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Technical optimization of biogas plants to deliver demand oriented power

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A Motivation and Objectives

The increasing share of alternating renewable energies from wind and solar introduces the necessity of flexible power generation to reduce the gap between production and demand. Flexible power generation can be provided by fossil fuels, but in the long term it should be provided by renewable energies. Biogas plants can provide flexible power generation in a wide range but the existing plants are designed to provide base load only.

Flexible power generation can be improved by increasing gas storage capacity, but the ability to provide a load profile is limited. A further improvement can be achieved by changing the current continuous feeding to feeding on demand where the biogas plant is fed according to load requirements.

Flexible operation is required for the successful implementation of biogas plants in countries where there are no fixed feed-in tariffs support schemes and the plants are forced to produce when the electricity price is high in order to be economically feasible.

In order to improve the capacity of an existing plant to deliver power on demand the following three technical aspects were identified as objectives for this work:

- Develop a heuristic biogas model that enables the generation of feeding programs restricted by commonly used parameters of the biogas industry. Feeding programs should optimize the usage of the existing gas storage allowing the plant to deliver a wider range of loads as well as to provide system services, such as offering control power in balancing markets.
- Develop an online monitoring system that allows the continuous supervision of the biological process. Sampling acquisition should be representative for the digester, automatic, and able to generate high data density. Online measurements should be adequate to characterize the stability of the anaerobic digestion process.
- Improve gas storage volume measurements and define operating ranges where the measurements are accurate and weather effects are minimized.

This required consideration and development of the following main topics:

1. Develop an optimization algorithm with the objective to obtain a feedstock feeding schedule whose biogas production follows a required load. This algorithm minimizes the required gas storage capacity, while keeping operational parameters like organic loading rate, hydraulic residence time, nitrogen content, maximum dry matter, carbon to nitrogen ratio, gas storage operating level and cost within a desired range.
2. Determine the best suited biogas yield curves for the algorithm based on measurements in a laboratory and full scale biogas reactors. Identify the criteria to determine if the obtained biogas yield curves represent the full scale digester conditions.
3. Develop a sampling system that generates representative samples of the digester to improve the accuracy of the online monitoring based on the theory of sampling.

4. Calibrate the online monitoring to increase the representative sampling in a full scale biogas plant.
5. Develop a gas management system and a control philosophy to optimize the use of the existing gas storage and improve volume measurement accuracy.
6. Measure the main factors affecting the air supported double layer gas storage (the most used system in biogas plants in Germany), to improve measurement quality.
7. Determine the degree of suitability of existing gas storage equipment in the test plant for power on demand. Gas is transferred from one storage to the other by a pressure gradient generated by speed reduction of the membrane support fan in one storage. It is then necessary to verify if the implementation of gas management guarantees a minimum pressure and volume to keep the system stable at different gas storage levels.

B Main Results

The main results of this thesis are described as follow:

1. It was shown in laboratory reactors that the biogas curves obtained by a single feeding, simulating a batch test, do not represent the behavior of a full scale digester, due to differences in the biogas yield kinetics. The curves obtained in the lab from a continuous feeding schedule were closer to the behavior observed at the full scale reactor used in this work. But, as has been reported, reaction times are different between lab reactor and full scale. Because of this it was concluded that the curves should be obtained directly from the full scale digester. Furthermore, as observed in the lab reactor, biogas production curves vary with operating conditions and it is to be expected that changes generated in the feeding may affect the microbial activity and therefore biogas yield. These changes are not likely to be simulated in the lab reactor
2. Mathematical formulation of the optimization algorithm was achieved and tested in a theoretical scenario, but for its implementation further improvements of gas volume measurement are required to evaluate the gas production. The proposed mathematical model has the property that the step response of the system can be updated based on measurements done in the same plant as yield is expected to change with feeding changes.
3. Online monitoring was successfully implemented in a full scale biogas plant enabling the representative sampling from heterogeneous liquid systems, e.g. biogas slurry, where the sample size is 1 0 -9 of the digestate volume. The proof of suitability of the system was given in a 2 years operational phase on an agricultural biogas plant. Process stability, especially when operating the biogas plant by feeding-on-demand, could be frequently and reliably analyzed.
4. Online monitoring device was configured to determine the sampling parameters with the lowest standard deviation. It was found that the configuration with the largest subsample volume and maximum number of increments had the lowest standard deviation. Other configurations are also accurate, which makes them also suitable, but to agree with sampling theory the larger sample volume was selected.

