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Adaptation of Biogas Production to the Residual Load of an Electricity Self-Sufficient Community

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ABSTRACT

In this work, the biogas production of laboratory-scale anaerobic digestion reactors was adapted to the residual load of an electricity self-sufficient municipality. The adaptation of biogas production to such an irregular course, as specified by the residual load, has not yet been investigated. By using rapidly degrading sugar beet and medium-fast degrading maize silage, it was possible to achieve a high level of agreement. Compared to a continuously fed reactor, the gas yield was not negatively affected. Various parameters assessing process stability were continuously observed and indicate a stable operation even at high organic loading rates up to 5.9 kg VS m^{-3} d^{-1}. This mode of operation can minimize the necessary gas storage capacity and prevent investments in gas storage expansions.

Keywords: Anaerobic digestion, Biogas technology, Demand-driven energy supply, Flexibility, Feed management

1. INTRODUCTION

The share of renewable energies in electricity production is steadily increasing [1]. The great challenge of the next few years is to continue this development and at the same time develop strategies to compensate for the naturally caused fluctuations of wind and solar energy. In addition to various storage technologies, the demand-oriented production of biogas can also contribute to this. This approach, which could enable biogas plant operators to avoid an expansion of gas storage capacities, is considered promising by the German government. This is reflected in the increased promotion of flexible biogas production in the new edition of the German Renewable Energy Act (EEG 2021) [2]. Electricity from biogas can not only be fed into the grid. Biogas also offers the possibility of being used decentrally as a balancing energy carrier, for example in an energy self-sufficient municipality.

In order to experimentally investigate flexible biogas production, quasi-continuous tests were carried out in which the biogas production of several laboratory digesters was adapted to the residual load of the real, electricity-autonomous community of Simris (Sweden, data from Rosvall et al., 2020 [3]) by variable substrate feeding. Simris has about 200 inhabitants and features a solar plant, a wind turbine and a control system. At times when more electricity is produced from wind and solar power than is consumed, the excess electricity is fed into the grid. If more electricity is needed than is produced by wind turbine and solar plant, this difference (residual load) is obtained from the grid. Since the residual load depends on various factors and is therefore very irregular, adapting biogas production to the course of the residual load opens up new insights in terms of feasibility and process stability. In previous studies on demand-driven biogas production, attempts were mostly made to reproduce daily load profiles (Mauky et al., 2015 [4], Mauky et al., 2017 [5]). Since there are indications that microorganisms can adapt to regular loads (Golkowska et al., 2012 [6]), it is interesting to observe whether they are also capable of doing so under irregular loads.

2. MATERIALS AND METHODS

To investigate to what extent the adaption of the anaerobic digestion process is possible and which influence this dynamic mode of operation has on the

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process stability, three laboratory-scale fermenters (A, B, C) were operated over a period of more than 100 days. After the start-up of the process and several tests with intermittent substrate input, from the 65th day, the biogas production of reactors A and B was adapted to the residual load of February 2019 of the Simris municipality. Reactor C was operated as a continuously fed reference.

2.1 *Experimental Setup*

The experiments were carried out in three 40-L continuously stirred tank reactors (CSTR) with a liquid working volume of 30 L (see Fig.1). In order not to disturb the agglomerates of the different symbiotic microorganisms, the reactors were mixed at slow stirring speeds with an anchor stirrer. The temperature of the digester content was maintained at mesophilic conditions at 38 °C (± 1 °C) using an electric heating tape and an insulation layer. The feeding of dry matter was realized using a feeding carousel, which has 24 chambers and allows hourly feeding, and a piston that transports the substrate below the liquid surface. Liquid substrate was added manually.

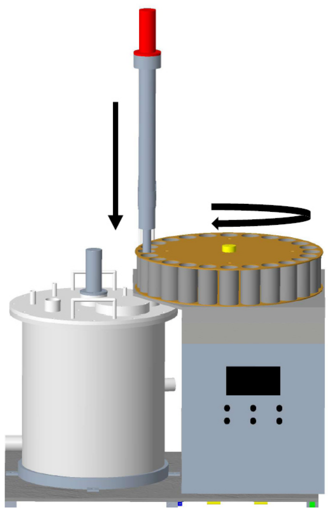

Fig. 1. Technical drawing of one reactor, including feeding mechanism and control unit

The inoculum, which contains the microorganisms necessary for the conversion of organic matter into biogas, was obtained from a full-scale biogas plant operated with maize silage and cattle slurry. The substrates used in this experiment were maize silage and shredded sugar beet. Furthermore, cattle slurry was added to maintain the flowability of the fermenter content if required. Experiments were determined according to the Guidelines for the Fermentation of Organic Material (VDI 4630, 2016 [7]).

