

Robin Eccleston*
Michael Bongards

Determining Conditions of Intermittently Fed Digesters from Biogas Production Rate Data

As the contribution from renewable energy to the power grid increases, biogas plants could profit from on-demand production. Flexible feeding can supplement gas storage for further benefits. Changing to flexible feeding introduces transient events to the feeding, and by monitoring the system response to the feeding transients it is possible to gain information about the system stability. Testing was performed at the laboratory and pilot scale to investigate the response characteristics. A statistical analysis was carried out to assess the response to feeding events and make an estimate of the system stability. This analysis was then used as the input to a proportional integral derivative controller for controlling the feeding rate for an anaerobic digestion model No. 1 simulation.

 This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Keywords: Biogas production, Demand-driven biogas, Intermittent feeding, Process control

Received: June 28, 2019; *revised:* August 29, 2019; *accepted:* October 04, 2019

DOI: 10.1002/ceat.201900354

1 Introduction

Each individual anaerobic digester has different levels for the various process parameters which are suitable and which can cause inhibition [1]. The bacteria are adaptable, and so a generalized approach is necessary that can be transferred to other digesters, rather than relying on specific values as thresholds.

This work is considering the application whereby biogas production is used to generate electricity, and the electricity is sold to the grid. In Germany, until 2017, this procedure primarily has been financially viable as a result of the subsidies provided by government programs and as such operate continuously to maximize income. As subsidies are cut, there is a requirement for an alternative source of income. There is a fluctuation in the wholesale electricity price over the day, which is generally reflected by the demand. On-demand power can be sold at a higher rate than continuously produced power. By implementing non-continuous operation to generate more income, fluctuations will be introduced to the feeding schedule. By considering the relationship between feeding to a reactor and the generated gas, it is possible to gain some knowledge about the operating conditions of the reactor. This information can then be used to make an informed decision on the feeding level based on the estimated plant condition.

Similar work has been performed [2], which used a comparable principle, however, with a different analytical technique and different mode of operation. The work was focused on the use of a continuously fed reactor with an artificially introduced disturbance to the feeding rate, with the change in the gas production being used to estimate the conditions in the reactor. The work presented in this paper is employing the same relationship, however using the disturbances that would be neces-

sary to run an anaerobic digester for flexible power production. This has the advantage that the disturbances will not significantly affect the total loading rate of the digester. Mauky et al. [3] tested two 208-m³ digesters and a 923-m³ digester and found that on both the smaller digesters and the full-scale digester, the process was stable under the flexible feeding regime with the gas production only shifting in time.

In anaerobic digestion (AD), there is always one step in the process which is the rate-limiting step. This will be visible by comparing the change in feed to the change in produced gas, as the rate-limiting step will be the bottleneck in the process. Intermittent feeding will result in a transient at the input to the feeding system, and the gas response is the response of the system to the transient. The analysis of the transient event can thus provide information about the state of the system, and by looking for various features in the response it is possible to determine information about the system. The parameter of most value is how close the system is to inhibition, as this will then allow the plant operator to make the decision to increase or decrease the loading rate. Analysis of the transient response is of interest, since it can be performed on each individual plant and provide recommendations for the feeding levels and the level of stress/inhibition that the plant is experiencing.

Robin Eccleston, Prof. Michael Bongards
robin.eccleston@th-koeln.de

Institut für Automation und Industrial IT (AIT), Fakultät für Informatik und Ingenieurwissenschaften, Technische Hochschule Köln, Gummersbach Campus, Steinmuellerallee 1, 51643 Gummersbach, Germany.

2 Reference Measurements

In this work, a combination of simulations, laboratory testing, and testing on a pilot-scale reactor was applied. For the laboratory- and pilot-scale testing, a range of loads were fed to the digesters, and the effect on the output of the digesters was recorded. An implementation of the anaerobic digestion model No. 1 (ADM1) [4] was then used to generate more test data with similar characteristics to that from the physical measurements. Tab. 1 gives an overview of the feedstock properties for the testing.

Table 1. Feedstock properties; FM: fresh matter, DM: dry matter.

Substrate type	Dry matter [% of FM]	Volatile solids [% of FM]	Volatile solids [% of DM]
Dried grass silage ^{a)}	84.60	78.20	92.44
Cattle slurry ^{a)}	6.89	5.25	76.21
Maize silage ^{b)}	31.46	30.61	97.30

^{a)} Laboratory testing; ^{b)} pilot-scale testing.

2.1 Laboratory Test Setup

The test setup is illustrated in Fig. 1. There are eight reactors, each with a total volume of 5.3 L, and a filling level of 4.5 L. The reactors were filled with inoculum from a nearby maize-fed full-scale AD plant. Due to the limited time available during testing, a short adaption phase of only five days was possible. Each reactor had individually controlled stirrers which were operated continuously throughout the experiment at 35 rpm. The stirrer construction consisted of two horizontal bars near the top and bottom of the reactor, connected directly to the motor through a central shaft. The reactors were built and supplied by G. H. Lawrence Welding and Engineering, Cornwall, UK. Gas production rates were measured using a tipping bucket meter with a resolution of 17 mL, also provided by the digester manufacturer. The gas meters were individually calibrated with gas syringes before starting the experiment.

The temperature of the reactors was measured to be 36–39 °C. There was some temperature variation between the reactors due to the order in which hot water was delivered to the heating coils. Half of the reactors were fed with cattle slurry, the other half with milled grass silage. For each group, two served as control reactors and two were fed with rising amounts to observe the changes that occur with increasing feeding levels.

The same amount of volatile solids was fed to the test and control reactors for both feed types. The properties for the feedstock are listed in Tab. 1. The dried grass silage was milled, and the cattle slurry was blended in a food processor to ensure homogeneity. Feeding was performed at the same



Figure 1. CSTR laboratory setup.

time for all digesters to ensure that the same feeding rates were applied to digesters for both feed types. Feeding was performed once the gas production rate for all digesters had dropped to a significantly reduced level. This was done in order to be able to distinguish the different events from one another and to ensure minimal overlap between the feeding responses.

