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EFFICIENT ENERGY PRODUCTION IN MODERN BIOGAS PLANTS AS AN EFFECTIVE MEANS OF LIMITING CH₄ AND CO₂ EMISSIONS

CH₄ and CO₂ are dangerous pollutants, mainly responsible for greenhouse effect. Energy production in the biogas plants can significantly reduce emissions of these gases into the atmosphere. This is possible because such plants use input renewable resources, whose lifecycle is almost CO₂-neutral, and organic wastes, if not properly treated, can produce CH₄ emissions. This paper presents some examples of efficient energy production in the modern full-scale biogas plants, using innovative process engineering and instrumentation, control and automation techniques.

1. INTRODUCTION

Very fast industrial development in the recent decades caused an increase in CO₂ emissions (combustion of fossil fuels, e.g., coal and brown coal) and CH₄ emissions (e.g. uncontrolled emissions of landfill gas). Because of the above and also because of other numerous advantages, the production of energy from regenerative CO₂-neutral sources, e.g. wind, water, sun and biomass, gains more and more importance. Agricultural as well as (industrial) co-digestion biogas plants (BP) seem to be a perfect solution to minimizing CO₂ and CH₄ emissions, provided that energy production in these plants is optimal and they work at full capacity.

According to Holm-Nielsen and Al Seadi (in LENS et al. [4]) the cycle of biogas production is an integrated system of resources utilization, organic waste treatment, nutrient recycling/redistribution and renewable energy production, which brings numerous energetic, environmental and agricultural benefits. In those plants, biogas can be produced using numerous different input substrates such as:

- Farm products: liquid manure, poultry droppings, grain, maize, green rye, Sudanese grass, rape, sunflowers, fodder beets, sugar beets, Jerusalem artichoke, et cetera.

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- Organic waste, primarily from food industries, i.e. breweries, distilleries and gelatin/jam production, and also from canteen kitchens, food markets, glycerin, fuller's earth, slaughter-houses, sewage sludge from wastewater treatment plants, et cetera.

The energy production in the biogas plants can be divided into two stages. In the first stage, the biogas is produced from organic wastes or farm products, while in the second one, e.g. in the Combined Heat and Power unit (CHP), it is converted into heat and electrical energy.

2. BIOGAS PRODUCTION – THE BEST WAY TO AVOID CO₂ AND CH₄ EMISSIONS

The biogas is produced in digestion tanks as a result of biochemical processes. This is a very efficient way to convert primary energy included in the biomass into methane which is shown in figure 1 in order to compare the efficiencies of biomass conversion in several important fuel production processes. It can be seen that the process is much more effective than, e.g., biodiesel and bioethanol production and more effective than biomass to liquid process (BtL). However, BtL requires very high investment costs and high energy consumption.

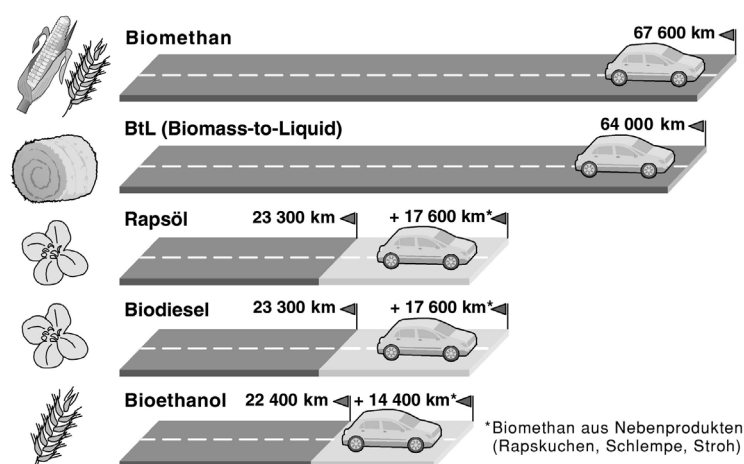


Fig. 1. Comparison of different technologies for biomass to fuel conversion. Maximal car cruising range per one hectare of area under crops (rapsöl = rape oil, source: German Agency for Renewable Resources "FNR")

In figure 2, the emissions of greenhouse gases are compared for several biofuels. It is easy to observe that using proper strategies and substrates, even negative emission can occur. Of all greenhouse gases the biogas has the highest potential reduction.

