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Flexible biogas production for demand-driven energy supply – Feeding strategies and types of substrates

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HIGHLIGHTS

- Biogas can be produced highly flexible in CSTR systems with feeding management.
- Daily alternation of the methane and acids corresponding to the feeding.
- Longtime process stability at high OLRs of up to 6 kg VS m^{-3} d^{-1}.
- Necessary gas storage capacity can be minimized with flexible gas production.

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ABSTRACT

Purpose of this work was the evaluation of demand driven biogas production. In laboratory-scale experiments it could be demonstrated that with diurnal flexible feeding and specific combination of substrates with different degradation kinetics biogas can be produced highly flexible in CSTR systems. Corresponding to the feedings the diurnal variation leads to alternations of the methane, carbon dioxide and acid concentrations as well as the pH-value. The long-time process stability was not negatively affected by the dynamic feeding regime at high OLRs of up to 6 kg VS m^{-3} d^{-1}. It is concluded that the flexible gas production can give the opportunity to minimize the necessary gas storage capacity which can save investments for non-required gas storage at site.

1. Introduction

The financial support by the Renewable Energy Sources Act (EEG) led to an increasing number of biogas plants in Germany. The plants have been designed and constructed to produce a stable and constant energy output (base load energy). With the changing conditions within the energy sector in Germany biogas plants have to meet new requirements, especially the flexible supply of electricity to compensate for the divergence between energy demand and energy supply by uncontrolled sources like wind and solar power (Lund et al., 2012). On one hand the extent of flexibility is characterized by the possibility to shift the periods of power provision to other time points. This includes the scheduled energy production (i.e. with planned ahead and agreed on daily or weekly timetables) and the “ad hoc” provision of positive and negative balancing energy. On the other hand, the flexibility depends on the feasibility to change the height of the current amount of power provision. However, this is restricted to temporal displacements while preserving the same total power output on average. Szarka et al. (2013) and Hahn et al. (2014) remarked that bioenergy concepts seem to be a promising option to fulfill most of the requirements in the transition of the energy system from fossile to renewable sources. As opposed to wind and solar power, the production of energy from biomass is weather-independent. Moreover, through its small-scaled characteristics bioenergy is available decentrally and widely distributed and could thus contribute to the stabilization of the mains frequency.

The ability for flexible electricity supply from biogas is dependent on different factors. Possible points of action to enhance flexibility of a biogas plant are:

- type (combustion engine, turbine etc.) and capacity of biogas utilization,
- gas storage capacity on site,
- type of conversion process (plant design/applied technology),

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- substrate type and feeding management.

Each of the components of the production chain has its own limitations, altogether resulting in the overall flexibility of the plant. In practice, the shift from continuous to flexible and demand-oriented conversion of biogas to electrical power is mainly thought to be realized by installing further conversion capacities. Therewith the plant can is still meant to produce the same average energy output. Instead of a continuous production of energy this takes place during mutable periods of time and at higher conversion rates. Optimally, these periods match the time when the demand for electricity is the highest. One scenario for flexibilisation of biogas plants is the operation of CHPs in blocks during defined periods of a day. In scenarios with 8, 12 and 16 h of gas utilization of the same daily gas quantity, the additional CHP-capacity needs to be extend by 3, 2 and 1.5 times of the original power. Furthermore, adding extra gas storage capacity to a level where the amounts of gas produced during CHP standstill can be intermittently stored is possible or necessary. Under normal conditions of constant biogas production the average German biogas plant fills its gas storage within 2–8 h (unpublished data of an DBFZ operator survey). While older plants mostly have rather small storage capacities. Newer plants are usually equipped with storage capacities of up to 12 h and more. Thus, when the gas storage capacity is small, the plant is only able to pause the CHP for a relatively short time before the capacity is filled.

