CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761153

Dynamic Simulation of a Biogas Plant Providing Control Energy Reserves

Ervin Saracevic[a,*], David Woess[b], Anton Friedl[a], Angela Miltner[a]

[a]Institute of Chemical Engineering, TU Wien, Getreidemarkt 9/166, 1060 Vienna, Austria
[b]University of Natural Resources and Life Sciences, Vienna, Austria
ervin.saracevic@tuwien.ac.at

The increasing integration of renewable energy sources leads to challenges for the power grid balance. The share of power plants with intermittent energy production is rising. The increasing volatility of supply and demand has to be compensated by more flexibility in the energy system. Biomass-based plants are qualified for providing flexibility due to the almost infinite storability of the energy carrier.
In this work dynamic models for the simulation of flexible operation of an Austrian biogas plant with biomethane production using the process simulation tool IPSEpro are presented. The models base on data collected during a one-year-monitoring. The plants main focus lies on biogas upgrading with two additional CHP units for production of heat and power on demand. For the simulation detailed models of the CHP units and various dynamic models including a gas storage model were developed and are described in this work.
Additionally the effects of providing positive secondary control reserves on the needed gas and heat storage capacities were investigated in a case study. For this purpose one month of operation was simulated ex-post. The results show that the existing gas storage capacities are sufficient to provide control reserves while upgrading biogas steadily and simultaneously. Furthermore, the results of a cost efficiency analysis regarding optimal heat storage capacity are used to identify the most economic size of a hot water tank for short-term storage of heat for the investigated case.

1. Introduction

The transformation of the energy system towards a climate-friendly system on the basis of renewable energy sources has become a widely accepted necessity. In accordance to the climate targets of the European Union the national targets of Austria for 2020 aim for a 16 % reduction of greenhouse gas emissions in comparison to 2005 and a 34 % share of renewable energy sources from the final energy consumption. Prognoses show that these targets can only be achieved by realising additional measures until 2020 (EAA, 2017).
The increasing integration of renewables with intermittent energy production, especially photovoltaic and wind power plants, challenges the balancing of demand and supply. In Austria the installed capacity of wind power plants increased from 1,850 MW in 2010 to 3,438 MW in 2015 and the share of photovoltaic power plants rose from 154 MW to 1,260 MW in the same period (Energy Control Austria, 2016). In order to ensure grid stability and compensate fluctuations more flexibility is needed in the grid. Flexibility can be provided i.a. by energy storage systems and plants that are operated flexibly.
Plants that operate on biomass-based technologies, like biogas plants, have a high potential for producing energy on demand due to the almost infinite storability of the energy carrier. Heat and power can be produced flexibly at biogas plants by using CHP units. Various studies, primarily from Germany, deal with the financial aspects of operating biogas plants flexibly. Hochloff and Braun (2014) investigated the economics of biogas plants in various electricity markets. They concluded that biogas plants can profitably participate at electricity spot markets and markets that organize tertiary control reserves. Control reserves are needed for frequency control and can be activated by the transmission system operator (TSO). They are differentiated into positive products (increasing engine power on demand) and negative products (decreasing engine power on demand). Furthermore, they are classified by reaction time of the power unit, whereby primary reserves have to be activated within 30 s, secondary reserves within 5 min and tertiary reserves within 15 min.

Please cite this article as: Saracevic E., Woess D., Friedl A., Miltner A., 2017, Dynamic simulation of a biogas plant providing control energy reserves, Chemical Engineering Transactions, 61, 931-936 DOI:10.3303/CET1761153

It is predicted that the demand for control reserves will rise with increasing integration of renewable energy sources. In 2010 the costs for control energy in Austria amounted to 22.4 M €, in 2015 they rose to 46.7 M € (APG, 2017). In Austria control reserves are mainly provided by hydropower plants, although CHP plants show great potential for power regulation by being operated flexibly.