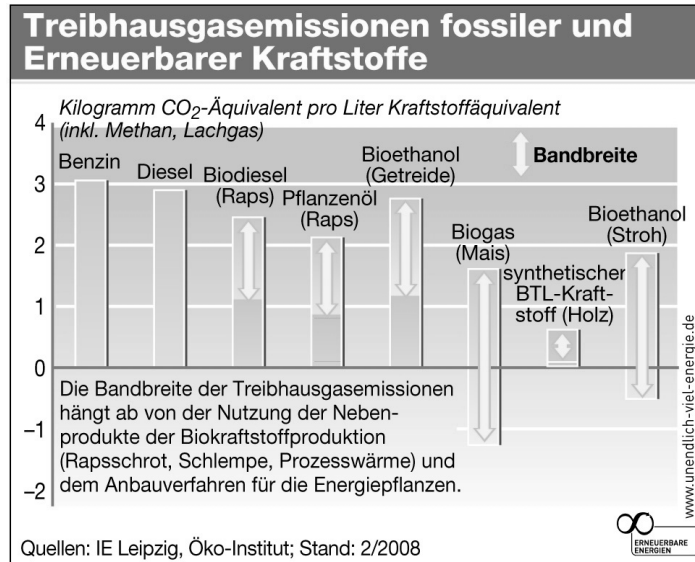


Fig. 2. Comparison of emissions of greenhouse gases in CO₂-equivalent for several biofuels. (Pflanzenöl = vegetable oil, BTL = biomass to liquid, Stroh = straw; source: IE Leipzig, Öko Institut, Stand: 2/2008)

Summing up, biogas, also in comparison with another biomass fuels, is unbeatable and there is no evidence of adopting an opposite viewpoint in the near future.

3. ENERGY PRODUCTION IN BIOGAS PLANTS

Conversion of biogas into power and heat occurs in most biogas plants in the CHP unit which consists of: gas-engine, converting the biogas into the mechanical energy; current generator, producing electricity from the mechanical power; and heat recovery system. The total efficiency of heat and power production via CHP unit due to B.KWK can reach approximately 88%, whereas about 38% is electrical efficiency, and only approximately 12% are losses relating to biogas energy. The heat produced is used partially (approximately 10%) for the heating of digesters.

Most of the existing biogas plants, due to economical and logistical reasons, produce electrical power in the range between 300 and 3.000 kW_{el}. This fact predestines them as ideal to decentralized energy production. Figure 3 compares efficiencies of two types of energy production: centralized-separate (conventional) one and decentralized-combined (heat and power) one. According to figure 3, for the same energy production, in the centralized-separate system the fuel consumption is by 66% higher than that in the decentralized-combined one. Hence, the heat consumption, which increases significantly the total efficiency of energy conversion and ratability of the

investment, plays a crucial role during making the decision about the plant location. Last but not least, as regards heat, loss or transmission loss of energy is an obvious disadvantage of centralized energy supply systems.

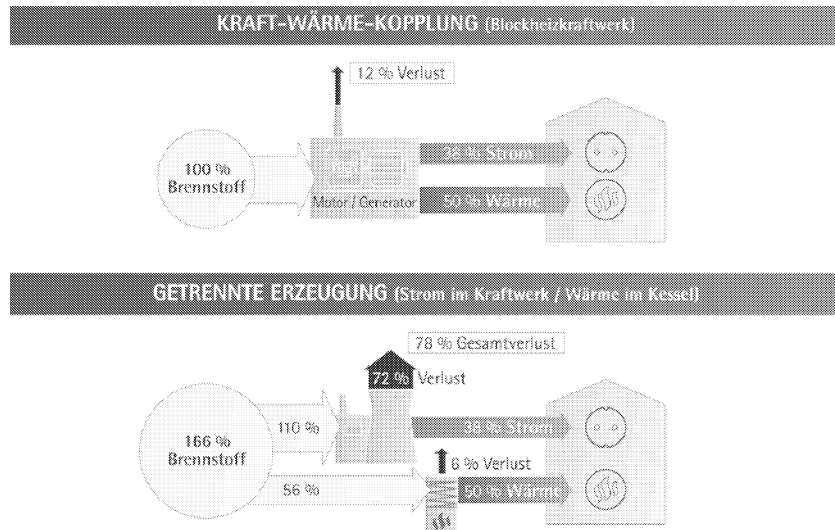


Fig. 3. Comparison between old, separate and centralized energy production and combined, decentralized energy production (B.KWK)

