Biogas Production Modelling: A Control System Engineering Approach

D Stollenwerk¹, C Rieke¹, M Dahmen¹, M Pieper¹

¹ Institut NOWUM-Energy, FH Aachen - University of Applied Science, Heinrich-Mussmannstr. 1, 52428 Jülich, DE

E-mail: info@nowum-energy.com

Abstract. Due to the Renewable Energy Act, in Germany it is planned to increase the amount of renewable energy carriers up to 60%. One of the main problems is the fluctuating supply of wind and solar energy. Here biogas plants provide a solution, because a demand-driven supply is possible. Before running such a plant, it is necessary to simulate and optimize the process feeding strategy. Current simulation models are either very detailed like the ADM 1, which leads to very long optimization runtimes or not accurate enough to handle the biogas production kinetics. Therefore this paper provides a new model of a biogas plant, which is easy to parametrize but also has the needed accuracy for the output prediction. It is based on the control system approach of system identification and validated with laboratory results of a real biogas production testing facility.

1. Introduction

The restructuring of the energy sector as a result of the European climate targets is a big challenge in Germany. The greenhouse gas emissions should be reduced to at least 50% below 1990 levels by 2050 [1,2]. As a result, in Germany the dispatch of renewable energy sources increased up to 25% in 2013 caused by the Renewable Energy Act [3].

The security of supply can be increased by many options, as an improvement in weather forecasting, development of long and short-term storages and grid expansion [4,5]. Since biogas plants are weather-independent and can be used locally, they are an alternative and offer a high potential for grid stabilization. Today more than 7850 biogas plants operate with an installed capacity of about 3.5 GW [6]. With the introduction of direct marketing of the produced energy and the flexibility bonus it becomes economically interesting to run these plants in grid stabilizing configuration. In order to achieve the highest possible return on the exchange, the production must be accurately predicted. Consequently a simple, fast and reliable model for the biogas production is required.

Today the standard model of the anaerobic fermentation process is the Anaerobic Digestion Model No.1 (ADM1) [7]. It describes the degradation of biomass with 42 Parameters and 19 ordinary differential equations (ODEs). Additional models like the agriADM1 simplify and aggregate the input variables, but the basic model concept remains.

In this paper, in order to reduce the number of free parameters, we characterize the degradation process with a new approach. We show that it is possible to depict the process with only two parameters and one differential equation which can be determined by single additional feeding and response characterization. On the one hand, this eliminates complex and expensive substrate analysis. Due to the
small number of parameters, the new model can be simple adjusted for various substrates. On the other hand, we can show that the output prediction accuracy is sufficient to predict the gas amount of the fermenter.

2. Model
The widely accepted standard model of the anaerobic digestion process is the ADM1. Unfortunately it requires numerous parameters, which have to be measured. Especially if a new substrate should be fed to an existing plant for every substrate the model has to be parameterized again which is time consuming, not economically and often not possible, due to the numerous measurements required for the parameters. Thus we developed a new model, which is reduced to the most important parameters.

To define the degradation characteristics, some assumptions were applied: First the biogas process was considered as linear, similar to ADM1. Second the coefficients of the equations were assumed to be time independent. Furthermore, an inhibition up to the maximum amount of substrate was excluded. Consequently the degradation of biomass could be described by one simple ODE, represented as transfer function in the Laplace domain.

The fundamental idea behind the model is that the process can be simplified by using model reductions and aggregations. So we considered the fermenter as grey box, summarized in Figure 1

![Figure 1. Block diagram of the biogas process.](image)

The feed substrate is used as input variable \( u(t) \). The output variable represents the volume flow \( V_{\text{total}} \).

As demonstrated in independent experiments [8,9], it is possible to model the volume flow \( V_{\text{total}} \) by means of ordinary differential equations of first order. The corresponding transfer function in the Laplace domain is:

\[
G(s) = \frac{K}{1 + sT} \quad (1)
\]

This result in

\[
V_{\text{total}} = G(s) \cdot U \quad (2)
\]

The dynamic parameters \( K \) and \( T \) are determined by a conventional method in control theory, the system identification.

Since the feeding period is small compared to the expected large time constants, the feeding can be regarded as Dirac Delta pulse. Due to the integrative measurement and the linear behaviour the response of the system was characterized by typical step response.

The objective is now to determine the parameters of the transfer function as seen in equation (1). The required parameters are \( K \) and \( T \). The gain value \( K \) represents the biogas amount. \( T \) is the corresponding time constants, which determines the time response.

Therefore an additional feeding was carried out at an arbitrary time \( t \). The feeding amount corresponded to 6 kg.