The content of total solid (TS) and volatile solid (VS) of the substrates were determined according to DIN EN 12880 [8] and DIN EN 12879 [9], respectively. Organic composition of the input substrate was determined using wet chemistry and near-infrared spectroscopy (NIR). The results of the characterization of the used substrates are given in table 1.

Table 1. Composition of the used substrates

Component	Unit	Maize silage	Sugar beet	Cattle slurry
Total Solid (TS)	[% FM]	41.3	19.8	7.6
Volatile Solid	[% TS]	96.6	96.6	81.9
Ash	[% TS]	3.4	3.4	18.1
Celluloses	[% TS]	18.2	5.3	
Hemicelluloses	[% TS]	15.4	4.5	
Lignin	[% TS]	3.0	0.5	
Sugar	[% TS]	1.6	82.4	
Starch	[% TS]	42.5	< 0.5	
Crude protein	[% TS]	7.9	3.3	
Crude lipids	[% TS]	3.1	< 0.5	
Crude fiber	[% TS]	25.5	4.6	

FM: fresh matter.

Based on this characterization and the degradation kinetics of the substrates determined in preliminary tests on the reactors, type and quantity of substrates as well as the feeding times, necessary to follow the predefined curve of biogas production, were specified. The biogas production was constantly monitored in order to be able to react to deviations between the biogas production and the residual load. While reactors A and B were operated flexibly, reactor C was fed with a constant amount of substrate to be able to compare the different modes of operation in terms of gas yield and process stability. Reactor C received the average amount added over the entire month of adaptation in equal hourly feedings, which corresponds to an amount of 7 g of maize silage and 2.3 g of sugar beet per hour. The added substrate quantities of reactors A and B are shown in Fig. 2. The chambers of the feeding carousels were usually filled once a day. Sampling for the analysis of the process parameters took place once a working day, with the amount of sample taken being based on the amount of feeding from the previous days in order to keep the liquid level constant.

2.2 *Process monitoring*

Biogas production was measured continuously using drum-type gas meters (TG05/2, Dr.-Ing. Ritter Apparatebau GmbH & CO. KG, Germany) and corrected to dry standard conditions (273.15 K and 101.315 kPa) according to VDI guideline 4630 (VDI, 2016). Biogas composition was determined three times a week using a gas chromatograph (Agilent 490 Micro GC, Agilent

Technologies, USA) equipped with a thermal conductivity detector. The ratio of volatile organic acids (VOA) and buffer capacity (TAC) of digester content was determined three times a week by titration, which was carried out automatically by a titrator (Titroline 6000, SI Analytics, Germany) using 0.1 N hydrochloric acid solution. For this purpose, 5 g of digester content were diluted with 45 g of deionized water to ensure proper mixing during the titration. VOA- and TAC-values were calculated according to Nordmann (1977) [10]. Furthermore, pH values were measured three times a week using the same titrator.

The measurements of individual concentrations of volatile fatty acids (VFA) were carried out twice a week with a combination of a gas chromatograph (Focus GC, Thermo Fisher Scientific Inc., USA) and a mass spectrometer (DSQ II, Thermo Fisher Scientific Inc., USA). Sample preparation for the headspace analysis was carried out with a modified method from Boe et al. (2007) [11]. To this end, 2 g of digester content were put into a vial with a total volume of 20 mL. As an internal standard 100 µL of 2-ethyl butyric acid was added. To enhance the transfer of VFAs into the gas phase, 1 mL of a sodium hydrogen sulfate solution (620 $g \cdot L^{-1}$) and 1 mL of a phosphoric acid solution (30.6 vol-%) were added. The vials were sealed and put into a water bad at 70 °C for 10 minutes. Afterward, 400 µL of the gas phase were taken out and injected into the GC/MS system. Details of the GC/MS method used can be found at Spielmann (2019) [12].

3. RESULTS AND DISCUSSION

3.1 *Influence of substrate composition on biogas production*

The flexibility of the anaerobic digestion process primarily depends on the degradation kinetics of the fed substrates. Short-chain carbohydrates such as sugars pass through the various phases of the biogas formation process much faster than complex polymers like the structural elements cellulose or hemicellulose. Due to the high proportion of these slowly degradable components, but the high proportion of relatively quickly degradable starch, maize is generally regarded as a substrate with a medium-fast degradation kinetic (Mauky et al., 2015). As shown in table 1, sugar beet, in contrast, consists largely of rapidly degradable sugar and has a smaller amount of slowly degradable structural elements. For this reason, the addition of sugar beet can be used to induce rapid increases in gas production, whereas maize silage is suitable for maintaining gas production at a high level over a longer period of time.

