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Eric Mauky aus Leipzig,

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Gutachter

Prof. Dr. Michael Nelles
Universität Rostock, AUF, Professur Abfall- und Stoffstromwirtschaft

Prof. Dr. Christina Dornack
Technische Universität Dresden, Institut für Abfall- und Kreislaufwirtschaft

Dr.-Ing. Jan Liebetrau
Deutsches Biomasseforschungszentrum gGmbH Leipzig
Bereichsleiter Biochemische Konversion

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Executive Summary

Agricultural biogas plants in Germany are predominantly based on the principle of the continuous stirred tank reactor (CSTR) and designed for a uniformly constant energy output. With the expansion of highly fluctuating renewable energies (like wind power and photovoltaics) in the last few years, the intelligent integration of these new energy sources into the German energy system is becoming one of the central challenges. Biogas plants can play a key role in this transition. In contrast to wind power and photovoltaics, the supply of energy based on biogas is controllable. The duration and the utilization degree of combined heat and power plant (CHP) can be technically controlled and quickly changed. However, to meet the demand, the required biogas must either be kept in gas storage or produced according to these needs. In addition to considerable gas storage facilities or multi-stage concepts, which confront the operators with large investments, a promising alternative is the targeted influence of the anaerobic degradation process.

In this context, the present thesis investigates the **possibilities, underlying mechanisms and dependencies (e.g. response times, measurement range and operational stability)** establishing a flexible biogas production by means of demand-driven feeding. For this purpose, it was necessary to develop criteria for the characterization and evaluation of flexibly operated processes. This includes criteria, describing the course of the process variables directly and also indirectly with the saving of the gas storage demand when comparing flexible and constant gas production rate based on standardized utilization timetables.

Furthermore, a **robust control concept for demand-driven operation** has to be developed and **demonstrated in full-scale**. In this context, practical requirements and limitations, as minimal equipment of measurements and complex substrate compositions have to be considered. The investigations were performed in **laboratory-scale** (10 and 35 liters liquid volume) as well as in **full-scale** experiments (165 and 800 m^3 liquid volume).

The experiments demonstrate a high degree of **intraday flexibility** in the gas production. In full-scale, the gas production rate could be variated up and down by more than 50 % based on average rate (at OLRs of up to 4 $kg_{VS}\ m^{-3}\ d^{-1}$). Laboratory-scale results show even higher intraday flexibility potentials of more than 200 % based on average rate (at organic loading rates (OLRs) of up to 6 $kg_{VS}\ m^{-3}\ d^{-1}$). Additionally, the experiments demonstrated the potential

of **feeding pauses of up to 3 days** (decreasing gas production rate by more than 60 %) by flexible feeding in full-scale. In consequence, a demand-driven biogas production may enable significant savings in terms of the required gas storage volume (of up to 68 %) and permit far greater plant flexibility compared to constant gas production.

In general, flexible feeding resulted in a variable rate of gas production and a dynamic fluctuation of individual acids, gas quality parameters and the respective pH-value. However, even though the average level of the parameters differs between the scales during the flexible feeding, they stay below critical values. It is important to note that the **long-term process stability** was not affected negatively due to the flexible feeding.

In order to integrate the degradation dynamics of the anaerobic process into the control, the concept of **model predictive control (MPC)** was used. Based on the investigations about effects of flexible operation on common stability criteria, a minimal necessary measurement scenario, the general control structure and an appropriate model complexity for the MPC was defined. Due to their low computational cost and limited available measurements in practice the model predictive control bases on a **simplified anaerobic digestion model No.1** (ADM1).

The results indicate that the used model was able to predict the course of the flexible gas production in suitable accuracy (daily deviations between 4 % and 10 %). Moreover, in full-scale, the process could be operated according to a given demand schedule. However, the control results show that the gas production rate in the full-scale experiments is influenced by different effects (i.e. pressure fluctuations by feeding events), which are not included in the ADM1 (simplified and also original version). Especially, an observed **delay effect after feeding pauses** could not be modeled adequately by the simplified model approach. Delays of up to 6 h between expected and measured production and high daily deviation of up to 20 % were observed, though no indication of inhibition by an acid accumulation was found.

Rounding off the thesis, an additional **economic investigation** showed that flexible biogas production by feeding management needs low additional costs and allows a doubling of the revenues (based on data from the European Power Exchange) compared to constant gas production.

In this work, it could be shown that with modifications in the feeding strategy common agricultural CSTR-based biogas plants can be operated much more flexible than usual. A variable, demand-oriented gas generation can thus create leeway for the flexibility of biogas plants, which otherwise could only be used with very large gas storage volumes.

Zusammenfassung

Landwirtschaftliche Biogasanlagen in Deutschland basieren in der überwiegenden Zahl auf dem Prinzip des kontinuierlichen volldurchmischten Rührkesselfermenters (engl. CSTR) und sind für einen gleichmäßig konstanten Energieoutput ausgelegt. Mit dem in den letzten Jahren verstärkten Ausbau von hochgradig fluktuierenden erneuerbaren Energien (Windkraft, Photovoltaik) und dem voraussichtlichen Weiterschreiten dieser Entwicklung wird die intelligente Integration dieser neuen Energiequellen in das deutsche Energieversorgungssystem zur zentralen Herausforderung. Biogasanlagen besitzen dabei eine Schlüsselrolle, denn bei Biogas gestaltet sich die Kontrollierbarkeit der Energiebereitstellung anders als bei Wind- und Sonnenenergie. Bei Biogasanlagen können Laufzeit und Auslastungsgrad des Blockheizkraftwerks (BHKW) und damit Zeit und Menge der Einspeisung elektrischer Energie technisch einfach kontrolliert und schnell geändert werden. Für eine bedarfsgerechte Verstromung ist allerdings das dafür nötige Biogas entweder in Gasspeichern vorzuhalten oder bedarfsgerecht zu produzieren. Neben erheblichem Gasspeicherzubau oder dem Umbau in mehrstufige Konzepte, welche die Betreiber vor große Investitionen stellen, ist die gezielte Einflussnahme auf den anaeroben Abbauprozess eine vielversprechende Alternative an Bestandsanlagen.

Die vorliegende Dissertation untersucht die **Möglichkeiten, zugrundeliegende Mechanismen und Abhängigkeiten (z.B. Reaktionszeiten, Messbereiche und Stabilität)** zur Etablierung einer flexiblen Biogasproduktion durch bedarfsgesteuerte Fütterung. Dafür ist es notwendig, Kriterien für die Charakterisierung und Bewertung der flexibel betriebenen Prozesse zu entwickeln. Diese Bewertungsmethoden basieren auf der direkten Beschreibung des Verlaufes von Prozessvariablen, aber auch auf indirekten Kriterien, wie beispielsweise der Einsparung des Gasspeicherbedarfes beim Vergleich von flexibler und kontinuierlicher Gasproduktion anhand von standardisierten Verbrauchsfahrplänen.

Darüber hinaus ist ein **robustes Regelungskonzept für den bedarfsgerechten Betrieb** unter Einbeziehung praxisnaher Anforderungen und Limitierungen zu entwickeln und **großtechnisch zu demonstrieren**. Dazu wurden Versuche im **Labor-** (10 und 35 Liter Gärvolumen) sowie **großtechnischen Maßstab** (165 und 800 m^3 Flüssigkeitsvolumen) durchgeführt. Die Experimente zeigen, dass ein hohes Maß an **Gasproduktionsflexibilität innerhalb eines Tages** möglich ist. Im großtechnischen Maßstab konnte die Gasproduktionsrate um mehr als 50 %, bezogen auf die durchschnittliche Biogasrate (bei Raumbelastungen von bis zu 4 $kg_{oTS}\ m^{-3}\ d^{-1}$)

variiert werden. Im Labormaßstab bei Raumbelastungen von bis zu 6 $kg_{oTS}\, m^{-3}\, d^{-1}$ erreichte die Flexibilität Werte von bis zu 200 %, basierend auf der Durchschnittsbiogasrate. Darüber hinaus konnten **Beschickungspausen von bis zu 3 Tagen** realisiert werden (Reduktion der Gasproduktionsrate um mehr als 60 %). Infolgedessen kann eine bedarfsgesteuerte Biogaserzeugung erhebliche Einsparungen hinsichtlich des erforderlichen Gasspeichervolumens (bis zu 68 %) ermöglichen und eine größere Anlagenflexibilität im Vergleich zu einer konstanten Gasproduktion ermöglichen.

Die flexible Fütterung resultierte neben einer variablen Gasproduktionsrate in einer dynamischen Schwankung einzelner Säuren, Gasqualitätsparameter und dem jeweiligen pH-Wert. Die jeweiligen Ausprägungen unterscheiden sich zwischen den Fermentergrößen, bleiben aber bei allen Versuchen unter kritischen Werten. Besonders Hervorzuheben ist, dass die **Langzeitprozessstabilität** durch die flexible Fütterung nicht negativ beeinflusst wurde.

Um die Dynamik des anaeroben Prozesses in die Regelung zu integrieren, wurde das Konzept der **Modellprädiktiven Regelung (MPC)** verwendet. Es wurden Untersuchungen zu Stabilitätskriterien durchgeführt, um die Auswahl der Messgrößen im Regelungskonzept, die allgemeine Reglerstruktur und die Eignung der verwendeten Modellkomplexität für die Regelung zu evaluieren. Aufgrund von Begrenzungen bei der Verfügbarkeit von Messtechnik in der Praxis und des geringen Rechenaufwandes basiert die modellprädiktive Regelung auf einem **vereinfachten Anaerobic digestion model No.1** (ADM1). Die Ergebnisse zeigen, dass das Modell in der Lage ist, den Verlauf der flexiblen Gasproduktion vorherzusagen (Abweichung innerhalb des Tages zwischen 4 % und 10 %) und dass die Regelung den Prozess nach einem vorgegebenen Bedarfsplan betreiben kann. Es wurde jedoch auch gezeigt, dass die Gasproduktion im großtechnischen Versuch von verschiedenen Effekten beeinflusst wird (vor allem Druckschwankungen und die Durchmischung im Fermenter), welche nicht im ADM1 (in der vereinfachten aber auch in der Originalversion) enthalten sind. Insbesondere konnte ein beobachteter **Verzögerungseffekt nach Fütterungspausen** nicht ausreichend durch den vereinfachten Modellansatz modelliert werden. Es wurden Verzögerungen von bis zu 6 Stunden zur erwarteten Gasproduktion und hohe tägliche Abweichungen in der Prognose von bis zu 20 % beobachtet. Dennoch deuten Messungen nicht auf eine Hemmung durch eine Säureakkumulation hin.

Eine ergänzende **ökonomische Betrachtung** zeigt, dass eine flexible Biogasproduktion durch Fütterungsmanagements eine Verdopplung der Einnahmen ermöglicht (basierend auf Daten der European Power Exchange) und nur geringe Mehrkosten nach sich zieht.

Die Arbeit konnte zeigen, dass CSTR-basierte Biogasanlagen wesentlich flexibler als bisher üblich betrieben werden können. Eine variable, bedarfsgerechte Gaserzeugung kann somit Flexibilitätsspielräume schaffen, welche sonst nur von Biogasanlagen mit deutlich größeren Gasspeichern realisiert werden könnten.

Abbreviations

AD	Anaerobic digestion
ADF	Acid detergent fiber
ADM1	Anaerobic digestion model No.1
AM2	Acidogenesis/methanogenisis model
BImSchV	German federal pollutant control act
CF	Crude fiber
CFD	Computational fluid dynamics
CH_4	Methane
CHP	Combined heat and power unit
CL	Crude lipids
CO_2	Carbon dioxide
CP	Crude protein
CS	Cattle slurry
CSTR	Continuous stirred tank reactor
DBFZ	Deutsches Biomasseforschungszentrum
DDGS	Dried distillers grains with solubles
DM	Dry matter
DMGS	Double membrane gas storage
DT	Digestate from primary digester
EEG	Erneuerbare-Energien-Gesetz (engl. Renewable energy source act)
EPEX	European power exchange SE
ERDF	European regional development fund
EXP	Experiment
FM	Fresh matter
FOS	Flüchtige organische Säuren (engl. Volatile fatty acids (VFA))
FOS/TAC	Buffer capacity relative to calcium carbonate measured by titration
GC	Gas chromatograph
GS	Grass silage
GWG	Ground wheat grain
GmbH	Gesellschaft mit beschränkter Haftung (cf. Ltd.)
H_2	Hydrogen
H_2S	Hydrogen sulfide
IPCC	Intergovernmental panel on climate change

HRT	Hydraulic retention time
MPC	Model predictive control
MS	Maize silage / corn silage
N_2	Nitrogen dioxide
NDF	Neutral detergent fiber
NFE	Nitrogen free extracts
NFC	Non-fiber carbohydrates
NH_3	Ammonia
NH_4-N	Ammonium
NOx	Nitrogen oxides
OLR	Organic loading rate
OECD	Organization for economic co-operation and development
PFR	Plug flow reactor
ReBi	Concept abbreviation for "Regelbare Biogasanlage" (engl. controllable biogas plant)
RES	Renewable energy sources
RESA	Renewable energy sources act (cf. EEG)
SAB	Sächsische Aufbaubank – Förderbank (a development bank of Saxony)
SBS	Sugar beet silage
SLP	Standard load profile (cf. Standardlastprofil)
UASB	Upflow anaerobic sludge blanket
VDI	Verein Deutscher Ingenieure (engl. German Association of Engineers)
VFA	Volatile fatty acids
VS	Organic dry matter / volatile solids

Symbols

A, Aeq	[-]	matrices describing linear equalities and inequalities position in u
b, beq	[kg h^{-1}]	defines the maximal substrate amount per fermenter and unit of time
B_0,B_1,B_2,B_3,B_4	[-]	coefficients
c	[-]	nonlinear inequalities
ceq	[-]	nonlinear equalities
e_s	[m^3]	course of the gas storage filling level
f	[-]	function
H_c	[d]	control horizon
H_i	[d]	identification horizon
H_p	[d]	prediction horizon
i, j	[n]	number of values
$k_{ch,fast}$, $k_{ch,slow}$, k_{pr} ,k_{li}	[d^{-1}]	first-order rate constants for degradation of fast or slowly degradable carbohydrates, proteins and lipids
k_{dec}	[d^{-1}]	first-order rate constants for decay of microbial biomass
$K_{H,ch4}$, $K_{H,co2}$	[mol l^{-1} bar^{-1}]	Henry constant for methane and carbon dioxide in water
k_{La}	[d^{-1}]	volumetric mass transfer coefficient
k_p	[m^3 d^{-1} bar^{-1}]	friction coefficient in the gas outlet
n	[-]	number of pairs
p_{ch4}, p_{co2}, p_{h2o}	[bar]	partial pressure of methane, carbon dioxide and water vapor
p_{gas}, P_{atm}	[bar]	total gas and atmospheric pressure
p_i	[-]	model parameters
PRESS	[-]	Predicted Residual Error Sum of Squares
q_{gas}, q_{CH4}, q_{liq}	[m^3 d^{-1}]	volume flow (biogas, methane, liquid)
R	[bar l mol^{-1} K^{-1}]	universal gas constant
R^2	[-]	coefficient of determination of predictions
r_{gas}	[m^3 h^{-1}]	gas utilization (set point)

S_{ch4}, S_{co2}	[kg m^{-3}]	concentration of soluble methane and carbon dioxide
$S_{gas,ch4}$, $S_{gas,co2}$	[kg m^{-3}]	concentration of gaseous methane and carbon dioxide
u	[kg h^{-1}]	manipulated value / substrate feeding slot
ub, lb	[kg]	upper and lower boundaries
T	[K]	operating temperature
t_s	[h]	time steps
t	[h]	time
V_{liq}, V_{gas}	[m^3]	liquid and gas volume
w	[-]	weighting coefficient
y	[-]	measured values
$\hat{y}$	[-]	predicted values
$\overline{y}$	[-]	mean of measured values
x	[-]	variable
$X_{ch,}$, X_{pr}, X_{li}, X_{bac}	[kg m^{-3}]	concentration of particulate carbohydrates, proteins, lipids and microbial biomass (bacteria)
σ_{est}	[%]	standard error of the estimate

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Part A - THESIS FRAMEWORK AND BACKGROUND

1 Introduction

The warming of the climate system is clear and it is highly probable that human influence was the main cause of the observed warming since the middle of the 20th century.[1]

The current fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1] shows in an intensity and immediacy the causes and consequences of global warming. Limiting this climate change would require substantial and sustained reductions in greenhouse gas emissions. This is only possible with a fundamental reduction in energy consumption on the one hand and a comprehensive transition of energy production towards a renewable energy system on the other hand. The share of energy – in the power, heating and cooling as well as transport sector – from renewable energy sources (RES) is constantly increasing [2]. In 2015, annual renewable electricity capacity growth reached an all-time record at 153 GW and is mainly driven by the countries of the Organization for Economic Co-operation and Development (OECD) [3]. OECD gross electricity production from RES reached 2,471 TWh in 2015. This represents 23 % of total OECD power production in 2015. But this is by far not enough and must be further increased in the next decades.

