Demand-driven biogas production by substrate management –
Investigations in process stability at different scales

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Abstract
Biogas plants have the potential to supply demand-driven electricity to compensate the divergence between energy demand and supply by intermittent sources like wind and solar power. So far biogas plants have been designed to produce a stable and constant energy output. The aim of the study was to proof the ability of the anaerobic digestion processes to produce biogas on demand in lab-scale as well as full-scale (biogas plant with 923 m³ fermenter volume) experiments. The results demonstrated a high degree of intraday flexibility (up to 50% compared to the average gas production rate) and a potential for an electricity shutdown of up to 3 days by flexible feeding. Furthermore, the long-term process stability was not affected negatively due to the flexible feeding. The flexible feeding resulted in a variable rate of gas production and a dynamic progression of single acids and the respective pH-value. Depending on the used substrates, the necessary gas storage demand could be reduced by 30 - 68% compared to constant feeding operation.

Keywords demand-driven; feeding management; full-scale

INTRODUCTION
Biogas plants are a promising flexibility option for future energy-supply-systems with a high share of intermittent renewable energy sources, e.g. sun and wind. The extent of flexibility depends on the possibility to shift periods of power production to times with high energy demand as well as to change the height of power output. In practice, the shift from continuous to demand-oriented conversion of biogas to electrical power and heat is mainly realized by installing extra combined heat and power plants (CHP) combined with extra gas storage capacity. An additional option is the direct adaption of gas production to times with high demand for electrical power. Demand driven feeding with the aim of discontinuous gas production has only rarely been discussed in scientific studies. Hahn et al. (2014), Lemmer et al. (2017) and Terboven et al. (2017) described discontinuous feeding of fixed bed reactors. Wall et al. (2016) discussed two-phase applications for demand-driven biogas production. However, fixed-bed technology can hardly be implemented into existing biogas plants taking into account that the majority of biogas plants in Germany are designed as a series of continuous stirred tank reactors (CSTR). Only a few experiments (De Vrieze et al., 2013 and Mauky et al., 2015) investigated the potentials and long-time stability of AD-processes, even under highly dynamic operation modes.

Accordingly, the aim of the study was to
- investigate the flexibility potential of the anaerobic processes at biogas plants fed on energy plants and agricultural residues,
- examine the effects of discontinuous feeding on daily and long-term process stability and
- evaluate dependencies between possible disturbances, digester scale and flexible operation.

MATERIALS & METHODS
For lab-scale experiments, continuous stirred tank reactors (CSTR) with 15 and 40 L total volume (10 and 35 L liquid volume) are used. The full-scale experiments were carried at two research biogas plants (CSTR, liquid volume 180 m³ and 800 m³), located in Leipzig and Hohenheim
Further details of the plant configuration can be found in Naegele et al., (2014) and Mauky et al., (2017). Variable shares and combinations of corn silage, grass silage, wheat grist, sugar beet silage and cattle slurry were investigated in the experiments. The feeding regimes were calculated by model predictive control (figure 1), described in Mauky et al (2016). The used process model is based on the Anaerobic Digestion Model No.1 (ADM1, Batstone et al., 2002). However, the complex model structure was simplified to simulate the anaerobic digestion of carbohydrates, proteins and lipids to biogas (first-order kinetics) according to Weinrich and Nelles (2015). Supporting calculations on disturbances and performance were done with the full ADM1. Process relevant parameters, e.g. volatile fatty acids (VFAs) and pH were monitored throughout the whole experiment.

RESULTS AND CONCLUSION
Figure 2a shows real biogas production rates compared to model results according to the predicted substrate feedings. The prognosis horizon of the MPC was 7 days. Only the first day of each prognosis is depicted, as the prognosis and the schedule were updated daily. Over the days, a high correlation between predicted and measured gas production rate is observed. Figure 2b show the related biogas utilization timetable (gray bars) and the course of the resulting gas storage filling level. A constant feeding regime requires a significantly larger gas storage volume, if the same utilization regime is realized. Accordingly, the gas storage demand is decreased by feeding by more than 40 % based on timetable A. An alternative Timetable B in Figure 2c, assumes that 40 % of the energy is supplied by a continuous working CHP and 60 % by an additional CHP. If this mode of operation is used, an even larger reduction of 68 % of the gas storage requirement can be achieved (see figure 2c).

Figure 3 shows the gas production rate and gas quality achieved with flexible feeding. The results show that the daily gas production rate can be modulated up to ± 50 % of the daily average gas production rate (e.g. day 33 with min/max values of 14 m³ h⁻¹ and 38 m³ h⁻¹). Reducing the amount of substrate over the weekend reduces the gas production rate below 12 m³ h⁻¹. The CH₄ concentration drops below 50 % and the CO₂ concentration rises after a feeding event. This can be explained by immediate onset of hydrolysis after feeding. The process shows no long-term accumulation of VFAs due to variable substrate feeding. High frequent sampling of VFA concentration at day 15 and 21 reveals a parallel rise in acid concentrations and gas production rate but the fluctuations do not influence the overall process stability (Drosg 2013).
Additional pages

Figure 1. Main Control scheme with Model predictive control for the calculation of the optimal feeding regime based on a given demand timetable

Figure 2. Flexible biogas production in full-scale experiment. a) Measured gas production rate of one week compared with the daily forecasts within the model predictive control of the particular day. c) and d) Course of the theoretical gas storage filling level based on flexible and continuous gas production of different utilization timetable
Figure 3. Experimental results at the DBFZ research biogas plant (experimental day 9 to 36) with biogas production, methane and carbon dioxide concentration and acid concentrations (acetic and propionic acid), performed by a model predictive control procedure

REFERENCES