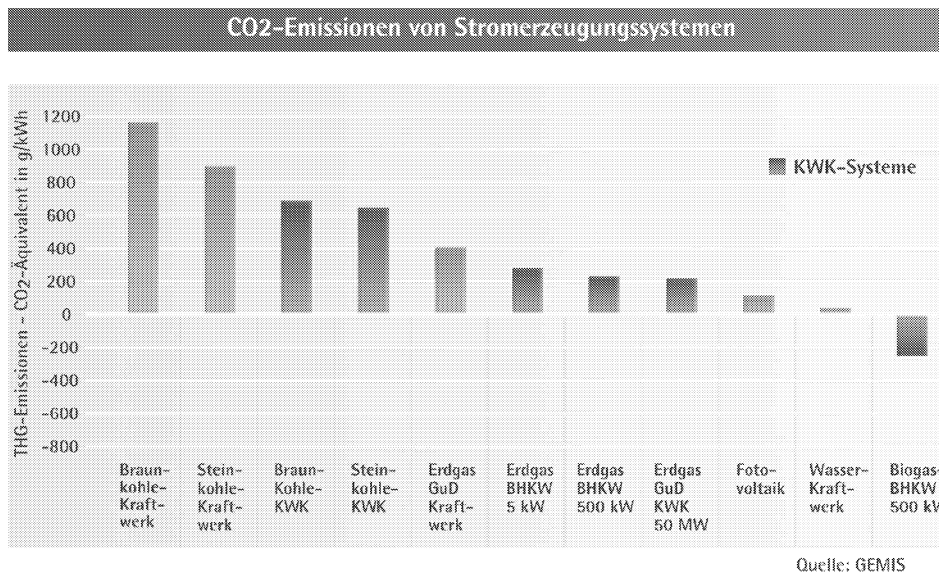


Fig. 4. CO₂ emissions from units generating electricity (B.KWK)

Figure 4 shows the examples of the emissions of greenhouse gases in CO₂ equivalent in different energy production systems. Coal and brown coal combustion is responsible for the highest emissions of GHG. Combined heat and power production causes much lower GHG emissions. CO₂ emissions from biogas plants were calculated for organic wastes. If these wastes are not handled, uncontrolled emissions of CH₄ and CO₂ can occur (methane is considered as a potent greenhouse gas because it is 23 times more effective than carbon dioxide at trapping heat in the atmosphere over a 100-year period). That is why the emissions as a result of biogas production in CO₂-equivalents are negative.

4. OPTIMIZATION OF BIOGAS AND ENERGY PRODUCTION

4.1. APPLICATION OF INNOVATIVE OPERATIONAL CONCEPTS AND PROCESS ENGINEERING – SELECTED EXAMPLES

1. The agricultural biogas plant “pumping station III” – 2.500 kW_{el}

Description

Year of construction: The biogas plant “pumping station III” was built in 2007 in Lower Saxony, a federal state of Germany. At the end of 2007 the plant began its operation.

Key components: The biogas plant consists of the following key components (figure 5): four silos for biosolids (4 × 3.200 m²), two digesters (2 × 5.000 m³), one post-digester (3.500 m³), 3 storage tanks for fully digested substrate (3 × 3.500 m³), machine hall, in which one can find a control room, switch chamber, a dosage system for biosolids and a combined heat and power generation unit (500 kW_{el}).