1.1 Needs and options for demand-driven biogas plants

The major challenge for the next decades is – beside a massive expansion of the share of RES and a phase-out of fossil fuels - the efficient integration of RES in the energy system. Due to the fluctuation within production of solar and wind energy it is essential to evolve capacity utilization management, powerful transmission networks, as well as new storage technologies [4]. The demand for energy varies depending on the time of day and the season. Due to the increase of intermitted power production from wind and solar the influence of weather is gaining importance. Power generation from wind and solar energies are not controllable. Other controllable energy sources need to counteract these fluctuations, since supply and demand have to be balanced out in a smart energy system [5]. Bioenergy and especial the biogas technology can play a key role

[1] One of the central statements of the Climate Change 2014: Synthesis Report [1]

in smart energy system [5]–[8], since the energy supply based on biogas is controllable. Beyond that, the good availability of biogas plays a decisive role. Thus, biogas plants are geographically widespread and distributed in the distribution grid level. The strong political support for biogas by the German Renewable Energy Sources Act (RESA, German "EEG") over the past decade has greatly affected agricultural sectors in Germany, which led to a boost in biogas production [9]. Particularly between 2006 and 2011, the total number of plants doubled and the total capacity increased by more than 150 %. In 2016, more than 8200 biogas plants[2] with a total capacity of up to 4400 MW_{el} produced renewable energy in Germany [10]–[12]. A study published by the German Federal Environment Agency showed temporary deficits of up to 50 GW residual basic load in a 100 % renewable energy system without using energy from biomass [13]. This deficit has to be balanced in order to enable a demand driven power production and an energy system based on renewable sources [14].

These individual demands could be classified based on its timescale of supply. Figure 1 gives an overview of temporal deadlines for participating in the different system service products, and summarizes the ways to optimize the electricity market from intraday to long-term.

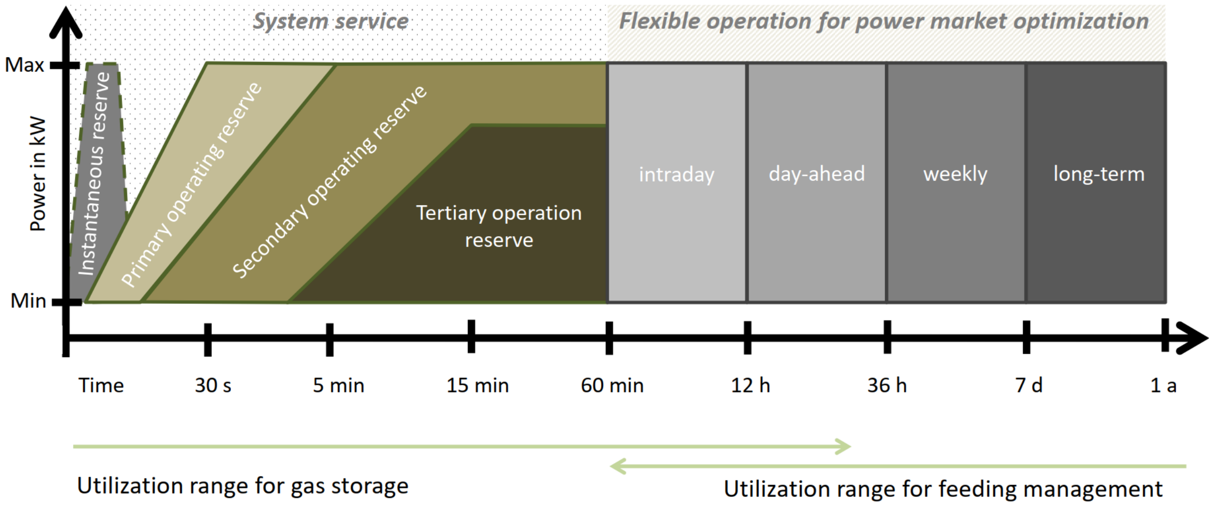

Figure 1: Temporal classification for different types of operating reserve und flexibilization for power market optimization; Qualitative indication of utilization range which can be operated by gas storage and feeding management (based on [15])

Currently, the focus in the power sector is often on short-term flexibility demands, corresponding to the balancing energy, intraday and spot markets (system service part in Figure 1). Biogas plants already participate in these markets by direct marketing of power. But there are also medium (from hourly to weekly preliminary planning periods) and long-term flexibility demands, which are still covered at the moment by fossil fuel power capacities. Depending on weather

[2]Biogas "production" plants with on-site power generation

conditions, long-term fluctuations also occur in the scale of time of several days, several weeks or seasonal. These needs must also be supported by renewable energies in a future without fossil fuels. Regarding this background, the flexible and demand oriented energy production is a sustainable perspective for biogas plants [16], [17]. However, on-site heat demand and heat sales from biogas plants are also to be mentioned as restrictions [18], [19], which influence the possibilities of demand oriented power supply.

Agricultural biogas plants in Germany are mainly based on the principle of the continuous stirred tank reactor (CSTR) and have originally been designed for a constant substrate input and constant energy output (base load energy). In terms of flexible power generation, biogas has to be available in a way that it can be used to produce power during phases of high energy demand, reduce the production in phases with less demand and stabilize the grid during phases with high fluctuations. In general there are different options for increasing flexibility along the biogas production chain, e.g., substrate management, storage of intermediates (i.e. acids), heat and/or gas use and upgrading the generated biogas to bio-methane and its subsequent feed into the gas grid [14]. Possible options to improve the overall flexibility potential (as a single measure or combination) along the entire chain are shown in Figure 2. However, the resulting quality of flexibility of a biogas plant is defined by the entire chain.

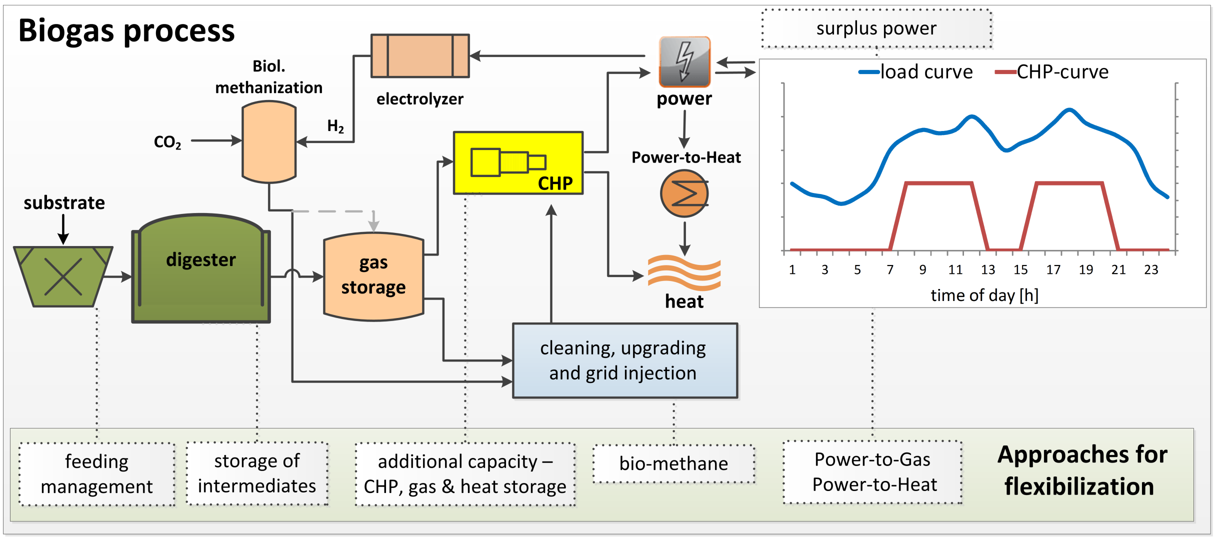

Figure 2: Approaches for flexibilization of biogas plants (adapted from [14])

Based on Mauky et al. [20], the following stages are conceivable with increasing flexibility, whereby a corresponding overcapacity in the CHP is assumed to be given:

- **Flexible CHP operation without structural and with minor operational changes:** The possibilities of flexible plant operation with the original conditions are strongly dependent on the plant design. With a sufficiently large gas storage volume, timetables can be implemented, but the shifts of power generation times and quantities are limited. Technical prerequisites are the possibility of monitoring the gas storage filling level and the adequate dimensioning of all gas-conducting system parts with regard to fluctuating flow rates.

- **Increasing gas storage volume:** This measure is associated with high costs and can be constructively difficult to implement. The coverage of open residue storage tanks is a possibility here, which, in addition to the increase gas storage volume, reduces emissions and achieves an additional gas yield. However, with increasing on-site gas amounts, the plant needs to deal with stronger safety regulation.

- **Addition of technical components or processes (Storage of Intermediates, High-Load Fermenters, Power-to-Gas):** A series of two-phase processes are being developed to dose pre-hydrolysis medium demand-driven at special high-load reactors to produce flexible biogas [21]–[24]. Furthermore, Power2Gas technology can be used to store energy overloads and compensate load fluctuations [25]. The methods for biological methanization are currently still in the research stage and have so far only been available on a pilot scale [26]. All of these alternative process configurations have a correspondingly high level of equipment and financial resources, which makes it difficult to expand existing facilities.

- **Flexibilization of gas production through feeding management:** The biogas process can be influenced to a varying extent by the time, amount and compositions of the rations through controlled feeding management. Adjustments to feeding are already carried out in many plants for various reasons. The aim here is often to achieve uniform gas production and / or adaptation to changing availability of substrates. Through the variation of the feed, the gas production can be adapted to the requirements of the utilization in such a way that the demand for an intermediate storage of the gas can be minimized.

For all variants, under the assumption of constant annual output the CHP capacity has to be extended for the planned operation, either by installation of new one with larger capacity or installation of a second additional unit. The extent of flexibilization which can be made within existing regulations ultimately depends on the level of additional investments, e.g. in CHP and gas storage. The management of feeding can be an interesting alternative reducing necessary expansion of gas storage capacities and respectively reducing additional investments.

Figure 1 illustrates the overlap between the utilization range of feeding management and gas storage as a load-displacement option. In particular, the complementary view of gas storage and feeding management has promising potentials. On the one hand, by means of feeding management, flexibilization margins can be used, which otherwise would only be used with very large gas storage volumes. On the other hand, the feeding management can also serve to make the existing gas reservoir more able to contribute to the provision of flexibility. Under normal conditions of constant biogas production, an average German biogas plant fills its gas storage within 4 hours[3] [27]. Older systems are usually equipped with less buffer than newer ones. Newer plants are partly equipped with storage potentials of 12 h and more (unpublished data of a DBFZ operator survey). However, the local storage is still used only for buffering irregularities in gas production. An actual provision of storage reserves per plant design for flexible power generation is rather the exception.

Hitherto a demand driven feeding with the aim of dynamic gas production in CSTR has been discussed in scientific studies rarely. There is a series of investigations about dynamic operations of biological systems against the background of seasonal substrate changes and process start-ups [28]–[30]. Also yield increases by periodic operations (pH-modulation, input modulation such as a substrate or a nutrient concentration) of biochemical systems were described [31]. Few lab-scale studies [32]–[34] discussed a dynamic biogas production by flexible feeding[4]. Further literature of dynamic anaerobic digestion processes are discussed in the introduction section of Article 1 and 2 in this thesis. Although these promising results are achieved under controlled lab scale conditions, the question remains, if these results can be reproduced and transferred from lab- to full-scale. No studies have been published showing the effects of flexible feeding in the agricultural biogas sector on process stability and performance. So far, a flexible operation mode has not been envisaged in the design of common agricultural biogas plants.

1.2 Basics of anaerobic digestion and influencing parameters

The anaerobic digestion process has four key stages performed by a wide range of microorganisms. The produced biogas is a moisture-saturated mix of mainly methane (CH_4) and carbon dioxide (CO_2) with traces of nitrogen (N_2), ammonia (NH_3), hydrogen sulfide (H_2S) and hydrogen (H_2). The following briefly description of the AD stages based on Gerardi 2002 [35].

Stages of the anaerobic digestion process

In the ***hydrolysis* -** the first stage of the AD process - macromolecules like fats, proteins and polysaccharides are broken down by different enzymes, into soluble oligomeric as well as di- and monomeric components (e.g. fatty and amino acids and monosaccharides). In the second stage of the AD process - called ***acidogenesis*** - the monosaccharides, VFA and amino acids were fermented to different organic acids (mainly acetate, propionate and butyrate), hydrogen, carbon dioxide and alcohols. In the third stage – called ***acetogenesis*** - the different fermentation products of the acidogenesis (*e.g.* longer chain fatty acids and alcohols) are converted to acetate, carbon dioxide and hydrogen. In the final stage of AD, the ***methanogenesis***, strict

[3] Assuming that about 60 % of the total gas storage volume can be used for a flexible filling.
[4] In literature also called Pulse feeding or Intermitted feeding

anaerobic archaea produce methane via different pathways. The two most important pathways of methanogenesis are the acetoclastic methanogenesis using acetate and the hydrogenotrophic methanogenesis with hydrogen and carbon dioxide. The respective shares of the different metabolic pathways depend on process condition and substrates. When solid substrates are used, hydrolysis is often the rate-limiting stage of AD. For easily biodegradable materials (e.g. food waste or dairy wastewater) the rate-limiting stage is often the methanogenesis. Further detailed information about the AD process stages and involved microorganisms could be find in literature [35]–[38].

AD Influencing parameters

The AD process is influenced by different physical, chemical and microbiological parameters, described detailed in literature [35], [36], [39]. However, the following section should give a briefly description of important parameters.

The most important factor for anaerobic digestion is the feedstock and the feed regime. Changes in the feed regime results in changing **organic loading rates** or **dilution rates**. Regarding process stability, the key point is the time course and the amplitude of the changes. Since the microorganism groups involved in the process have different growth rates, they can adapt to the new conditions at different speeds. When exceeding the maximum growth rate, the bacteria can no longer sufficiently reproduce. At the end, the population is flushed out when the dilution rate is greater than the maximum growth rate. The amount of fed substrate and the degradation rate are the determining parameters for process stability. The change of the substrate composition can lead to altered metabolic products and to a faster release of intermediates. If the process is unable to process these suddenly more released intermediates, there may be an accumulation of intermediates. Beside the supply of organic material, microorganisms need access to a variety of **mineral nutrients** and **trace elements**, to achieve the maximal growth rate. However, light metal ions (Na, K, Mg, Ca, Al) and heavy metals could also be potential inhibitors.

Temperature has also a direct impact on anaerobic digestion. Three different ranges are defined as orientation to describe the temperature regime:

- Psychrophilic: up to 25 °C
- Mesophilic: 35 – 42 °C
- Thermophilic: 55 – 60 °C

The choice of the temperature ranges depends on specific biological, energetically and process properties (e.g. water content, microbial consortia, relevant substances like ammonia and the need of sanitation).

Another important AD Influencing parameter is the **pH-value**. On the one hand, the pH value controls the dissociation of metabolites and thus their biological activity. On the other hand, enzyme activities highly dependent on the pH value, which are fundamentally important for the metabolic processes [36]. The pH value must be within a range that allows adequate metabolic activity for all involved microorganism species[5] and ensured low concentrations of inhibitory substances.

Organic acids are intermediates in the anaerobic digestion process. Only acetic acid can be directly converted to methane. All other acids need to be first converted to acetic acid and/or hydrogen and carbon dioxide. This interlinked process is only unstable when the equilibrium between acid production and acid degradation is permanently disturbed, resulting in an increasing concentration of acids in the system. With increasing concentration two phenomena are connected. On one hand, the undissociated portion of the acids has an inhibiting effect on methane formation and acetic acid formation. On the other hand, the acid-forming bacteria produce due to altered thermodynamic ratios increasingly higher-chain fatty acids. Nevertheless, their further degradation is blocked by the inhibition.

