Energy Proceedings
Vol 27, 2022
ISSN 2004-2965

Demand Side Management in Biogas Plants - Dynamic Simulation of the Influence of Time-varying Agitation on Biogas Production

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ABSTRACT

In this contribution, monetary benefits that result from demand side management (DSM) integration in biogas digesters are analyzed. A model-based study to describe the influence of an electricity price-adjusted agitation (EPAA) control on biogas production is presented. Three price limits were calculated, which decide on the operation of four different predefined EPAA intervals. Results show that especially at very high and very low electricity prices, DSM strategies in biogas plants can lead to an increase in profit of the plant.

Keywords: flexible biogas plants, renewable energy integration, clean biofuel production, dynamic operability, anaerobic digestion modeling

NOMENCLATURE

Abbreviations	
CSTR	continuously stirred tank reactor
DSM	demand side management
EPAA	electricity price-adjusted agitation
FODM	fermentable organic dry matter
RE	renewable energies

1. INTRODUCTION

Biogas has an important function in the energy system, such as providing balancing power in the electricity grid or being used as an alternative fuel. When used as a form of energy storage, it can be can conveniently be directly fed into an existing gas grid. In many energy scenarios, relevant quantities of biomethane are expected in the future [1]. With the renewal of the Renewable Energy (RE) Source Act 2017, the promotion of RE will be changed from fixed remuneration to a tender model. This means that a limited amount of electricity from biomass and year will be put out to tender and the operators of biogas plants must first acquire their subsidy entitlement by successfully participating in the tender. As a consequence, the operation of biogas plants with the purpose of electricity remuneration now provides only little financial incentive. Various models are currently being discussed for the profitability of the future operation of biogas plants. These include conversion of on-site electricity generation with combined heat and power plants to plants for the provision of biomethane through the use of upgrading technologies and provision of biomethane as fuel (compressed natural gas or liquefied natural gas) [2]. However, this technology conversion sacrifices the ecological advantage that biogas plants produce their own green electricity and heat. A considerable amount of electricity is required in the production of biogas, especially for the agitation of the fermentation broth during anaerobic digestion [3]. If the ecological balance of production is to be sustained, a conceivable solution is the enhanced use of volatile RE sources such as solar and wind. This could be achieved through reacting to volatile price signals as electricity prices are usually lowest when a high share of RE energy is fed into the grid. The advantage that this could entail does not only mean lower CO_2-emissions for electricity consumption but also lower energy costs. The adjustment of a system's power demand to follow the current power generation is commonly referred to as demand side management (DSM).

The objective of this paper is to investigate whether flexible control of the agitator in biogas digesters can provide monetary benefits within the framework of DSM. The possibilities of the flexibility in agitation scheduling and the benefits that can be derived thereof are to be quantitatively evaluated. For this purpose, a simplified anaerobic digestion model with the dynamic influence of the agitation on the gas production is conducted. This in turn allows a dynamic DSM scheduling. The scheduling aims to provide a sequence of electricity price-adjusted agitation (EPAA) intervals in response to volatile electricity prices, minimizing operating costs, without compromising product quantity and quality beyond operational boundaries.

2. DESIGN PROBLEM

A thorough literature review conducted by Singh et al. [1] concludes that although the agitation of the fermentation broth has been proven by many researchers to enhance performance in anaerobic digestion, an optimum agitation strategy is still unclear. Hofmann et al. [2] state that during the anaerobic fermentation process, insufficient agitation will lead to reduced utilization of the fermenter volume. This in turn leads to a decrease in the active reaction volume and a reduction in the biogas yield. Thus, the hydrodynamic effects of substrate disintegration are not limited to improved agitation in terms of viscosity reduction, but additionally, cause improved agitation in terms of increased reaction volume. Insufficient agitation can also result in poor temperature and nutrient distribution. Longer agitation time also ensures a better gas release and higher operational safety. In general, it has been noted in literature that the rise in relative gas production decreases exponentially with rising agitation [1, 2, 4]. It was also noted, that permanent agitation has a negative impact on biogas production and leads to higher power consumption. Intermittent agitation in intervals seems more promising. However, optimal agitation time and intensity cannot be summarized in general as it depends strongly on digester and agitator geometry, as well as biomass input composition.

