0273-2289/03/109/0263/$20.00

Production and Energetic Use of Biogas from Energy Crops and Wastes in Germany

PETER WEILAND

Federal Agricultural Research Centre (FAL), Institute of Technology and Biosystems Engineering, Bundesallee 50, D-38116 Braunschweig, Germany, E-mail: peter.weiland@fal.de

Abstract

The production of biogas for reducing fossil CO_2 emissions is one of the key strategic issues of the German government and has resulted in the development of new process techniques and new technologies for the energetic use of biogas. Progress has been made in cultivating energy crops for biogas production, in using new reactor systems for anaerobic digestion, and in applying more efficient technologies for combined heat and power production. Recently, integration of fuel cells within the anaerobic digestion process was started, and new technologies for biogas upgrading and conversion to hydrogen were tested. This article describes the trends in Germany for achieving more efficient energy production.

Index Entries: Biogas production; biogas processes; digestion systems; energy crops; fuel cells.

Introduction

The application of anaerobic fermentation processes for the production of biogas has increased significantly in Germany since the Renewable Energy Sources Act (EEG), which guarantees a fixed compensation paid for the produced electricity for a period of 20 yr after the year of commissioning was enforced on April 1, 2000 *(1)*. The compensation that is paid in the year 2002 per kilowatt-hour is between 10.1 and 8.6 Euro-Cent (∈-Cent) depending on the installed electrical capacity. Therefore, the production of biogas has become an attractive source of extra income for many farmers. At the same time, environmental protection aspects have gained additional importance, so that anaerobic treatment processes have become a key technology for environmental and climate protection and for the conservation of fossil fuel resources.

In the agricultural sector, conceptually strong different types of biogas plants are applied in Germany that differ in size, reactor design, operation conditions, and the feedstocks used for biogas production. At the end of

2001, approx 1650 agricultural biogas plants with an installed electrical capacity of 140 MW were in operation *(2)*. Approximately 95% of all biogas plants are of farm scale, with typical reactor sizes between 200 and 1200 m^3. Only about 5% of all biogas plants are large centralized installations based on the utilization of animal manure delivered from a group of suppliers together with non-agricultural cosubstrates. The typical treatment capacities of these plants are between 30,000 and 90,000 m^3/yr, but plants with capacities up to 140,000 m^3/yr are also in operation.

Feedstocks

With energy production as the main objective of anaerobic digestion, the type of feedstocks used for anaerobic digestion is highly relevant because the biogas yield obtained per cubic meter of reactor volume depends on the energy density and biologic degradability of the applied feedstocks. The biogas yield from cow and pig manure is only between 25 and 36 m^3/t of fresh mass, because the organic dry matter (ODM) content is low (2–10%) and most of the energy-rich substances have already been digested by the animals. Therefore, the use of manure as the only substrate for biogas production is not economical in most applications, which makes the digestion of cosubstrates necessary. More than 90% of the running biogas plants in Germany are operated with cosubstrates that mainly come from food and agricultural industries, markets, canteens, and the municipal sector. Cofermentation of energy crops was started in 1999 for the first time, and even today more than 50% of all biogas plants that were put into operation since 1999 use energy crops for codigestion. Only 7% of all biogas plants are operated exclusively with manure as the only substrate *(3)*.

The use of pig and cow manure as a basic substrate for cofermentation has the advantages that the high buffer capacity of manure stabilizes the process pH value and that its complex composition balances any lack of trace elements or nutrients. Many wastes and byproducts from food and agricultural industries (e.g., fruit and vegetable pulps, oil seed residues, or overlaid foodstuffs) are ideal cosubstrates for digestion, because these materials are normally free of contaminants, pathogens, and heavy metals. Grease- and fat-containing residues result in the highest biogas yield, but because of the occurrence of different animal diseases, only vegetable oils and fats can be used today. Residues from restaurants, markets, and the municipal area need pretreatment for reducing particle size, separation of contaminants that disturb the digestion process, and land application of the digester residues. In addition, they need to be pasteurized at 70°C for 1 h in order to reduce the content of pathogenic germs. These wastes are mainly used in large centralized plants, because installations for the pretreatment are expensive and pretreatment on farms often makes special structural measures necessary in order to reduce hygienic risks for animal breeding.