Nitrogen is an important nutrient for the bacteria involved in the fermentation processes. In solution in water, the equilibrium of ammonia/ammonium depends largely on pH and temperature. The position of the equilibrium is important because it is not the ammonium ion concentration but the ammonia concentration that is attributed to the inhibitory effect on the methanogenic stage. Thus, the inhibitory effect increases with increasing pH value and increasing temperature. However, ammonia provides buffer capacity and can stabilize also the pH-value at higher acid concentrations. The inhibitory effect of **hydrogen sulfide** is subject to the same factors as ammonia inhibition (temperature, concentration and pH value). Aside from that, microorganisms are able to adapt to increased concentration in certain measure. However, such processes are more sensitive to disturbances. Further information's and limitation ranges of inhibitory substances could be find in Drosg [42].

For all disturbances, it should be noted that the groups of microorganisms involved in the degradation have different maximum growth rates and are different tolerant to changes in environmental conditions. The slowest growing methanogenic and acetogenesis microorganisms are simultaneously the most sensitive groups to disturbances. The acid-forming acidogenic bacteria, are more tolerant to disturbances and can adapt faster to changing conditions due to the higher grow rates. If such an accumulation of acids cannot be reduced, an irreversible disturbance occurs. As a consequence, a disturbance thus influences the degradation of intermediates to a greater extent than the formation of these intermediates. However, an occurring inhibition does not mean that the process collapses immediately. A short-term exceedance of the limits may be

[5]The acid-forming bacteria are more resistant to pH changes than the methanogenic microorganisms. There are different recommendations for optimal pH ranges for different microorganism groups in literature [35], [40], [41]. Single-stage fermentation plants should have pH values between 7 and 8.

intercepted by an increased metabolic activity due to the increased substrate concentration.

At the end, the process stability is not exactly bound to limits of concentrations of inhibiting substances. More crucial for valuation of process stability are trends of concentrations and the achievement of high degradation results.

1.3 Monitoring and control of biogas plants

For a control of the anaerobic digestion process, it is necessary to evaluate the process status by observing relevant measurements. Holm-Nielsen und Oleskowicz-Popiel [43] give an overview of typical measurements at biogas plants. In the gas phase the biogas volume flow rate and the composition (especial CH_4 and CO_2) were measured. In the liquid phase, the temperature and pH-value are the most commonly measured values. Also intermediates, like hydrogen and volatile fatty acids could be measured. Especially volatile fatty acids are considered as good early warning parameters for disturbances, but are often not determined due to the measuring effort [39]. In the solid phase primarily the microbial biomass is of interest (e.g. concentration of methanogenic microorganisms [33], [44] or microbiome analysis [45]). However, these measurements have various measuring efforts and require partly cost-intensive laboratory equipment.

The question which measurements are relevant for the recognition of process disturbances has been investigated in individual experimental works. Various parameters were analyzed after disturbances about influences by the dilution rate or the composition of the substrate (e.g. [46], [47]). It was found that, volatile fatty acids, in particular acetic and propionic acid, characterize the process state at the best. In a similar work by Molina et al. [48] it was found that the alkalinity should also be included as a measure for the buffering of the pH value.

It can be stated, that there is a great discrepancy between measurement possibilities and the actual equipment available at typical practical biogas plants. Instruments for monitoring gas and liquid flows unfortunately are still not standard. Rough mass flow estimations as determining the daily ration by counting the wheel-loader shovel fed to the systems are still in use. But there are also examples with sufficient measurement of gas volume flow rate and composition, as well as input characterization and monitoring of stability indicators, like concentrations of volatile fatty acids and pH values.

In the scientific literature, a wide range of advanced instrumentation and control methods are available [49], which are partly already adapted to the special requirements at biogas plants. But they have often not yet found the way into the practice. Table 1 shows an overview, based on a German biogas monitoring program (*Biogas-Messprogramm II,* [50]) about the degree of equipment for online[6] and offline[7] measurements at a common practical biogas plant in Germany. It is stated that often only the feeding quantity of the input substrates and the CHP-power or biogas production rates as well as the gas quality at the output side are available as online measurements. Also measurements of the pH value can be carried out online and are relatively widely used in practice [43]. Nevertheless, the pH is regarded as not suitable for diagnosis in well buffered systems because of its time delay in responds [51].

Table 1: Comparison of available measurements at practical biogas plants on the input and output side, with an indication of the typical type of implementation (adapted from Weinrich/DBFZ, based on [50]

substrate characterization (input)		**digester characterization (output)**	
quantity / feeding rate	online	gas quantity / CHP-power	online
volatile solids (VS)	offline	gas quality	on/offline
feedstock analysis	offline	digestate analyses	offline
volatile fatty acids (GC)	offline	volatile fatty acids (GC)	offline
FOS and FOS/TAC	offline	FOS and FOS/TAC	offline
pH-value	offline	pH-value	on/offline
ammonium nitrogen	offline	ammonium nitrogen	offline

Also, the control objectives span from the regulation of key variables (e.g. CH_4) to the prediction of overall process performance to optimize the feeding of the process [49]. Currently, many plants in Germany are controlled on the basis of the operator's experience with the aim of stationary operation. The plant operators adapt the respective actuating variables, such as the substrate quantity or feed intervals, in order to intervene in the fermentation process.

However, in the transition from stationary to flexible plant operation, new requirements would arise. For example, the shorter the lead times and / or smaller the available gas storage capacity in a context of demand-driven energy production, the more precise the prediction of the process performance (primarily the biogas production rate) must be. Minimum requirements for controlling biogas plants are a precise substrate dosage with quantity measurement (preferably down to kilogram) on the input side and an adequate measurement of gas production rate (usually in cubic meters per hour) on the output side. Eventually, the effort involved in measurement and control is dependent on this specific control objective.

[6] Online measurements are attached to the process and the analysis is automated. The analysis is performed under a high frequency, so data produced by these sensors is considered continuous compared to process time scale.

[7] Offline measurements are those in which the sample is taken usually manually (low sample frequency) and analyzed by an operator; the data will be available after hours or days.

In Addition, this also depends on the considered anaerobic process conditions. In a first approximation, the process could be classified in non- or low-inhibited and inhibited processes[8]. On one side, non- or low-inhibited processes have usually moderate OLRs, using substrates with low content of nitrogen and sulfide and have a sufficient trace element supply. For monitoring and control of such a process, a less complex measurement (less quantities and frequency) and control concept may be sufficient. On the other side, inhibited processes, for example with high ammonia concentrations require a higher complexity of the control concept with detailed measurements of intermediates.

If the stock of biogas plants should be made more flexible based on the available measuring equipment shown in Table 1, compromises are necessary in the complexity of the concept. According to Gaida [52], the main challenges for a practical implementation of feed control concepts are a lack of robust and reliable process monitoring tools as well as the difficulty of convincing a conservative industry of the benefits of monitoring and feed control.

However, currently there are no control concepts in the agricultural biogas sector with the target of operating the biogas process flexibly and following a fluctuating time table of energy demand. Such a control concept needs to have the ability to foresee the process, since the anaerobic process has a certain time lag. For these requirements the use of model-based process controls are seen as a suitable option. In literature, different complexities, tasks and applications as well as used model types for model predictive control (MPC) can be found [53]–[57]. An overview of State-of-the-art models give the work of Manchala et al. [58]. The most prominent and widely used model is the IWA Anaerobic Digestion Model No. 1 (ADM1) [59], which is currently one of the most complex models for anaerobic digestion. Donoso-Bravo [60] point out the necessity of parameter reduction and simplification as a basis for the successful practical application of ADM1. He cites as well four principles (developed by Spriet [61]) which should be considered in order to allow practical implementation of model structure:

- "Simplicity (the model should be as simple as possible),
- Causality (the model approach should represent the most relevant cause-effect-relationships),
- Identifiability (the values of the unknown parameters should be identifiable from the available data) and
- Predictive capability (the model should remain valid under reasonable alternative or future conditions)".

Deduced from these principles, the model complexity itself and the MPC procedure should depend on the end on the specific objective and the available data. In the study of Weinrich and Nelles [62], a simplified anaerobic model approach (based on the stoichiometry of the ADM1) is

[8] A sharply subdivision between inhibited and un-inhibited process is difficult, since inhibition processes affect in a fluent intensity on the degradation processes and are not always directly apparent in the process variables.

described, which requires only the input characterization of the substrates to model the biogas production rate. This simplification of models could be a promising approach for the development of model-based control concepts with short processing times and according to available measuring equipment in practice.

1.4 Résumé

The establishment of a full-regenerative energy system is one of the major challenges of the next decades. In order to achieve this goal, further expansion of solar and wind energy is unavoidable. However, this expansion requires new paths in terms of grid stability and supply security. In particular, biogas is suitable for supporting the transition towards a regenerative energy system. Biogas is weather independent, in contrast to wind and solar energy, and widely distributed in the grid and region. There are many options for making biogas plants more flexible with regard to energy output. In contrast to complex new reactor concepts and further extensions in gas storage capacities, the flexible feeding of the anaerobic process itself is a promising option to adapt the energy output to the demand. Moreover, the current cost pressure (in particular with regard to the expiring of the RESA) will not allow expensive upgrades on existing biogas plants. Therefore, the maximum level of flexibility has to be demonstrated on the basis of the current state of technology. However in literature, hardly any investigations about flexible biogas production could be found, not to mention for the implementation in agricultural practice.

At the moment there is a lack of reliable statements on the potential, limits and mechanisms for a flexible operation under practical conditions. In addition, there is a need of a method for predictive substrate planning, which includes the specific conditions and constraints of practical operation. Especially, the low level of measurement equipment at biogas plants is a constraint for establishing advanced operation, monitoring and control concepts. In result, developing a control concept of flexible plant operation and practical implementation has to take into account this situation and find a reliable compromise. In particular the non-availability of online measurements, such as intermediates like acetic and propionic acid, impede the use of more complex model structures in control concepts because of the lack of short-term feedback and lacking calibration of corresponding model parameters. However, the measurement expense at biogas plants should also be limited to a required minimum. Larger extensions in the measuring equipment do not appear at the moment. The use of robust simplified model structures could be a way to meet the requirements of flexible operation with the state of the distribution in measurements. Furthermore, the starting point for investigating the flexibilization should be a non- or low-inhibited process. This must be taken into account both in substrate selection and in process design. A literature research showed that a control concept for flexible feeding has not yet been implemented under the specific full-scale and practical conditions in the current agricultural sector, which are:

- mainly solid substrates (hydrolysis considered as rate limiting step),
- limited availability of measurements (especially online-measurements of intermediates),
- demand-driven electricity timetables in advance with possible short-term adjustments and
- operational requirements and limitations (e.g. feed-in velocity, gas storage capacities and filling level).

2 General and specific objectives

Against the background of the potential of biogas sustaining an arising renewable energy system, it is essential to utilize the full potential of demand-driven biogas production. On the one hand, the technological standard in measurement and control needs to be raised. On the other hand, a trade-off with the practical availability and the economic and operational needs has to be achieved.

The general objective of this work is the development and demonstration of an applied-oriented control concept for flexible operation in agricultural full-scale and investigations on process-biological and procedural capabilities of flexible biogas production.

In this context, more specific questions and objectives are:

A – Potentials of flexible biogas production by feeding

- *A.1* *Investigating the possibilities of variation in substrate type and quantity to receive a flexible gas production*
- *A.2* *Determining the response dynamics and latency and identifying the differences by the digester scale*
- *A.3* *Evaluating the potential of flexible biogas production in a procedural and economical point of view*

B – Process stability within flexible feeding strategies in short and long-time context

- *B.1* *Defining criteria and limits for stability evaluation*
- *B.2* *Assessing the stability of conducted flexible operated experiments and estimating dependencies between possible disturbances, digester scale and a flexible operation.*

C – Control concept for flexible feeding

- *C.1* *Developing a model-based control structure (connection of processes, objective function, data handling, optimization strategy and implementation) based on a defined minimal measurement selection and practical requirements (e.g. gas storage and variable substrates)*
- *C.2* *Proving the concept and demonstrating the control concept in full-scale*
- *C.3* *Evaluating the concept with regard to measuring scenario and procedural aspects*

3 Approach and experimental design

In order to clarify the general approach of flexible gas production by means of flexible feeding and to investigate the underlying processes, in the present thesis, various studies have been carried out from laboratory, full-scale to theoretical scenario studies. Figure 3 illustrates the connection and sequence of the investigations in this thesis.

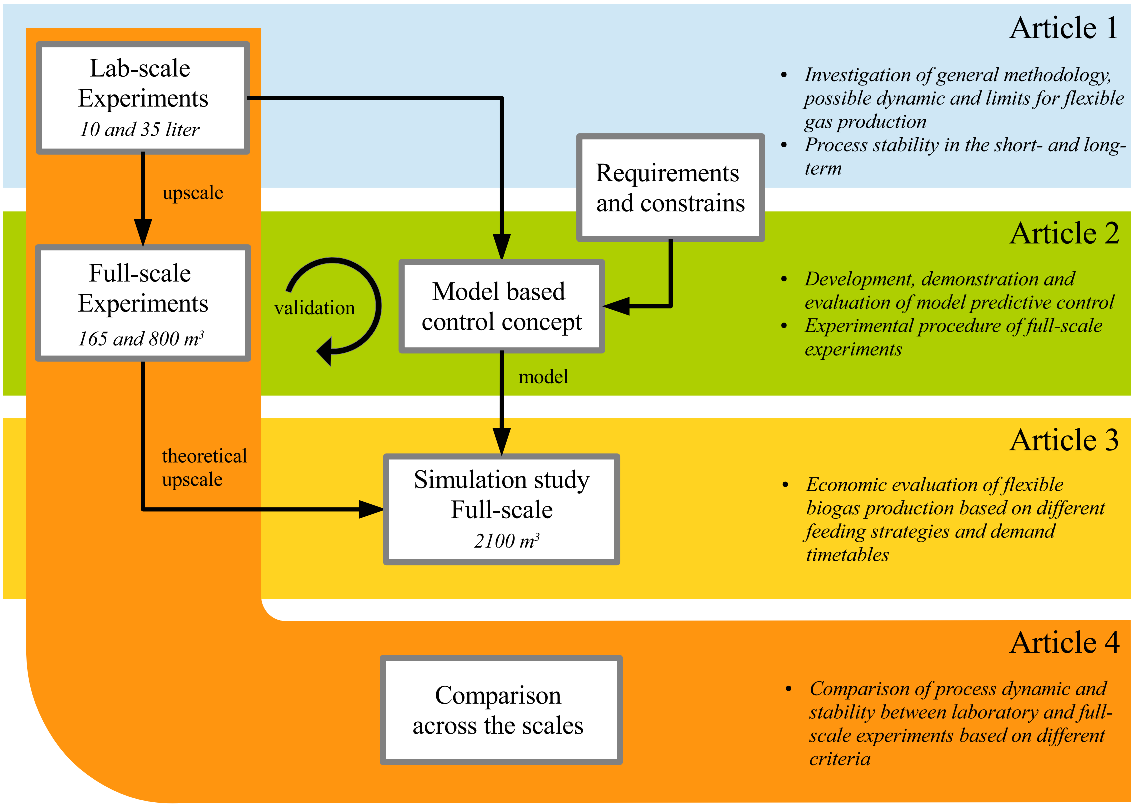

Figure 3: Illustration of the general approach of the thesis and sequence of tasks and articles; values (Liter and m^3) describe the liquid digester volumes of the individual experiments

In a first step, lab-scale experiments were carried out (see **Article 1**), to investigate the general mechanisms and effects on gas production dynamic by means of flexible feeding *(Objective A)*. Therefore, a range of substrates with different degradation properties were selected based on feedstock analyses and batch arrays. This selection includes maize silage, sugar beet silage and cattle slurry, since they are common agricultural substrates in Germany. In order to investigates the tasks *flexibility potential (Objective A)* and *process stability* (*Objective B)* at one side and *control development (Objective C)* on the other side, different measuring scenarios were defined. Also more specific stability criteria were defined, in order to evaluate the stability of the biogas process under the conditions of a flexible operated system. For both, measuring scenarios and definition of stability, see chapter "Analytics and measurements" at page 22.