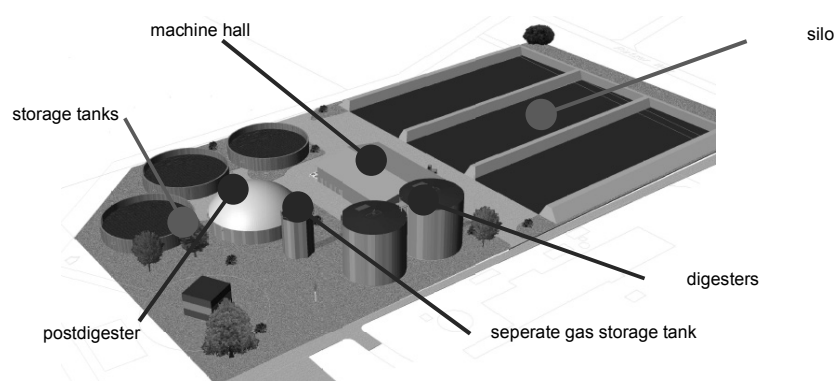


Fig. 5. Key components of BP “Pumping station III” (one to one virtual model)

Operational concept: The biogas plant was designed according to following principles:

- two-stage process with two digesters and one post-digester to improve plant safety and degradation of biosolids,
- post-digester is equipped with gas membrane cover for collection and storage of biogas,
- simultaneous wet fermentation at pH range of 7.3–7.8,
- temperature optimal for mesophilic microorganisms, i.e. approx. 40 °C,
- hydraulic retention time (*HRT*) > 90 days for efficient use of ensiled maize,
- automatic dosage system for biosolids: floor scrapers with weighing machine, push rod, discharger and screw conveyors,
- central pumping station with automatically controlled slides,
- separate tank for gas storage,
- aerobic hydrogen sulfide removal; in order to reduce H₂S concentration (<< 250 ppm) in the biogas, a small amount of air (<0.5% O₂) is injected into the gas stored in digester and post-digester.

Innovative operational concepts and process engineering

Input substrates and internal substrate cycles: In this plant, biogas is produced using only agricultural products (ensiled maize, green rye). After digestion, substrate can be dewaterated from 5–7% to 28–32% TSS in two press screw separators. The separated solids are put into intermediate storage tank and used as dung. The liquid part can be returned to the digesters in order to achieve the desired TSS concentration in the digesters.

Energy production: In order to use optimally the produced biogas, it is transported to the city of Brunswick through an earth-laid pipeline. After drying biogas is passing through a gas measurement device which records its quality and quantity. Using two CHP units ($2 \times 1 \text{ MW}_{\text{el}}$) the biogas is converted by the Brunswick energy provider (BS/ENERGY) in such a way that it can be used for power generation and as a heating medium. The heat required for the fermentation is produced using an additional combined heat and power unit with 500 kW_{el} performance at site. The power produced is fed into the mains network.

2. The industrial biogas plant “Gemüse-Meyer” – 500 kW_{el}.

Description

Year of construction: The biogas plant “Gemüse-Meyer” is the part of the company Gemüse-Meyer wastewater and waste treatment plant constructed in 2007. The plant is located in Lower Saxony, a federal state of Germany. In November 2007, the plant began its operation.

Key components: The biogas plant “Gemüse-Meyer” consists of the following key components (figure 6): two digesters ($2 \times 950 \text{ m}^3$) and two FAR-reactors (FAR = Faulschlamm-Anreicherungs-Reactor, i.e., the reactor for enriching a digested sludge),

a storage tank for fully digested substrate (3,000 m³) and machine hall, in which one can find a control room, switch chamber, hammer mill for disintegration/homogenisation as well as a dosage system for biosolids and a combined heat and power generation unit ($2 \times 256 \text{ kW}_{\text{el}}$).