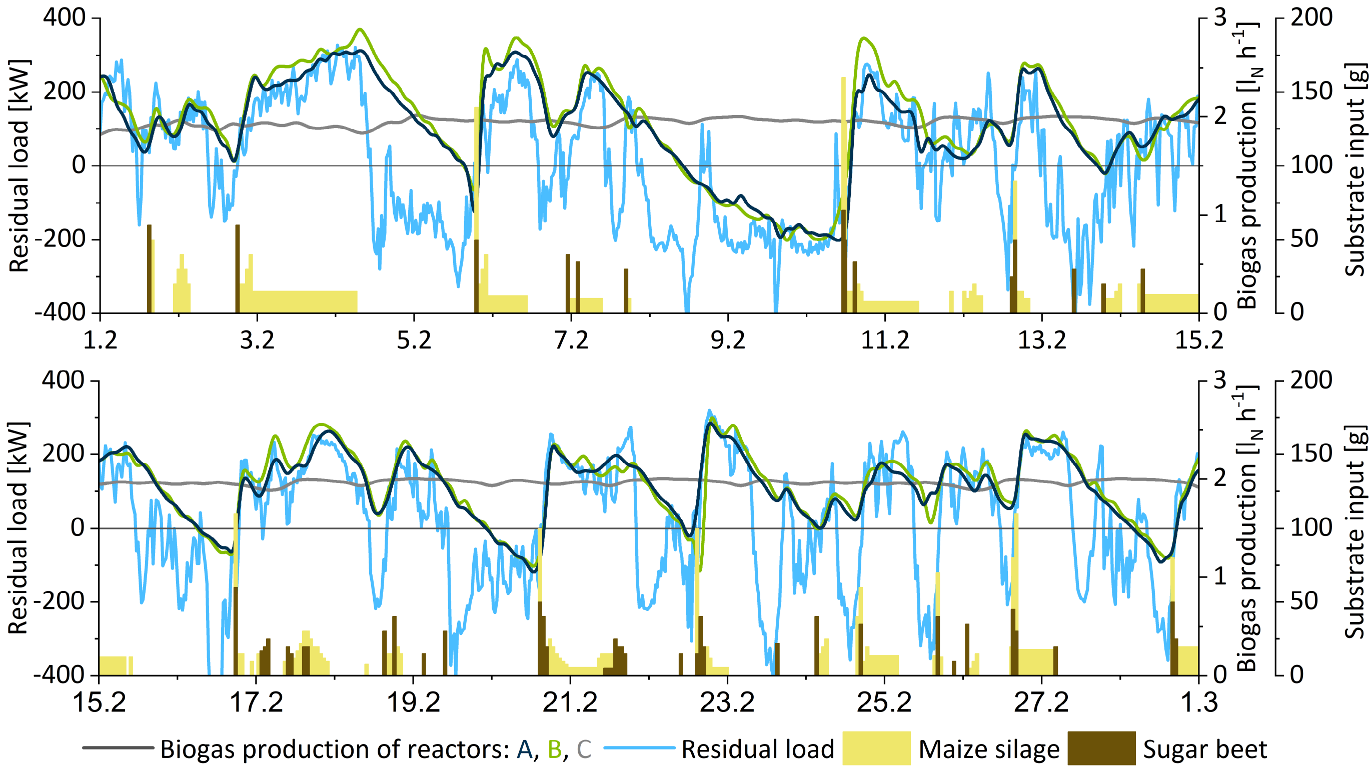

Fig. 2. Residual load of the Simris municipality in February 2019 as well as the biogas production of the two adapted reactors A and B and the constantly fed reference reactor C. In addition, the added substrate quantities of reactors A and B are shown.