Secondly, these experiments are intended to characterize the process response, with its dynamics and latencies, in short and long-time context to define limits and strategies for the control development *(Objective C)*. Furthermore, the lab-scale results should serve as basis for the experimental design of the following full-scale demonstration *(Objective B1 and C)*.

In a next step, the practical-oriented control concept has to be developed (see **Article 2),** which takes into account the different requirements from a practical context *(Objective C1)*. As shown in chapter 1, there are different requirements from temporal maturity in supply of energy to technical and organizational terms at practical biogas plants (availability of measurements, integration of a gas storage and plant topologies). The aim is to calculate the optimal feeding strategy in advance to fulfill a given demand-oriented gas utilization timetable. A literature study revealed the model predictive control concept based on an anaerobic model as a promising method. However, for the internal model an simplified approach based on the common ADM1 [59] should adapted, to meet the specific requirements of fast and easy adjustment, based on the given reduced measurements (measuring scenario II, page 22). Defining the general control structure the scope of application (flexible gas production in an un-inhibited process based on agricultural substrates) should be taken into account. Furthermore, a comprehensive and robust objective function and optimization structure have to be developed, to take into account the dependencies between gas production, storage and gas utilization.

Subsequently, the developed model predictive feed control has to be demonstrated and validated (*Objective C2)*. Therefore, two research biogas plants were chosen, which have different scales and use different substrates. For validation, a standardized demand schedule has to be provided, based on real data from the power exchange, in order to map realistically the existing requirements. Furthermore, the concept has to evaluate according to measuring and procedural aspects *(Objective C3)*.

In addition to the technical and process-biological aspects, the evaluation of flexible operation modes should also include a view on the economic feasibility *(Objective A3)*. Therefore, the interaction between the schedule processing by means of electricity exchange forecasts and the economic potentials of flexible biogas production using various feeding profiles should be investigated (**Article 3**). In this way, statements on the optimal schedule design that take into account the characteristics and flexibility potential of a biogas process are possible. The model-based optimization method from the developed control concept (**Article 2)** were used for this simulation study (kinetic parameters based on the realized full-scale experiments).

Finally, the results from different lab and full-scale experiments have to be compared against the flexibility potential and process stability in an overarching manner *(Objective A and B)*. Based on results in **Article 1**, the study of **Article 4** aims to prove the general flexibility of the biological process in particular under the full-scale conditions *(Objective A2)*. Therefore, methods for comparison *(Objective A3)* were developed and set the results in relation with other flexible biogas configurations in literature. In particular the limits and potentials of flexible feeding are discussed critically in this final study.

4 Description of experimental systems and methods

4.1 Laboratory scale digesters

For lab-scale experiments, continuous stirred tank reactors (CSTR) with 15 and 40 L total volume (10 and 35 L liquid volume) are used (see Figure 4). The reactors were continuously stirred. During the experiments the reactors temperature was maintained at mesophilic conditions ($38 \pm 1\,°C$). The general operation took place according to the Guidelines for the Fermentation of organic material (VDI 4630) [63].

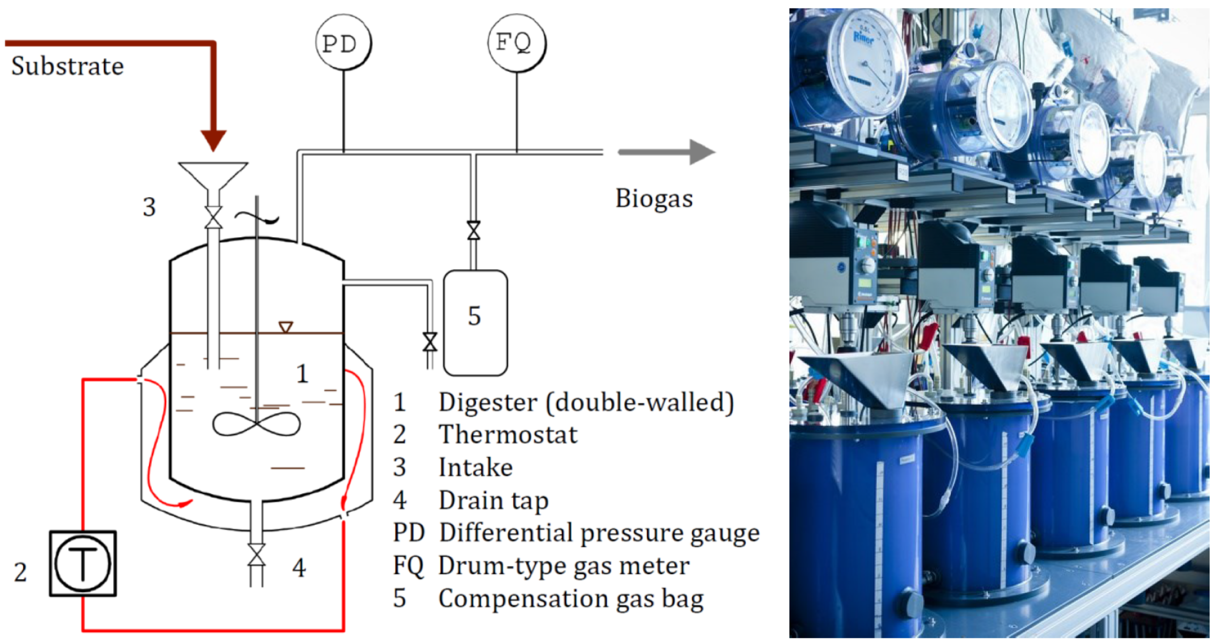

Figure 4: (left) Schematic setup of laboratory-scale digesters ©*Eric Mauky/DBFZ*; (right) 15 L CSTR reactors at the DBFZ, ©*Jan Gutzeit*

4.2 DBFZ – Research biogas plant (Plant A)

The DBFZ-research biogas plant (Figure 6) is located at the institute site of the DBFZ - Deutsches Biomasseforschungszentrum in Leipzig (Germany). The two main digesters have a volume of 209 m^3 (maximal liquid volume = 180 m^3). Furthermore, on site one primary Plug flow digester (75 m^3), an optional pre-digester (90 m^3), one secondary digester (200 m^3), one liquid manure tank (215 m^3) and one digestate storing tank (215 m^3) are available. For piping- and instrumentation diagram see Figure 5.

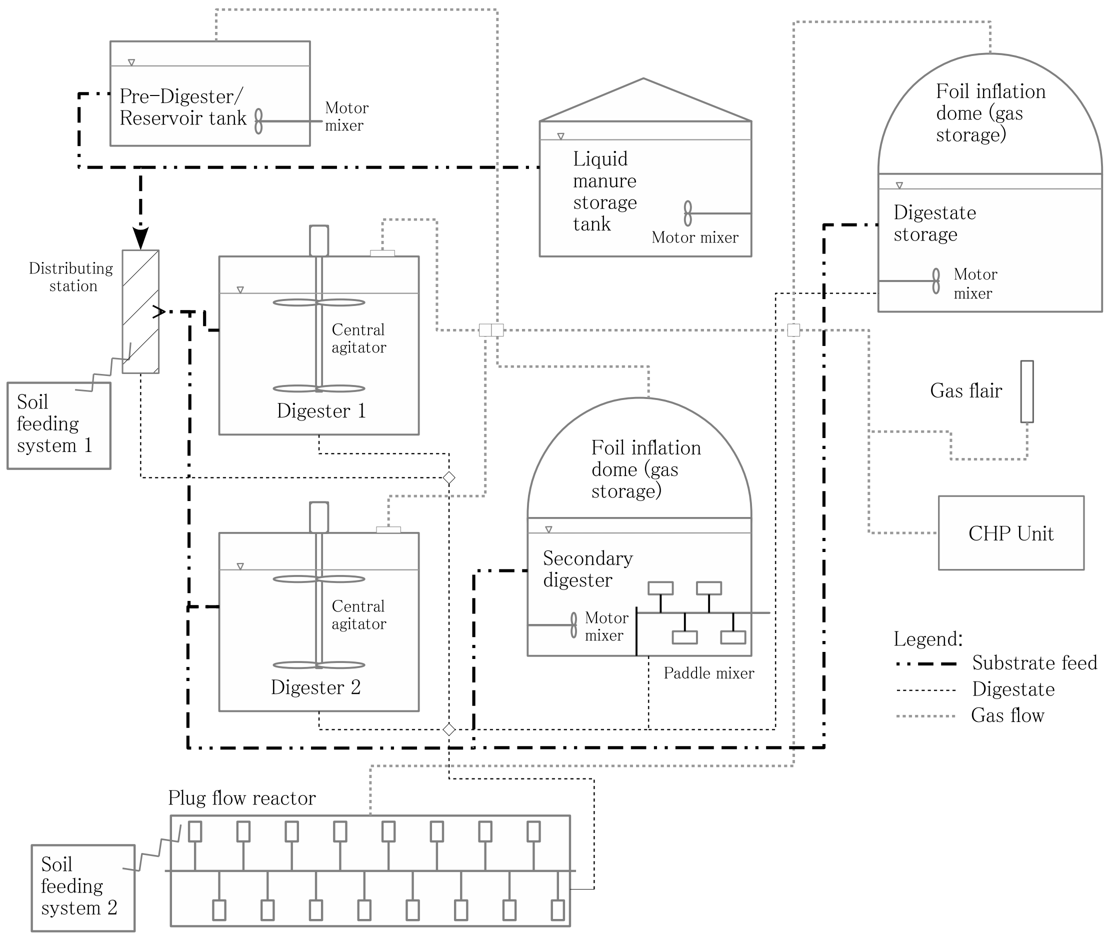

Figure 5: Piping- and instrumentation diagram of the DBFZ- Research Biogas plant, ©*Eric Mauky/DBFZ*

Figure 6: Overview of the DBFZ–Research Biogas plant ©*Paul Trainer/DBFZ*

4.3 Research biogas plant "Unterer Lindenhof" (Plant B)

The research biogas plant from the University of Hohenheim (Figure 7) is located at Eningen u. Achalm/ Germany. The CSTR primary reactors have a digester volume of 923 m^3 (liquid volume 800 m^3). The technical design of the biogas plant with technical equipment is shown in Figure 8. Further details can be found in Nägele et al. [64].

Figure 7: Research biogas plant "Unterer Lindenhof", ©*Eric Mauky/DBFZ*

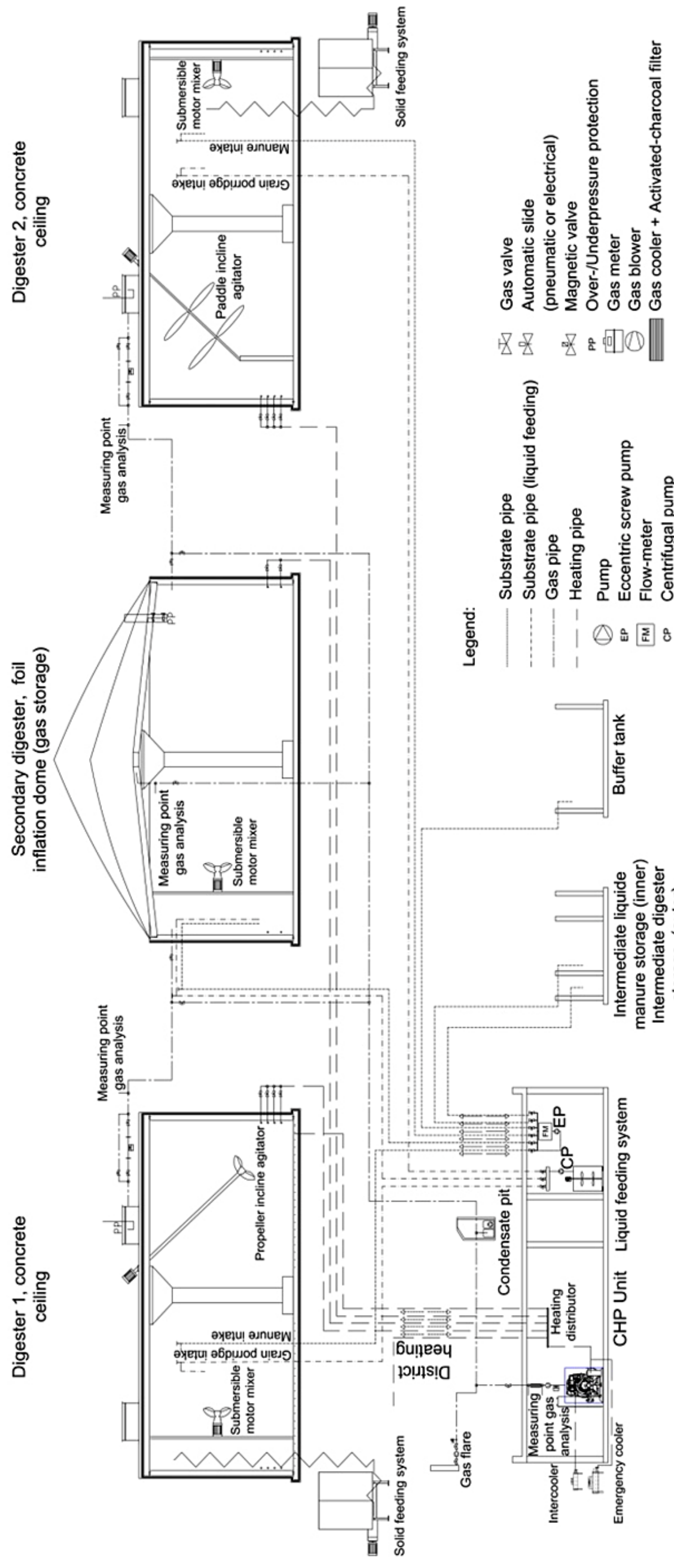

Figure 8: Piping- and instrumentation diagram of the Research Biogas Plant “Unterer Lindenhof” [64]

4.4 Analytics and measurements

For the studies in this thesis, different measuring scenarios were applied (Table 2). With **measuring scenario I**, the process should be monitored with intensive and frequent measurements, to investigate the flexibility potential and process stability *(objectives A and B)*. Measuring scenario I includes the sum parameter of volatile fatty acids (FOS[1]) and buffer capacity relative to calcium carbonate (FOS/TAC[2]) by means of titration, ammonia nitrogen, dry matter (DM) and volatile solids (VS). The feedstock composition of substrates was analyzed by Weender and extended Van Soest method. The concentration of individual volatile fatty acids (VFAs) was determined chromatographically. Sample preparation and measurement of the mentioned parameters was performed according to Liebetrau et al.[65]. In general, reactor samples were taken and prepared for further measurement prior to the first feeding. Additionally, at particular days the course of measurements was monitored by frequent sampling throughout the day. Also gas quality measurements (e.g. ratio of CH_4 and CO_2 or H_2 parameter) were used as indicator of imbalances. The general monitoring includes furthermore the analysis of trace elements for substrates and process, to guarantee an optimal supply based on literature advices [66], [67]. Further details to the used analytics and measurements can be found for the lab-scale experiments in *Article 1* (page 32) and for the two full-scale experiments in *Article 2* (page 55) and *Article 4* (page 94).

For developing the control concept *(Objective C)*, a minimal **measuring scenario II** (Table 2) was defined according to the usual equipment level at common agricultural biogas plants in practice [50]. Further details about measurements in the concept could be found in *Article 2*. Additionally, Table 2 gives information about the type of measurements (online/offline) and their measuring frequency.

The two main aims of the process control are at one side the controlling of the gas production rate and on the other side the ensuring of **process stability**. As outlined in chapter 1.2, the trend of concentrations is more crucial for valuation of process stability than exact limits. Therefore, a more specific definition of “process stability” under the conditions of a flexibly operated system is necessary.