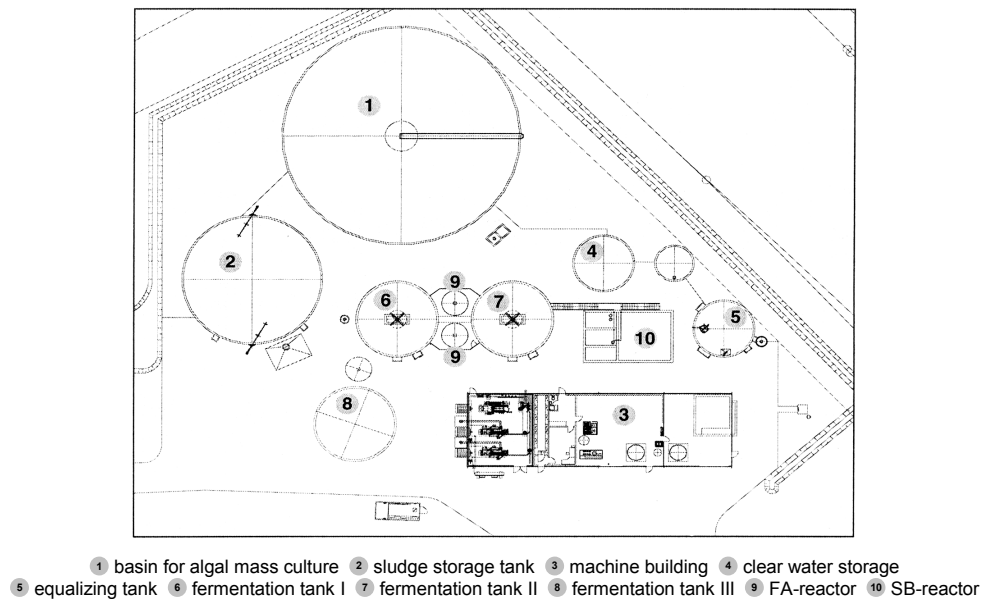


Fig. 6. Key components of Gemüse-Meyer company wastewater treatment plant

Innovative operational concepts and process engineering

Operational concept: The biogas plant was designed adopting the following principles and according to specific demands of the client:

- one mesophilic digester and one thermophilic digester to improve the plant safety and degradation of biosolids,
- simultaneous wet fermentation at pH range of 7.0–7.3,
- temperature optimal for thermophilic microorganisms, i.e. approx. 55 °C , which ensures hygienisation and higher gas production,
- hydraulic retention time (*HRT*) > 10 days,
- automatic dosage system for biosolids: container with weighing machine, push rod, discharger and screw conveyors,
- central pumping station with automatically controlled slides,
- storage tank for digested substrate covered with membranes for collection and storage of biogas,
- aerobic hydrogen sulfide removal; in order to reduce H₂S concentration (<< 250 ppm) in biogas, a small amount of air (< 0.5% O₂) is injected into the gas stored in digester and post-digester.

Input substrates and internal substrate/wastewater cycles: The digesters are fed with the following vegetable wastes: carrots, sugar beets, potatoes, onions and approximately 100 m³/d wastewater. Liquid phase and sludge separated in the FARs can be circulated and pumped to any optional reaction tank. But most of the liquid fraction is transported to Sequencing Batch Reactor (SBR) where wastewater is purified and aerated. The biologically purified wastewater is further treated via ultrafiltration and reverse osmosis and returned to the production process.

Energy production: The CHP capacity is equal to 510 kW_{el}. The whole heat is used for the production processes of the Gemüse-Meyer company and for the heating of digesters.

FAR-SBR process: To avoid the flushing-out of the biomass and the insufficient degradation rate of organic vegetable wastes in the digestion tanks, the FAR–SBR process was developed and applied. The digesters were being intermittently fed with wastewater from the prestorage tank and with solid waste. Immediately after feeding, the produced biogas quantity reached its maximum and then it uniformly decreased (figure 7). The feeding of the digested sludge enrichment reactor (FAR) took place during the transition phase, and the next feeding (next cycle) of the digester only took place afterwards.