Feeding was initially expected to be performed each three to four days, and the target organic loading rate (OLR) was $3 \text{ g}_{\text{VS}} \text{ L}^{-1} \text{ d}^{-1}$, where VS means volatile solids. For the test reactors, this would be significantly increased to ensure that the overloading state was reached. An OLR of $6 \text{ g}_{\text{VS}} \text{ L}^{-1} \text{ d}^{-1}$ was taken as a practical upper limit [5]. As the response to the feeding events took longer than anticipated, the effective OLR is reduced. The calculated OLR is given in Tabs. 2 and 3. When feeding, the same volume added to the digester was also removed before feeding to ensure a constant filling level. When feeding slurry, the slurry was incubated until the temperature had reached 37 °C to prevent the temperature of the reactor dropping significantly. For the final feeding event, a larger amount was also fed to the control digesters to observe if there was any change in the output observable as a result of the different feeding history. The feeding dates and amounts are summarized in Tabs. 2 and 3.

2.2 Laboratory Gas Production Profiles

Fig. 2 displays the gas production rate profiles for the laboratory reactors. Figs. 2a and 2b show the gas production rate for the control and test grass-fed reactors, respectively. Figs. 2c and 2d indicate the result of the control and test cattle slurry-fed reactors. The organic loading rates are plotted against the right

Table 2. Feeding for laboratory-scale test grass-fed reactors.

Date	Grass control reactors			Grass test reactors		
	Feed amount [g]	Feed VS [g]	OLR [$\text{g}_{\text{VS}} \text{ L}^{-1} \text{ d}^{-1}$]	Feed amount [g]	VS [g]	OLR [$\text{g}_{\text{VS}} \text{ L}^{-1} \text{ d}^{-1}$]
April 11, 2016	14.61	13.51	3.00	14.61	13.51	3.00
April 19, 2016	14.61	13.51	3.00	29.22	27.01	6.00
April 26, 2016	14.61	13.51	3.00	58.44	54.02	12.00
May 03, 2016	87.66	81.03	18.01	116.88	108.04	24.01

Table 3. Feeding for laboratory-scale test cattle slurry-fed reactors.

Date	Slurry control reactors			Slurry test reactors		
	Feed amount [mL]	VS [g]	OLR [g _{VS} L ⁻¹ d ⁻¹]	Feed amount [mL]	VS [g]	OLR [g _{VS} L ⁻¹ d ⁻¹]
April 11, 2016	264	13.86	3.08	264	13.86	3.08
April 19, 2016	264	13.86	3.08	528	27.72	6.16
April 26, 2016	264	13.86	3.08	1056	55.44	12.32
May 03, 2016	1584	83.16	18.48	2112	110.88	24.64

y-axis. The y-axis scale changes between the grass- and cattle slurry-fed reactors. This is due to the significantly lower gas production rates from the slurry-fed reactors.

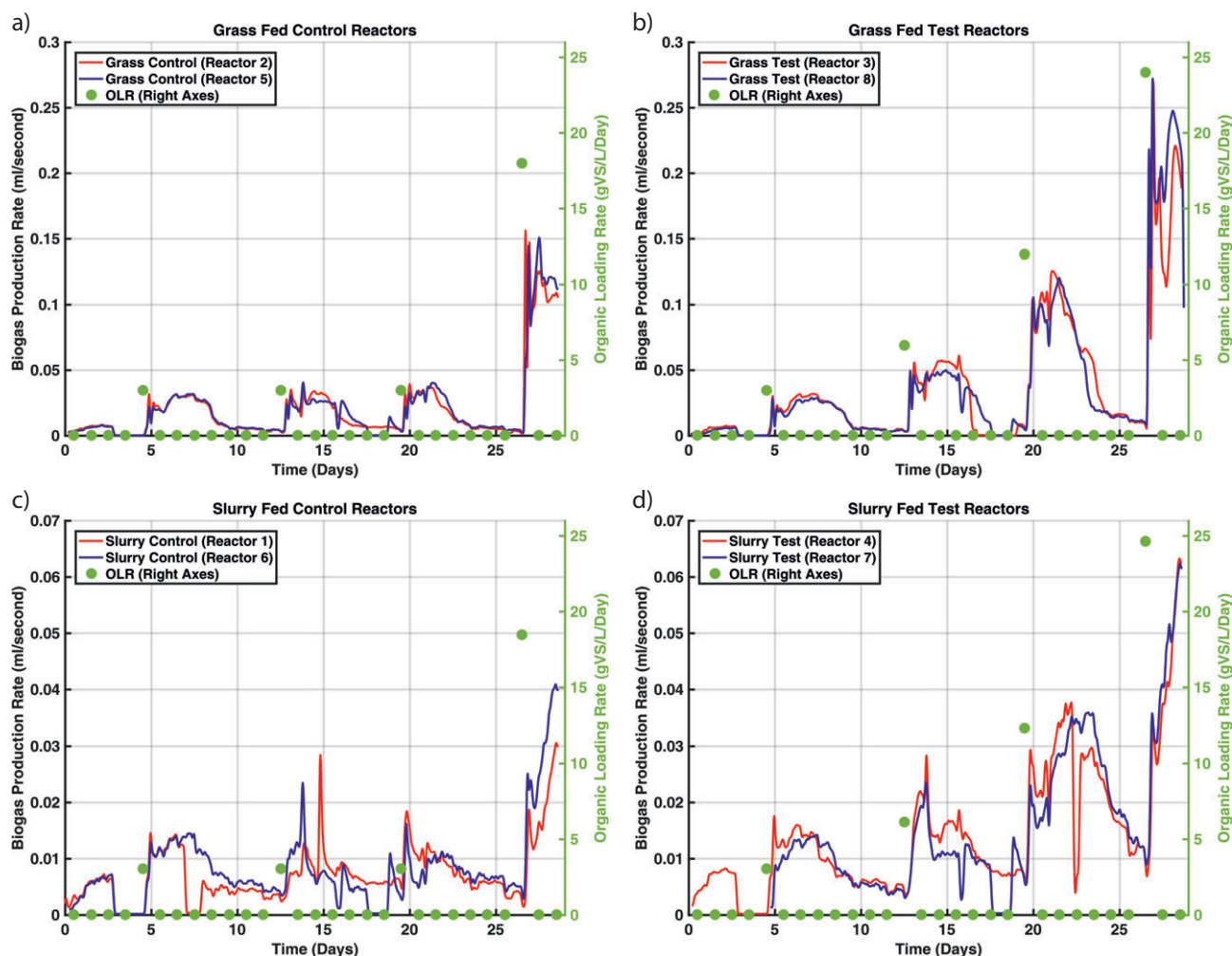
At low loading rates, all reactors exhibit a similar response to the feeding. The grass-fed reactors in Figs. 2a and 2b have more distinct characteristics. After feeding, there is an increased gas production for approximately four days, followed by a decrease until the next feeding event. The same response is visible in the

slurry-fed reactors in Figs. 2c and 2d, although not as clearly defined. The slurry-fed reactors have a lot more variation in the gas production, which is believed to be due to the slurry being non-homogeneous, unlike the milled grass silage, which exhibited much better homogeneity.