[1] Also called Total VFA (measured by titration)
[2] Also called IA/PA ratio, VFA/bicarbonate or VFA/ALK

Table 2: Definition of measuring scenarios for (**I**): monitoring and analysis of flexible process performance and stability, and (**II**): measurement inputs for the model-based control concept, regarding the available measurements at common agricultural biogas plant in Germany [50]

analytics	**measuring scenario I**	**measuring scenario II**
	for investigating and analyzing of flexibility potential, performance and stability	*available input specification for control development according to the common state of the equipment at commercial biogas plants* [50]
Gas production rate $^{(a)}$	X	X
Gas quality $^{(b)}$		
CH_4	X	X
CO_2	X	X
H_2S	X	
H_2 $^{(c)}$	X	
O_2	X	
Dry matter $^{(f)}$	X $^{(d)}$	X $^{(e)}$
Volatile solids $^{(f)}$	X $^{(d)}$	X $^{(e)}$
Feedstock analysis $^{(f)}$	X	X $^{(e)}$
FOS $^{(f)}$	X $^{(d)}$	(X) $^{(g)}$
FOS/TAC $^{(f)}$	X $^{(d)}$	(X) $^{(g)}$
Ammonia nitrogen $^{(f)}$	X $^{(d)}$	
VFAs and alcohols (GC)$^{(f)}$	X $^{(d)}$	
pH $^{(f)}$	X $^{(d)}$	(X) $^{(g)}$
Redox potential $^{(c)}$	X $^{(d)}$	
Trace elements $^{(f)}$	X	

(a) measured online (minimal 5-min-summarization level of data)

(b) minimal 6 measurements per day

(c) parameter not available at the experiments on research biogas plant B “unterer Lindenhof”

(d) high measuring frequency up to diurnal cycles every hour

(e) provided to the control by sliding mean only when a new substrate batch is used or a predefined interval is reached

(f) measured offline for substrate and process

(g) values not a input for the model predictive feed controller (Article 2); offline values used for simulating a state of the art monitoring of long-term stability by an plant operator (overall control concept see discussion section, page 126)

At this point of the Thesis, the process would be considered as stable in the following bounds:

- pH-value between 7.0 and 8.0,
- No **long-term** (> one week) accumulation of acids and inhibitors over common limits [3] [42],
- Alternation of measurements (e.g. VFAs) outside these common limits in the range of hours up to days (**short-term**) are tolerable, if the measurements return back to the initial range in the phases of reduced or intermitted feeding,
- An feeding event have to followed by an increase in gas production rate,
- Alkalinity ratio (FOS/TAC) < 0.4,
- Constant high ratio of acetic and propionic acid (acetic acid/propionic acid > 2).

Based on the experimental results, these definitions were further adjusted in the course of the work (Discussion section 5.2 and 5.3).

4.5 Soft- and Hardware

The developed methods in this thesis had been implemented and performed in *Matlab / Simulink* software environment (*The MathWorks Inc* [68], Versions from R2014a to 2016b). For specific investigations, additional Matlab toolboxes were used for optimization [69], global optimization [70] and statistics [71]. Further calculations performed in *Microsoft Excel*. All following calculations were performed on a 64-bit Intel(R) i5-3470 CPU@3.2GHz, 8 GB RAM computer. The software *Origin 8.1G* [72] and the open source tool *R* [73] was used for statistical investigations and visualization.

[3] Acetic acid < 1,000 $mg\ l^{-1}$; Propionic acid < 250 $mg\ l^{-1}$; Longer chained VFA (butyric, valeric) < 50 $mg\ l^{-1}$; NH_4-N < 5,000 $mg\ l^{-1}$

Part B – SCIENTIFIC ARTICLES

List of Publications

The investigations described in this work were carried out at the DBFZ (Deutsches Biomasseforschungszentrum gemeinnützige GmbH) within the project "RegEnFlx – Bedarfsgenaue Regelung von Energie aus Biomasse" funded by European Regional Development Fund (ERDF) through the Sächsische Aufbaubank – Förderbank with grant 100143221 as well as in the context of complementary experiments in the year 2012 to 2016.

The present cumulative dissertation bases on the following publications:

Article 1: Flexible biogas production for demand-driven energy supply – feeding strategies and types of substrates (page 27)

Published in: *Bioresource Technology 178, (2015), 262–269*
Authors: Eric Mauky, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles
DOI: 10.1016/j.biortech.2014.08.123

Article 2: Model predictive control for demand-driven biogas production in full-scale (page 43)

Published in: *Chem. Eng. Technol. 39, 4, (2016), 652–664*
Authors: Eric Mauky, Sören Weinrich, Hans-Joachim Nägele, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles
DOI: 10.1002/ceat.201500412

Article 3: Expanding the flexibility of biogas plants - substrate management, schedule synthesis and economic assessment (page 67)

Published in: *Agricultural Engineering 71, 6, (2016), 233–251*
Authors: Tino Barchmann, Eric Mauky, Martin Dotzauer, Mathias Stur, Sören Weinrich, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles
DOI: 10.15150/lt.2016.3146

Article 4: Demand-driven biogas production by flexible feeding in full-scale - process stability and flexibility potentials (page 89)

Published in: *Anaerobe 46, (2017), 86–95*
Authors: Eric Mauky, Sören Weinrich, H. Fabian Jacobi, Hans-Joachim Nägele, Jan Liebetrau, Michael Nelles
DOI: 10.1016/j.anaerobe.2017.03.010

Article 1: Flexible biogas production for demand-driven energy supply – feeding strategies and types of substrates

Published in: Bioresource Technology 178, (2015), 262–269

Eric Mauky[a,b], H. Fabian Jacobi [a], Jan Liebetrau [a], Michael Nelles [a,b]

[a] DBFZ - Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Department Biochemical Conversion, Torgauer Straße 116, 04347 Leipzig, Germany

[b] University of Rostock, Faculty of Agricultural and Environmental Sciences, Chair of Waste Management, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany

Abstract Purpose of this work was the evaluation of demand driven biogas production. In lab-scale experiments it could be demonstrated that with diurnal flexible feeding and specific combination of substrates with different degradation kinetics biogas can be produced highly flexibly in CSTR systems. Corresponding to the feedings, the diurnal variation leads to alternations of the methane, carbon dioxide and acid concentrations as well as the pH-value. The long-time process stability was not negatively affected by the dynamic feeding regime at high OLRs of up to 6 $kg_{VS}\,m^{-3}\,d^{-1}$. It is concluded that the flexible gas production can give the opportunity to minimize the necessary gas storage capacity, which can save investments for non-required gas storage at site.

Keywords: biogas, demand-driven energy supply, feed management, flexibility, sugar beet silage

1. Introduction

The financial support by the Renewable Energy Sources Act (EEG) led to an increasing number of biogas plants in Germany. The plants have been designed and constructed to produce a stable and constant energy output (base load energy). With the changing conditions within the energy sector in Germany, biogas plants have to meet new requirements, especially the flexible supply of electricity to compensate for the divergence between energy demand and energy supply by uncontrolled sources like wind and solar power [1]. On one hand the extent of flexibility is characterized by the possibility to shift the periods of power provision to other time points. This includes the scheduled energy production (i.e. with planned ahead and agreed on daily or weekly timetables) and the “ad hoc” provision of positive and negative balancing energy. On the other hand, the flexibility depends on the feasibility of changing the height of the current amount of power provision. However, this is restricted to temporal displacements while preserving the same total power output on average. Szarka et al. [2] and Hahn et al. [3] remarked that bioenergy concepts seem to be a promising option to fulfill most of the requirements in the transition of the energy system from fossil to renewable sources. As opposed to wind and solar power, the production of energy from biomass is weather-independent. Moreover, through its small-scaled characteristics bioenergy is available decentrally and widely distributed and could thus contribute to the stabilization of the mains frequency.

The ability for flexible electricity supply from biogas is dependent on different factors. Possible points of action to enhance flexibility of a biogas plant are:

- type (combustion engine, turbine etc.) and capacity of biogas utilization
- gas storage capacity on site
- type of conversion process (plant design / applied technology)
- substrate type and feeding management

Each of the components of the production chain has its own limitations, altogether resulting in the overall flexibility of the plant. In practice, the shift from continuous to flexible and demand-oriented conversion of biogas to electrical power is mainly thought to be realized by installing further conversion capacities. With this the plant can still be meant to produce the same average energy output. Instead of a continuous production of energy, this takes place during mutable periods of time and at higher conversion rates. Optimally, these periods match the time when the demand for electricity is the highest. One scenario for flexibilization of biogas plants is the operation of CHPs in blocks during defined periods of a day. In scenarios with 8, 12 and 16 hours of gas utilization of the same daily gas quantity, the additional CHP-capacity needs to be extended by 3, 2 and 1.5 times of the original power. Furthermore, adding extra gas storage capacity to a level where the amounts of gas produced during CHP standstill can be intermittently stored is possible or necessary. Under normal conditions of constant biogas production, the average German biogas plant fills its gas storage within 2 to 8 hours (unpublished data of an operator survey). While older plants mostly have rather small storage capacities, newer plants are usually equipped with storage capacities of up to 12 h and more. Thus, when the gas storage capacity is small, the plant is only able to pause the CHP for a relatively short time before the capacity is filled.

An additional option for flexibilization - besides expansion of CHP and storage capacity - can be the direct adaption of the gas production to the times when electrical power is supposed to be produced. The accepted opinion is that the biological process of anaerobic conversion of the substrates to biogas shows an optimal performance when operated in steady state (constant input and output, constant process parameters). Golkowska et al. [4] investigated the degradation of maize silage in batch, semi-batch and continuous feeding mode. In contrast to the common opinion in the sector, the results confirmed an extremely high adaptation capability of anaerobic biocenosis to various frequent feedings. Lv et al. [5] investigated the influences of the substrate feeding regime on methanogenic activity by molecular and stable isotope methods. They have shown that alteration of the substrate feeding did not negatively change the overall gas yield. However, the feeding can influence the anaerobic digestion concerning the changes of concentration of volatile fatty acids (VFA) (especially acetic acid) and other process parameters [6-9]. It is obvious that the specific response of an anaerobic process, i.e. the degradation kinetics of substrates depends on their composition (amount of easily degradable components and the proportion of structural components). In order to overcome composition-related hindrance of degradation, a wide range of investigations look after methods to pretreat substrates with extruder [10], enzymes [11] and chemical/physical decomposition [12]. However, if substrate preparation can reach a faster overall degradation rate, it can become considerable for demand driven energy supplies. The demand driven feeding with the aim of discontinuous gas production has previously only rarely been discussed in scientific studies. Hahn et al. [3] described the discontinuous feeding of a fixed bed reactor for demand driven biogas production. However, taking into account the fact that the majority of German biogas plants are designed as continuous stirred tank reactors (CSTR), fixed-bed technology can hardly be broadly implemented into existing biogas plants. In a study of Müller et al. [16], a standard load profile (SLP) for household energy demand in lab-scale (CSTR) successfully followed with flexible feeding of grain stillage. However, grain stillage is a rather unusual substrate in some industrial biogas plants. Besides that, the flexible energy supply by directly acting at the process of biomass conversion in CSTR systems is currently rarely investigated experimentally.

Therefore the aim of the presented study was to

- investigate the general flexibility of the CSTR-based anaerobic digestion processes applying substrates typical for agricultural German biogas plants,
- examine the effect of discontinuous feeding on daily and long term process stability,
- evaluate whether an alteration of feeding regimes could significantly alter the daily biogas production profile so that it benefits the flexibilization of electrical power production,
- find out, whether the different degradation characteristics of various substrates can be used to optimize such altered feeding and gas production profiles and
- examine, which effects a discontinuous gas production could have on plant design.

2. Material and Methods

2.1 Experimental Setup and Substrates

The experiments were carried out in lab-scale biogas fermenters; two 15-L continuous stirred tank reactors (CSTR) with 10 L working volume and one 40-L CSTR with 35 L working volume. The reactors were continuously stirred using an anchor stirrer. During the experiment the reactors' temperature was maintained at mesophilic conditions (38 ± 1 °C) using double-walled reactor constructions. The Inoculum for the fermentation was obtained from a full-scale biogas plant operated with maize silage and cattle slurry. An industrial trace element mixture was added weekly (novoDYN, Schmack Biogas, Germany). The general operation took place according to the Guidelines for the Fermentation of organic material (VDI Standard 4630). For foaming suppression when using sugar beet silage rapeseed oil was used. From minimum of 1 ml up to 0.5 % of daily input mass was given proportional to the feeding regime, respectively. The feeding substrates were cattle slurry, maize silage and sugar beet silage, which are commonly used in agricultural practice. The two experiments were operated and divided each into 2 phases. Table 3 gives an overview about the topology of the different performed experiments with the operation time, used substrates, organic loading rate (OLR) and working volumes of the CSTRs. The feedings in the experiment phases were split into various portions and spread throughout parts of each day. In the experiments two different batches of maize silage and sugar beet silage were used. The results of the characterization of the used substrates are given in Table 3.

Table 3: Overview of the test series performed during the study

	Period	**Days** [d]	**Digester**	**Substrates**	**OLR** [$kg_{VS}\ m^{-3} d^{-1}$]	**Annotation**
Exp. 1	**A**	0 - 160	Primary	MS I + SBS I	3.6 - 5.5	Diverse regimes (1 till 5 feedings per day)
	B	161 - 300	Primary	SBS I	1.0 - 6.0	Diverse regimes (1 till 5 feedings per day)
Exp. 2	**A**	0 - 70	Primary Secondary	MS II DT + SBS II	4.8 – 5.5 3.3 – 7.0	One or two feeding events per day
	B	71 - 200	Primary Secondary	MS II + CS DT + SBS II	3.0 – 5.6 2.2 – 6.0	Diverse regimes (1 till 6 feedings per day)

Acronyms: MS-maize silage; SBS-sugar beet silage; CS-cattle slurry; DT-digestate primary, numbering refers to different batches of substrates (characterized in Table 4).

Table 4: Composition of the used substrates (maize silage MS I and MS II, cattle slurry CS and sugar beet silage SBS I and SBS II)

Component	**Unit**	**Maize**		**Cattle slurry**	**Sugar beet silage**	
		MS I	**MS II**	**CS**	**SBS I**	**SBS II**
Dry matter (DM)	[% FM]	32.6	28.4	5.9	19.4	20.3
Organic dry matter (VS)	[% DM]	95.6	96.4	77.9	82.2	86.2
Crude protein	[g kg_{DM} $^{-1}$]	84.7	77.4	190.4	46.1	42.3
Crude lipids	[g kg_{DM} $^{-1}$]	11.6	11.5	5.3	4.5	2.9
Crude fiber	[g kg_{DM} $^{-1}$]	253.8	280.1	239.3	64.6	63.3
Nitrogen free Extracts (NFE)	[g kg_{DM} $^{-1}$]	605.6	595.3	343.8	707.2	753.7
Non-fiber carbohydrates (NFC)	[g kg_{DM} $^{-1}$]	279.4	220.7	87.9	612.0	652.2
Neutral Detergent fiber (NDF)	[g kg_{DM} $^{-1}$]	580.0	654.7	495.2	159.8	164.8
Acid Detergent fiber (ADF)	[g kg_{DM} $^{-1}$]	279.3	276.1	359.2	111.1	96.1
Acid Detergent Lignin (ADL)	[g kg_{DM} $^{-1}$]	62.6	60.8	183.7	65.2	49.5
Celluloses	[g kg_{DM} $^{-1}$]	216.7	215.3	175.5	45.9	46.6
Hemicellulosis	[g kg_{DM} $^{-1}$]	300.7	378.6	135.9	48.7	68.7
Ash	[g kg_{DM} $^{-1}$]	44.2	35.7	221.2	177.6	137.8
1^{st} order constant k (batch test)	[d^{-1}]	1.5	-	0.4	2.8	-

Acronyms: FM - fresh matter

For experimental period of Exp.1 A and B, maize silage (MS I) and sugar beet silage (SBS I) were used. In the second period (Exp.1 B) sugar beet silage was used as single substrate. Both experimental periods took place consecutively in one digester (35L working volume).

In the experimental period (Exp.2 A) the primary digester was fed with maize silage (MS II) and the secondary with sugar beet silage (SBS II) additionally to the digestate transfer (DT) from the first one. In period (Exp.2 B) cattle slurry (CS) is additionally fed together with the maize silage to the primary digester. The experiment 2 was realized in a cascade of two identical CSTRs (10 L working volume) as primary and secondary digester.

The maize silage was stored in a cooling chamber at 4 °C in shrink-wrapped packs of 1 kg portions. The sugar beet silage was stored under a nitrogen atmosphere at 4 °C as well.