Flexible power production at biogas plants can mainly be realised by two different approaches. Additional CHP capacity with gas storage provides flexibility without adaption of the feeding. Alternatively the feeding management can be adapted to produce biogas demand-driven. This reduces the necessary gas storage capacity (Hahn et al., 2014).

Process simulation proved to be an adequate tool to simulate the flexible operation of biogas plants. Grim et al. (2015) developed the Dynamic Biogas plant Model (DyBiM) in MATLAB Simulink to investigate technical and economic consequences of demand-driven power production from biogas at an agricultural biogas plant. Hochloff and Braun (2014) calculated maximum market revenues for biogas plants with flexible power production using mixed-integer linear programming (MILP) and integrated their model in the RedSim simulation framework to simulate various scenarios.

The technical and economic consequences of flexible operation of biogas plants with biogas upgrading to biomethane have not been investigated thoroughly yet. This work aims to present dynamic models for simulation of biogas plants in order to investigate the effects on the needed storage capacities when providing control reserves with a biomethane producing biogas plant.

The objectives of this work are:

- Development of a detailed dynamic model of a biogas plant with biomethane production in a flow sheeting process simulation program in order to simulate flexible operation
- Ex-post simulation of one month of plant operation with providing positive secondary control reserves while steadily and simultaneously upgrading biogas to biomethane
- Evaluation of the feasibility of providing control reserves with the installed gas storage capacity and determination of the optimal heat storage capacity in course of a cost efficiency analysis

2. Methodology

2.1 IPSEpro

The process simulation tool used in this work was IPSEpro version 7.0. It is an equation-orientated flow sheeting program that makes it possible to calculate heat balances and simulate processes. The solver used for calculations bases on the Newton-Raphson-algorithm. The main focus of this program lies upon steady-state processes. In the most recent release a new module including a dynamic solver was added. This makes it possible to perform dynamic calculations and solve time-dependent cases additionally.

In the graphical user interface of the program environment various components can be selected from a model library and connected to form a flow sheet. An advantage of this program is that new models can be developed and implemented into existing libraries very easily. The library used in this work was the Biogas and Bioethanol Library that was developed by Schausberger et al. (2010). This library was extended with models for dynamic calculations in this work.

2.2 Simulation of the Biogas Plant

IPSEpro was used to develop a model of the investigated biogas plant with biogas upgrading to biomethane. The plant under investigation is a waste recycling plant with a yearly production of about 4.4 Mio. m^3 biogas and an installed gas storage capacity of 4,800 m^3. The plant's operation is currently designed to convert biogas to biomethane by a gas permeation process. Alternatively the produced biogas can be converted to heat and power by two CHP units with a total capacity of 1.36 MW. The developed simulation model is shown in Figure 1. The model bases on data that was collected during a one-year-monitoring in 2015. Additionally data from 2016 was used for the ex-post simulation described in this work.

The biogas production process (a) consists of hygienisation tanks, mixing tanks, fermenters and post-fermenters. As the focus of this work does not lie on the variation of the feeding management, the biogas production process was not simulated dynamically but defined via time tables by evaluation of the collected data. It is planned to investigate the effects of adapting the feeding management in future work.

The produced biogas is gathered in a gas storage (b), from where it can be forwarded to the gas upgrading and to the CHP units. The gas upgrading process (c) is modeled by simple black box models. The two CHP units (d) were modeled in more detail and are described afterwards, same as the newly developed model for dynamic simulation of the gas storage.

Functions for heat demand and production were defined by evaluation of the collected data. The major heat consumers are the hygienisation tanks, the fermenters and the storage depots. The functions were directly implemented in the models. Additionally a simple heat storage model (e) was developed, where the total heat demand and production of the plant are registered and can be further evaluated after the simulation.