The above mentioned agitation influences are summarized and simplified in a model-based analysis to demonstrate the effect the flexibilization of agitation intervals in biogas digesters could entail. The interaction of cost savings due to responding to electricity prices and revenue losses due to reducing the agitation time is placed in focus.

2.1 STEADY-STATE ANAEROBIC DIGESTION MODEL

The investigated anaerobic digestion process is shown in Figure 1. A fresh biomass water mixture of 1.290 tons per hour made up of fermentable organic dry matter (FODM) (10 w/w%), ammonia (1 w/w%), and water (89 w/w%) is fed into a semi-batch reactor in hourly intervals with a duration of 15 min at ambient temperature. The biomass input stream is heated to 312 K creating ideal conditions for mesophilic operation. The total reaction volume of the continuously stirred tank reactor (CSTR) is 3600 m³ with a diameter of 16.815 m. Within the CSTR the FODM reacts to biogas. The gas mixture is separated within the CSTR represented in a flash split of the biogas and digestate.

The net chemical reaction for anaerobic digestion described by Boyle [3] and extended by adding the microbial biomass yield according to McCarthy [5] gives the result to a stoichiometric description of the anaerobic digestion. For the model used in this contribution a simplified version was applied, in which the FODM of biomass was summarized into a single component $C_6H_{10}O_5$. The stoichiometric description of the resulting reaction was implemented using a kinetic Power-Law model as follows:

$$C_6H_{10}O_5 + 0.4102\, H_2O + 0.1966\, NH_3 \rightarrow$$
$$2.5085\, CO_2 + 2.5085\, CH_4 + 0.1966\, C_5H_7O_2N$$

Kinetics were entered to yield 106 Nm³$_{\text{biogas}}$/kg$_{\text{biomass}}$ as a typical yield value of biogas production from agricultural residues [6]. The entire process was modeled in Aspen Plus and transferred as a flow-driven simulation to Aspen Custom Modeler (ACM) v10. PID control of fermenter temperature, content levels, and pressure was implemented. The property method IDEAL is used as a calculation method that assumes ideal characteristics of all phases.

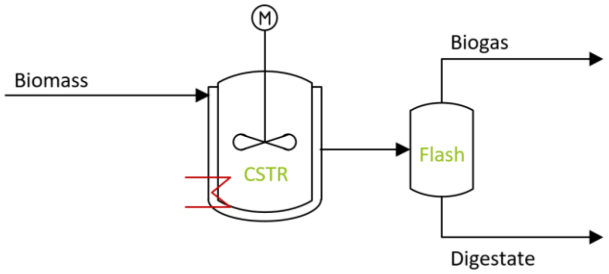

Figure 1: Simplified flow sheet of the anaerobic fermentation process

2.2 DYNAMIC ANAEROBIC DIGESTION MODEL

To be able to model the effect of EPAA strategies, the static model just described was converted into a dynamic simulation environment in ACM. The dynamic model reacts time-dependently to changing electricity prices, influencing the agitation interval accordingly. In ACM the model was manipulated in such a way, that the amount of time the fermenter agitator is switched on influences the accessibility of the FODM within the reactor, assuming the agitation time directly influences the proportion of fermenter broth that is thoroughly mixed. The time delay and mass inertia of the fermentation broth were neglected. The effects of agitation within the fermenter on methane production were derived from the ELIRAS report [2]. The stirring intensity is assumedly constant. The influence of varying stirring intensity was not implemented in the model. We assumed a comparatively fast fermentability of the biomass and a retention time of 90 days in the main and secondary fermenters [2, p. 31]. Figure 2 demonstrates the modeled influence of the agitation time (minutes per hour) on the accessibility of FODM and energy consumption. The colored bars in the upper graph represent the time at which the agitator is ON, and the uncolored sections represent the time at which the agitator is OFF. The sum of one colored and uncolored bar always represents one full hour. The longer the agitator is switched ON, the more accessible the FODM within the reactor becomes. The rise in agitation time, however, also leads to a rise in energy consumption (cf. lower graph in Figure 2).