One characteristic that was observed in the grass-fed reactors (Figs. 2a and 2b) was an initial quick response, followed by a slight

dip in the gas production rate and then by the rate increasing again more slowly. This pattern can be seen in the following day after feeding. This becomes more pronounced at higher OLR values and is most substantial in the test reactors (Fig. 2b) at day 27 to day 29. For the feeding at lower rates, this feature is still present but not as significant.

For the slurry reactors (Figs. 2c and 2d), the variations in gas production due to the non-homogeneity are the most clear

**Figure 2.** Gas production rates for laboratory reactors. (a) Grass-fed control reactors; (b) grass-fed test reactors; (c) slurry-fed control reactors; (d) slurry-fed test reactors.

features. These can be seen as rapid changes in the gas production rate, e.g., in Fig. 2c for reactor 1 at day 15 and for reactor 2 at day 15. There are also increases after feeding, but the change in gas production rate is much slower than when feeding grass silage. This is partly due to the low VS of the cattle slurry, requiring a large volume to be fed to add the same quantity of VS as the grass-fed reactors.

As the reactors had a 4.5-L liquid volume, for the slurry-fed reactors, the feeding of 27 g VS requires 528 mL of slurry, which is approximately 12 % of the liquid volume. For the last feeding event, the slurry makes up almost half of the liquid volume. By comparison, the grass silage being fed never exceeds 3 % of the liquid volume. Thus, for the slurry-fed reactors, one of the reasons for a difference in response is washout. Furthermore, due to the characteristics of the slurry being different to the milled grass silage, there will be differences in the response. For example, the milled grass silage had a large surface area and low moisture content, meaning that once fed, the liquid in the digester which contained the bacteria would quickly have access to a large surface in which to work. By comparison, the slurry resulted in a slower response after feeding.

2.3 Pilot-Scale Test Setup

Fig. 3 illustrates the pilot-scale plant setup that was used for testing in the metabolon facility [6]. There are two systems running in parallel, which can be used to duplicate testing: a primary reactor, a secondary reactor, and a final storage tank. The first two reactors are heated and have gas counters fitted to measure the produced gas. The last reactor is an unheated final storage tank, where the gas production is not quantified. The system consists of six reactors, each with a total volume of 1000 L and a liquid level of 800 L. The pilot plant was constructed by Bremer pro aqua Wasser- & Abwassertechnik GmbH (Bremen, Germany). Measurement of the biogas volume was performed with a TG3/2 drum type gas meter manufactured by Dr.-Ing. RITTER Apparatebau GmbH & Co. KG (Bochum, Germany). The gas composition was determined using an AwiFLEX Cool+ from Awite Bioenergie GmbH (Langenbach, Germany). Measurements were performed each 2 h, to assess the concentrations of methane, carbon dioxide, hydrogen, and hydrogen sulfide.



Figure 3. Pilot-scale plant used for testing.

For the three months before the start of the testing, the biogas plant was fed daily with maize silage. The average OLR for the first month was $0.197 \text{ g}_{\text{VS}}\text{L}^{-1}\text{d}^{-1}$, for the second month

$0.474 \text{ g}_{\text{VS}}\text{L}^{-1}\text{d}^{-1}$, and for the third month $0.459 \text{ g}_{\text{VS}}\text{L}^{-1}\text{d}^{-1}$. Due to the liquid level in the reactors not being adequately high, during some of the testing it was possible for gas from the first digester to pass through the counter for the second digester. For this reason, the gas production volumes from both digesters were added together. The reactors for this test were fed with maize silage from a local farm. The feeding amounts are given in Tab. 4. With the highest feeding level of 60 kg of maize, there were problems with maize floating on the surface of the liquid in the digester, and filling the headspace in the digester led to concerns that the gas pipes would become blocked.

Table 4. Feeding for pilot-scale test.

Days into experiment	Weight of maize fed [kg]	Total solids fed [kg]	Volatile solids fed [kg]	OLR [$\text{g}_{\text{VS}}\text{L}^{-1}\text{d}^{-1}$]
0	2.5	0.787	0.765	0.765
2	5	1.573	1.531	1.531
5	10	3.146	3.061	3.061
7	20	6.292	6.122	6.122
9	40	12.584	12.244	12.244
11	60	18.877	18.366	18.366

2.4 Pilot-Scale Gas Production Profiles

The results from the pilot-scale tests are presented in Fig. 4. The plots demonstrate that as with the continuous stirred-tank reactor (CSTR) results shown previously, there is a rapid increase followed by a gradual tapering of the gas production. Both reactors behave differently once higher organic loading rates are employed. Up to and including the 10-kg feeding, both reactors behave similarly. At 20 kg, System 2 is able to tolerate this better. Initially, there is a small drop in gas production which shows the first signs of disturbance for this reactor. System 1 already has a significantly lower gas production, indicating that a threshold has been exceeded. It is clear that less gas has been produced by this reactor than System 2, and so inhibition is occurring. However, at the 40-kg feeding, then there is still gas produced, which means that the system is not completely inhibited. For the 40-kg feeding, both systems start to behave erratically. They exhibit rapid increases in the gas production rate for a short period, followed by gas production dropping just as quickly. For the 60-kg feeding, the same trend can be seen where there are short peaks followed by a time period of diminished gas production.