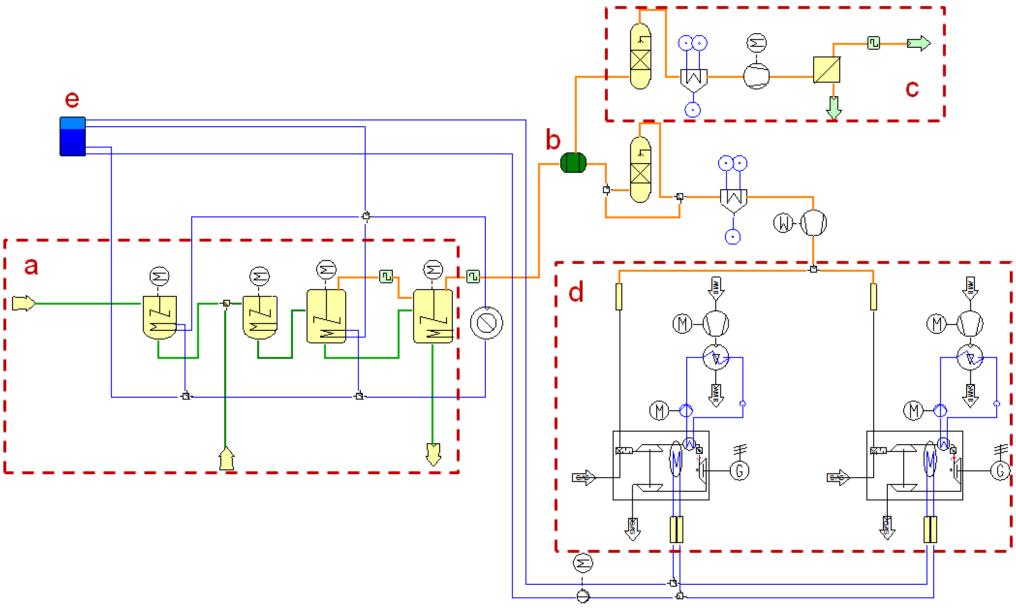

Figure 1: Flow sheet of the simulated biogas plant in IPSEpro (a, b, c, d, e are described in the text)

Gas Storage

For dynamic simulation of the biogas utilization a gas storage model was developed, with which the current gas storage level can be calculated and displayed. The stored biogas can either be directed to the gas upgrading or to the CHP units, in case of activation of control reserves. The volume flow V_{CH4} to the gas upgrading is held constant to $\dot{V}_{N,}$ whenever the storage is not full and is increased to the flow of the incoming biogas $\dot{V}_{IN}$ if the storage is full. At the beginning of the simulation the gas storage level c was set to be half of the maximum level c_{max}. In this work $\dot{V}_N$ was set to 600 m³ h^{-1}, c_{max} to 3,800 m³ and c_{min} to 240 m³.

$$c_0 = 0.5 * c_{max}, \qquad t = t_0 \tag{1}$$

$$\dot{V}_{CH4} = \begin{cases} \dot{V}_N, & c_{min} \leq c \leq c_{max} \\ \dot{V}_{IN}, & c > c_{max} \end{cases} \tag{2}$$

CHP Units

For the calculation of the produced heat and power a sound simulation model of the CHP unit is cruelly important. A new CHP model was designed, implemented and tested (Figure 1d). The model is based on mass and energy balances. The electrical efficiency curve of the gas engine was implemented. This was done by defining the engine's power efficiency at three operation points (full-load, 75 % part-load and 50 % part-load). These operation points are also defined in the documentation of the CHP units and, therefore, other gas engines (brands and sizes) can be implemented easily. Between the defined points, a linear interpolation was done.

At first, calibration of the electrical efficiency points had to be done. Therefore, hourly measurement data from 2015 of the CHP units of the biogas plant was used. These data include biogas conditions (composition, thermodynamic state), ambient conditions and engine parameters (power, produced energy, cooling temperatures etc.). The measured data was implemented in IPSEpro via com-link through MATLAB. The detailed simulation process is described in Woess et al. (2009). Mass and energy balances were calculated for each measurement point and the current power efficiency was calculated. By using this validation mode the full- and part-load electrical efficiency points were defined.

The model validation procedure is shown in Figure 2. New plant data from February 2016 was used, and only the biogas condition and the ambient conditions were prescribed according to the measurements.