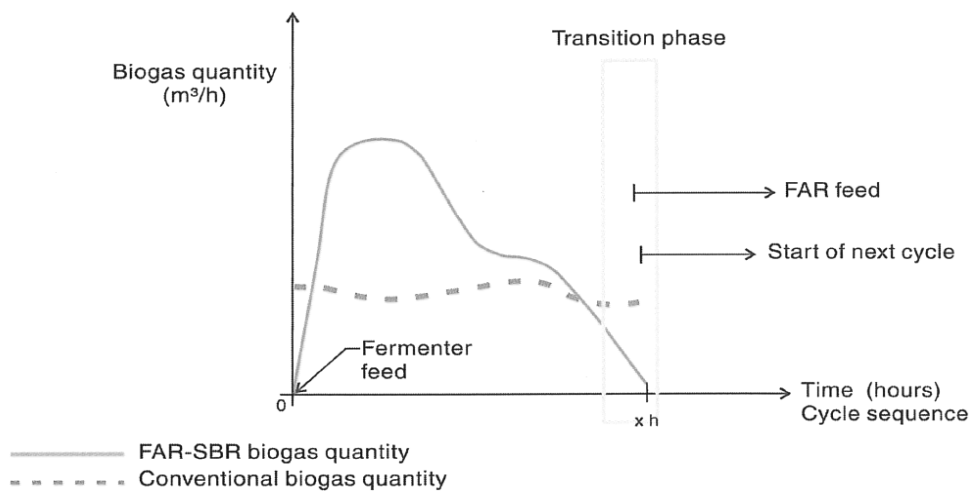


Fig. 7. FAR–SBR cycle

4.2. APPLICATION OF INSTRUMENTATION CONTROL AND AUTOMATION (ICA) IN MODERN BIOGAS PLANTS

There are still several objectives which managers of biogas plants should seek to pursue. They can be itemized as follows:

- Maximization of energy production and usage (especially heat) → higher revenues, e.g., CHP, gas purification, usage of heat for heating or electricity production (ORC process).
- Minimization of input substrates → lower costs, e.g., due to increasing prices on the market of energy crops.
- Minimization of energy demand (e.g., stirring devices) → lower costs.
- Minimization of operational risks → higher plant availability.
- Different input substrates → use of market opportunities.

These multicriteria optimization problems in many cases cannot be solved by manpower only. Therefore instrumentation, control and automation gain more and more importance in biogas plants.

Actual state: Based on the results of German research (FNR [2], [3]) it may be inferred that an average utilization level or CHP capacities in the German biogas plants is too low and equal to 60–70%. The authors emphasize that this low utilization is caused mainly by a very low level of instrumentation, control and automation as well as by the lack of data on the biogas plants (black-box). However, the utilization level in well equipped plants achieves very stable and high levels equal to approximately 95% (WIESE et al. [6], [7]).

Measuring techniques: During recent years a significant development in the measuring techniques in biogas plants has occurred, but still the operation of many plants is based on very few measuring devices. For example, only 25% of the plants investigated by WIELAND [5] have essential measuring equipment and only approximately 3%, other advanced measuring techniques. As a consequence, plants are operating in suboptimal ways (e.g. critical load ranges or low load). More and more plants use reliable and relatively cost-effective on-line measurements of many important parameters, e.g., pH, ORP, substrate flow rate and biogas flow rate/composition.

A very promising technology is near-infrared spectroscopy (NIRS) (760–2.500 nm), being used in agribusiness (e.g., quality control) or in chemical industry. In the case of agricultural applications, it is already possible to measure on-line and off-line the concentrations of DM, oDM, proteins, crude fibres as well as fat content by using NIRS. The results achieved in the first biogas plants are very promising. The predictions made for, e.g., volatile fatty acids, ammonia, DM and oDM contents (WIESE et al. [7]) proved to be reliable.

Control and automation: Many plants are only scarcely automated, which means they are still manually controlled. If one can find RTC (Real-Time-Control) strategies, these concepts are usually simple strategies, e.g., time-based sequential controller (e.g., feeding strategies, stirring devices). Most plants are not equipped with supervisory control and data acquisition systems (SCADA). Even if one can find the SCADA systems, these are in many cases self-developed programs, which are not comparable with industrial standards.

Because of the rapid technological progress in the area of electrical engineering, modern supervisory control and data acquisition (SCADA) systems and programmable logic controllers (PLC) have become powerful tools. So, today it is possible to implement even complex RTC strategies with thousands of variables. The operators often do not have any sufficient knowledge and skills to analyse and use an available plant/process information. The development of such systems could be the first step in constructing complex and universal algorithms for the control of biogas plants.