As the reactors were fed with maize silage, a significant amount of the maize could be seen floating on top of the liquid after feeding. The stirrers were run continuously in an attempt to reduce this; however, it was not effective at the highest loading rate of 60 kg. At lower loading rates, the maize silage was mixed more effectively, with no floating layers visible. After the 60-kg feeding, there was a large layer of floating maize silage in the digester, which the stirrers were unable to mix effectively. After running for a further two days, the primary digester in

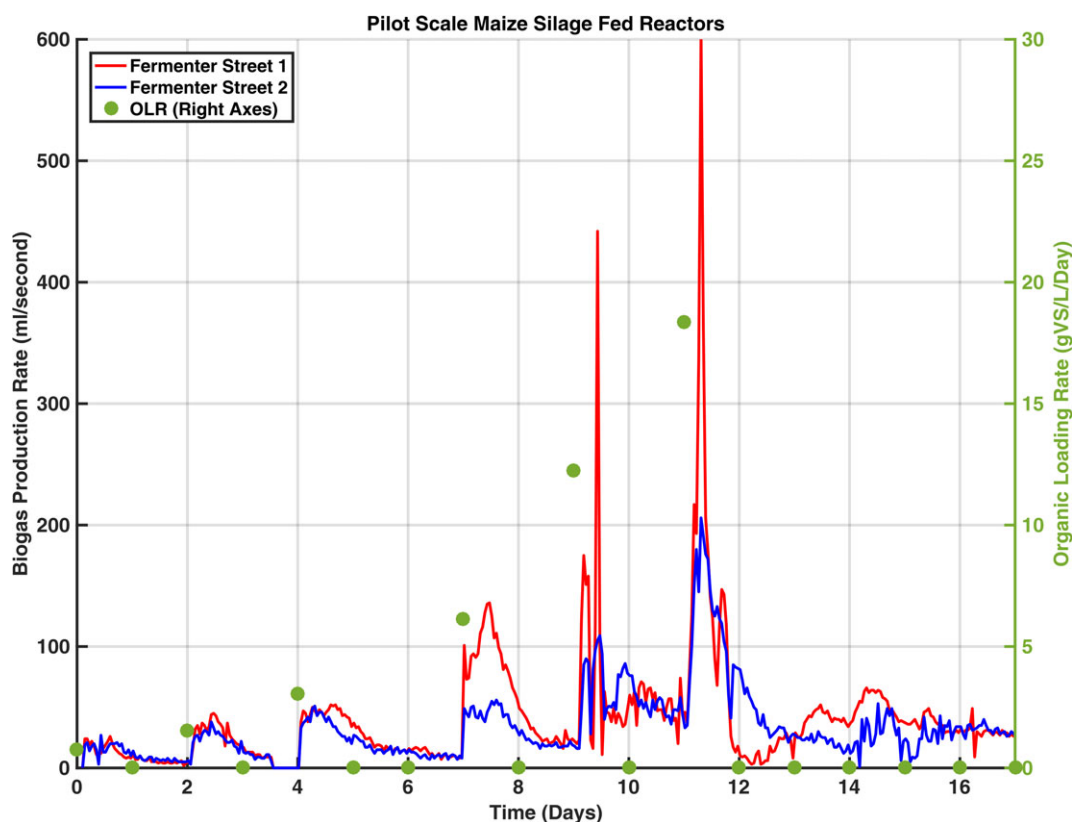


Figure 4. Biogas production rates for pilot-scale digesters.

Street 1 had a floating layer of maize silage approximately 6 cm thick covering most of the surface, but the primary digester in Street 2 had a significantly lower amount of maize floating on the surface, suggesting that the process was still functioning, but in a less stable operating condition.

3 Estimation of Digester Conditions

Initial attempts to estimate the digester conditions were performed by using a kinetic model, namely, the modified Gompertz model [7]; however, this did not provide satisfactory results. This is a much simpler modeling compared to the ADM1, as the kinetic model used takes only variables for the specific biomethane production rate, the lag phase, and the time in days. The model then calculates the value for the cumulative specific methane yield at a given time. It was then fitted to the biogas production profiles by means of a genetic algorithm. As the kinetic model does not model inhibition, it was expanded to include inhibition. Other modeling approaches were considered but models such as ADM1 require more information, e.g., measurement of substrate parameters. The focus of this work was an attempt to create a more generic method that could be applied to digesters with limited instrumentation and without laboratory analysis, and for this reason the approach with kinetic models was chosen.

The results from this work proved that the kinetic model was only able to achieve a good fit when there were low levels of in-

hibition, and achieved a poor fit when there was inhibition present. It was observed that the model typically found a solution that was similar to applying a low pass filter to the gas production profile. From this result, further efforts were made to apply a low pass filter and then statistically calculate how good the fit was. The changes arising as a result of inhibition occurred much faster than the uninhibited responses, and so the model matches the slower changes well and the fast changes poorly.

3.1 Statistical Analysis of Data

Both curve fitting and low pass filtering were investigated. With low pass filtering, there is a trade-off when adjusting the window size, as a larger window size results in slower changes and a slower output, but a smaller window size means that short events have a much stronger effect on the output. For these reasons, curve fitting was found to function better whilst still running very quickly on a standard desktop computer.

Curve fitting can be performed with a coefficient which determines how closely the curve will match the data and how high a frequency the curve can be. By selecting the correct value, datasets with little or no inhibition are well matched, and datasets with inhibition have larger differences. The smoothing spline function of Matlab[®] was used [8], and a value for p , the smoothing parameter, of 0.005 was selected.

