potential from agriculture in Europe in 2030 of up to 6 EJ. Based on this figure, the environmentally compatible land area would rise by 50 % to 19 million hectare by 2030.

A rough calculation underlines the possible significance of biogas. Assuming a mean biogas net energy yield of 150 GJ / hectare, then about 10 % of the arable land would provide 21 EJ (worldwide), or 4.5 EJ (Europe) from bio-methanation of crops.

If energy crops could be cultivated on 30 % of the existing arable land, about 16 % (worldwide) or 18 % (Europe) of the overall primary energy demand could be covered.

Even when using theoretically all of the available arable land, just about 53 % of the worldwide, or 60 % of the European energy demand would be satisfied through bio-methanation of energy crops.

A further biogas contribution could be expected from pasture land resources, although harvest may be more expensive and the overall energy yields may be lower than from dedicated cultivated energy crops.

Despite all the limits cited, anaerobic digestion can contribute substantially to the renewable energy supply, but cannot be considered as the main source of bio-energy.

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Glossary, terms

Biomethanation

Biomethanation is the bacterial degradation of organic substances under exclusion of oxygen. The degradation process is also called anaerobic digestion and delivers biogas, which typically contains between 50 and 70% methane, 20 to 45% carbon dioxide and some trace gases.

Combined heat & power plant (CHP)

A power generator driven by a combustion engine, fuelled with biogas, resulting in approx. 60 % heat and 40 % electrical power.

Dry digestion (syn. dry fermentation)

Anaerobic digestion at elevated dry matter content of about 30 % total solids in the digester.

Dry matter (DM)
Residual substance after complete elimination (drying) of water.

Fermentation (syn. digestion)
Anaerobic metabolic processes caused through microbial enzymatic activities.

Greenhouse gas (GHG)
Trace gas in the atmosphere, a reason for climate change.

Hydraulic residence time
Mean statistical retention time of substrates in a bio-reactor.

Mesophilic
Temperature area of about 20 – 42°C.

Methane number
Defines the pre-ignition resistance (knock rating) of a burnable gas

Odour units
That amount of odorant(s) that, when evaporated into one cubic metre of neutral gas at standard conditions, elicits a physiological response from a panel (detection threshold) equivalent to that elicited by one European Reference Odour Mass (EROM), evaporated in one cubic meter of neutral gas at standard conditions. [CEN TC264 Draft]

Thermophilic
Temperature area above 45°C, usually about 53 – 57°C

TS – Total solids
Total amount if insoluble matter in a liquid.

VS – Volatile solids
Total amount of organic matter in a substance.

Abbreviations

a	Year	
BOD	[mg $O_2.l^{-1}$]	Biochemical oxygen demand
B_{TS}	[$kg.kg^{-1}.d^{-1}$]	Sludge loading rate
B_V	[$kg.m^{-3}.d^{-1}$]	Hydraulic or volumetric loading rate
COD	[mg $O_2.l^{-1}$]	Chemical oxygen demand
CHP		Combined heat and power plant
d		Day
DM		Dry matter
ΔG_O`	[kJ/Mol]	Enthalpy
EJ	[10^{18} J]	Exajoule
GHG		Greenhouse gas
GJ	[10^9 J]	Gigajoule
MJ	[10^6J]	Megajoule
Mtoe	[10^7 Gcal]	Million tons of oil equivalent
Nm^3		Volume at standard conditions of 0˚C, 101.325 kPa
NMHC		Non methane hydrocarbons
Pa	[1 N/m^2]	Pascal (1 bar = 10^5 Pa)
PJ	[10^{15} J]	Petajoule
ppm		Parts per million
θ	[d]	Hydraulic residence time
TJ	[10^{12} J]	Terajoule
TS	[%]	Total solids
VS	[%]	Volatile solids
v / v	[%]	Percent referred to volume
Wobbe index	[$MJ.m^{-3}$]	Amount of energy introduced to the burner
w / w	[%]	Percent referred to weight