Today common control strategies for biogas plants are almost exclusively based on conventional controllers; in most cases a manual control taken by the operators is also necessary. However, because of the complex dynamics and structures of anaerobic processes and/or biogas plants, these controllers as well as the operators are often overstretched. If a biogas plant operation is close to its capacity limit and at the same time the operating costs and the amount of output/input substances are minimized, the consideration of these boundary conditions in the controller strategy is absolutely essential. In these cases, it is necessary to use complex controllers, which could be based on model predictive control, soft sensors, multivariable and/or multi-objective decisions and sometimes artificial intelligence.

Modern plants that use modern ICA equipment and reliable/adapted machines can reach very good operational results. Those plants can produce reliably baseload electricity. Due to the fact that biogas can also be stored, biogas plants could also produce a peak load energy. Thus, the biogas plant is an ideal complement to other sources of renewable energy, which cannot produce peakload and baseload (e.g., solar cells, wind turbines). For example, by using modern ICA it is possible and promising to merge numerous biogas plants (and maybe other renewable energy plants) into one virtual large-scale power plant, which could be an alternative to centralized power stations.

Example of ICA solution in a modern agricultural biogas plant

Design criteria: The BP Nordholz, which was built in 2007. In this plant, biogas is produced only from cattle liquid manure and ensiled maize and utilized in a modern CHP unit (gas engine, maximum: 537 kW_{el}, electrical efficiency: 40%).

Procedural principles: The biogas plant was designed according to following principles:

- two-stage process with digester and post-digester to improve plant safety,
- simultaneous wet fermentation at pH 7.3–7.8, 5–9% of total suspended solids (TSS),
- temperature optimal for mesophilic microorganisms, i.e. approx. 40 °C,
- hydraulic retention time (*HRT*) > 60 days for efficient use of ensiled maize and manure,

- automatic dosage system for biosolids: container with weighing machine, push rod, discharger and several vertical and horizontal screw-conveyors,
- central pumping station,
- digester tanks covered with membranes for collection and storage of biogas,
- high-level instrumentation and automation (see below),
- internal aerobic hydrogen sulphide removal.

The examples of the results of online and offline measurements used for controlling the agricultural biogas plant being correlated with the load of digester are shown in figures 8 and 9. Several measurement signals correspond in a very plausible way to the load of digester in the start up phase, especially the values of VOA/TIC and online measurements are very useful (and sometimes essential) parameters for control and supervision during the start up period of the plant. As a result, the duration needed to achieve a stable full-load operation was significantly reduced (forecast: 12 to 16 weeks, practice: 6 to 7 weeks), which caused higher revenues of approx. 60,000 €.