Therefore, the use of energy crops is an interesting alternative to cofermentation, because sufficient fallow agricultural land is available in

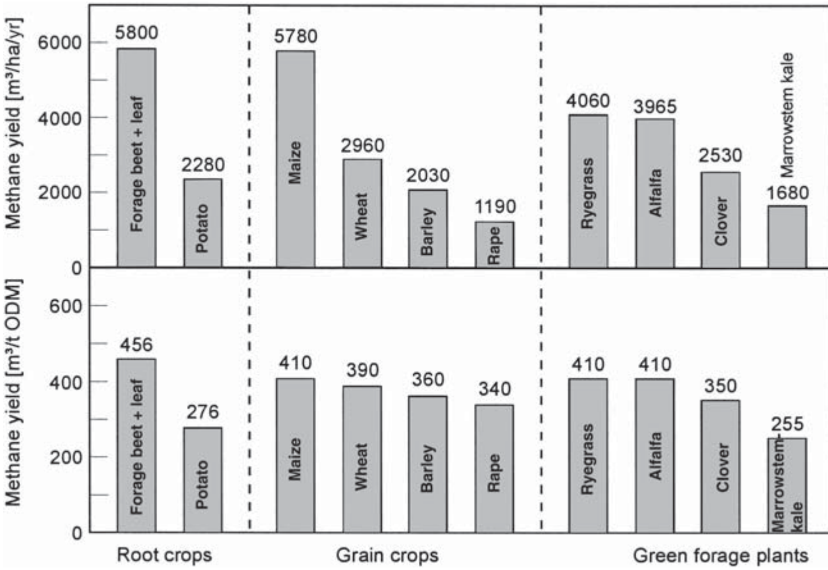

Fig. 1. Methane yield of various crops *(4)*.

Germany as well as in other European countries for crop cultivation. Most of the conventional agricultural crops are suitable for anaerobic digestion if they are harvested before lignification begins. High methane yields can be achieved by root crops, grain crops, and several green forage plants (Fig. 1).

The methane yield per ton of ODM is between 250 and 450 m^3, with strong differences in the specific methane yield per hectare and year. The highest methane yields per hectare can be achieved by forage beets, forage maize, and several multiple, cutting green forage plants such as ryegrass, sudan grass, or alfalfa *(4)*. For the production of energy crops, new types of cultivation can be applied, because the necessary quality standards are completely different compared to those for food production. To achieve high mass yields per hectare, two-culture systems that allow the production of two different crops within only one vegetation period can be utilized *(5)*.

The first culture (e.g., winter barley) is harvested in the milk ripeness stadium at the end of May before lignification begins. The time of milk ripeness often corresponds with the time of the highest dry mass yield per hectare. Therefore, a high yield of easy biodegradable biomass can be obtained. The early time for harvesting allows the cultivation of a second crop (e.g., maize) that can be harvested in October before full ripeness. This allows dry mass yields of more than 20 t per hectare and year, which is above the maximum mass output of high-yield crops (12–15 t of dry mass/ha yr).

All energy crops can be preserved by ensiling, which allows storage over prolonged periods of time. The use of forage beets for biogas produc-

Table 1
Properties of Forage Beets
for Anaerobic Digestion *(7)*

Substrate property	Value
Forage beet yield (t/ha)	100
Beet leaf yield (t/ha)	25
DM content (%)	11
ODM content (%)	10
pH (–)	3.3

Table 2
Typical Process Dates from Anaerobic Digestion *(7)*

Parameter	Mesophilic	Thermophilic
Maximum loading rate (kg ODM/[$m^3 \cdot d$])	3.5	3.5
Degradation efficiency (% COD)[a]	90	92
Methane yield (m^3/t FM)[b]	45	46
Methane productivity (m^3/[$m^3 \cdot d$])	1.95	2.1
Methane content (vol %)	54	53

[a]COD, chemical oxygen demand.
[b]FM, fresh mass.

tion is of particular interest not only because of the high biomass yield per hectare but also because of the easy handling properties of the ensiled beets. After grinding and ensiling, the beet pulp consistency is like a slurry, which can be discharged from the storage tank by conventional displacement pumps. This allows an automatic controlled feed inlet to the digester and an exact adjustment of substrate mixtures.

