Biomass Digestion in Agriculture: A Successful Pathway for the Energy Production and Waste Treatment in Germany

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Microbial conversion of energy crops and organic wastes to biogas has become one of the most attractive technologies for energy production, resource recovery, and waste treatment. It creates a wide breadth of positive environmental impacts because it reduces emissions of greenhouse gases, improves the management of manure and organic wastes, and replaces mineral fertilizer. Biogas is used today mainly for electricity and heat production, but it can also be applied as a vehicle fuel or for the production of hydrogen which is necessary for fuel cells. Biogas production in the agricultural sector is a very fast growing market in many European countries. This paper presents the current situation in Germany which has the highest number of agricultural biogas plants in Europe.

1 Introduction

Anaerobic digestion of organic wastes and by-products from agriculture and the food industry is a process known for many years and is widely used for waste stabilization, pollution control, improvement of manure quality and biogas production. During the recent years, the governments of many European countries – especially Germany, Denmark, Austria and Sweden – increased their interest in biogas production because biogas is an environmentally friendly energy which has a large potential for reducing green house gas emissions. Therefore, several acts on granting priority to renewable energy sources have come into force and different governmental programs have given subsidies in order to promote the development of biogas plants.

Anaerobic digestion is a technology which demonstrates many advantages. It can convert a disposal problem into a profit center, it allows agricultural crops to be converted into a highly valuable fuel and it can replace mineral fertilization by nutrient recovery. Therefore, anaerobic digestion has become a key method for both waste treatment and the production of renewable fuels.

In the following, the application of biomass digestion for biogas production in the agricultural sector will be shown and discussed in detail for the German conditions, because in Europe, Germany is the leading country in this field with the highest number of installed biogas plants. In Germany, biogas is produced mainly from manure, organic waste from household, the food- and agro-industry and especially cultivated energy crops.

Fig. 1 shows that the biogas yield of these different substrates is strongly dependent on the type and concentration of the organic matter.

The fermentation of manure alone results in relatively low biogas yields, but it has a positive effect on process stability due to its high buffering capacity and its high content of trace elements. In order to increase the gas yield most of the biogas plants are operated today by co-fermentation of manure together with non-agricultural organic wastes, harvesting residues and energy crops (see Fig. 2).

Nevertheless, the treatment of organic wastes in agricultural co-fermentation plants is declining, because the regulations concerning hygiene and nutrient recycling are more stringent and the legal conditions are much more complicated as well [1]. Considerably higher investment and operating costs are the result, which reduce the economic benefits due to the entrance fee and the increased gas yield. On the other hand, a higher compensation is paid for the produced electricity according to the Renewable Energy Act (EEG) if only substrates from agriculture are used for biogas production [2]. Therefore, the application of the monofermentation of energy crops is a fast increasing market. The biomass bonus is paid in addition to the basic compensation for a period of 20 years. The height of biomass bonus depends on the electrical capacity of the plant and is between 4 and 6 €-Cent per kWh (see Tab. 1).

The Renewable Energy Act is the driving force for the development and application of agricultural biogas plants for electricity generation and the key element for climate protection, environmental protection and for the fast growing biogas market. A study of the Federal Agricultural Research Centre (FAL) has shown that at the end of the year 2005 approx. 3 000 biogas plants with a total installed electrical capacity of almost 600 MW were in operation in Germany (see Fig. 3).

The total biogas potential in Germany on the basis of the available organic wastes, by-products and energy crops is calculated by the Federal Agricultural Research Centre (FAL) as 24 bil. m^3 biogas per year. The main sources are energy crops produced on approx. 1.4 mil. hectares, manure and by-products from crop production, and processing whereas organic wastes from households and wastewater treatment have only a low potential (see Fig. 4).

For the complete utilization of the total biomass potential, at least 20 000 biogas plants with an installed electrical capacity of approx. 300 kW are necessary.