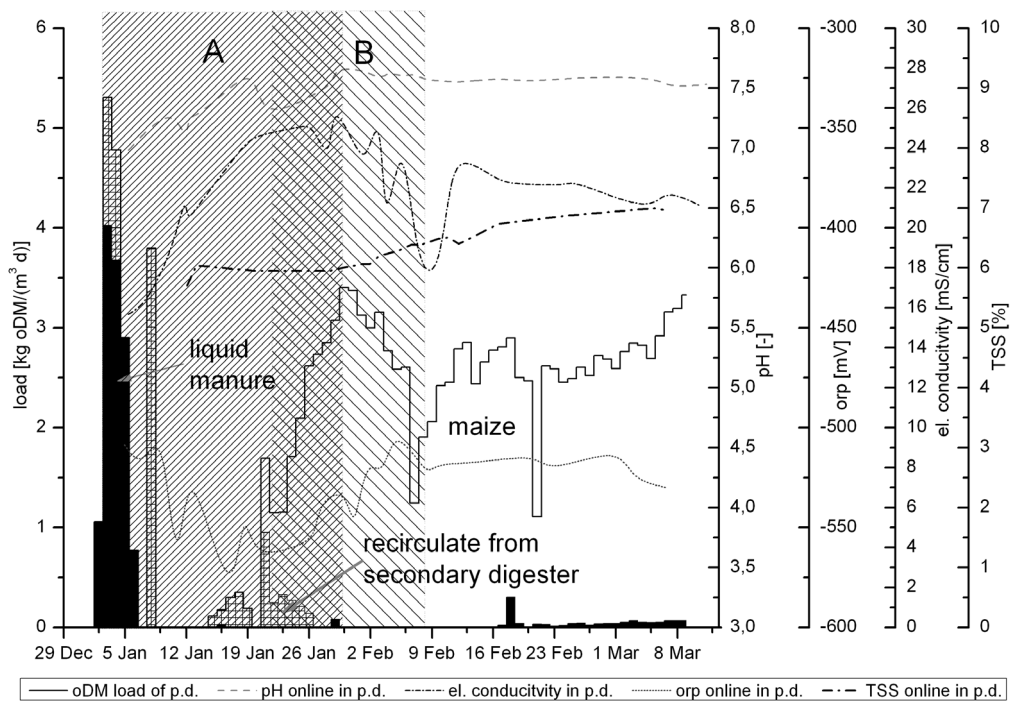


Fig. 8. Organic load of primary digester and measuring signals of pH, ORP, TSS, and electrical conductivity in BP Nordholz during start up period

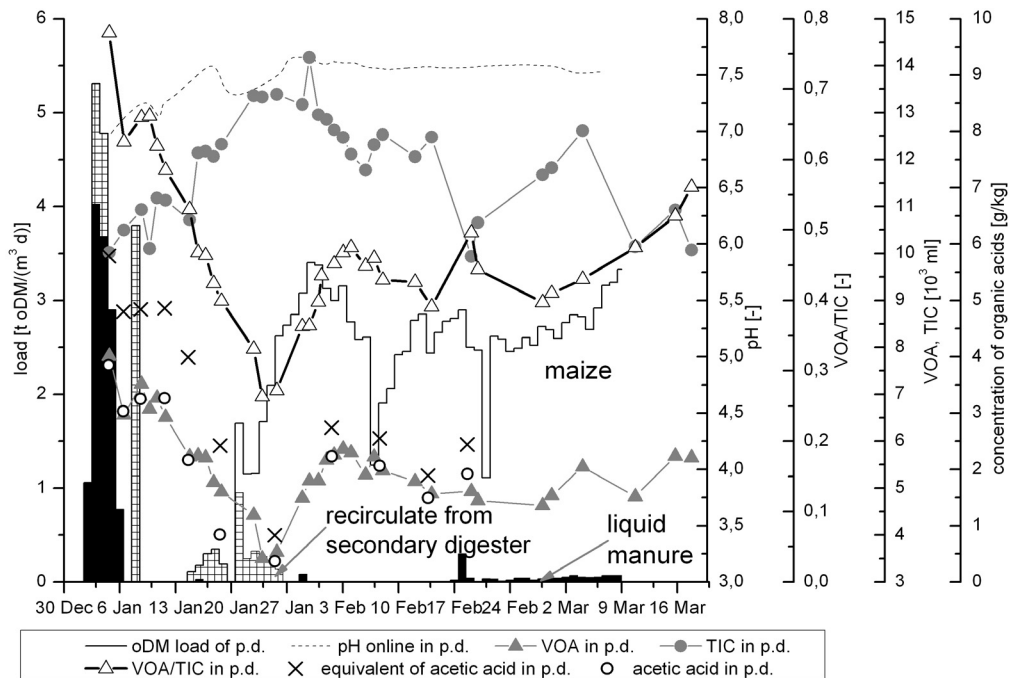


Fig. 9. Organic load of primary digester and corresponding values of measurements of VOA/TIC, VOA, TIC, and organic acids in BP Nordholz during start up period

5. SUMMARY AND OUTLOOK

The biogas technology is a very useful and in some cases (e.g. organic wastes) essential technology to reduce greenhouse gas emissions. These emissions from agricultural biogas plants are almost neutral, and from industrial plants – even negative. Moreover, a decentralised combined production of electricity and heat from biogas is one of the most effective ways of energy supply and production. However, a very important issue is to use the heat produced on site.

Last but not least, better process concepts and more effective production of energy can significantly increase emissions of greenhouse gases. Since the production of energy from biogas has still great optimisation potential, we could produce and use effectively even now much more energy. Especially in the fields of more effective process engineering and application of instrumentation control and automation, there is still a great demand and potential for optimisation.

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