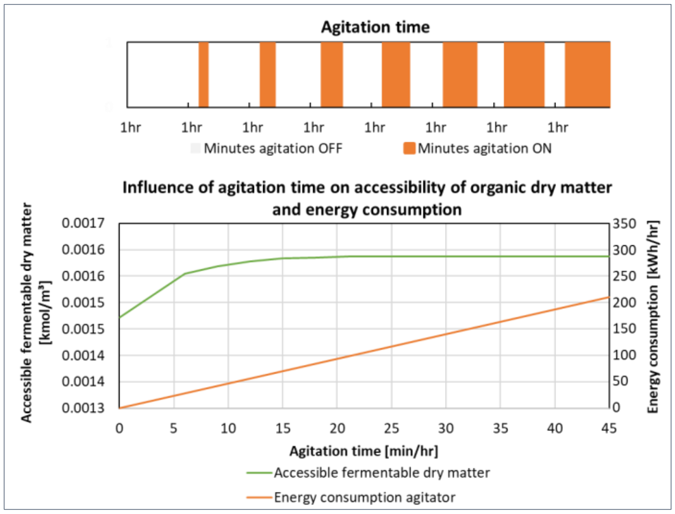

Figure 2: Accessibility of fermentable organic dry matter and agitation energy consumption as a function of the agitation time

Based on the influence shown in Figure 2, the model presented in this contribution strives to find a flexible EPAA schedule for time-varying electricity prices. The agitation time influences the accessibility of the FODM and energy consumption of the agitator. The accessibility of the FODM in turn influences the methane production, which ultimately affects the revenues that can be generated from methane sales. The energy consumption of the agitator directly affects the energy costs. At varying electricity prices, varying EPAA times are expected for maximum profit. Following equations were implemented in the model to calculate the revenue that can be generated by methane sales, the costs of energy consumption, and the profit that can thus be obtained:

$$Profit = \int_{0h}^{24h} methane\ revenue - energy\ costs\ \ dt$$

$$Profit = \int_{0h}^{24h} HHV_{CH4} * C_{CH4} * m_{CH4} - I_{Agit}\ P_{Agit} * C_{elec} dt$$

The profit is composed of the integral of the price for which methane is sold C_{CH4}, the higher heating value of methane HHV_{CH4}, and the total amount of methane produced m_{CH4} over time. The energy costs are calculated by multiplication of the time-dependent EPAA time interval I_{Agit}, the power consumption of the agitator P_{Agit}, and the time-varying electricity prices C_{elec}. The time period considered in this analysis is 24 hours. Table 1 summarizes the implemented parameters.

Table 1: Summary of model parameter

Abbreviation			Value	Source
$\boldsymbol{HHV_{CH4}}$	higher heating value methane	kWh/t	15.4	[7]
$\boldsymbol{C_{CH4}}$	methane price	€/kWh	0.058	[7]
$\boldsymbol{P_{Agit}}$	power consumption agitator	kW	280	[8]
$\boldsymbol{C_{elec}}$	electricity price	€/kWh		[9]

The amount of methane produced ($\mathrm{m_{CH4}}$) is determined based on the ACM model. $\mathrm{I_{Agit}}$ represents the operational variable that is to be flexibly adapted for maximum profit. This simplified calculation of profit only considers the difference between methane revenues and energy costs, other operating and fixed costs were excluded from this model. Furthermore, the impact of time-varying agitation on downstream processes was neglected.