The Institute of Technology and Biosystems Engineering has intensively evaluated the digestion of forage beets *(6)*. The experiments showed that forage beet silage can be digested as the only feedstock up to loading rates of 3.5 kg of ODM/($m^3 \cdot d$). Cofermentation with manure enhances the process stability, making loadings of up to 5 kg of ODM/($m^3 \cdot d$) possible *(7)*. The main substrate characteristics and typical process dates from long-time experiments are shown in Tables 1 and 2.

Process Design

The typical process chain that has to be applied for biogas production from energy crops is shown in Fig. 2. If possible, harvesting and size reduction of the energy crops should be done simultaneously in one step, but this technology is not available for all important energy crops. For example, for forage beets, a first prototype of a beet harvester has been tested that can harvest and grind the total plant, including the leaves, in one process step.

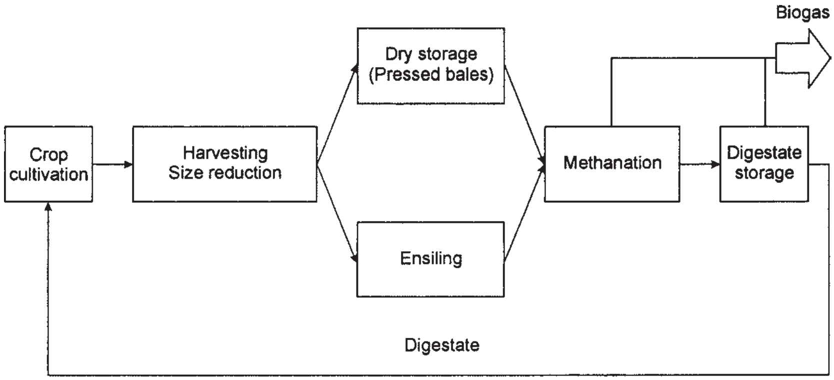

Fig. 2. Process chain for biogas production with energy crops.

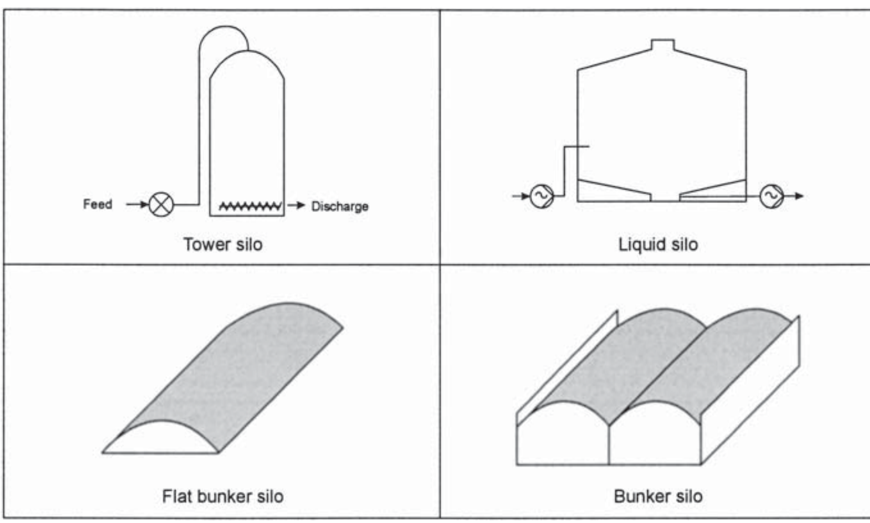

Fig. 3. Silos for ensiling and storage of energy crops.

Depending on the biomass properties, different types of silos can be used for ensiling and storage of crops (Fig. 3). Tower silos have the advantage that they can be discharged automatically by a bottom unloader, which allows continuous feeding of the digester, whereas bunker silos can be discharged only by mobile front loaders. The disadvantage of bunker silos, and especially flat bunker silos, is their high area demand, but because of the low investment costs both silo types are most often applied for storage.