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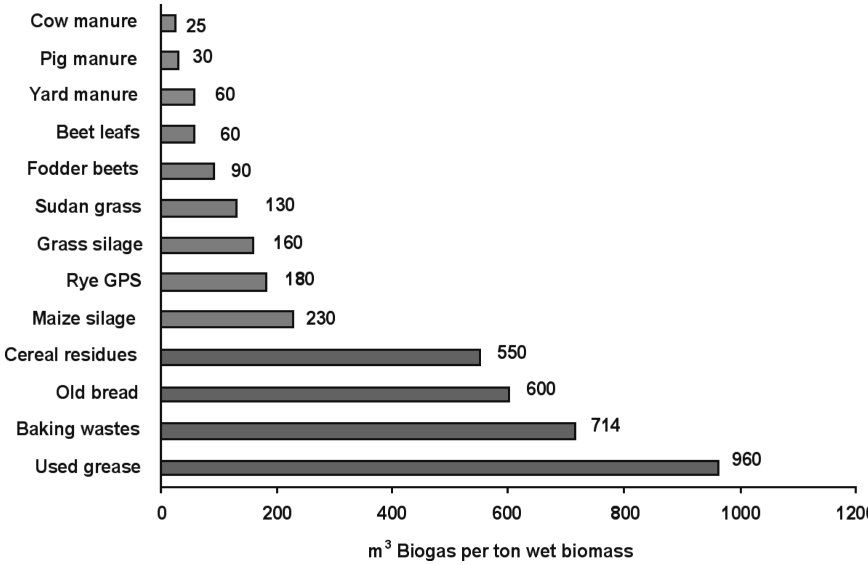

Figure 1. Biogas yield from different substrates.

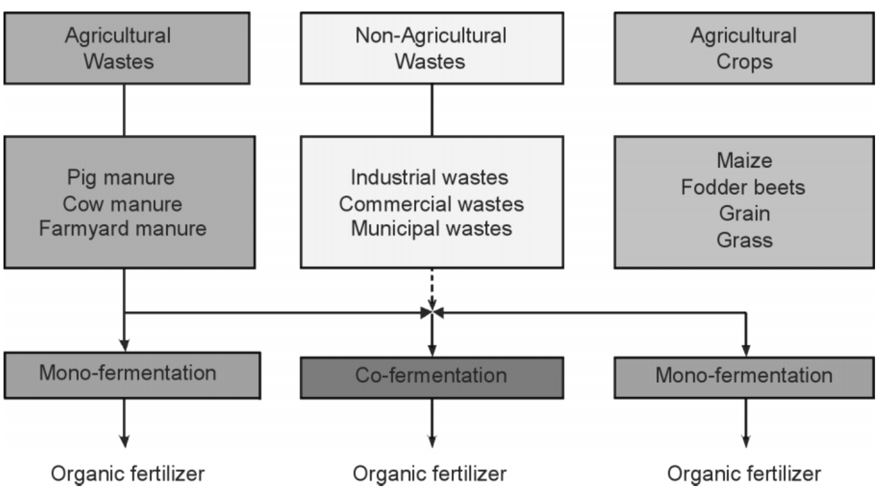

Figure 2. Substrates used for mono- and co-fermentation.

Table 1. Renewable Energy Act (EEG).

Electrical capacity [kW]	Compensation paid for electricity [Cent/kWh$_{el}$]	Bonus for biomass [Cent/kWh$_{el}$]
150	11.33	6.0
150–500	9.75	6.0
500–5000	8.77	4.0
CHP bonus: 2 Cent/kWh$_{el}$ for external heat utilization		
Technology bonus: 2 Cent/kWh$_{el}$ (e.g., dry fermentation)		

2 Substrates

The evaluation of modern biogas plants, which were analyzed between 2002 and 2004, showed that maize and grass silage are the most applied co-substrates in agricultural biogas plants. 80 % of all plants were operated with simultaneous fermentation of manure and maize silage and 50 % used grass silage for co-fermentation [3]. More than 30 different energy-rich organic wastes from agriculture and the food- and agro-industry were applied, which were often treated simultaneously with manure and energy crops (see Fig. 5).

Basically all agricultural crops can be used for biogas production if the crops are not lignified and have a high yield of dry matter per hectare. Tab. 2 shows some typical crops which are suitable for biogas production.