3. RESULTS

This section presents the results of the study. Taking three exemplarily days into account (cf. Figure 3), the influence of the agitation time at very different average electricity prices is demonstrated. The lower diagrams in Figure 3 show the methane revenue, the energy costs, and the difference between the aforementioned, referred to as profit. The graphs depict these values after 24 hours for the three different average electricity prices as a function of the agitation time. During days with very favorable electricity prices (see Figure 3 day 1), agitation time has little influence on the profit of the biogas plant. If the electricity price is lower than zero, a higher agitation time can however even lead to an exceeding of profit over revenue.

During days with comparably high electricity prices, e.g. day 2 or 3, the agitation time has an increased influence on the profit that can be achieved through methane sales. According to the model, the highest increase in revenue occurs between no agitation and 15 minutes of agitation per hour. On the exemplary days 2 and 3 shown in Figure 3, an optimal profit is reached at

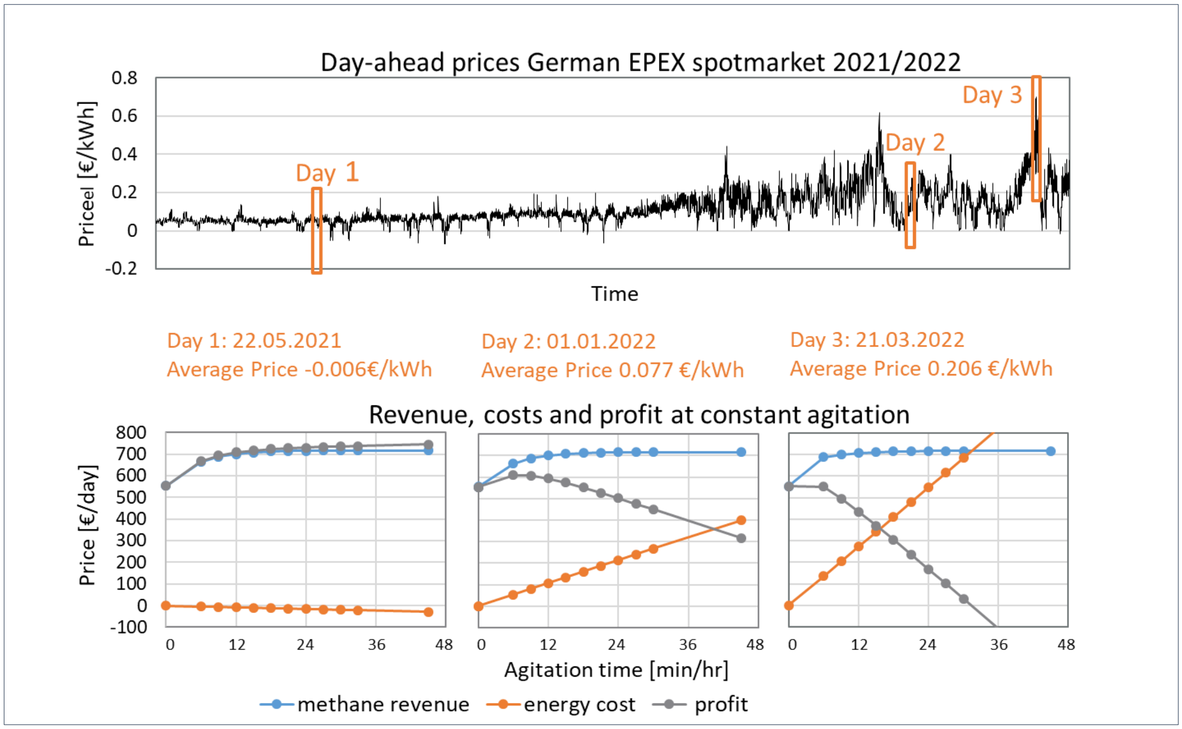

Figure 3: Revenue, costs and profit of a biogas plant at different electricity prices as a function of the agitation time.

an average agitation time of 6 min/hr. The increase in profit between 0 min/hr and 6 min/hr agitation results from the steep increase in revenue that occurs at short agitation times. Only at even higher electricity prices than at day 3 would the gradient of the energy costs exceed that of the methane revenue at short agitation times and a complete switch-off of the agitator would be profitable.