For ensiling of forage beets, liquid silos have to be applied because the beet pulp is converted into a liquid slurry during the ensiling process *(6)*. Good protection against corrosion is necessary because the pH value of ensiled root crops is low (≤3.5) and the lactic acid concentration is extremely high (35 and 40 g/kg). Therefore, stainless steel tanks or enamel steel tanks

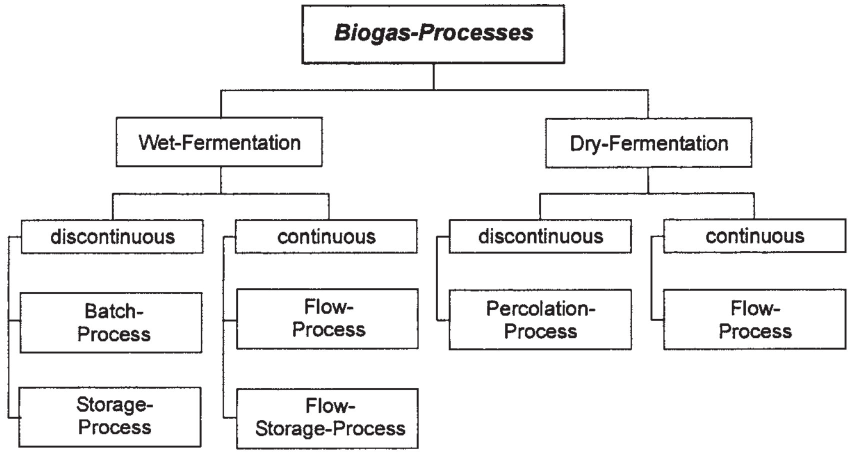

Fig. 4. Different types of processes for biogas production *(9)*.

must be used. Concrete silos can be applied also, but the inner walls must be protected by special plastic inlayers.

Depending on the substrate properties, wet and dry fermentation processes are applied for anaerobic digestion of energy crops and mixtures of crops together with manure or high-loaded effluents from agroindustry (Fig. 4). Wet fermentation processes are operated with a maximum total solids (TS) content of 10–13% dry matter. Mainly continuously operated throughflow reactors and throughflow storage tank reactors are applied. Both process types differ only in the construction of the storage tank, which is open in conventional throughflow plants and completely closed and coupled with the gas storage tank in throughflow storage tank systems. Depending on the substrate properties and the operation conditions of the biogas reactor, approx 5–15% of the total biogas yield is formed in the storage tank *(8)*. If only 5% of the produced methane is emitted from the storage tank, the positive climate effect of the energetic use of biogas is completely canceled because the global warming effect of methane is at least a factor of 23 higher than CO_2. Therefore, only biogas reactor systems with a closed secondary digestion tank should be applied for energy crop fermentation.

For the digestion of solid energy crops, either the substrate can be mixed with recirculated process water or manure in a preconditioning mixing tank or the solids can be fed directly into the reactor by applying special charging systems. Mixing in a separate preconditioning tank can be applied for all types of substrates, but the energy demand is relatively high because the whole tank has to be mixed before every feeding. Therefore, different charging systems have been developed *(9)*. Mainly flushing systems and screw-feeder systems are used, which transport the solid substrate directly into the reactor tank (Fig. 5). Flushing systems can be used only for substrates of higher densities, whereas the application of screw