The methane yield of the crops depends on the sort of crop, the harvesting time, the harvesting and conservation technology and many other parameters like climate and rainfall. The dry matter yield of maize is between 15 and 30 t dm/ha and the resulting methane yield per ton of organic dry matter between 300 and 380 Nm^3/t odm. The mean gas yields of other energy crops were published by the

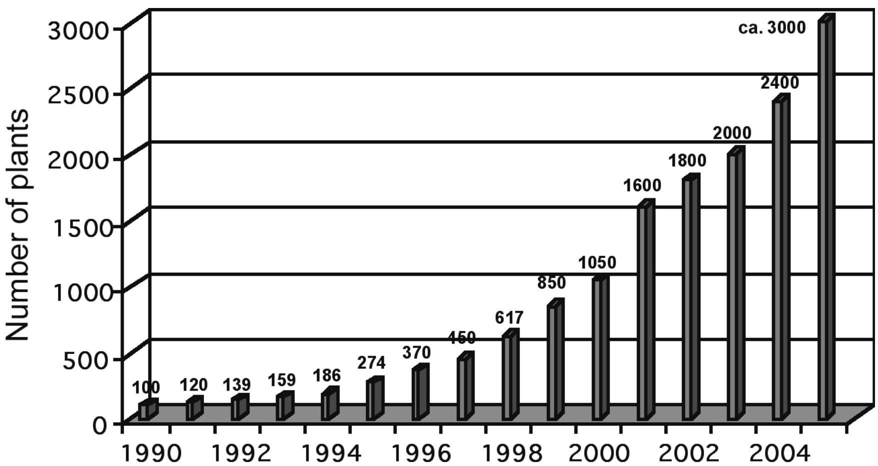

Figure 3. Number of biogas plants in Germany.

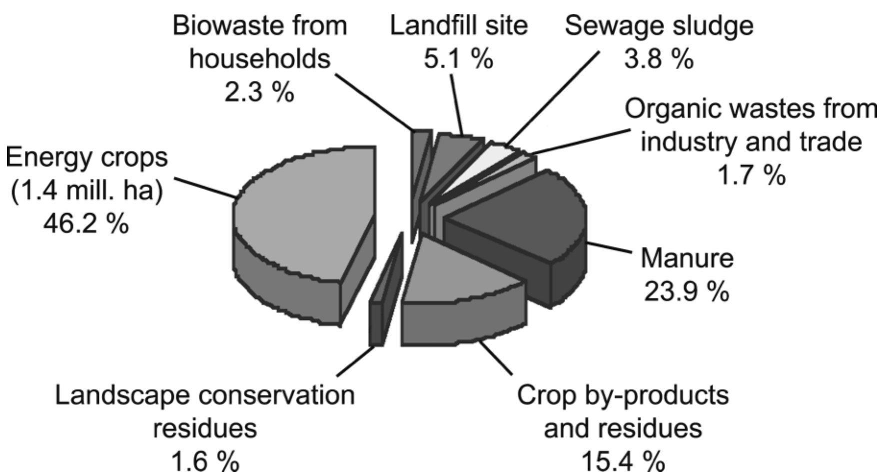

Figure 4. Biogas potential and the share of substrates in Germany. (24 bill. m^3 biogas per year or 13 bill. m^3 methane per year, electricity 50 TWh/a and heat TWh/a, natural gas consumption 2005: ca. 90 bill. m^3).

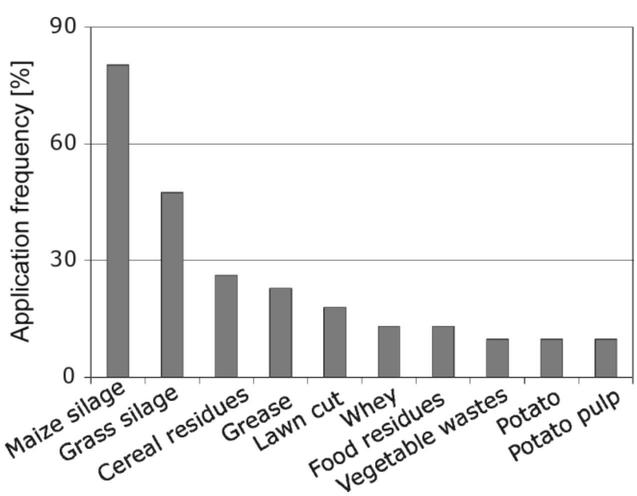

Figure 5. Application frequency of various co-substrates.

KTBL [4]. In order to achieve high biomass yields at low input, the application of specific crop rotation systems is necessary [5].

Table 2. Suitable crops for biogas production.