To find price ranges in which the selected EPAA time achieves a maximum profit, the profit after one day as a function of the electricity price at different agitation times was calculated in the ACM model (cf. Figure 4). For this purpose, following agitation time intervals were selected:

ON: It is assumed that the agitator can be switched on continuously.

15 min/hr: This agitator interval is determined by the fact that no actual increase in FODM accessibility is achieved above a certain agitation time (cf. Figure 3). Longer agitation time would result in more electricity costs, but no additional revenues from methane sales.

6 min/hr: This agitator interval represents the minimum tolerable agitation interval that the agitator can be permanently operated at, where no sedimentation and floating layer are formed in the fermenter. Since minimum tolerable agitation intervals depend strongly on different factors e.g. the choice of substrate or fermenter dimensions, this is an assumption that needs to be adjusted for individual considerations.

OFF: It is assumed that the agitator can be switched off completely within a certain time limit. A maximum switch-OFF time of 5 hours is defined after which agitation must be restarted so that the fermentation process is not permanently impaired.

Results presented in Figure 4 show that there is a certain price range in which the profit of the respective agitation intervals is the highest. If a higher number of interval options was considered, a function for the optimal agitation interval per electricity price could be derived accordingly. In practice, however, it is not possible to constantly change the agitation interval beyond a certain time limit, which is why we specified 4 agitation intervals.

As mentioned, an agitation time longer than 15 min/hr does not lead to higher revenue. However, if electricity prices are negative, profit can be increased through a rise in electricity consumption. The interval setting "ON" therefore shows an optimal effect at electricity prices below 0 €/kWh. The interval setting of 15 min/hr shows an optimal profit at electricity prices between 0 €/kWh and 0.064 €/kWh. The interval setting of 6 min/hr shows an optimal profit at electricity prices between 0.064 €/kWh and 0.261 €/kWh. Above

0.261 €/kWh the greatest monetary advantage is obtained by switching the agitator "OFF" completely.

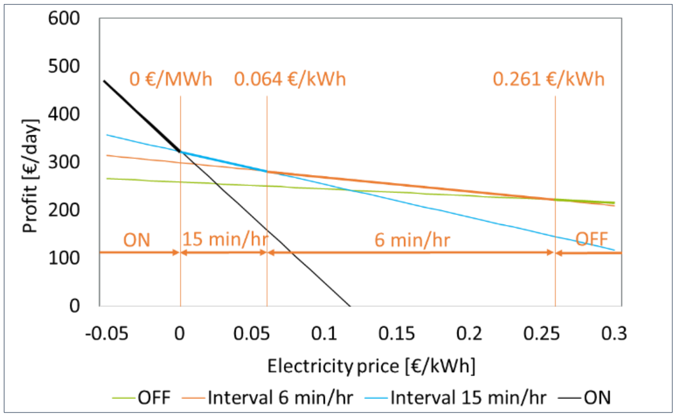

Figure 4: Profit of a biogas plant at different agitation times dependent on electricity price

Evaluating the monetary benefit of the EPAA scheduling, the profit at three exemplary days shown in Figure 3 was calculated. For each day, two dynamic simulations were performed over a period of 24 hours, comparing the profit difference for the same day with regular agitation intervals of 15 min/hr and EPAA intervals (see Figure 5).