2.2 Analytical methods

Gas production was measured by a chamber gas counter (RITTER TG 05/5, Bochum, Germany). Gas production values were corrected to standard temperature and pressure conditions (dry biogas). Behind the chamber gas counter the biogas was collected in bags for composition measurements. Several times a day the biogas composition (CH_4, CO_2, H_2S, H_2, N_2, O_2) was measured with an AWIFLEX gas analyzer (Awite Bioenergy GmbH, Germany). The pH-value and digestion temperature were measured with a pH-electrode (WTW Typ pH 3310 SenTix 41, Germany) and a thermometer (Almemo 2390-1, Germany), respectively. Previous to the first feeding, reactor samples were taken and immediately prepared for further measurement. The concentrations of volatile fatty acids (VFA) were determined by using a 5890 series II gas chromatograph (Hewlett Packard, USA) equipped with an HS40 automatic headspace sampler (Perkin Elmer, USA) and an Agilent HP-FFAP column (30 m x 0.32 mm x 0.25 mm) for chromatographic separation.

The composition of substrates was analyzed by Weender analysis and extended Weender method by Van Soest. The result of the Weender analysis indicates a fractionation of the organic matter into crude protein (CP), crude lipids (CL), crude fiber (CF) and nitrogen-free extract (NFE). The sum of CF and NFE represents the carbohydrate content of the substrate. A further split into starch, cellulose, hemicellulose and lignin can be reached with the Van Soest extension, where four other fractions are introduced: neutral detergent fiber (NDF), non-fiber carbohydrates (NFC), acid detergent fiber (ADF) and acid detergent lignin (ADL). The ADF fraction consists of celluloses and the ADL-fraction. Together with the hemicellulose they represent the NDF-fraction. The preparation and measurement of FOS, FOS/TAC, ammonia nitrogen concentration, sample preparation for VFA analysis, feedstock analysis and pH analysis were described in Liebetrau et al [13].

To define the degradation characteristic of the used substrates, a first order kinetic was assumed [4]. For calculating the kinetic constants *k*, the first 5 days of biogas production based on batch experiments were used. The batch experiments were carried out according to VDI Standard 4630. For identification of the *k*-value, the summated difference between every value of measured and calculated first-order kinetic was minimized with the excel solver.

3. Results and Discussion

3.1 Influence of substrate fractions on the gas production

As outlined in Chapter 1 of this article, the flexibility of the anaerobic digestion process mainly depends on the degradation kinetics of the substrates and as a result in an overall degradation rate of a given substrate. Table 4 shows the fractionation of the dry matter of cattle slurry (CS), maize silage (MS I) and sugar beet silage (SBS I) based on the Weender analysis and the extended Weender analysis by Van Soest. Cattle slurry - as a slowly degradable substrate - had a high amount of protein, crude fiber and a low amount of NFE. Maize silage is considered as substrate with a medium fast degradation kinetic. The fraction of crude fiber and especially the NFE fraction are larger than in slurry. Sugar beet silage consists nearly of two thirds of fast degradable NFE; thus the classification as fast degradable substrate.

Considering the fractionation by Van Soest, the difference between cattle slurry, maize silage and sugar beet silage becomes more obvious. The further splitting of the carbohydrates shows a very high amount of NFC and a low content of cellulose, hemicellulose and lignin in sugar beet silage. The contents of cellulose and hemicellulose in maize silage are higher than in sugar beet silage. The high amount of these easily degradable components and the low amounts of more rigid structural components represented by ADL and ADF are the cause for the rapid degradation characteristic of such substrates. In contrast, cattle slurry had less than 10 % NFC components and a quarter of the organics are cellulose and hemicellulose. Here hemicellulose is an easier degradable structure than lignocellulose. However, for cellulose degradation less enzymes and energy are necessary [14]. This explains the slow degradation kinetic of slurry. Maize silage is in this context fairly balanced between fast, medium and slowly degradable components. Yet it has high methane yields [15].

The calculated 1^{st} order constant k in Table 4 for cattle slurry, maize silage and sugar beet silage, based on batch experiments (un-shown data), are 0.4, 1.5 and 2.8 d^{-1}. It can be seen that the classification of degradation kinetics corresponds with the amount of readily available and therefore fast degradable components in the organics fraction. The combination of these different degradation characteristics was used in the continuous trials to optimally distribute the different substrates throughout the day to obtain a maximum dynamic gas production and fulfill characteristic utilization regimes.

3.2 Flexible biogas production in a CSTR system

Experiments were conducted throughout 300 days (Exp.1 A & B) and 200 days (Exp.2 A & B), see Table 3. During the different periods the reactor or reactors were adapted to the then used substrates and at the same time variations in organic loading rates and feeding regimes were conducted. The aim was to reach high loading rates and also high and as well controlled variations within the intraday gas production rates according to the aims of the experiments stated in chapter 1. In the following, representative periods of the experiments showing the extent to which gas production could be flexibilized are presented in detail.

3.2.1 Effect of flexible feeding on biogas production

Figure 9a shows the course of the gas production of 4 days of Exp.1 A. In order to assess the effect of feeding on the biogas production, different feeding regimes, i.e. feeding given daily load of maize silage in one portion or separating the same amount into various portions were investigated. In day 47 - 49 (Figure 9a) the reactor was fed four times per day. The initial dose contained the full daily ration of maize silage and a fraction of the daily amount of sugar beet silage. The following three feedings consisted of increasing amounts of sugar beet silage every four hours. According to its slower degradation kinetics, maize silage was fed first in order to obtain as much biogas from this fraction as possible within the intended window of biogas production. With the small amounts of easily degradable sugar beet silage, very sharp responses in the gas production could be observed. The gas production increases significantly from around 2 l h^{-1} to the fourfold level of 8 l h^{-1}. With the following feedings of sugar beet silage the gas production was kept around the same high level during 9 hours. The different portions of sugar beet silage were increased from 25 to 50, 60 and 80 g per feeding to compensate the decreasing biogas production rate from the initial and slower degrading single maize silage portion and later on the (faster degrading) portions of sugar beet silage. The fast degradation of the high amount of easily available fractions in the sugar beet silage leads on one hand to a fast increase of gas production after each feeding and on the other hand to a fast decrease of the gas production within two hours after the last feeding event. Within two hours the average rate of 8 l h^{-1} was reduced on a level under a value of 3 l h^{-1}.

For illustrating the distribution of intraday gas production, the day was split into two halves. In a practical context the first half can be understood as a utilization phase during which biogas is consumed and electrical power produced, whereas the second half resembles the storage phase, when no gas is needed (see chapter 1). The usual, evenly distributed, consecutive feeding of a biogas plant would lead to 50 % of the daily gas production to be produced in each half of the day. With the applied feeding regime the gas production - produced during the first half - was raised to over 70 %. Accordingly, in the storage phase, the production could be reduced to a minimum of below 30 % of the daily gas production. The main amount of gas is produced from maize silage. The sugar beet silage is used to hold up the production level throughout the utilization phase and to allow a fast decrease of the gas production rate at the end of the imaginary 12 hour block.

Figure 9b shows the course of biogas production of four days in Exp.1 B. There the gas production is generated only from sugar beet silage. In the first two days, the total daily input is given to the reactor in two rations. As described before, the subsequent input amounts are slightly reduced to hold a constant level of gas production. Directly after the first feeding event, the gas production rises from 1 l h^{-1} to 9 l h^{-1}. With the second portion, the production is stabilized on a high level.

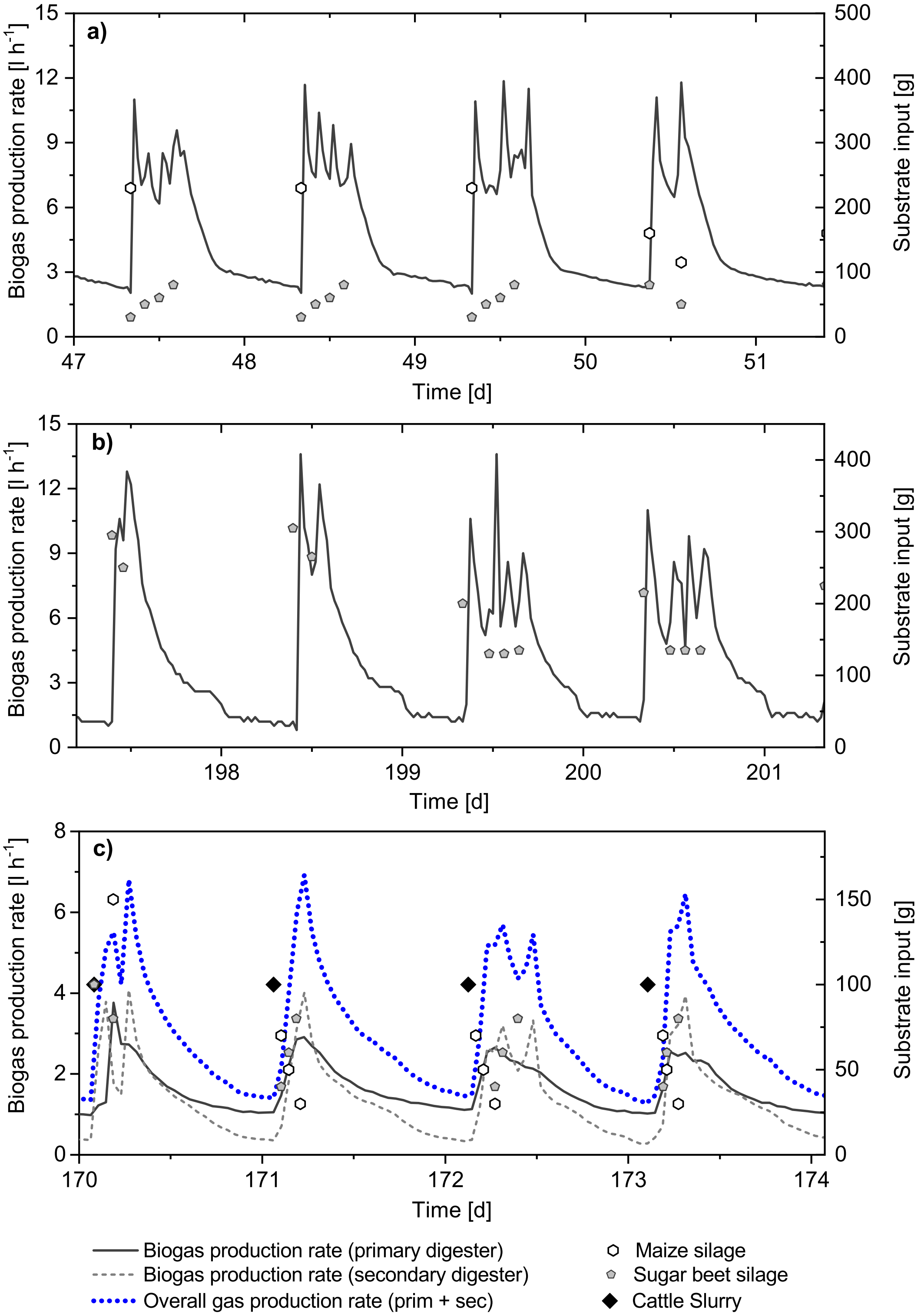

Figure 9: Course of the gas production with the feeding events for **(a)** Exp.1 A, **(b)** for Exp.1 B and for **(c)** Exp.2 B

At the third and fourth day the inputs were spread to four feeding events with the first feeding exceeding again the subsequent feedings, yielding a relatively constant average level of 6.5 l h^{-1}. Through the high level of production compared to the low ground level in the non-feeding time, the proportion can shifted to 78:22 between first and second 12 h-phase. Figure 9c shows the results in the course of the gas production of Exp.B 2. The aim of the experiment was the implementation of a primary and secondary digester with the separate feedings of both fermenters. Here, the more slowly degradable substrates cattle slurry and maize silage were fed to the primary digester. Sugar beet silage was fed to the secondary fermenter. Because of its fast degradability characteristics, it can be fully degraded within a lower hydraulic retention time (HRT). At day 170, the cattle slurry was given solely and two hours later the maize silage. The sugar beet silage was given in two portions to the secondary digester. With the maize silage and cattle slurry fed, a raise in the gas production from 1 l h^{-1} to 3 l h^{-1} was observed. The gas production in the secondary digester, fed with sugar beet silage, increased from 0.5 l h^{-1} to 4 l h^{-1}. Between the two feeding events of the secondary digester, the production decreased to 1.5 l h^{-1} and went back to 4 l h^{-1} with the second feeding. Over the following 12 hours the biogas production constantly fell down to 0.5 l h^{-1}.

In order to simulate the gas production of a whole biogas plant, the gas production rates of primary and secondary fermenter were added up. The combined biogas production rate varied between 1.5 to 5 l h^{-1}. The proportion of both 12h phases (based on the data of Figure 9c) yielded an average ratio for utilization:storage phase of 70:30 for the overall system. During days 171 to 173 effects of varying the feeding regime on the gas production could be observed. The portions of maize silage and sugar beet silage were split into three feedings each. Maize silage was fed in decreasing and the sugar beet silage in increasing portions. On days 171 and 173 the three portions of sugar beet silage were fed together with the maize silage, resulting in similar summarized gas production curves. On day 172 the first sugar beet silage ration was given together with the last maize silage portion. The resulting gas production curves showed a plateau of 6 hours. This resulted in a ratio of 73:27 between the gas utilization and gas storage phase for day 172.

3.2.2 Process stability

The results presented in the preceding chapter show the effects of combining substrates with different degradation rates on the gas production and thus the flexibility of the process itself. However, the realized flexible feeding strategies impose alternating stress levels on the biocenosis, possibly leading to instable situations, e.g. long time accumulation of acids. Figure 10a shows full Exp.1 A with the courses of gas production, acetic and propionic acid concentrations and the OLR. The samples for analyses were always taken before the first daily feeding. Additionally, at day 27 and 75 the course of the acids was monitored by frequent sampling throughout the day. Here no significant long term accumulation of VFAs was observed.

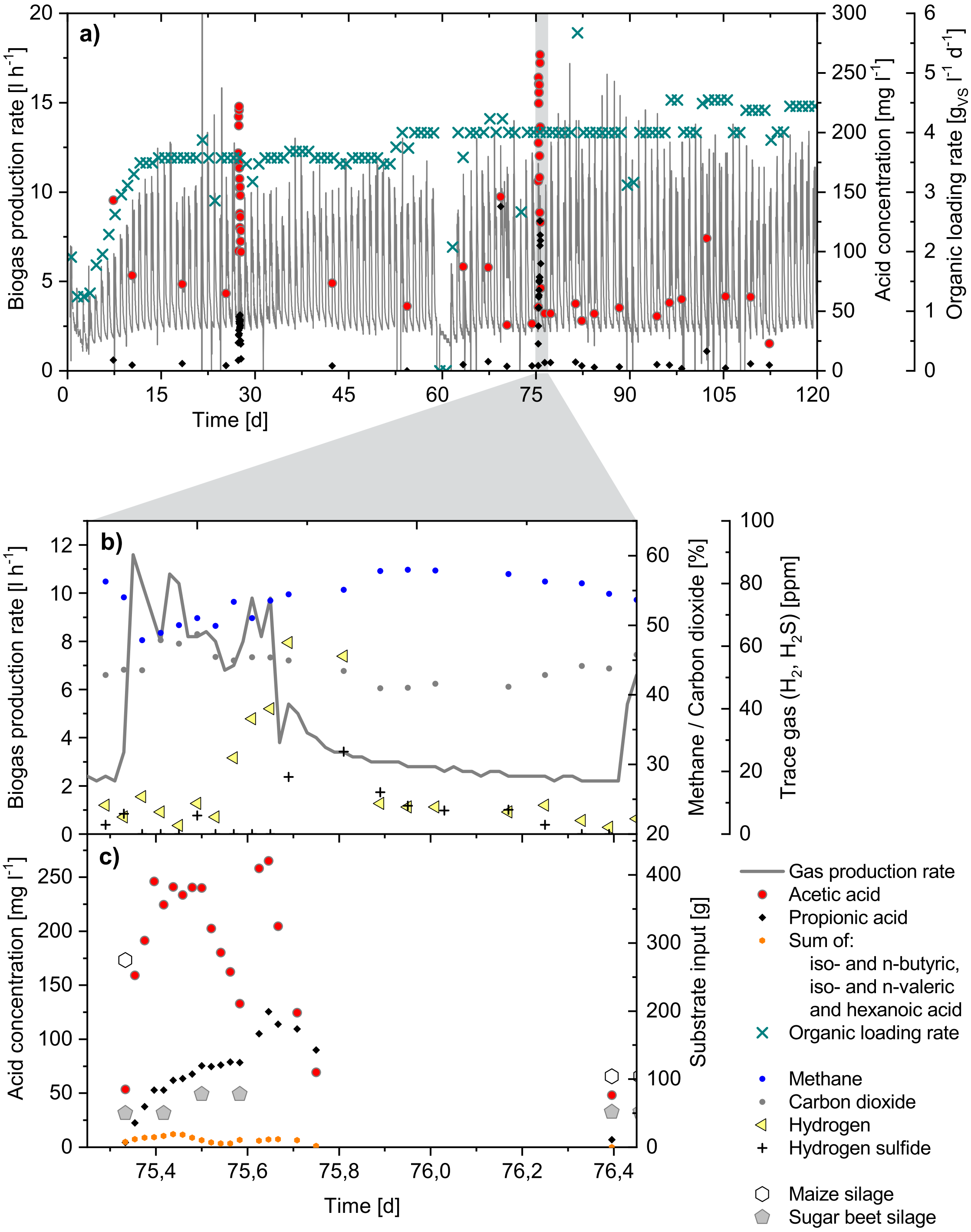

Figure 10: **(a)** Course of biogas production, concentrations of acetic and propionic acid and OLR throughout the Exp.1 A; **(b)** Daily course of concentrations of methane and carbon dioxide and other gas components of day 75; **(c)** Feeding regime and resulting daily course of acid concentrations at day 75

Figure 10b shows the daily course of the biogas production of day 75 and the biogas components (CH_4, CO_2, H_2 and H_2S) over the daily course. After a feeding event the proportions of CH_4 and CO_2 converge towards 50 %. In further progress, the methane content rises again, exceeding 55 %, whereas carbon dioxide content decreases accordingly. Methane is the part of biogas which is used for combustion in CHP units. The variation of the biogas quality relativizes the achieved shift related to the energy potential to a small extent. Phases with higher gas production after feeding events yielded poorer gas qualities regarding methane content. However, in full scale plants the gas is collected in the storage over several hours. Thus different qualities are mixed, leading to lower variations in the quality of the gas as it reaches the CHP. Furthermore, modern CHP units with combustion control can process gas of varying quality within the observed margin. In Figure 10c the feeding events and the course of the acetic and propionic acids are shown. The sum of butyric-, valeric- and hexanoic acid remained below 50 mg l^{-1}, which is very low. The acids increase slightly, corresponding to the feeding events and return to the initial level during the phase of non-feeding. Also, the pH-value decreases and stabilizes again during the course of one day (data not shown). Similar to the acids, the H_2 and H_2S concentrations increase after the feeding and come back to a normal level within the 24-hour-cycle.