In Fig. 5, an example is given applying curve fitting to the raw data from the pilot-scale test, where increasing loads were

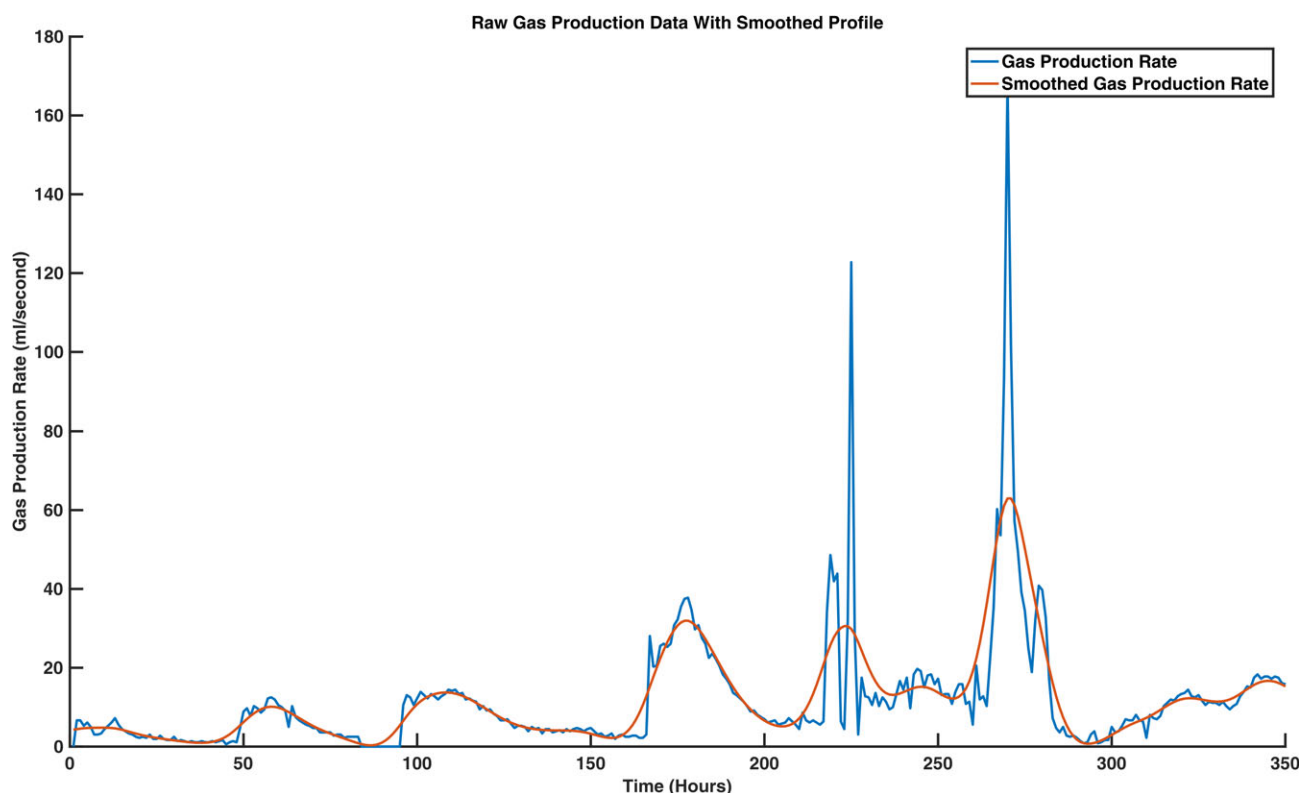


Figure 5. Demonstration of curve fitting applied to data from pilot-scale plant fed increasing amounts of maize silage.

fed. It can be seen that for the early feeding events, the curve fitting can create a closer approximation and the error between the raw value and the fitted value is small. When the digester is showing stronger inhibition, there are large sections where the error between the fitted curve and the measured values is much more significant. Thresholds for the acceptable error range are set as a level of gas production in liters per hour, per liter of reactor liquid level. An error level of $0.005 \text{ L h}^{-1} \text{ L}^{-1}$ and below was used to indicate a good reactor performance with minimal detected stress, and a level above $0.01 \text{ L h}^{-1} \text{ L}^{-1}$ was set to reveal poor conditions and that the digester is experiencing a high amount of stress, and given the maximum value for the normalized stress.

Error levels in between these values are scaled linearly as demonstrated in Eq. (1). This process is performed on the data in hourly increments, with each time point being the total biogas produced in the last hour.

$$se = \begin{cases} 0 & \text{if } |e| < L_{\text{Thresh}} \\ \frac{|e| - L_{\text{Thresh}}}{U_{\text{Thresh}} - L_{\text{Thresh}}} & \text{if } L_{\text{Thresh}} \leq |e| < U_{\text{Thresh}} \\ 1 & \text{if } |e| \geq U_{\text{Thresh}} \end{cases} \quad (1)$$

where e is the error between the raw value and the smoother fitted curve, se is the scaled error, i.e., the result of the calculation, $L_{\text{Thresh}} = 0.005$ means the lower threshold for the error in $\text{L h}^{-1} \text{ L}^{-1}$, and $U_{\text{Thresh}} = 0.01$, being the upper threshold for the error in $\text{L h}^{-1} \text{ L}^{-1}$.

The correlation between the fitted curve and the raw data was also tested. A combination of the two parameters was found to give the best performance. The correlation R^2 was performed over the previous 18 h of data for the raw data and fitted curve data. The R^2 value has a maximum of 1. A value of zero implies no correlation between the two parameters being tested. A negative R^2 denotes an inverse correlation between the variables. When the digester is stable, then the curve fitting function will perform well and the fitted curve will match the raw data well. When an increase in system stress occurs, then there will be drops in the biogas production, and the R^2 value will decrease. The value is clipped between 0 and 1, and then the product of the R^2 value and the scaled error level is taken. The average for the product for the last 12 h is taken, which ensures that one high reading will not cause a false positive. This average is finally presented as the stress factor. The combination of both parameters then acts as a filter to show only events that represent a larger concern where both parameters demonstrate that there are problems.

As the calculated stress value quickly returns to lower values, a decay factor is also added, which causes the maximum calculated stress to decay slower. The current implementation requires around 12 h to return to a low value from the maximum possible stress. This could be increased as desired, e.g., if it was estimated that the digester was highly stressed, then it would most likely be advisable to reduce the feeding amount for a number of feeding cycles to give the digester time to recover.

In Fig. 6, two plots present the resulting data. In the top figure, there is the gas production rate normalized to the volume of the reactor, which is shown as the blue line. The feeding events are visible at days 2, 4, 7, 9, and 11. The lower plot indicates the calculated inhibition as a number between 0 and 1, with 0 being no major signs of stress, 1 being a large stress detected. This is also used to set the background color on the top plot.