The simulated engine power is compared with the biogas plant's power recording. It can be seen, that the model fits the reality quite well (Figure 2A). The mean deviation from the real power is about 1.2 kW for the first engine (836 kW, full-load) and about 1.3 kW for the second engine (526 kW, full-load).

The stability index for the comparison of the simulation to the real measured data is 0.9947 for the first engine and 0.9971 for the second one (Figure 2B).

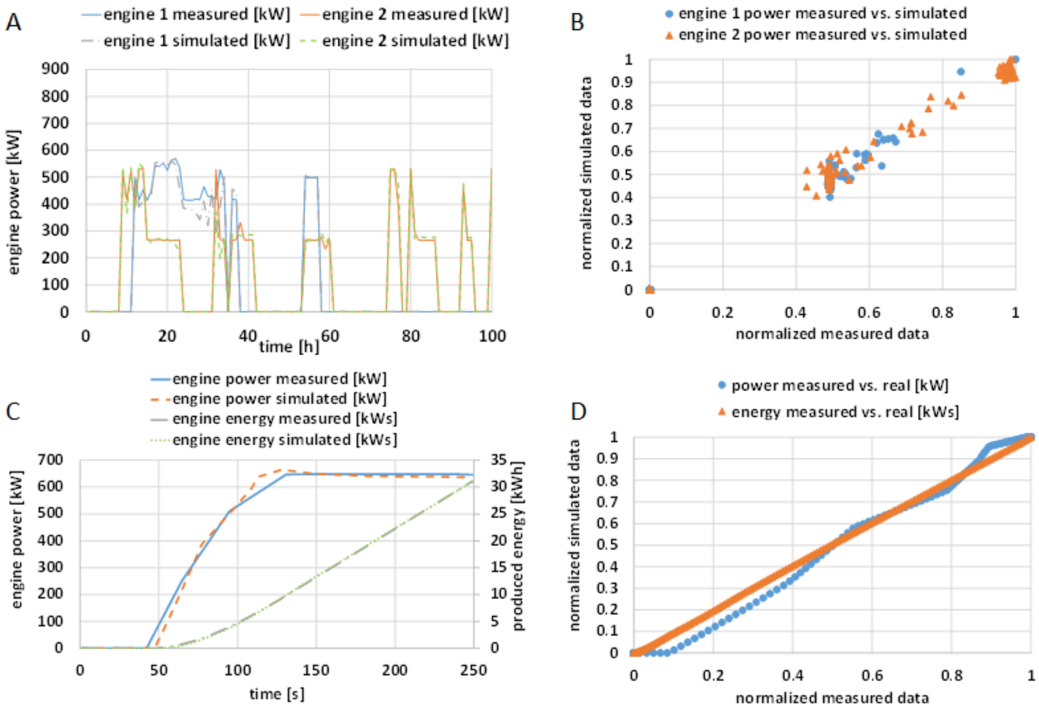

Figure 2: Comparison between simulation and measured data, long term view (A+B) and start-up procedure (C+D)

The model even works for shorter time steps as it can be seen in Figure 2C. In this case, instead of the hourly data seconds are used to display the engine's start-up procedure in detail. The mean deviation in this case is 1.3 kW for the 836 kW engine. Considering the produced electricity the mean deviation is only 16 Wh.
The simulation model of the CHP units is considerable to be sufficiently accurate and can be used for the overall plant simulation. As mentioned before the model can easily be calibrated for other engine brands and sizes.