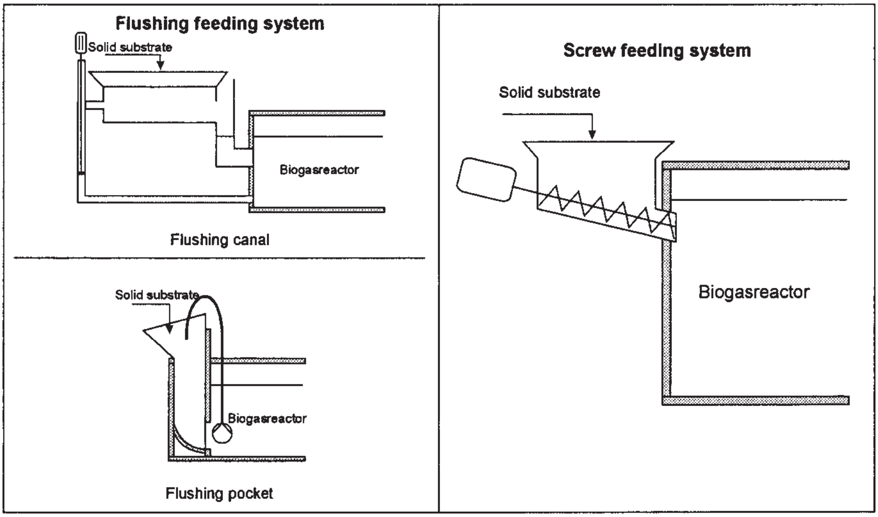

Fig. 5. Feeding systems for solid energy crops.

conveyor systems is limited to silage of short fibrous material, such as maize silage or corncob mix.

Dry fermentation processes with a digestate dry matter (DM) content of 20–40% TS have been applied for many years for the treatment of source-separated municipal solid wastes. Most of theses processes are operated continuously with both completely mixed or plug-flow reactor systems. However, in the agricultural sector, dry fermentation processes have been seldom applied, but, recently, several new concepts were developed especially for the treatment of energy crops *(10)*. Only batch systems without mixing are used in agriculture. A relatively simple system that uses a gastight transportable container box for fermentation is shown in Fig. 6 *(11)*.

In the first step, the substrate is loaded into a lattice box that is brought into a gastight container. In the second step, the substrate is aerated for a short time in order to achieve the digestion temperature by aerobic rotting. In the next step, the reactor is closed and leachate from the base of the reactor is recirculated to maintain a uniform moisture content and to redistribute methane bacteria and soluble substrates throughout the substrate bed. When the digestion is complete, the reactor is aerated once more for a short time, reopened, unloaded, and refilled with a new charge of fresh substrates. To achieve a constant gas production at least three reactors have to be operated in parallel run with different startup times of the individual reactors.

In contrast to wet fermentation, only structured substrates can be applied for dry fermentation. Dry fermentation processes are cost-effective, especially in the case of low treatment capacities because the process technique is simple and the machineries for loading and unloading the digester can be applied for other activities as well.

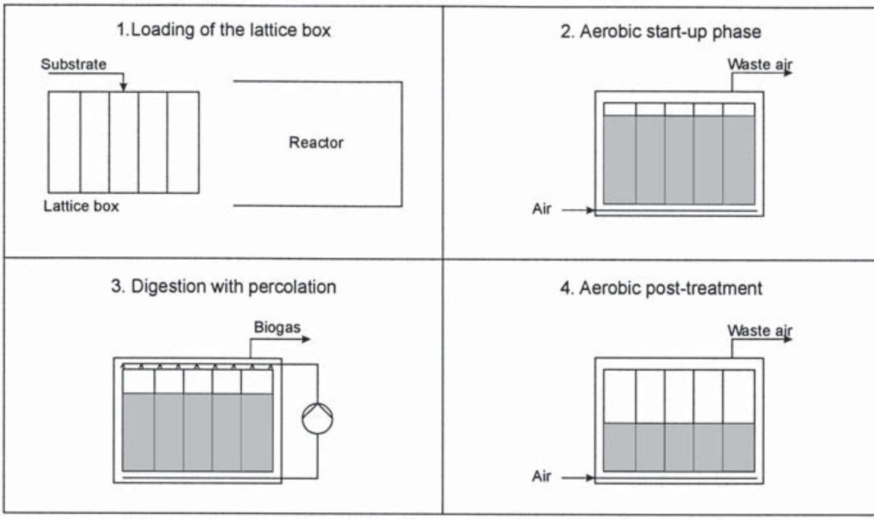

Fig. 6. Typical dry fermentation system.