Annual crops	Biennial/triennial crops	Permanent crops
Maize silage Total cereal silage Sorghum silage Fodder beets silage Sugar beets silage Sunflower silage Intercropping crops silage Rye corn Triticale corn	Clover-grass silage Alfalfa-grass silage Jerusalem artichoke tops silage	Ley crops silage

3 Biogas Processes

Biogas can be produced by wet- or dry-fermentation processes (see Fig. 6). Today about 90 % of German agricultural biogas plants are operated by wet fermentation, which allows for a continuous treatment of liquid, pasty or solid substrates.

The typical total solids content of the digester content is in a range of between 8 and 10 % TS which permits conven-

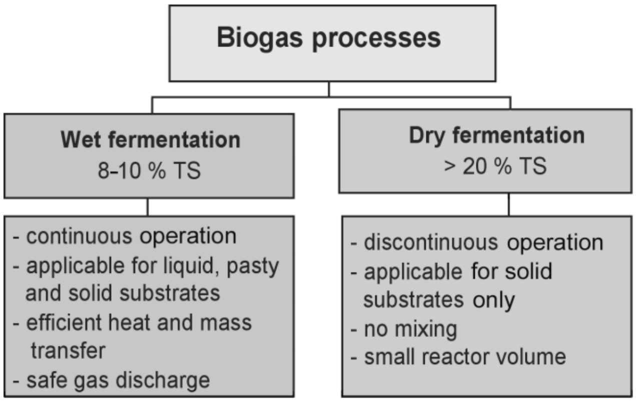

Figure 6. Process alternatives for anaerobic treatment.

tional pumps and mixers to be used. Dry-fermentation processes are operated with solid substrates with a resulting total solids content in the digester of at least 20 % TS. These processes are mainly operated discontinuously without any mixing of the solid substrate [6]. Dry fermentation is of increasing interest because an extra technology bonus of 2 €-Cent/kWh$_{el}$ is paid according the Renewable Energy Act in order to progress this technology, but the definition of dry fermentation is actually under discussion.

The most common reactor configuration employed for wet fermentation is the vertical continuously stirred tank fermenter which is applied in nearly 90 % of modern biogas plants (see Fig. 7).

Different types of mixers are applied in order to avoid scum formation or bottom layers. Central mixers with stirrer blades at different heights are very efficient if solid substrates should be mixed with manure or recycled process water. If submerged mixers are applied, at least two stirrers are necessary in order to avoid the formation of scum or bottom layers. Pneumatic mixers with recirculation of biogas are only applied in a few large fermenters but with negative results in the mono-fermentation of maize. The typical size of completely mixed digesters is in a range from 1000 to 4000 m^3 reactor volume. Horizontal plug-flow fermenters are mainly applied in two-stage processes for the high loaded first stage because due to technical and economical aspects the reactor volume is limited to a maximum of about 700 m^3.

More than 50 % of the vertical stirred tank fermenters are covered with a single or double membrane roof in order to store the gas in the top of the fermenter (see Fig. 8). For these digester types submerged stirrers or special long axle stirrers with inclined or horizontal arrangement are applied.

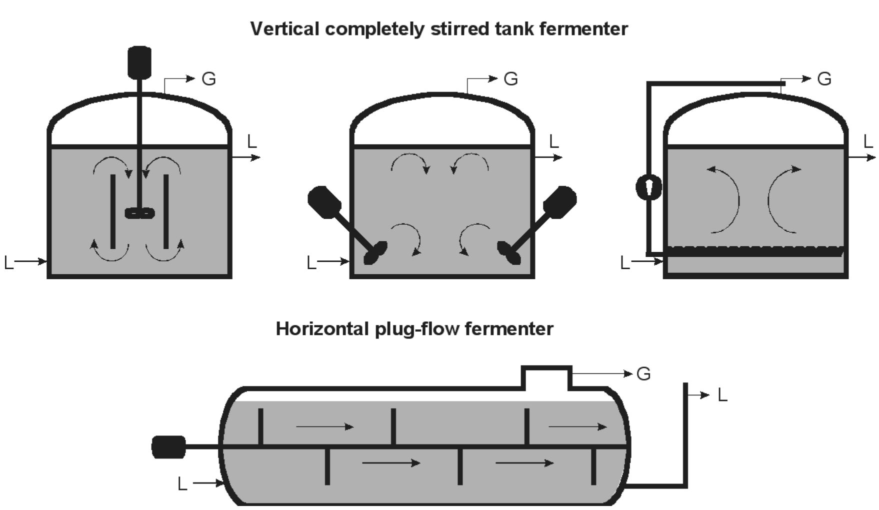

Figure 7. Fermenter types for wet fermentation.