2.3 Parameters of Case Study

One month of operation was simulated ex-post using the described model with providing positive secondary control reserves at a working price of 180 € MWh^{-1}. The month that was chosen for simulation was October 2016 since control reserves were activated very frequently during this period. The times of activation of control reserves were determined by evaluation of published data by the Austrian transmission system operator APG.
The effects of activation of control reserves on the gas storage level can directly be evaluated from the simulation results. Additionally, the heat production and heat demand curves were evaluated to determine the optimal heat storage size (hot water tank) and whether the investment in a storage is economic. The method used in course of the cost efficiency analysis was the annuity method as described in VDI 2067 (2012). The parameters chosen for the analysis are shown in Table 1. The profitability was defined as a simplified measure for determination of the profit of an investment. It is defined in Eq(3). A negative profitability equals an uneconomic investment.

$$\text{profitability} = \frac{\text{annuity}}{\text{investment costs}} \tag{3}$$

Table 1: Key parameters of cost efficiency analysis

Parameter	Value	Source
Investment cost [€]	18.179*volume (in L)^0.6347	IUTA (2002)
Heat cost [€ kWh^{-1}]	0.055	
Amortization period [y]	15	
Maintenance cost [% of investment]	2	VDI 2067 (2012)
Insurance cost [% of investment]	0.5	VDI 2067 (2012)
CO_2 savings (replacement of fuel oil) [kg kWh^{-1}]	0.310	PE International (2016)

3. Results and Discussion

3.1 Gas Storage

The simulation results regarding the effects of providing control energy reserves on the gas storage capacity can be seen in Figure 3. In the left figure the times of activation of control reserves are shown. Usually power plants on basis of renewable energies participate on the markets for control energy as part of a pool operated by a Virtual Power Plant Operator. The reasons for this lie in the minimum of 5 MW for one offer at the market for secondary control reserves and the high technical prerequisites stipulated by the TSO. Usually not every time a pool is activated all plants of the corresponding pool are activated too. In this work it was assumed that the investigated biogas plant is being recalled every second time the corresponding pool is activated. Additionally it was assumed that whenever control reserves are activated the total CHP capacity of 1.36 MW is recalled for half of the maximum activation time of 15 minutes. Past experience shows that these assumptions regarding activation frequency and length represent high values within the common range.

The right part of Figure 3 shows the gas storage level during the simulated period while providing control reserves (dashed line) and without providing control reserves (solid line). The installed gas storage capacity of 4,800 m³ proves to be sufficient for providing positive secondary control reserves while processing at least 600 m³ h^{-1} biogas to the gas upgrading in the simulated period.

Due to the fact that during the simulated period (October 2016) positive secondary control reserves were activated very frequently in comparison to other months and because of the assumptions described before it can be concluded that positive secondary control reserves can be provided with the installed gas storage capacity while producing biomethane simultaneously. Nevertheless the results show that fluctuations of the biogas production have an effect. During times of low production and activation of control reserves the gas storage level decreased noticeably. In these times it might be necessary to reduce the performance of gas upgrading.

An additional parameter that has to be considered is the maximum outflow of the gas storage. The gas lines are designed for a certain maximum flow rate and sudden drops of the gas pressure within the storage have to be avoided as well. The maximum outflow in the investigated scenario is about 1,100 m_N^3 h^{-1}. According to information of the manufacturer this flow rate is acceptable for the investigated biogas plant. However this might be an issue for other biogas plants that consider providing control reserves.

3.2 Heat Storage

Heat integration is always an issue when considering the efficiency of a biogas plant. The investigated plant is characterized by a high heat demand due to the high amount of substrate that needs to be hygienised. Therefore it is of interest to utilize as much of the heat produced with the CHP units as possible. For optimal heat integration at biogas plants thermal storage systems are used often. Usually hot water tanks for short-term storage of heat over a period of several hours or days are used. The determination of the optimal size of the water tank is of high relevance regarding economic and efficiency aspects.

For this purpose a cost efficiency analysis on the basis of the annuity method was done to determine the optimal heat storage size for the investigated case. The results of the analysis are shown in Figure 4. In the left figure the profitability as a function of the heat storage volume is shown. A hot water tank with a volume of 10 m³ proved to be most economic with a profitability of 0.0038 and an annuity of 111.4 €. Other tank volumes proved to be uneconomic. Approximately 55.4 MWh of heat can be integrated in the process additionally per year and does not have to be obtained from other sources with a storage volume of 10 m³. This equals a CO_2 saving of about 17.2 t/y if replacement of fuel oil is assumed.