The behavior of both acid and gas concentrations can be explained by the immediate onset of hydrolysis, where organic acids, CO_2 and H_2 are produced. Once these intermediates are available, the downstream processes and finally methanogenesis follow, leading all measured values back to the initial levels. Thus, regarding process stability, the experiments show no sign of negative influences through the heterogeneous feeding regime. This includes long-time experiments at OLRs of up to 6 $kg_{VS}\ m^{-3} d^{-1}$ with maize silage, cattle slurry and sugar beet silage. Although no parallel investigations were performed, it is presumed that the overall performance of the process and utilization of the substrates is not altered, as HRT is not affected through the discontinuous feedings. Whether the short-termed variations within the process parameters could even positively influence the degradation process remains to be investigated in further studies.

3.3 Theoretical saving of gas storage capacity based on the experimental data

This chapter illustrates the theoretical potentials of saving gas storage capacity in consequence of flexible feeding. Therefore, data from Exp.1 A, days 47–51, were selected to compare the gas storage demand for different gas consumption scenarios (see Figure 11a). A gas storage capacity capable of storing continuously produced biogas for 8 hours was presumed. The virtual plant was supposed to consume the full amount of biogas produced during one day within 8, 12 or 16 hours, resulting in a need to store the gas for the remaining 16, 12 or 8 hours of a day, respectively (see also chapter 1 in this article). In the following these scenarios are termed 8/16, 12/12 and 16/8, respectively. The virtual filling level of the gas storage was computed by summing up the produced gas according to the measurements from the experiment and subtracting the presumed amounts of gas used during power production periods at hourly intervals.

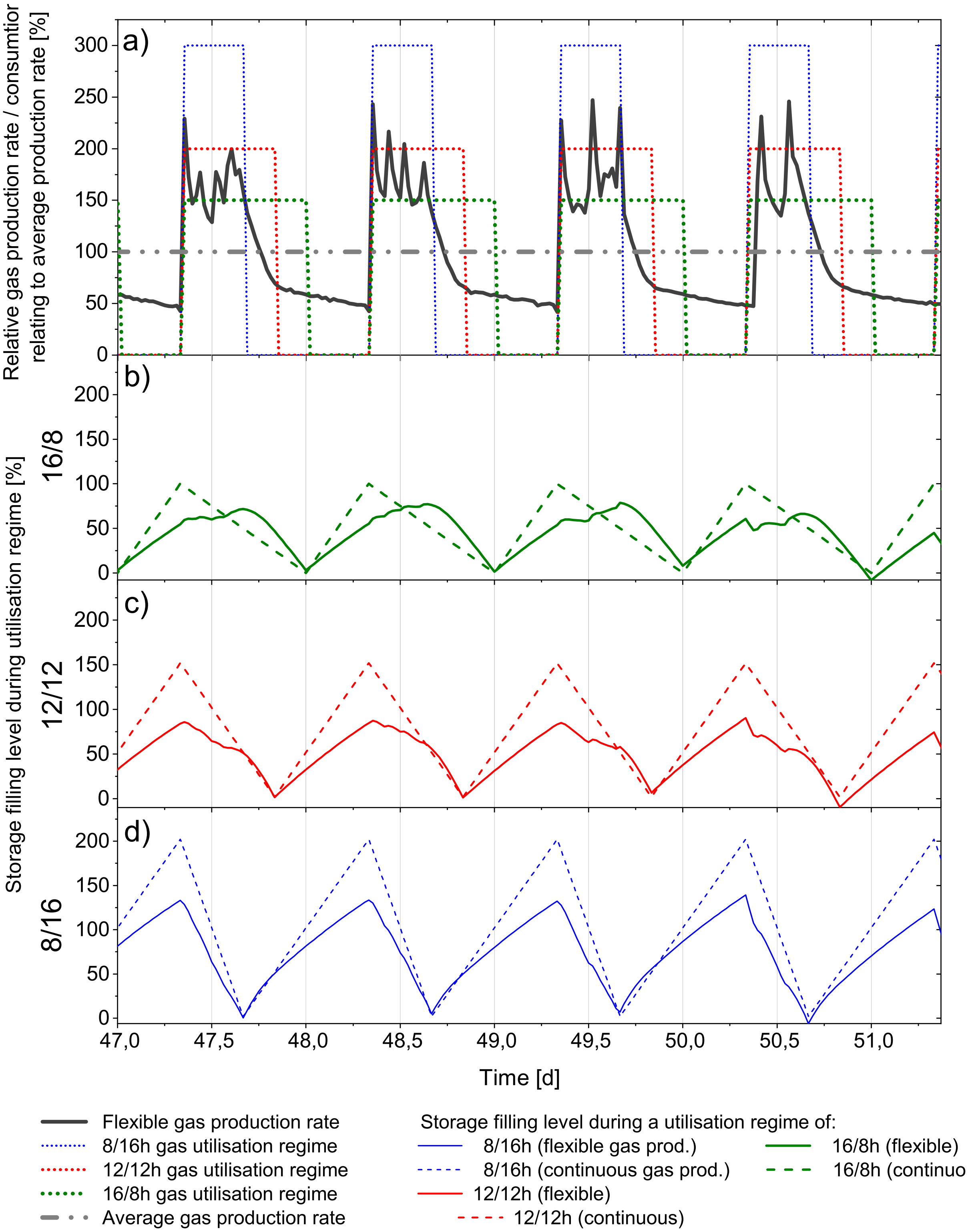

Figure 11: Gas storage demand by continuous feeding compared to flexible feeding using laboratory results

Figure 11a shows the course of the gas production together with the assumed utilization regimes. As 100 % of the daily produced gas needs to be consumed during the preset consumption period, different consumption period lengths lead to different consumption rates. In Figure 11b, c and d the courses of the storage filling levels for the three scenarios with and without flexible feeding are shown. The different utilization regimes for the presented dynamic feeding regime result in clearly different courses and maximum filling levels of the storage compared to a constant gas production. With a gas storage capacity of 8 h constant gas production, the utilization regime 16/8 can be fulfilled even with continuous gas production (see Figure 11b). With the flexible feeding the storage demand can be reduced to 85 %. If 12 hours gas utilization and 12 hours gas storing is assumed, the 8 h gas storage is not able (>100 % filling level) to store the gas from continuous gas production (Figure 11c). With the flexible feeding regime the demand can be nearly divided by half from 150 to 85 %. If assuming an 8/16 h utilization regime, then even with the dynamic gas production, the filling level cannot be kept under 100 % (see Figure 11d). However, the filling level can be reduced from 200 % to 140 %. When assuming the 12/12 h utilization regime, the reduction effect was the highest, because the feeding regime was optimized for 12 h (see chapter 3.2.1). With other feeding regimes and utilization regimes, the reduction effect can be higher. When the gas storage is extended from 8 h to 11 h capacity (not shown), the filling level can kept below 100 % with the flexible feeding, even using the 8/16 h utilization regime.

Besides the validation of the general possibility of flexible feeding and substrate use, the investigations hint at the possibilities of flexible biogas production for the practical application. This raises the question of whether the strategy can be scaled up to practice-sized biogas plants. Further research is necessary to demonstrate flexibility in large-scale fermenters. Ongoing research aims at repeating the trials in larger scale in research biogas plants with reactor volumes of 208 m^3 and 923 m^3.

4. Conclusion

In lab-scale experiments it could be demonstrated that with diurnal flexible feeding and specific combination of substrates with different degradation kinetics biogas can be produced highly flexibly in CSTR systems. The diurnal variation leads to a daily alternation of the methane, carbon dioxide and acid concentrations as well as the pH-value corresponding to the feeding. The long-time process stability was not negatively affected by the dynamic feeding regime. It is concluded that the flexible gas production can give the opportunity to minimize the necessary gas storage capacity, which can save investments for non-required gas storage at site.

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Article 2: Model predictive control for demand-driven biogas production in full-scale

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Mauky E. [a,b], Weinrich S. [a,b], Jacobi H.F. [d], Nägele H.J. [c], Liebetrau J. [a], Nelles M. [a,b]

[a] Department of Biochemical Conversion, DBFZ - Deutsches Biomasseforschungszentrum, Torgauer Straße 116, D-04347 Leipzig, Germany (E-mail: eric.mauky@dbfz.de)

[b] Faculty of Agricultural and Environmental Sciences, Chair of Waste Management, University of Rostock, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany

[c] State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim, Garbenstraße 9, Stuttgart 70599, Germany

[d] Hessian State Laboratory, Fachgebiet IV.5.4 Renewable Energies, Schubertstraße 60, 35392, Gießen

Abstract Biogas plants have the potential to supply demand-oriented electricity to compensate the occurring divergence between energy demand and supply by uncontrollable sources (i.e. wind and solar). Within that context this study aimed to demonstrate the general flexibility of the biological process in particular under full-scale conditions for a biogas production according to the grid demand. A model predictive control was developed to calculate feeding strategies to fulfill a demand-oriented gas utilization timetable. Full-scale experiments showed a high intraday flexibility ranging as far as 30 – 130 % of the average gas production and high process stability in reaction to pulse feeding. The gas storage demand could be reduced by up to 45 % compared to the common constant feeding operation.

Keywords: biogas; demand-oriented; feeding management; model predictive control; flexible; full scale

1. Introduction

The financial incentives set by the Renewable Energy Sources Act (EEG) led to an increasing number of biogas plants in Germany. Until 2012 the plants had been designed and constructed to produce a stable and constant electric energy output (base load energy). The changing conditions within the energy sector in Germany increases the need of controllable electric energy supply and forces biogas plants to be able to compensate the divergence between electric energy demand and electric energy supply with other uncontrolled sources like wind and solar power [1]. Szarka [2], Hochloff [3] and Hahn [4] stated that bioenergy concepts seem to be a promising option to fulfill most of the requirements in the transition of the energy system from fossil to renewable sources. The technical development of biogas plants nowadays focuses on expansion of gas storage capacity and different multi-phase digester concepts and implies high investments [4–7]. An alternative approach especially at existing biogas plants could be the adjustment of the feeding management [8]. Experiments in lab-scale-CSTRs to analyze different flexible feeding strategies with sugar beet silage, maize silage and cattle manure showed a long-time stable process, even under highly dynamic operating conditions [8]. Grim [9] investigated the economic effects of different flexibility scenarios for demand-oriented CHP operation under Swedish conditions and showed that feeding management reduced the storage requirement.

For full-scale application of flexible feeding strategies, a process control system is needed to avoid process failures and associated economic losses. Several authors discussed control scheme design and control methods in relation to biogas process control. Methods range from classical control methods such as feedback and feedforward control to advanced model based and multivariable control systems [10–16]. Here the respective objectives are quite different and reach from stabilizing gas production to the prevention of disturbances by ammonia and acidification. Especially model predictive control (MPC) is designated for a targeting operation to future set points. MPCs use an internal dynamic model of the process, a history of past control moves and an optimization objective function over the receding prediction horizon to calculate the optimal control moves [17]. In literature, different complexities, tasks and applications as well as used model types for MPC can be found. Bernard [18] designed a model-based adaptive control (based on the Acidogenesis/ Methanogenisis Model (AM2) [19]) and a fuzzy controller to regulate the ratio of alkalinity below an assumed desired value to stabilize the process. Méndez-Acosta [20] regulated the VFA and total alkalinity by a model-predictive feedforward control by the input flow rate. Puñal [21] developed a fuzzy-logic-based control system for a fixed-bed anaerobic reactor to maintain the VFA concentration at a set point by manipulating the input flow rate. Haugen [22] uses a modified Hill-model for control of input flow of a UASB-Reactor.

Only a few studies [23–26] have investigated the use of the Anaerobic Digestion Model No.1 (ADM1) [27] as basis for the development of process observers or control procedures for a constant biogas production. However, currently there are no control concepts with the target to flexibilize the process and follow a fluctuating time table of energy demand. A biogas plant serving this flexible market in the future will need a control concept which offers a predictive reaction to future changes in demand. By nature this will also avoid additional investments in gas storage capacity by the evasion of excess gas production. The article at hand presents the validation of an MPC used to feed the process in order to follow a given gas utilization time table. The used model is based on the ADM1, which was substantially simplified. To evaluate the MPC, the DBFZ-research biogas plant and the research biogas plant at the University of Hohenheim were used.

The aim of the presented study was to

- investigate the general flexibility of the anaerobic processes applying typical substrates for German agricultural biogas plants (renewable energy crops and manure from animal husbandry) in full-scale and
- evaluate, how feeding and daily biogas production profiles can be predicted and controlled by MPC within the target to contribute to the flexibilization of electrical power production.

2. Materials and Methods

2.1 Model predictive Control

In Figure 12 the MPC control loop is shown. The procedure consists of an optimization module with an objective function and constraint equations (see subsection 2.1.1) and an internal process model (see subsection 2.1.2). The aim is to find the optimal sequence of substrate feeds $u(t+H_p)$ to keep the course of the gas storage filling level $e_S\,(t+H_p)$ within the set limits while following a demand-oriented gas utilization schedule $r_{gas}(t+H_p)$ in a prediction horizon H_p. The value e_S serves as control variable. The value is calculated with the predicted gas production values $\hat{y}$ and the hypothetical gas consumption r_{gas}. The current starting value $e_S(t)$ for the course of the gas storage filling level $e_S(t+H_p)$ at each optimization is calculated with the past values from the utilization schedule $r_{gas}(t-1)$ and the recent real gas production measurements $y_{gas}(t-1)$ from the plant by:

$$e_S\,(t) = e_S(t-1) + y_{gas}(t-1) - r_{gas}(t-1)$$

In dependence on the available measurements, the calculation should consider that a flexible feeding leads to a reaction in the gas quality (see [8]). Observed was a rising CO_2 content after feeding and according to the degradation a delayed methane production.