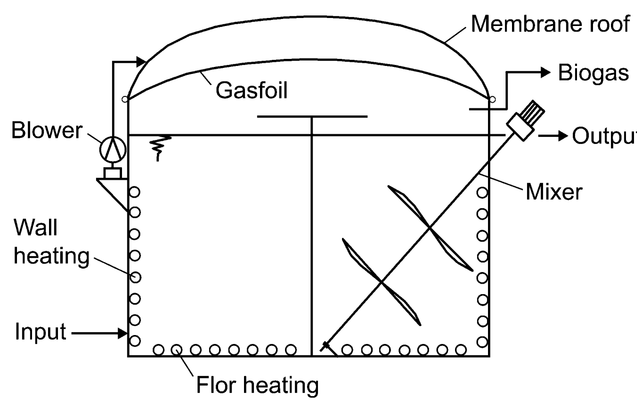

Figure 8. Biogas digester with double membrane roof.

For feeding solid wastes or energy crops into the fermenter, special direct feeding systems on the basis of feed screws, feed pistons or flushing systems have been developed recently (see Fig. 9).

In contrast to the conventional mixing of solid and liquid substrates in external tanks, direct feeding has the advantage that a lower energy demand is necessary for mixing, and energy losses by methane emissions can be avoided. The feeding of silage should be done with at least 12 to 24 charges per day, because the high lactic acid concentration and the low pH value can have a negative influence on process stability and gas yield [7].

Today about $^2/_3$ of the newly erected biogas plants in Germany are designed with two fermenters in series, which result in a higher gas yield than biogas plants with only one stage. Single stage processes have the disadvantage that a part of fresh substrate can directly flow into the storage tank, which reduces the gas yield and enhances the emission

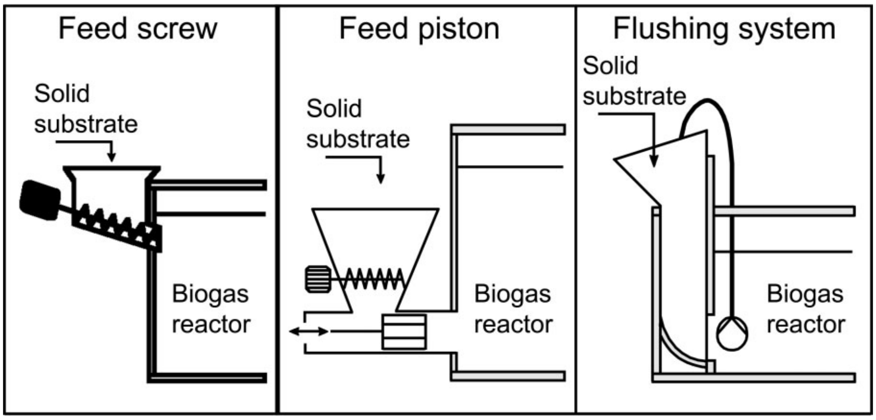

Figure 9. Direct feeding systems for solid wastes and energy crops.

of methane from open storage tanks. A study of modern biogas plants has recently shown that the methane losses from open storage tanks are between 5 and 15 % for more than 50 % of the evaluated biogas plants [3]. Only about 30 % of the biogas plants, which were built since 2004, are equipped with a gas tight storage tank. The emission of methane from the storage tank can considerably reduce the positive climate effect of biogas production, because the global warming potential of methane is a factor 21 times higher compared to carbon dioxide [8]. Therefore, processes with two fermenters in series equipped with a direct feeding system and a gas-tight covered storage tank should be preferred for the treatment of energy crops. Fig. 10 shows the typical design of such a plant.

Most of the biogas plants, which use energy crops for co-fermentation, are operated with relatively low loading rates of between 1 and 3 kg odm/($m^3 \times d$) because fibrous material is degraded at relatively slow rates. The typical retention time of biogas plants which treat energy crops together with manure and organic wastes are between 60 and 90 days [3]. Fig. 11 shows the broad range of hydraulic retention times of modern biogas plants. The relatively long retention times result from low loadings combined with direct feeding of biomass with high total solids contents. Retention times lower than 30 days are only used for substrate mixtures of manure with a low share of energy crops.