An additional option for flexibilisation – beside expansion of CHP and storage capacity – can be the direct adaption of the gas production to the times, when electrical power is supposed to be produced. The accepted opinion is that the biological process of anaerobic conversion of the substrates to biogas shows an optimal performance when operated in steady state (constant input and output, constant process parameters). Golkowska et al. (2012) investigated the degradation of maize silage in batch, semi-batch and continuous feeding mode. Opposingly to the common opinion in the sector, the results confirmed an extremely high adaptation capability of anaerobic biocenosis to various frequent feedings. Lv et al. (2014) investigated the influences of the substrate feeding regime on methanogenic activity by molecular and stable isotope methods. They have shown that alteration of the substrate feeding did not negatively change the overall gas yield. However, the feeding can influence the anaerobic digestion concerning the changes of concentration of volatile fatty acids (VFA) (especially acetic acid) and other process parameters (Ahring and Sandberg, 1995; Lindorfer et al., 2008; Hill and Bolte, 1989; Lübken et al., 2007). It is obvious that the specific response of an anaerobic process, i.e. the degradation kinetics of substrates depends on their composition (amount of easily degradable components and the proportion of structural components). In order to overcome composition-related hindrance of degradation a wide range of investigations looks after methods to pretreat substrates with extruder (Hjorth et al., 2011), enzymes (Merlin Christy et al., 2014) and chemical/physical decomposition (Zheng et al., 2014). However, if substrate preparation can reach a faster overall degradation rate, it can become considerable for demand driven energy supplies. The demand driven feeding with the aim of discontinuous gas production has previously only rarely been discussed in scientific studies. Hahn et al. (2014) described the discontinuous feeding of a fixed bed reactor. However, taking into account the fact that the majority of German biogas plants are designed as continuous stirred tank reactors (CSTR) fixed-bed technology can hardly be broadly implemented into existing biogas plants. In an unpublished study of the DBFZ – Deutsches Biomasseforschungszentrum gGmbH (German report in: Proceedings of 20th BIOGAS – Annual Conference & Trade Fair. Nuremberg, Germany, pp. 179–186) a standard load profile (SLP) for household energy demand in laboratory scale (CSTR) successfully followed with flexible feeding of grain stillage. However, grain stillage is a rather unusual substrate in some industrial biogas plants. Besides that, the flexible energy supply by directly acting at the process of biomass conversion in CSTR systems is currently rarely investigated experimentally.

Therefore the aim of the presented study was to

- investigate the general flexibility of the CSTR AD processes applying substrates typical for agricultural German biogas plants,
- examine the effect of discontinuous feeding on daily and long term process stability,
- evaluate whether an alteration of feeding regimes could significantly alter the daily biogas production profile so that it benefits the flexibilisation of electrical power production,
- find out, whether the different degradation characteristics of different substrates can be used to optimize such altered feeding and gas production profiles and
- examine, which effects a discontinuous gas production could have on plant design.

2. Methods

2.1. Experimental setup and substrates

The experiments were carried out in laboratory scale biogas fermenters; two 15-L continuous stirred tank reactors (CSTR) with 10 L working volume and one 40-L CSTRs with 35 L working volume. The reactors were continuously stirred using an anchor stirrer. During the experiment the reactors temperature was maintained at mesophilic conditions (38 ± 1 °C) using double-walled reactor constructions. The Inoculum for the fermentation was obtained from a full-scale biogas plant operated with maize silage and cattle slurry. An industrial trace element mixture was added weekly (*novoDYN, Schmack* Biogas, Germany). The general operation took place according to the Guidelines for the Fermentation of organic material (VDI Standard 4630). For foaming suppression when using sugar beet silage rapeseed oil was used. From minimum of 1 ml up to 0.5% of daily input mass was given proportional to the feeding regime, respective. The feeding substrates were cattle slurry, maize silage and sugar beet silage, which are commonly used in agricultural practice.

The two experiments were operated and divided each into 2 phases. Table 1 give an overview about the topology of different Experiments with the operation time, used substrates, OLR and working volumes of the CSTRs. The feedings in the experiment phases were split into various portions and spread throughout parts of each day. In the experiments two different batches of maize silage and sugar beet silage was used. The results of the characterization of the used substrates are given in Table 2. For experimental period Exp. 1A and B, maize silage (MS I) and sugar beet silage (SBS I) were used. In the second period (B) sugar beet silage ware used as single substrate. Both experimental periods took place consecutively in one digester (35 L working volume). In the experimental period (Exp. 2A) the primary digester was fed with maize silage (MS II) and the secondary with sugar beet silage (SBS II) additionally to the digestate transfer (DT) from the first one. In period (Exp. 2B) cattle slurry (CS) is additionally fed together with the maize silage to the primary digester. The Experiment 2 was realized in a cascade of two identical CSTRs (10 L working volume) as primary and secondary digester.

The maize silage was stored in a cooling chamber at 4 °C in shrink-wrapped packs of 1 kg portions. The sugar beet silage was stored under a nitrogen atmosphere at 4 °C as well. To define the degradation characteristic of the used substrates the first order kinetic was applied (Golkowska et al., 2012). For calculating the

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