It is obvious that the calculated stress corresponds to each feeding event, with larger feeding events having higher calculated stresses. At day 7, the calculated stress is already enough that the feeding level should no longer have been increased, and this data could be used to advise a plant operator to decrease the feeding level if such characteristics were observed.

The results for the maize silage-fed reactors and the grass silage-fed reactors exhibit similar characteristics as the processes approached inhibition, which is detected and shows an increase in the calculated stress factor. With a predictive control scheme this is expected that it would be sufficient to reduce the feeding rate with enough time to allow the digester to recover. For the systems fed on cattle slurry, no significant stress was found, due to washout and how it affects the transient response differently compared to systems fed with maize silage or grass silage. The reactors fed with grass silage illustrated that as the feeding level increased, this was seen as gradual increases in the stress level, which again proves that it would be suitable in these scenarios to use a control mechanism.

4 Simulations and Modeling

To test using more data than from the reference measurement tests, simulations were performed. The model used as part of this project was a Matlab[®] implementation of the ADM1. The implementation was created by Gaida [9] and is available from the author as a toolbox. A single reactor was simulated, with a final storage tank. The ADM1 substrate parameters were initially set using values from literature for maize silage and then manually adjusted to provide similar results to those obtained during the laboratory- and pilot-scale testing. The main observable difference with the ADM1 simulation outputs was the absence of the rapid increase followed by the short reduction in gas production rate, visible in Figs. 2a, 2b, and 4. The adjustments focused on ensuring the gas production profile in response to feeding events matched that seen during the physical measurements as closely as possible.

As inhibition is an edge case, there are larger variations between the ADM1 and experimental results in cases of inhibition than for with stable operations. However, when approaching inhibition, the ADM1 biogas output had similar high frequency transients when getting closer to process failure and so it was possible to use the same analysis techniques to detect the inhibition.

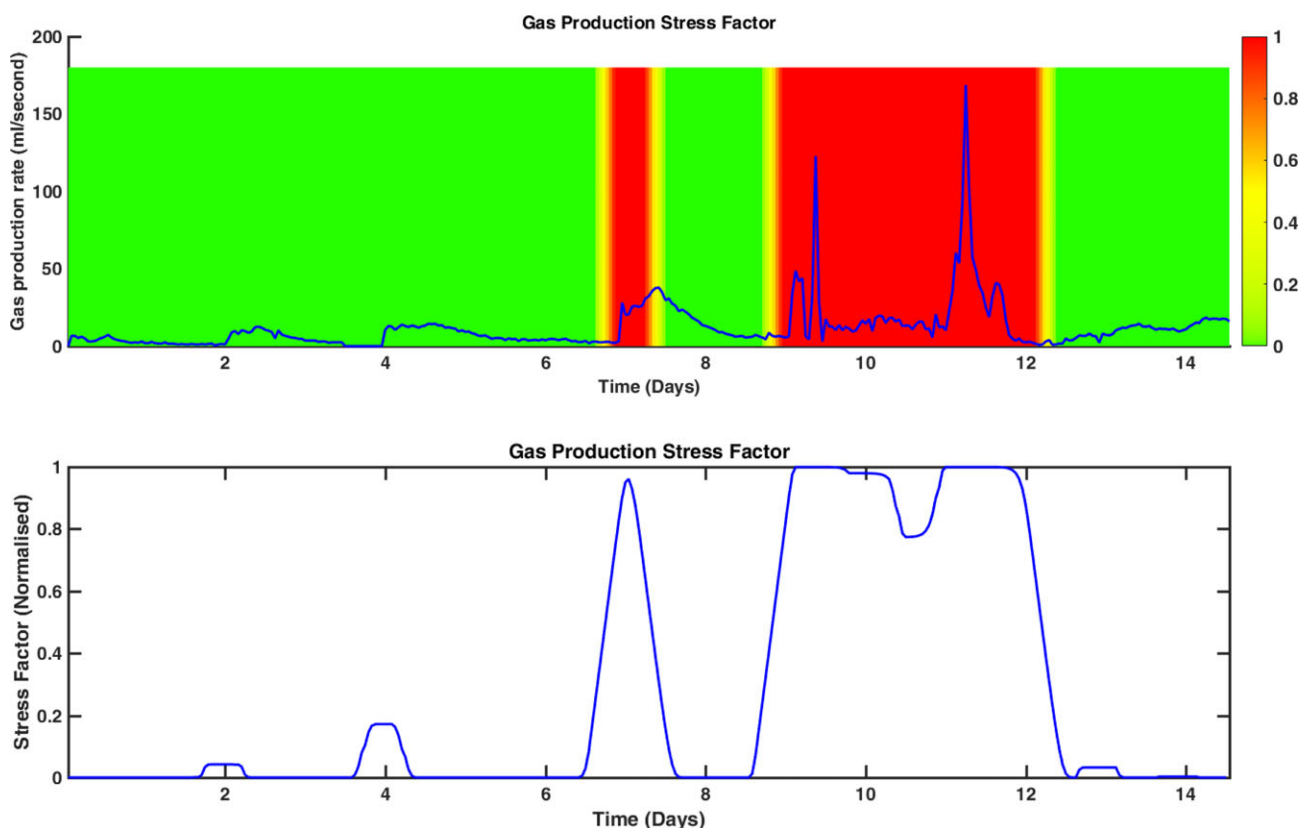


Figure 6. Gas production and calculated inhibition for one of the pilot-scale plants.

4.1 Implementation of a Proportional Integral Derivative Controller

The approach to estimating the digester conditions results in a numerical value for the amount of stress which the digester is experiencing as a result of high loading rates for substances with high levels of VS, such as maize silage. To use this information most effectively, a control scheme is needed, which will utilize this parameter and vary the feeding amount to result in the target being fulfilled. The target is that there should be a small amount of stress on the system, because with “no stress” as the target, the controller would converge on a feeding rate of zero. A small value for the stress suggests that the feeding rate can be safely increased slightly further and that there is some safety margin, however, there should also not be a large amount of unused capacity. Based on the experimental and simulation data, a target for the stress factor of 0.1 was selected, with 0 being no stress, and 1 being the highest possible value, meaning a very highly stressed system that would be expected to fail if such a loading rate was continued.