Utilization of Biogas

Biogas is an ideal energy source and can be used for all applications that are designed for natural gas, but the individual gas appliances require considerable different quality gas standards, which makes purification and upgrading of the gas necessary. Boilers have the lowest quality requirements, but they are seldom applied today. Approximately 98% of all biogas plants in Germany use combined heat and power plants for the utilization of biogas, because a fixed compensation is paid only for electricity, not for heat *(3)*. Up to an installed electrical power of 200–250 kW_{el}, mainly dual-fuel diesel engines are used, which need 8–10% diesel oil for gas ignition. The ignition jet diesel engines are characterized by a high electrical efficiency of 33–38% and medium costs of 450–700 euro/kW of installed capacity *(12)*.

For higher electric capacities, spark-ignited diesel engines are preferred because of their robustness and high reliability. The electrical efficiency is lower than 35% and the specific investment costs per kW_{el} are higher compared to dual-fuel engines of the same capacity. An important disadvantage of all engines is their limited electrical efficiency, because in most applications the cogenerated heat can be seldom used completely. Therefore, research is focused on the application of fuel cell power plants for biogas utilization, because the electrical efficiency of fuel cells is not thermodynamically limited by the Carnot process. Theoretically, electrical efficiencies of 95% are possible, but in practice the maximum electrical efficiency is limited to 40–60% *(13)*. Different types of fuel cells that are classified according to the electrolyte used and the temperatures that result in the best conductivity can be applied (Fig. 7).

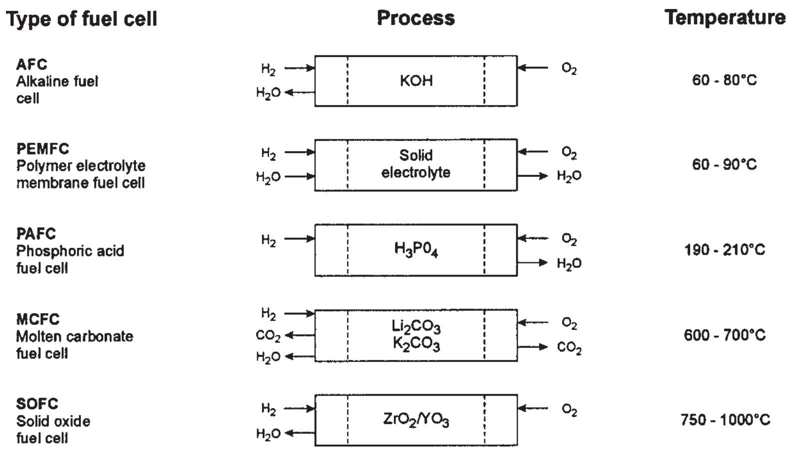

Fig. 7. Fuel cells for biogas utilization.

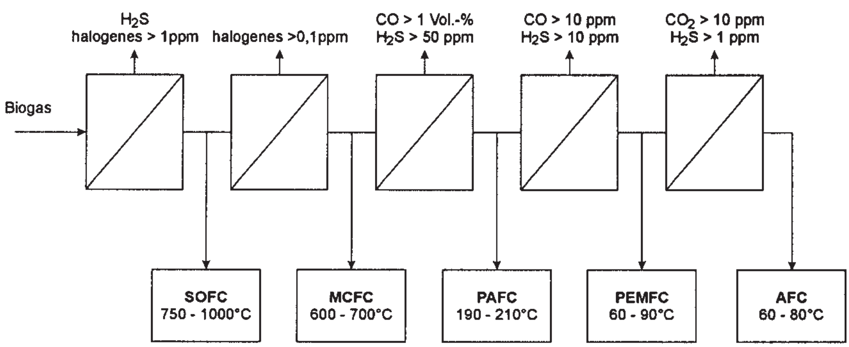

Fig. 8. Impurities to be removed prior to feeding gas to fuel cells.