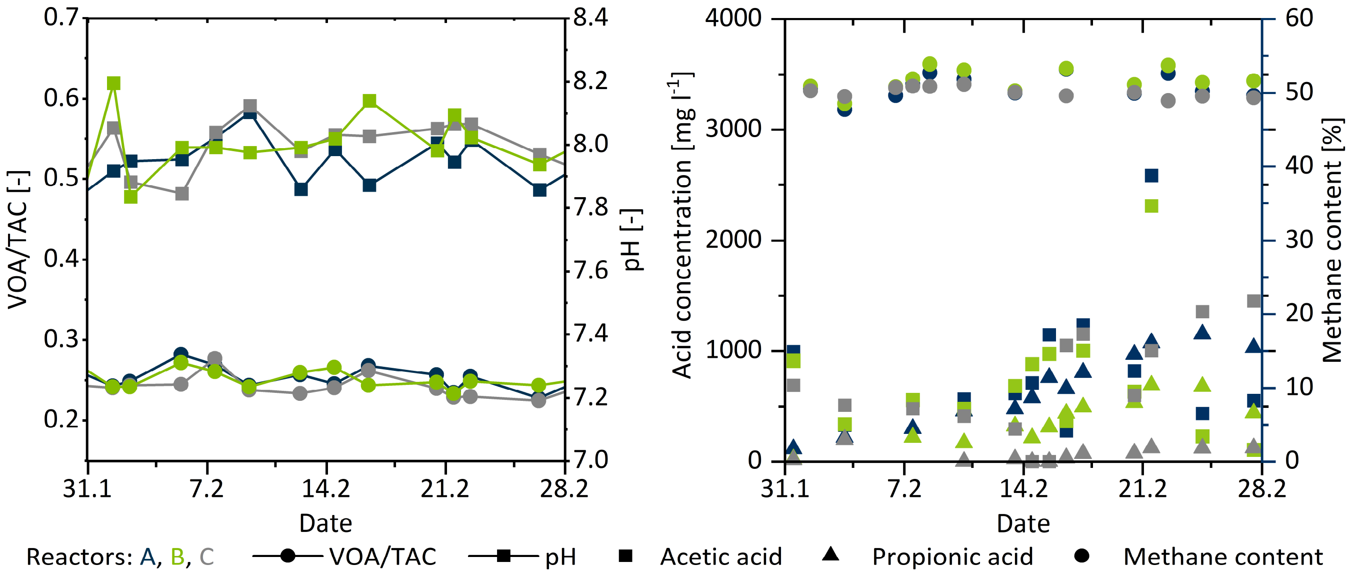

Fig. 3. Process stability evaluation parameters for the month of flexible biogas production. Left: VOA/TAC and pH-value. Right: VFA concentration in the fermenter content and methane content of the resulting biogas.

3.2 Adaption of the biogas production to the residual load of Simris

Fig. 2 shows the residual load of the Simris community of February 2019 and the biogas production that was adapted to it. Furthermore, it can be seen which types and quantities of substrate were added to the fermenters A and B at which times. Overall, the biogas production curve coincides very well with that of the residual load. As can be concluded from section 3.1, sugar beet was added to realize sudden increases in biogas production. Within one hour, the gas production could be doubled in relation to the baseline level even with moderate additions of 50 g of sugar beet, corresponding to an organic loading rate (OLR) of 0.33 kg VS m^{-3} d^{-1}. Other research results have even demonstrated a fourfold increase in biogas production (Mauky et al., 2015 [4]), yet this depends on OLR before feeding and the amount added. Maize silage was usually added afterward to maintain gas production at a high level or to slow down its decline. Since the gas production falls only slowly due to the inertia of the biological process, even when substrate input is stopped, it can only follow a sudden decrease in residual load with a delay. An example of this delay can be seen in Fig. 2 on February 4th. In practice, this oversupply of biogas would be buffered by the internal gas storage that each biogas plant is equipped with. Smaller demands for biogas, such as on February 8th, would also be compensated by the gas storage since it would be uneconomical in practice to intervene in the biological process for this purpose.

For the period considered here, no significant decrease in the total gas amount produced was observed due to variable feeding: reactor A produced 1288 l_N of biogas per month, reactor B produced 1310 l_N, and reactor C produced 1303 l_N. In the considered month, 4695 g of maize silage and 1539 g of sugar beet were fed into each reactor, corresponding to an average OLR of 2.59 kg VS m^{-3} d^{-1}. Averaged over the day, the OLR ranged from 0 to 5.9 kg VS m^{-3} d^{-1} for reactors A and B.

3.3 Process stability

Flexible feeding and changing substrates result in alternating stress levels on the biocenosis, which can lead to unstable conditions and process inhibitions. Due to the acid buffer system of the reactor content, disturbances in the process first manifest themselves in an accumulation of VFA, then in an increase of the VOA/TAC-value, and subsequently in a change in the pH-value before a collapse in gas production can be observed. Fig. 3 shows the course of the parameters assessing the process stability during the experiment. VOA/TAC, pH-value and methane content show no significant deviations between the flexibly and continuously operated reactors and no critical development. Thus, they indicate a stable operation. The concentration of total VFA and also the ratio of acetic to propionic acid remain predominantly in the range generally considered non-critical. In a few cases, VFA concentration notably went up after increased substrate input, such as observed on February 21th, but were quickly reduced again during periods of lower loading rates.

4. CONCLUSION AND OUTLOOK

In this laboratory-scale experiment, it could be demonstrated that the biogas production demanded by the residual load of an electricity self-sufficient community could be reproduced very well by targeted use of rapidly and medium-fast degradable substrates. In the period under consideration, the biogas process was stable and no inhibition was noticed. Furthermore, no reduction in gas production was observed compared to the continuously operated reference plant due to poorer substrate conversion. In practice, this flexible operating mode can minimize the necessary gas storage capacity and can avoid that plant operators need to expand their gas storage. Future studies are planned in which substrate input will be determined by an ADM1 based predictive model.

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