5. Solar radiation was found to have no direct effect on gas temperature, but outside temperature did. Gas temperature can be calculated by a linear relation with the outside temperature without an elaborated model, this depends on the digester size.
6. Gas storage behavior changes with filling levels. At high filling levels when the gas storage and weather protection membranes start to get in contact the gas temperature has high variations due to the heat transfer between the membranes. Based on this finding the maximum allowed gas storage level must be restricted, because temperature variations also create volume variations, generating a possible gas loss. At lower filling levels there is a linear relation between outside and gas temperature. When one of the gas storages approaches am empty condition estimations of gas production are incorrect due to the membrane folding.
7. Based on the above observation a control philosophy was implemented to keep gas storages at the same percentage level. This was successfully implemented in a full scale plant to optimize the gas storage use, avoiding as much as possible low operation levels in the membranes, in which measurements are inaccurate, and high levels where heat is transferred due to membrane contact.
8. The assumption that the internal membrane shape is a spherical cap used to calculate the gas storage volume is not correct. The manufactured shape of the internal membrane is fixed and conical and at lower volume levels is deformed by folding. In addition pressure variations are small. Elastic straps were installed to distribute the gas equally over the digester area but between the straps variations of gas volume generate membrane movements that cannot be detected. Volume measurements always have a response delay and this effect was observed at different filling levels. In that sense the volume measurements are an indication but not accurate enough to determine the gas production of the digester.
9. Only large gas yields can be properly measured with the elastics straps and gas management system, as the gas produced is divided between both gas storages. This is a limitation for a feeding on demand implementation, because production of gas from small feeding quantities, predicted by the model, cannot be measured. A feeding schedule to measure the step response of the digester was applied at both a lab reactor and the full scale reactor. In the lab reactor immediately after the feeding there is a peak in the biogas production, but in the full scale reactor only at certain filling levels. There was no evidence from online monitoring of a process imbalance which would suppress this peak. Feeding schedule was then modified, concentrating the daily feeding quantity in a single feeding, generating a good match between measurement and prediction, confirming that only large gas yield can be measured.
10. Modifying the feeding schema did not affect the biological process negatively. There were no relevant variations of VFA/TIC ratio even when feeding was concentrated to a few hours a day. The feeding daily quantity was not modified while its distribution in the day was, keeping the same OLR.
11. The current gas storage equipment configuration requires modification for the implementation of demand-oriented power generation. In the case that an additional 250 kW engine is installed increasing the gas volume consumption by 130 m³, the membrane support fan would not be

immediately able to fill the void generated by the change of gas consumption. A channel would also have to be installed in the air inlet to avoid mechanical blockage at maximum filling level. Pumped air between membranes gets warm decreasing the fan capacity. Fan should be sized at the higher temperature to be able to generate higher flows so that the volume of warmer air is enough to keep the system stable.

12. Different speed variation in the air supporting fan was required in the digester and storage to move the gas between membranes. The difference was due to the different diameters of the gas membranes. It was verified that the selected fan rpm reduction allowed the system to remain over the minimum pressure and volume criteria.

C Scientific evaluation of the results

The main relevance of this work is to provide technical solutions to the implementation of feeding on demand suited and tested in full scale biogas plant.

1. A full automatic online monitoring was successfully implemented in a full scale plant. The system was able to detect process disturbance and monitor the feeding changes. External lab results validated the indication given by online monitoring, which allows a high density of data to check the process evolution. The results are available immediately allowing a faster reaction time without waiting the 2 or 3 days required by the laboratory. Online monitoring allows a safer operation in a feeding on demand scenario because any major disturbance can be identified and actions can be taken to recover the process decreasing the risk to the plant owner. Online monitoring was patented and developed to the stage of a commercial product.

2. For the successful adoption of feeding on demand plant operators must feel comfortable in changing traditional practices by introducing variable feeding. The online monitoring system developed in this work can help to reduce this uncertainty for operators and, with adequate supervision, explore the potential of feeding on demand by operating at higher organic loads with periodic starving to improve flexibility.

3. Feeding schedules previously set when the plant was commissioned are now required to be flexible and determined by models that must not involve an elaborated calibration and be simple enough for use by the plant operators. The model developed in this work includes the capacity to update the system response from measurements generated in the plant itself. Model development includes mathematical description in a matrix formulation for faster calculation. Its application in an operational full-scale biogas plant was however not possible even after the gas volume determination improvements detailed in this work, as these were not able to provide sufficient accuracy in determining measurements of gas production. Model validation could be made with a fixed storage volume and a calibrated flow meter. Unfortunately, this configuration is not available in most biogas plants in Germany. Technical solutions are proposed to improve the gas volume measurements in double layer membranes.

4. Flexible power generation depends on the optimum use of the existing gas volume. The gas management develop here maximizes the gas volume utilization.

D General meaning of the results

For the implementation of flexible power generation in biogas plants the following practical aspects can be identified.

1. Substrate characteristics in agricultural biogas plants using energy crops are continuously changing due to various factors not in control of the plant operator. A continuous measurement for the dry matter is recommended to improve model predictions.
2. Trace element requirements also vary according to the imposed organic load to the system. A process imbalance was monitored in the test plant at a continuous feeding schedule, probably generated by a low concentration of trace elements. Feeding model predictions concentrate feeding in some few hours a day, which may modify bacteria trace element requirements. It is therefore important to implement a continuous control of trace elements and keep these at a minimum desired level according to the expected variations in the organic load.
3. Improvements of gas volume determination were achieved by implementing the Bauer "calming" system (elastic straps), and the gas management system developed in this work. Gas management also guarantees more complete use of the existing gas storage, so that gas is only flared when all storages have reached their maximum level. This is achieved by equal distribution of the produced gas in the available gas storages. The same equipment can be used to empty a gas storage when maintenance works are required, for example to change an agitator.
4. The procedure used to measure the gas storage in this work can be used in other biogas plants to determine if equipment is suitable for a planned degree of flexible generation.