3. Methods and Experimental Setup
The experiments were performed on a test biogas plant (depicted in Figure 2) with a fermenter volume of 1.5 m³. The volume is split into a 1 m³ working part and 0.5 m³ gas storage. The pH value of the test facility can be assumed on average as neutral.

The reactor temperature was managed by a control system and kept constant at 40°C. Thus, the process was maintained under mesophilic conditions. Furthermore, the installed stirrer operated with an on-off ratio of 10 minutes to 20 minutes.
The gas measurement was sampled every 30 minutes with an accuracy of 10 litres, so 48 values could be measured per day. The measurement was performed as soon as the installed pressure valve had reached a pressure difference of 2 mbar.

![Figure 2. Lab-Scale Fermenter](source)

Source: PlanET Biogastechnik GmbH Documentation.

### 4. Experimental Results

The additional feeding was carried out at an arbitrary time $t$. The feeding amount corresponded to 6kg. The response of the biogas fermenter is depicted in Figure 3.

![Figure 3. Comparison Experimental versus Simulation Data](source)

The parameters $K$ and $T$ are determined by a curve fitting based on the method of least squares in MATLAB. On that account, the square deviation between the set point and actual value was calculated and used as the objective function. As solver method "fmincon" was selected. The boundary conditions of the parameter fitting can be noted as follows, the time constants have to be bigger than zero. In addition the sum of the K Value should be close to the gas generation potential of maize silage. The literature value was specified with 586.1 N l/kg substrate. This corresponds to an amount of gas of 202 litres/kg [10,11].

The result of the parameter fitting can be summarized in equation (3) and (4)

$$G(s) = \frac{202 \text{ l/kg}}{21.3 \text{ h s} + 1}$$  \hspace{1cm} (3)

$$\dot{V}_{\text{total}} = \frac{202 \text{ l/kg}}{21.3 \text{ h s} + 1} \cdot U$$  \hspace{1cm} (4)
5. Discussion and Conclusion

The results show that it is possible to model the biogas production with one differential equation of 1st order. Thus, the process can be described by means of two parameters, one transfer coefficient and the associated time constant. The parameters can be determined for each substrate by an additional feeding at an arbitrary time t. This allows the determination during operation. It should be noted, that the fast response kinetics in the beginning cannot be modelled with one first order transfer function.

The validation shows that the model works qualitatively correct. Due to various factors, in particular the water content in the substrate, the result is quantitatively not matching with the set point specification. As part of future studies, the parameters and the interaction of different substrates should be investigated. In addition, the model should be extended to more than one transfer function and to an extent, so it is possible to divide the gas production in methane and carbon dioxide parts.

Acknowledgements

The authors are grateful to the company PlanET GmbH for providing the test facility. The research is partially financed by the Federal Ministry of Education and Research (BMBF). Contract No. 17N1011

6. References

[1] European Union. DECISION No 406/2009/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community’s greenhouse gas emission reduction commitments up to 2020: 406/2009/EC; 2009.

[2] European Union. DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC: 2009/28/EC; 2009.

[3] BDEW. Erneuerbare Energien und das EEG: Zahlen, Fakten, Grafiken (2014) Anlagen, installierte Leistung, Stromerzeugung, EEG-Auszahlungen, Marktintegration der Erneuerbaren Energien und regionale Verteilung der EEG-induzierten Zahlungsströme 2014.

[4] Szarka N, Scholwin F, et al. A novel role for bioenergy: A flexible, demand-oriented power supply. Energy 2013;61:18–26.

[5] Hahn H, Ganagin W, et al. Cost analysis of concepts for a demand oriented biogas supply for flexible power generation. Bioresource technology 2014;170:211–20.

[6] Fachverband Biogas e.V. German Biogas Association. Branchenzahlen. [April 17, 2015]; Available from: http://www.biogas.org/edcom/webfvb.nsf/id/DE_Branchenzahlen.

[7] Batstone D J, Keller J, et al. (2002). Anaerobic Digestion Model No. 1. IWA Task Group for Mathematical Modelling of Anaerobic Digestion Processes, Scientific and Technical Report No. 13, IWA Publishing

[8] Weinreich S, Praxisnahre Modellierung von Biogasanlagen. Leipzig; 2014.

[9] Engler N, Nelles, M, Messungen zur Abbaukinetik von Einzelsubstraten und Substratmischungen. Leipzig; 2014.

[10] Quaschning V. Regenerative Energiesysteme: Technologie - Berechnung - Simulation. 8th ed. München: Hanser; 2013.

[11] Biogasausbeuten verschiedener Substrate - Programm Berechnung - Bayerische Landesanstalt für Landwirtschaft (LfL). [May 02, 2015]