Dry fermentation is a relatively new application of anaerobic treatment processes in the agricultural sector, which is becoming more attractive for the treatment of yard manure from cows, pigs and poultries but also for the mono-fermentation of energy crops. Several batch processes with percolation and without mechanical mixing have been tested on a pilot-scale, but only a few concepts are currently being applied on a farm-scale [9]. Fig. 12 shows the typical process steps for dry fermentation in digestion boxes.

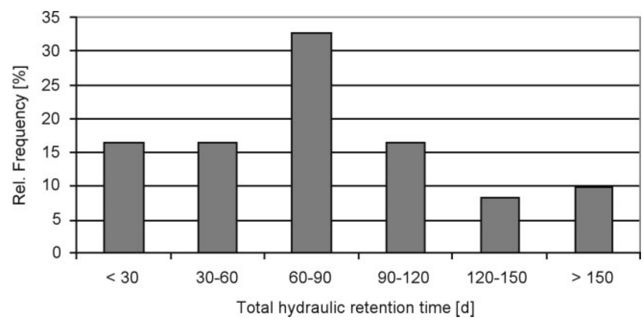

Figure 11. Hydraulic retention time of modern co-digestion biogas plants.

The substrate is loaded batchwise in a closed box and mixed with inoculum from a previous batch digestion. The necessary ratio of solid inoculum has to be determined individually for each substrate. While yard manure from cows requires only small ratios of solid inoculum, up to 70 % of the input is necessary for energy crops [10]. During the digestion period, process water is recirculated and sprinkled over the substrate to facilitate start-up and inoculation as well as for moisture control, heating and removal of volatile fatty acids.

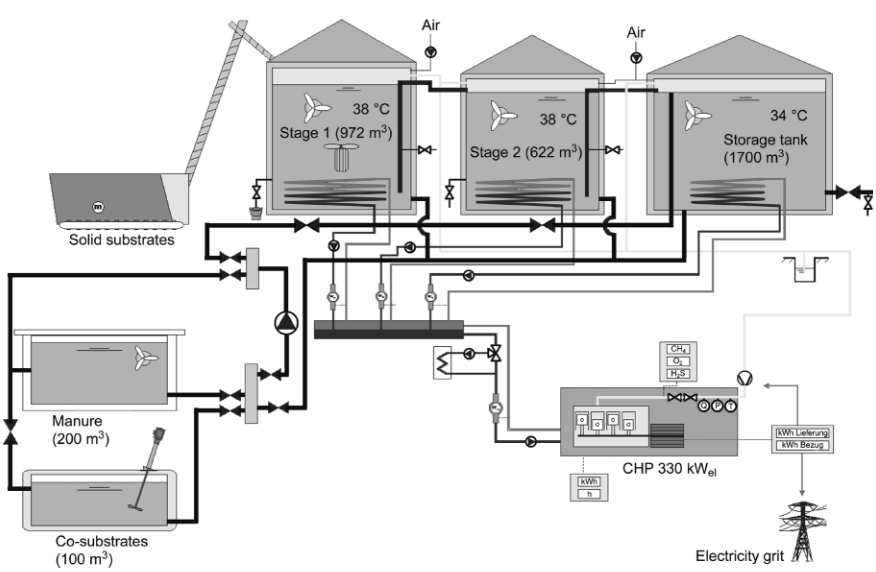

Figure 10. Two-stage biogas plant with gas-tight covered storage tank.