For the three chosen days, the fluctuating electricity price can be seen in the top graph with the predefined price limits, at 0.000, 0.064, and 0.261 €/kWh. The graphs in the middle show the EPAA interval. The colored bars represent the time when the agitator is on, and the non-colored sections represent the time when the agitator is off. This EPAA strategy results in the graphs shown in the bottom section, which depict the effect of the EPAA interval on the profit, hence the difference between the revenue achieved through methane sales and the energy costs.

May 22, 2021 (left) has an average electricity price of -0.006 €/kWh. It is noticeable that on this day at an electricity price of less than zero €, the agitator is in permanent operation. In the phase of very favorable electricity prices, minimum electricity prices are attained. By permanently switching on the agitator at these times, an additional profit of 11.8 % can be achieved after one day. Although the permanent agitation increases the methane revenue by only about 0.8 % per day, the additional load of the agitator at negative prices offers a revenue increase through electricity purchase at negative prices.

On January 01, 2022, the EPAA interval is reduced from 15 min/hr to 6 min/hr during the second half of the second day. As a result, less electricity is used for agitation at times when electricity prices are higher, but agitation is still sufficient to ensure that the methane revenue does not drop more than the costs that are saved. The shortened interval results in a loss of methane

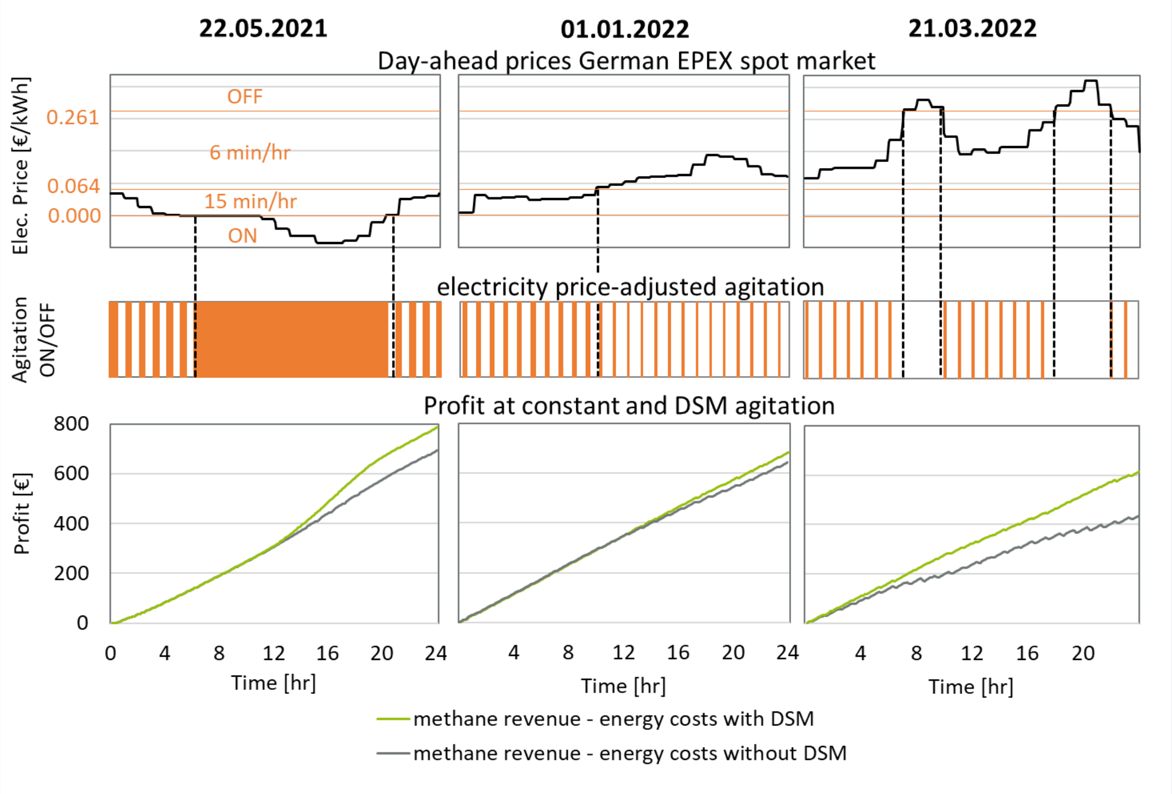

Figure 5: Electricity price-adjusted agitation strategy and the resulting profits in comparison with non-adapted operation of the agitator for three different days

revenue of 2.9 % per day, while the energy costs are reduced by 47.5 % per day. This leads to a total monetary benefit of 6.4 % per day.