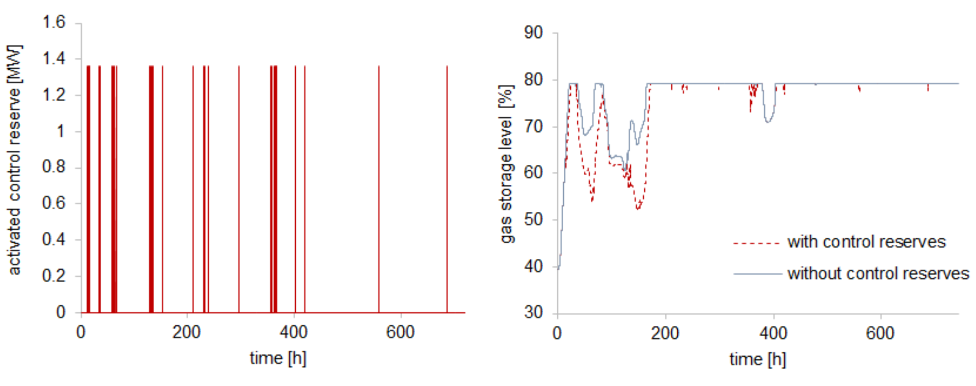

Figure 3: Results of ex-post simulation, times of activation of control reserves (left) and comparison of the gas storage level with and without providing control reserves (right)

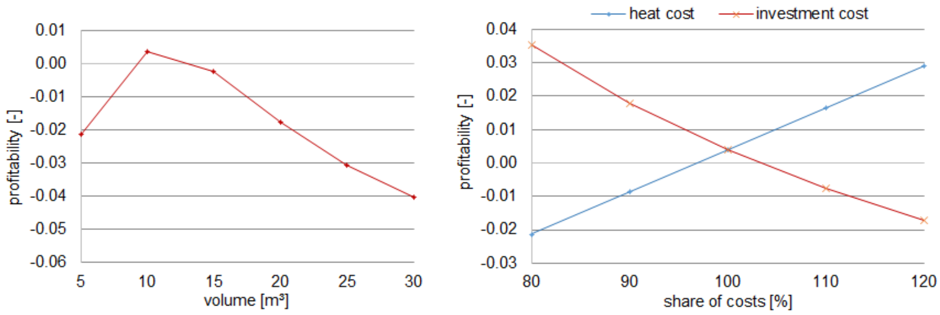

Figure 4: Results of cost efficiency analysis, profitability of different storage volumes (left) and sensitivity analysis regarding heat and investment costs (right)

Additionally a sensitivity analysis of the two factors cost of external heat consumption and investment cost was done regarding a heat storage volume of 10 m³. These costs influence the profitability most besides the frequency of activation of control energy. The results are shown in the right part of Figure 4. It can be seen that higher investment or lower heat costs can lead to a negative profitability.

4. Conclusion

A model for dynamic simulation of flexible operation of a biogas plant with biogas upgrading to biomethane was developed in the process simulation program IPSEpro. Detailed models of the CHP units and various dynamic models including a gas storage were designed and implemented in the model library. The plant model proved suitable for simulation of flexible plant operation. In a case study the effects on the storage units when providing positive secondary control reserves simultaneously to the biogas upgrading were investigated. For this reason, one month of real plant operation of a biogas plant with a yearly production of 4.4 M m³ biogas was simulated ex-post. The results show that the installed gas storage capacity of 4,800 m³ proved sufficient to provide control reserves and biomethane simultaneously. The results of a cost efficiency analysis show that a volume of 10 m³ for a hot water tank heat storage proved most economic with an annuity of 111.4 €. With a storage of this size 17.2 t of CO_2 can be saved if replacement of fuel oil is assumed.

Acknowledgments

This work was done in course of the project Bio(FLEX)Net supported by the Austrian Research Promotion Agency (FFG).

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