Proportional integral derivative (PID) controllers make up more than 90 % of industrial controllers [10] and for this reason were selected. In the PID controller equation, the PID constants were defined as follows: $k_p = 1.25 \times 10^{-6} \text{ Vol}$, $k_i = 0.94 \times 10^{-6} \text{ Vol}$, $k_d = 0.75 \times 10^{-6} \text{ Vol}$; where Vol is the digester volume in liters. These values were selected during testing as they provided a good balance between quickly converging and ensuring that oscillation and overshoot was not too significant.

4.2 Long-Term Simulation

Fig. 7 shows the results of a year-long simulation using the PID controller. For the first 365 d, the PID controller is aiming for a calculated stress level of 0.1. Then, for 30 d, the simulation was fed with the same amount as on day 365. After each subsequent 30 d, the loading amount was increased by 50 %. When considering the results, most attention is paid to the daily methane production, as methane is the component which is combusted in a combined heat and power (CHP) unit, and so methane production is of high importance.

At the beginning of the simulation, the controller slowly increases the feeding rate until reaching the target stress level for the system. As the composition of maize is unchanged for the duration of the simulation, then the total feeding amount each day is relatively constant. The daily feeding amount settled between 4 and 4.5 kg d⁻¹.

After day 365, as the feeding amount is not changing significantly, there is also little variation. After this day, the feeding rate is increased by 50 %, at which point the daily methane production rises; however, it becomes less stable with larger fluctuations each day. The system is less stable and is approaching inhibition.

From day 425, the feeding rate is increased again by another 50 %. There are larger variations in the produced methane each day. There is less correlation between the constant amount being fed and the amount of methane produced.

Finally after day 455, there is a further increase in the feeding amount, at which point the digester inhibition becomes too high for the system to continue producing methane. The meth-

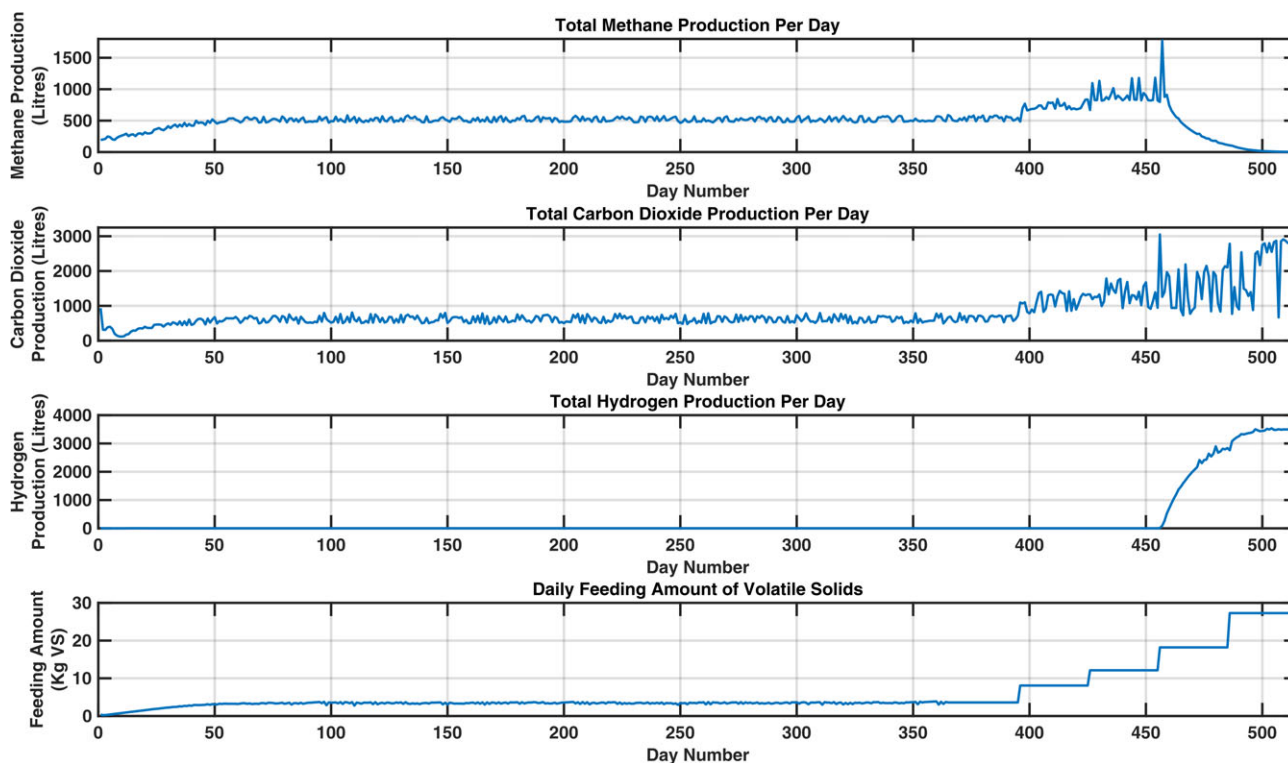


Figure 7. Gas production in simulation of PID control of pilot-scale plant for 365 d, with increased loading rates at the end to cause failure.

ane production approaches zero and inhibition disrupts the process. The ADM1 process has become strongly inhibited, and in the simulation this can be seen from the lack of methane or carbon dioxide production and the rise in hydrogen production. This highlights one of the differences between the ADM1 and the experimental data. However, as the ADM1 approaches inhibition, there were many similarities in the characteristics between the simulations and the experimental data. For this reason, the results are considered to give a good indication of what can be expected, although not representative of every scenario.

Fig. 8a presents the plot of the amount of VS that was fed to the digester against the volume of methane produced. The color of the point represents the calculated stress. The controller settled feeding around $3.0\text{--}3.75\text{ kg VS d}^{-1}$. At the higher feeding amounts around 3.75 kg , there is some growth in the calculated stress, with values up to around 0.5 . With a target of 0.1 , this is the reason that the controller never increased the feeding amount over 3.75 kg .