On March 21, 2022, electricity prices are very high. Throughout the day the EPAA interval is always set below the standard agitation interval or 15 min/hr. At times when electricity prices are higher than 0.261 €/kWh, the agitator is switched off completely. The maximum switch-off duration of 5 hours is not exceeded on this day. The shortened interval and complete switch-off result in a methane revenue loss of 10.6 % that day. However, the energy costs can be reduced by 76.5 %, which results in a total monetary benefit of 40.8 % per day.

In summary, this model-based study on the influence of the EPAA on biogas production showed that an EPAA scheduling in the fermentation process integrated into a biogas plant can generate monetary benefits. Controlling the agitator within the operating limits of the biogas plant can thus be an interesting option for biogas plant operators. Results show that especially at very high and very low electricity prices, DSM strategies in biogas plants can lead to an increase in profit.

4. CONCLUSION

In this contribution, we presented an approach to implement DSM strategies in biogas production. The aim was to design EPAA strategies in order to reduce energy costs. Electricity costs for the agitation of the fermentation broth increase in direct proportion to the agitation time. However, a shortening of the agitation time leads to a reduced biogas yield and thus a reduction in profit. Depending on electricity prices, different agitation intervals are therefore ideal. Three price limits were calculated, which decide on the operation of four different predefined EPAA intervals: Constant agitation if the electricity price is below 0 €/kWh, 15 minutes of agitation per hour when the electricity price is between 0 €/kWh and 0.064 €/kWh, 6 minutes of agitation per hour when the electricity price is between 0 €/kWh and 0.261 €/kWh, and no agitation when the electricity price is above 0.261 €/kWh. Results showed that although revenue from methane sales decreases when the agitation time is shortened, at high electricity prices savings from the reduced energy costs for agitation can still lead to an increased profit. During very low electricity prices, on the other hand, constant agitation of the fermenter contents can lead to additional income, given that electricity would be purchased at negative prices. Especially in these and future years, where price volatilities in electricity prices are steadily increasing, DSM implementation in biogas processes can become increasingly profitable.

For more detailed and realistic investigations of this profitability, the effects of permanent operation of the agitator on the stress of the microorganisms have to be investigated. Furthermore, assumptions were made regarding the direct dynamic effects on the methane yield and the direct influence of the agitation time on the proportion of mixed fermenter broth, without taking inertias in the system into consideration. Adjustments in the model with more detailed consideration of the rheology of the fermenter slurry would be helpful. The impact of agitation intensity on energy consumption and methane production could likewise be an interesting influencing factor to be implemented in the model. Finally, a more detailed economic analysis of these results would be required, considering the additional costs associated with the implementation of a DSM.

The results presented in this contribution, show the promising relevance of DSM for the future operation of biogas plants. Further research is intended to investigate the impact of fluctuations in agitator intervals and therefore also fluctuations in biogas and methane production on downstream processes. The benefits that could arise from DSM integration not only in biogas production pants but in biofuel production in total are aimed to be analyzed. The method presented for the determination of the increase in profit through electricity price-adjusted energy consumption is to be applied to other processes in biofuel production. Synergies and constraints resulting from the interdependence of the processes are of particular interest.

ACKNOWLEDGEMENT

These findings were gathered as part of the “Pilot plant for synthetic biogas (Pilot SBG)” project, commissioned by the Federal Ministry of Transport and Digital Infrastructure (BMVI).

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