All fuel cells need purification of the biogas because trace gases such as H_2S, halogens, and CO inhibit the chemical conversion process and can damage the fuel cell. Upgrading of biogas by CO_2 separation is necessary in order to achieve a high electrical efficiency. After gas upgrading, the methane-rich gas has to be converted into hydrogen, because only hydrogen can be used by fuel cells for production of electricity. Depending on the fuel cell type, a further process step may be necessary in order to convert CO into CO_2 prior to feeding the gas to the fuel cell. The requirements of gas quality depend on the fuel cell type (Fig. 8).

Solid oxide fuel cells have the lowest demand on gas quality, whereas polymer electrolyte membrane fuel cells and alkaline fuel cells need higher gas qualities. Therefore, the main criteria for the selection of a fuel cell are the required gas purity and the conditions for the utilization of the produced heat. Important advantages of all fuel cells are not only their high electrical and thermal efficiency but also their constant efficiency at different loads, the very low pollutant emissions, and the low noise and vibrations of fuel cell power plants.

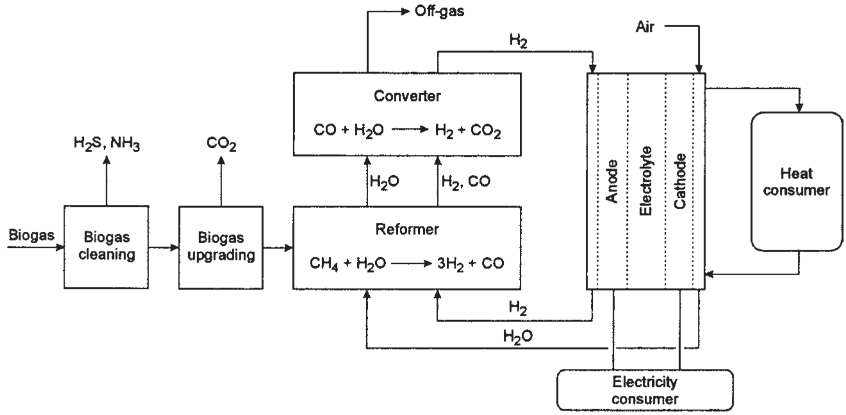

Fig. 9. Schematic sketch of FAL fuel cell plant.

In 2002, a first test for the application of fuel cells on a biogas plant was begun at the experimental station of the Federal Agricultural Research Centre (FAL) in Braunschweig, Germany, in cooperation with the companies Farmatic Biotech Energy AG in Nortorf, Germany, and Loock Consultants in Hamburg, Germany. Installation for the purification and upgrading of biogas allows the production of biogas with different qualities for testing different types of fuel cells. A schematic sketch of the process is shown in Fig. 9.

For the removal of H_2S, a biologic scrubber column that oxidizes H_2S to sulfate and molecular sulfur is used. After the removal of water, the remaining trace gases are removed by special adsorption systems prior to the gas being converted into a hydrogen-rich gas. For the hydrogen formation, a newly developed hydrogen generator system that combines the pressure swing adsorption on molecular sieves with the reforming step to methane is applied. A polymer electrolyte membrane fuel cell (PEMFC) is used for power generation. PEMFC technology has the advantage that the operation temperature is below the boiling point of water, which makes the application and utilization of the produced heat easier on farms. Furthermore, it can be expected that the investment costs for PEMFCs will decrease considerably within the next few years, as the number of PEMFCs produced for car industries increases. A further cost reduction is also expected owing to the decreasing amount of platinum catalyst necessary for the cell's construction and the development of cheaper membrane materials. The model project will demonstrate whether fuel cells will be the best available technique for the energetic use of biogas within the near future.

Other new technologies for the conversion of biogas into electrical energy are micro gas turbines and Stirling engines, whose commercial production has recently been started *(14,15)*. Both engines are characterized by lower electrical efficiencies, but the expected maintenance costs are lower compared to conventional combined heat and power stations. Micro gas turbines are more flexible with respect to the load, and the produced heat can be used for the production of process steam because the off-gas temperature is above 250°C.