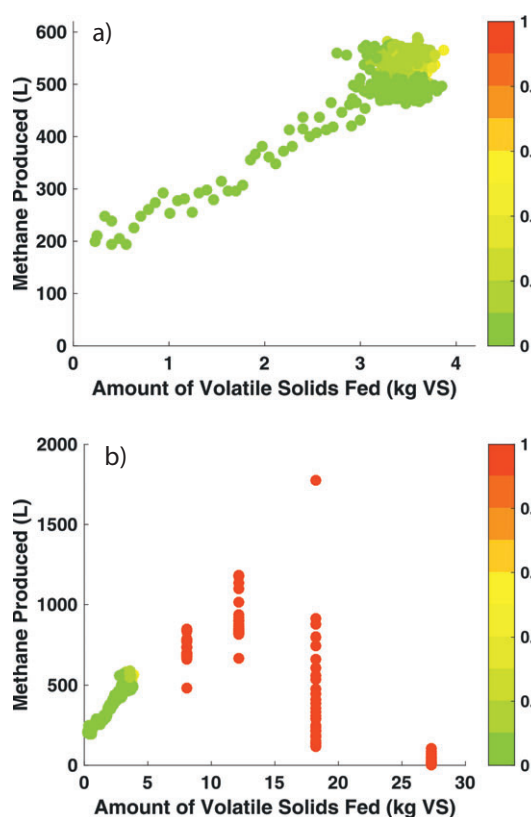


Figure 8. Amounts of volatile solids fed to ADM1 simulation compared with the volume of methane produced. Feeding rate against methane production (a) during stable operation period; (b) including overfeeding to reach inhibition.

Fig. 8b shows the same plot, expanded to include the points for the higher feeding levels to push the system to inhibition. From this plot, it can be seen that a single value for the feeding amount results in larger ranges of methane production, with the variation increasing at the system is more stressed. At the feeding rate of 12.1 kg , there is a significantly wider range with

variations between 668 and 1183 L of methane produced. This demonstrates that the system is very unstable and approaching inhibition. At the increased rate of 18.2 kg , there is a variation between 114 and 1776 L and the methane production is generally reduced compared to what would be expected under stable feeding. In a stable system, the change in methane production would be approximately linear with the feeding amount.

5 Summary

Testing was performed on pilot-scale and laboratory-scale digesters to investigate the change in response to increasing feeding levels. A method was presented for the online analysis of the biogas plant condition based on the results. Limits were identified that it is not possible to detect washout, and it is expected this method may not work for every type of inhibition and only for overfeeding for intermittently fed digesters. A wider range of testing and data collection is necessary to ensure that the conclusions reached during this test are applicable to further installations.

This work demonstrated that with intermittent feeding it is possible to estimate the level of inhibition from the gas production rate alone. Future testing could focus on reducing the gap between the feeding events and to feed on a daily schedule and to validate the work performed as part of the simulations with the PID controller.

A PID controller was implemented and used to control an ADM1 simulation. An alternative approach could be to apply this analysis as an advisory method, whereby there is a human operator deciding feeding amounts, and the data analysis provides an estimation of the digester condition, which could warn when an early stage of inhibition is detected.

The control system presented is of special interest when there are seasonal variations between the feed to the AD plant, which

result in higher levels of stress placed on the AD plant. This would be reflected in the analysis and result in the recommendation to feed less to prevent inhibition, whereas feeding a static value would not.

The principles presented here could be applied using alternative analysis techniques to detect a wider range of inhibition. Presently, a statistical approach is taken which looks for specific characteristics in the gas production. Future work could build a database of gas production responses to feeding transients and try to match the measurement data to the database to make an assessment, or an alternative approach could use machine learning to identify features in the gas profiles. This expansion may allow for detecting different types of process inhibition, e.g., washout or inhibition due to ammonia.

Acknowledgment

This work was funded by the Metabolon IIb project and from the European Union's Seventh Framework Program under grant agreement no. 316838.

The authors have declared no conflict of interest.

Symbols used

e	$[\text{mL s}^{-1}]$	error between the raw value and the smoother fitted curve
kd	$[\text{kg mL s}^{-1}]$	PID controller derivative constant
ki	$[\text{kg mL s}^{-1}]$	PID controller integral constant
kp	$[\text{kg mL s}^{-1}]$	PID controller proportionality constant
L_{Thresh}	$[\text{L h}^{-1}\text{L}^{-1}]$	lower threshold for the error
OLR	$[\text{g}_{\text{VS}}\text{L}^{-1}\text{d}^{-1}]$	organic loading rate
se	$[\text{mL s}^{-1}]$	scaled error
U_{Thresh}	$[\text{L h}^{-1}\text{L}^{-1}]$	upper threshold for the error
Vol	$[\text{L}]$	digester volume

Abbreviations

AD	anaerobic digestion
ADM1	anaerobic digestion model No. 1
CHP	combined heat and power
CSTR	continuous stirred-tank reactor
DM	dry matter
FM	fresh matter
PID	proportional integral derivative
VS	volatile solids

References

- [1] B. Drosig, *Process Monitoring in Biogas Plants*, Technical Brochure, IEA Bioenergy, Petten **2013**.
- [2] J. P. Steyer, P. Buffière, D. Rolland, R. Moletta, *Water Res.* **1999**, 33 (9), 2059–2068.
- [3] E. Mauky, S. Weinrich, H.-F. Jacobi, H.-J. Nägele, J. Liebert, M. Nelles, *Anaerobe* **2017**, 46, 86–95.
- [4] D. J. Batstone et al., *Water Sci. Technol.* **2002**, 45 (10), 65–73.
- [5] *The Practical Guide to AD*, Anaerobic Digestion & Biogas Association, London **2013**.
- [6] www.metabolon.de (Accessed on August 29, 2019)
- [7] D. M. Wall, P. O’Kiely, J. D. Murphy, *Bioresour. Technol.* **2013**, 149, 425–431.
- [8] <https://de.mathworks.com/help/curvefit/smoothing-splines.html> (Accessed on June 17, 2018)
- [9] D. Gaida, *Ph.D. Thesis*, Leiden University **2014**.
- [10] M. Araki, in *Control Systems, Robotics and Automation* (Ed: H. Unbehauen), Vol. 2, EOLSS Publishers, Oxford **2009**.