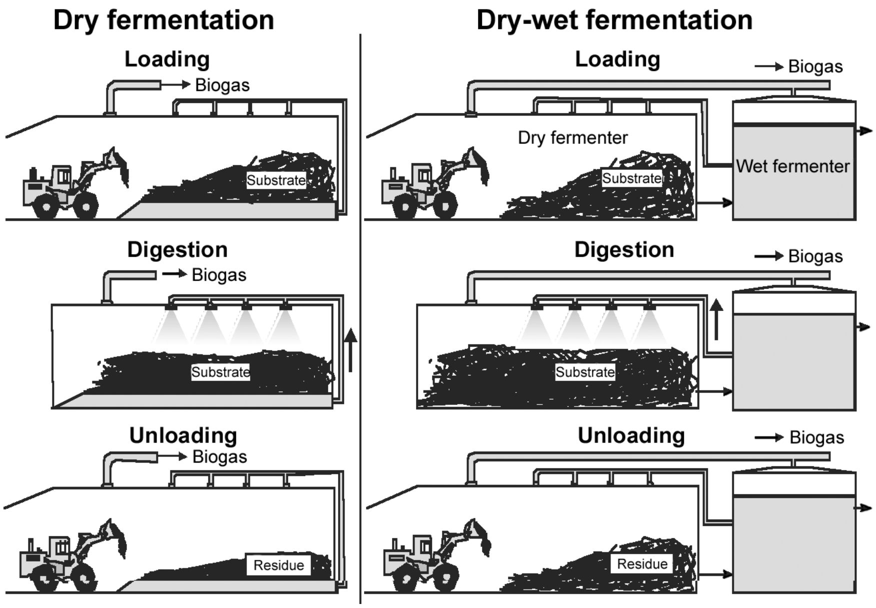

Figure 12. Process variations for dry fermentation in digestion boxes.

To achieve a constant gas production, at least three fermenters must be operated in parallel with different start-up times. In order to reduce the ratio of solid inoculum and to increase the process stability, the leachate should be exchanged between new and established batches. If the dry fermenter is coupled with a wet-digestion system (dry-wet fermentation), the effluent from the wet digester is used for leaching. For avoiding clogging of the leach bed, solids from the wet-fermenter effluent must be separated. When the digestion process is complete, the digested material is unloaded and a new batch is initiated.

4 Biogas Utilization

Biogas is a universal energy resource which can be used for many applications if the gas quality is adapted to the specific requirements of the applied techniques (see Fig. 13).

Today biogas is used in all German biogas plants in combined heat and power units (CHP) using dual-fuel injection engines or gas engines after desulfurization and removal of water. The electricity is fed into the public grid and the thermal energy is mainly used for the process and heating purposes in the house and farm but relatively seldom for decentralized public grid heating or drying processes. The efficiency for electricity generation ranges from 30 to 37 % without significant differences between the different combustion systems of the engines [3].

For the utilization of biogas as a vehicle fuel and for the feeding of biogas into the public grid or for the utilization in fuel cells much higher quality requirements have to be fulfilled. The main parameters that may require removal in upgrading systems are CO_2, H_2S, NH_3, water, and solid particles. The utilization of biogas as a vehicle fuel and the feeding of bio-methane into the public gas grid have been applied in Sweden and Switzerland for several years and recently also in Germany.

A number of technologies are available for biogas upgrading. Carbon dioxide is mainly removed by water scrubbing, pressure swing adsorption (PSA) and polyethylene glycol scrubbing [11, 12]. H_2S can be removed internal to the digestion process by biological desulfurization performed by microorganisms of the family *Thiobacillus* or by iron chloride dosing to the digester [13]. Using water-scrubbing systems, H_2S can be removed simultaneously with CO_2, and for PSA systems adsorption columns with activated carbon are usually employed for H_2S removal. If non-agricultural wastes are employed for biogas production, higher hydrocarbons, halogenated hydrocarbons and organic silicon compounds can also be present in biogas. They can be removed by adsorption with molecular sieves or absorption in a liquid medium.

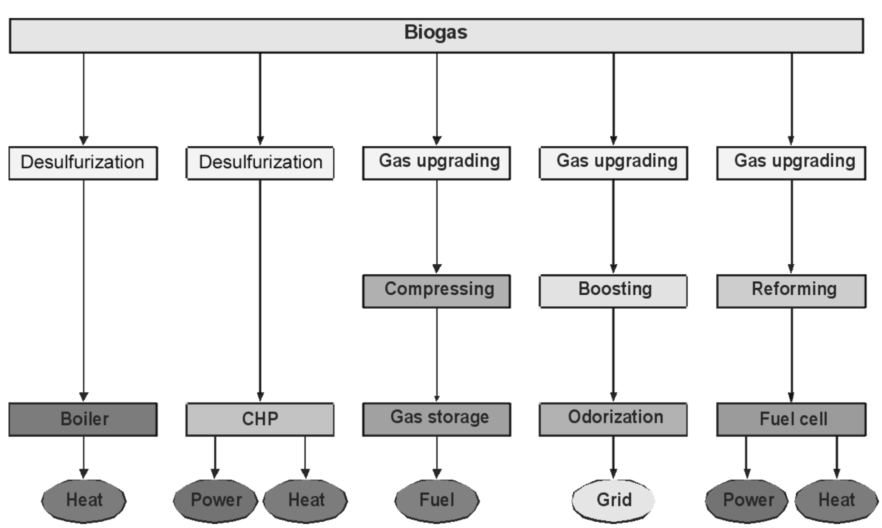

Figure 13. Alternatives for biogas utilization.