For utilization of biogas as a vehicle fuel, in 2003, the first large-scale demonstration plant will be started in Germany. The upgraded biogas will be a very clean vehicle fuel with respect to the environment, climate, and human health. The NO_x emissions are reduced by more than 50%, and emissions of carcinogenic organic compounds can be avoided. Feeding of upgraded biogas into the natural gas grid is done in Sweden, Switzerland, and The Netherlands, and a first pilot project will be started in 2003 in Germany. An opening of the gas grid for purified biogas is being discussed intensively in Germany, but currently the necessary legal regulations that guarantee a fixed compensation paid for the feeding of gas into the grid and obligations of the grid operators to connect biogas plants to their grids are not available.

Conclusion

Biogas production has gained great importance in Germany for achieving a sustainable energy supply in the interest of managing global warming, environmental protection, and fossil fuel conservation. For improving the economy of biogas plants and for increasing the capacity of biogas production, codigestion of energy crops has become popular in agriculture. Seed breeding companies have started to design high-yield energy crops, and farmers have tested new methods for achieving two harvestings of energy crops per year. More sophisticated digestion processes are applied and special reactor systems for the treatment of energy crops were recently developed. To ensure an economic utilization of biogas, several new technologies for the combined heat and power production and for the use of biogas as a vehicle fuel have been tested. The usage of biogas in fuel cells has a high potential for further research and development. Not only for the application of fuel cells but also for the utilization of biogas as a vehicle fuel, cheap technologies for gas purification and upgrading are necessary. Therefore, the development of low-cost processes for the desulfurization and upgrading of biogas is an important task for the future.

The recent, fast increase in the number of biogas plants in Germany has clearly demonstrated that besides the development of efficient and innovative technologies for the production and conversion of biogas, legislation is an important factor in order to achieve sustainable energy production.

References

1. EEG—Renewable Energy Sources Act. (2000), *Bundesgesetzblatt* **1(13),** 305–309.
2. Costa Gomez, C. (2001), in *Biogas International 2000*, erneuerbare energien Reutlingen, pp. 1–8.
3. Rieger, C. and Weiland, P. (2001), Report FNR-FKZ 00NR179, Bundesforschungsanstalt für Landwirtschaft (FAL) ed., Braunschweig.

4. Weiland, P. (2001), in *Erneuerbare Energie in der Landwirtschaft*, Medenbach, M., ed., Verlag für land(wirt)schaftliche Publikationen, Zeven, pp. 18–33.
5. Scheffer, K. (1998), in *Beiträge der Akademie für Natur- und Umweltschutz*, Bd. 27, Stuttgart, pp. 65–80.
6. Clemens, J., Rieger, C., Weiland, P., Vandré, R., Schumacher, I., and Wulf, S. (2001), in *Biogas—Mit neuer Energie Ressourcen schonen*, Fachverband Biogas, ed., Freising, pp. 44–51.
7. Hassan, H. and Weiland, P. (2001), Report BLE-AZ 99UM031, Bundesforschungsanstalt für Landwirtschaft (FAL) ed., Braunschweig.
8. Weiland, P. (2000), in *Energetische Nutzung von Biogas durch Kraft-Wärme-Kopplung*, Fachagentur Nachwachsende Rohstoffe, ed., Gülzow, pp. 90–104.
9. Köberle, E. (2001), in *Biogas—Mit neuer Energie Ressourcen schonen*, Fachverband Biogas, ed., Freising, pp. 26–43.
10. Hoffmann, M. (2000), *Landtechnik* **55,** 442–443.
11. Loock, R. (1996), *gwf-Gas-Erdgas* **137,** 284–288.
12. Mitterleitner, H. (2001), in *Erneuerbare Energie in der Landwirtschaft*, Verlag für land(wirt)schaftliche Publikationen, Medenbach, M., ed., Zeven, pp. 98–102.
13. Rösch, C. (1999), in *Energetische Nutzung von Biomasse in Brennstoffzellenverfahren*, Fachagentur Nachwachsende Rohstoffe, ed., Gülzow, pp. 7–33.
14. Scott, W. G. (1997), *Power Eng.* **101,** 46–50.
15. Carlsen, H. and Bovin, J. (2001), in *Proceedings of the International Stirling Engine Conference 2001*, VDI-GET, ed., Düsseldorf, pp. 278–285.