Water scrubbing is the most commonly applied technology for carbon dioxide removal. The regeneration of the loaded water is achieved by de-pressuring and air stripping. The schematic flow sheet of water scrubbing for the removal of CO_2 and H_2S with water recirculation is presented in Fig. 14.

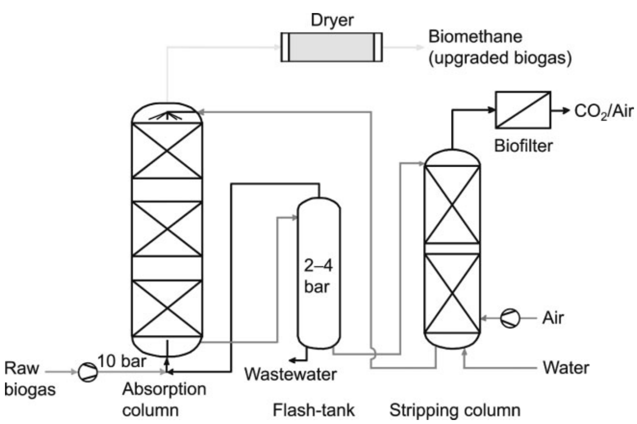

Figure 14. Pressure water scrubbing with regeneration of the loaded water.

There are no specific requirements defined for fuel gas, but the gas quality must be adapted to the standards of natural gas of type H. For the utilization of biogas as a vehicle fuel, the following quality requirements must be fulfilled (see Tab. 3).

Table 3. Quality specification of bio-methane as a vehicle fuel [14, 15].

Components	Properties
Methane	> 96 vol. %
Carbon dioxide	< 3 vol. %
Hydrogen sulfide	< 5 mg/Nm^3
Oxygen	< 0.5 vol. %
Particles	< 1 µm
Water content	< 32 mg/Nm^3

Upgraded biogas is a very clean vehicle fuel with respect to environment, climate and human health because carbon dioxide, hydrocarbon and NO_x emissions are strongly reduced and obviously no emissions of carcinogenic compounds occur. Therefore, biogas is fully free of fuel taxes in Germany and other European countries. If the upgraded gas is produced only by energy crops, the energy yield per hectare is higher by a factor of approx. four compared to rapeoil-methylester (RME), because from one hectare up to 4800 L of diesel$_{equ}$ can be obtained from biogas, but only 1200 L of diesel$_{equ}$ from RME.

The utilization of biogas in fuel cells has the advantage that the conversion efficiency to electricity is much higher compared to motor engines, but the transformation of biomethane into hydrogen by catalytic steam reforming necessitates higher quality specifications than vehicle fuel gas. Depending on the fuel cell type, the tolerance against H_2S, NH_3, and CO is very low [16]. Therefore, an efficient removal of these trace gases is necessary for fuel cell applications. Due to the high investment costs and the necessarily high gas quality only a few fuel cells are applied today in practice.

5 Summary and Outlook

Anaerobic digestion is an important way for handling of waste and for the utilization of agricultural biomass for energy production. While the application was previously focused on the stabilization of sewage sludge and manure, emphasis is today focused mainly on climate protection, environmental protection, conservation of natural resources, and the development of a sustainable energy supply. At the present time, biogas production has become a new income branch for farmers.

Anaerobic digestion is a mature technology today but the evaluation study of modern biogas plants, which use energy crops for biogas production, has demonstrated that further research is necessary for process optimization and improvement of process stability. Several new process configurations for the treatment of solid substrates were developed recently. An alternative to conventional wet-fermentation processes are leach bed processes, where the leachate from the base of one reactor is exchanged between established and new batches to facilitate the start up, inoculation and removal of organic acids in the active fermenter.

Furthermore, an improving of the digestibility of biomass is necessary because most of the biomass is only partly degraded. Multi-stage digestion systems and gas-tight storage tanks should be applied more often in order to reduce the emission of methane from biogas plants. A better understanding of the dynamics of the complex microflora which is involved in the anaerobic process can help to improve the digestion process. A higher performance of anaerobic biomass degradation can also be expected by the development and application of modern online monitoring systems.

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