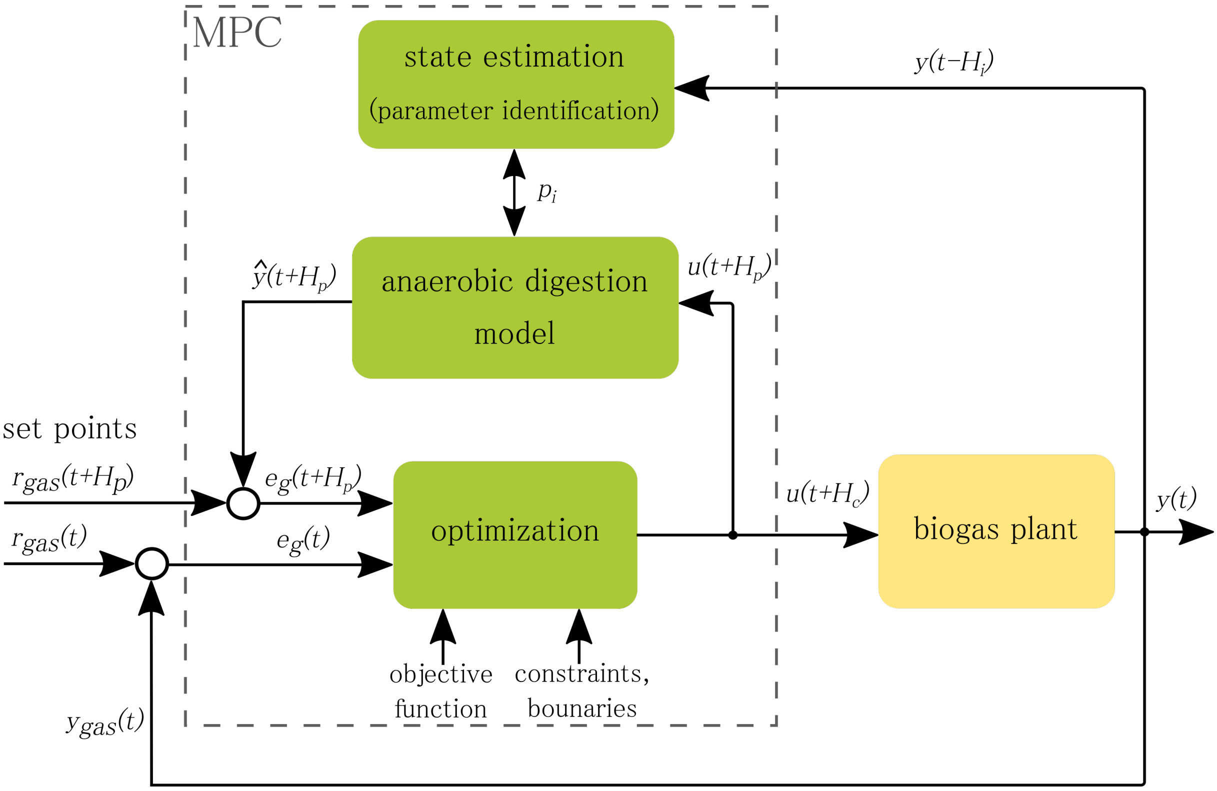

Figure 12: MPC control loop scheme for the calculation of the optimal feeding regime $r_{gas}(t+H_p)$ is the gas utilization timetable, H_i identification horizon, $\hat{y}$ are the predicted values, t is the time, p_i model parameters, u manipulated values, y measured values, H_p is the prediction horizon

In every control loop only a fraction $u(t+H_c)$ (in length of the control horizon H_c i.e. one day) of the total prediction horizon (H_p i.e. seven days) is applied. At time $t-1$ new measurements are collected and the optimization procedure was conducted for the next H_c. The model parameters p_i were identified on every MPC step for a set of real measured past process data in a receding identification horizon H_i (see subsection 2.1.2).

2.1.1 Optimization, objective function and constraints

The optimization objective of the predictive controller in Figure 12 is

$$\min_{u} f_{obj}$$

where the objective function is given by:

$$f_{obj}\left(H_p,H_c\right) = \sum_{j=t}^{t+H_p} w_{e_j} f_w(e_S) + \sum_{j=t}^{t+H_c} w_{u_j} \Delta {u_j}^2 \qquad where \quad t_s \ \leq \ H_c \ \leq \ H_p$$

The variable e_S is the calculated gas storage filling level along the predicted horizon (stepwise rated by weighing function f_w) and u_j is the j^{th} manipulated variable. t_s is the step size and H_c is the control horizon. The weighting coefficients w_{e_j} reflects the relative importance of u_j. w_{e_j} is the weighting coefficient penalizing big changes in u_j. The estimated course of the gas storage filling level$e_S(t+H_p)$ is calculated using the predicted biogas production $\hat{y}(t+H_p)$ and the biogas demand $r_{gas}(t+H_p)$ from the gas demand timetable. The resulting course of the storage filling level is rated by a weighting function $f_w(e_S)$, to control the influence of storage filling level on the feeding optimization. The used weighing function $f_w\ (e_S)$ is described by:

$$f_w\left(e_S\right) = \begin{cases} \frac{e_S}{V_{gas}} & if \qquad e_S > V_{gas} \\ \sum_{i=0}^{4} B_i \left(\frac{e_S}{V_{gas}}\right)^i & if \qquad \frac{V_{gas}}{2} < e_S \leq V_{gas} \quad or \quad 0 \leq e_S < \frac{V_{gas}}{2} \\ 0 & if \qquad e_S = \frac{V_{gas}}{2} \\ 1 + \frac{|e_S|}{V_{gas}} & if \qquad e_S < 0 \end{cases}$$

The parameter e_S represents the current gas storage filling level and V_{gas} is the given capacity of the gas storage. The coefficients B_0, B_1, B_2, B_3 and B_4 of the weighing function are given in Table 5. The function had a U-shape with a minimum at 0.5 storage filling level. The error values rise when the filling level runs near the upper (full) and lower (empty) storage boundary.

Table 5: Coefficients of the gas storage weighing function used in the MPC

	Coefficients for the weighing function depends on current level e_S	
	for $\frac{V_{gas}}{2} < e_S \leq V_{gas}$	for $0 \leq e_S < \frac{V_{gas}}{2}$
B_0	4,77169	0,99713
B_1	-31,92102	-9,37113
B_2	79,55245	34,96911
B_3	-87,77001	-59,82129
B_4	36,36364	38,92774

To find a minimum of the given optimization objective function the Matlab-solver *fmincon* was used. The aim is to minimize the function $f\left(u\right)$ regarding linear and non-linear constraints, specified by

$$\min_u f(u) \quad such\ that \begin{cases} \text{c(u)} & \leq & 0 \\ ceq\,(u) & = & 0 \\ A \cdot u & \leq & b \\ Aeq \cdot u & = & beq \\ lb \leq u & \leq & ub \end{cases}$$

The linear equalities and inequalities were used to force the substrate utilization A and Aeq are matrices with the dimension of the number of used substrates, feeding slots and number of fed fermenters. b and beq are vectors and define the maximum substrate amount allowed per fermenter within a certain time). Equalities are used to regulate which substrates can be used in Aeq up to the maximal amount beq. The inequalities regulate which substrates have been fed exactly. Hence, it is possible to force the daily usage of a certain amount of each substrate (i.e. cattle slurry), whereas others can be used only if necessary. The upper and lower boundaries (ub and lb) used to specify the maximal feeding velocity for each substrate at every feeding slot. Furthermore, the *fmincon* considers nonlinear inequalities c or equalities ceq. These are unused in the present application. Base-case parameters are given in Table 8.

2.1.2 Anaerobic digestion model

The utilized process model is based on the stoichiometric structure of the Anaerobic Digestion Model No.1 (ADM1, [27]). However, since the hydrolysis is the rate limiting process phase during the digestion of agricultural substrates and residues, the dynamic gas production of an uninhibited process can be entirely described by first-order kinetics [28]. In comparison to the complex ADM1, a reduced model based on first-order kinetics is numerically more stable, and the kinetic parameters can be identified more easily. Thus, following previous investigations of Weinrich and Nelles [28], the complex model structure of the ADM1 was simplified to simulate the anaerobic digestion of carbohydrates, proteins and lipids to biogas based on the superposition of first-order kinetics. Furthermore, the total input of particulate carbohydrates was split into a rapidly and slowly degradable fraction. The resulting differential and algebraic equations as well as the model parameters are shown in Table 6 and Table 7.

The characteristic kinetics constants ($k_{\text{ch,fast}}$, $k_{\text{ch,slow}}$, k_{pr}, k_{li}) as well as the substrate fraction of fast degradable carbohydrates (f_{ch}) of the resulting single-step model were continuously identified in a proceeding moving horizon H_{i}. Therefore, the difference between the measured and the predicted gas production was minimized by least square estimation (Matlab-solver *fminsearch*) to adapt the model dynamics inside the moving horizon [29].

Table 6: Differential and algebraic equations of the simplified anaerobic digestion model

Differential equations

$$\frac{dX_{ch,fast}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{ch,in}f_{ch} - X_{ch,fast}\right) - k_{ch,fast}X_{ch,fast} + 0.095\, k_{dec}X_{bac}$$

$$\frac{dX_{ch,slow}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{ch,in}\left(1 - f_{ch}\right) - X_{ch}\right) - 0.095\, k_{ch,slow}X_{ch,slow}$$

$$\frac{dX_{pr}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{pr,in} - X_{pr}\right) - k_{pr}X_{pr} + 0.77\, k_{dec}X_{bac}$$

$$\frac{dX_{li}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{li,in} - X_{li}\right) - k_{li}X_{li} + 0.04\, k_{dec}X_{bac}$$

$$\frac{dX_{bac}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{bac,in} - X_{bac}\right) - k_{dec}X_{bac} + 0.1125\, \left(k_{ch,fast}X_{ch,fast} + k_{ch,slow}X_{ch,slow}\right) + 0.1723\, k_{pr}X_{pr} + 0.2286\, k_{li}X_{li}$$

$$\frac{dS_{ch4}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{ch4,in} - X_{ch4}\right) - k_{La}\left(S_{ch4} - 16\, K_{H,ch4}p_{ch4}\right) + 0.2482\, \left(k_{ch,fast}X_{ch,fast} + k_{ch,slow}X_{ch,slow}\right) + 0.3221\, k_{pr}X_{pr} + 0.6393\, k_{li}X_{li}$$

$$\frac{dS_{co2}}{dt} = \frac{q_{liq}}{V_{liq}}\left(X_{co2,in} - X_{co2}\right) - k_{La}\left(S_{co2} - 44\, K_{H,co2}p_{co2}\right) + 0.6809\, \left(k_{ch,fast}X_{ch,fast} + k_{ch,slow}X_{ch,slow}\right) + 0.7954\, k_{pr}X_{pr} + 0.5817\, k_{li}X_{li}$$

$$\frac{dS_{gas,ch4}}{dt} = -\frac{q_{liq}}{V_{liq}}S_{gas,ch4} + \frac{V_{liq}}{V_{gas}}k_{La}\left(S_{ch4} - 16\, K_{H,ch4}p_{ch4}\right)$$

$$\frac{dS_{gas,co2}}{dt} = -\frac{q_{liq}}{V_{liq}}S_{gas,co2} + \frac{V_{liq}}{V_{gas}}k_{La}\left(S_{co2} - 44\, K_{H,co2}p_{co2}\right)$$

Algebraic equations

$$p_{ch4} = S_{gas,ch4}\frac{RT}{16}$$

$$p_{co2} = S_{gas,co2}\frac{RT}{44}$$

$$p_{gas} = p_{ch4} + p_{co2} + p_{h2o}$$

$$q_{gas} = k_p\left(p_{gas} - p_{atm}\right)\frac{p_{gas}}{p_{atm}}$$

Table 7: Kinetic and physico-chemical model parameters

Kinetic parameters and substrate fraction [a]					
		Research biogas plant A		Research biogas plant B	
$k_{ch,fast}$	$[d^{-1}]$	2.142 – 5.568		0.613 – 3.725	
$K_{ch,slow}$	$[d^{-1}]$	0.055 – 0.124		0.036 – 0.609	
k_{pr}	$[d^{-1}]$	0.462 – 2.477		0.383 – 1.281	
k_{li}	$[d^{-1}]$	0.123 – 0.695		0.286 – 0.986	
k_{dec}	$[d^{-1}]$	0.02		0.02	
f_{ch}	[-]	0.140 – 0.491		0.0 – 0.776	
Physico-chemical parameters (gas-liquid transfer) [b]					
P_{atm}	1.0133	[bar]	$K_{H,ch4}$	0.0011	$[mol\ l^{-1}\ bar^{-1}]$
P_{h2o}	0.0556	[bar]	$K_{H,co2}$	0.0271	$[mol\ l^{-1}\ bar^{-1}]$
k_p	10^5	$[l\ d^{-1}\ bar^{-1}]$	k_{La}	200	$[d^{-1}]$
Universal and system parameters					
T	311.15	[K]	V_{liq}	165 / 800	$[m^3]$
R	0.083145	$[bar\ l\ mol^{-1}\ K^{-1}]$	V_{gas}	43 / 123	$[m^3]$

a) Constantly adapted in a proceeding moving horizon (see chapter 2.1.2 in Article 2)

b) Calculated for mesophilic temperatures (311.15 K)

2.1.3 Practical implementation

The MPC procedure has been implemented in Matlab / Simulink R2014a software environment. All following experiments were performed on a 64-bit Intel(R) Core i5-3470 CPU@3.2GHz, 8 GB RAM computer with Windows 7 professional. For the following experiments, the prediction horizon (H_p) was set to 7 days, the control horizon (H_c) to 1 day and the sample time t_s to *48/d*. These values were identified in preliminary studies (not shown). For technical and safety reasons, the MPC system could not be integrated directly into the plant control system.

In the practical procedure the following steps were performed in each MPC-loop:

1. Selection of the process data up to the current time t from the plant control system.

2. Identification of the model parameters on a set of measured data from the biogas plant. The moving identification horizon H_i extends from t to $t - 20d$.

3. Calculating the current gas storage filling level based on the newly measured gas production rates (retroactive adjustment between measured and forecasted gas production in the period

of the recent MPC-increment.) The resulting value of the gas storage filling level is used as the new starting value of the next MPC loop.

4. The solution of the former optimization step is set with $N_c + 1$ as starting values for the optimization variable $u_0(t + H_c - 1)$. The starting values for $u_0(t + H_p)$ are set as the substrate demand required by the gas demand at this step.

5. Starting the optimization described in subsection 2.1.1.

6. Implementation of the found solution for the feeding regime only for the length of the specified MPC increment H_c; discarding the remaining solutions in the forecast horizon except for the use as starting values for point 5 in the next MPC step.

7. Moving to the next step of the MPC increment for a new optimization run (start the routine again at point 1.)

2.2 Evaluation of the accuracy of prediction

In the current study, the Predicted Residual Error Sum of Squares ($PRESS$) [30] is used to assess the model's predictive ability, i.e. between model prediction and practically measured course.

$$PRESS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

Thereby, y_i denote new observation values and $\hat{y}_i$ their predicted values. $PRESS$ is further used to calculate the R^2 of predicted values, which is the percentage of the response variable variation that is explained by a model.

$$R^2_{predict} = 1 - \frac{PRESS}{\sum_{i=1}^{n} (y_i - \overline{y})^2}$$

In addition, the standard error of the estimate σ_{est} is used to measure the accuracy of predictions. $\overline{y}$ is the mean of the measured values. The calculation is comparable to the parameter variance, but σ_{est} is the standard deviation of the errors of prediction.

$$\sigma_{est} = \sqrt{\frac{\sum (y - \hat{y}_i)^2}{n}}$$

The value y represents the actual measured score, $\hat{y}_i$ the predicted score and n is the number of pairs of scores.

2.3 Experimental Setup, analysis and input substrates

2.3.1 Research biogas plant A (DBFZ)

The research biogas plant is located at the institute site of the DBFZ in Leipzig (Germany). The main digester used in this study has a volume of 208 m^3. For piping- and instrumentation diagram of the used components, see Figure 13a. The digesters are equipped with a central agitator and a fixed flat ceiling. During experiment 1 (DBFZ research biogas plant), liquid cattle manure and maize silage were used. The liquid cattle manure was fed every night in a fixed amount of 2 m^3 d^{-1}. The amount of maize silage was calculated daily by the MPC. The experiment consisted of a startup-phase from the 1^{st} to 3^{rd} month followed by the testing-phase of the MPC in month 4. In this paper only the 4^{th} month of the experiment was chosen for detailed examination and for the evaluation of the MPC procedure. The OLR and the composition of the used substrates are given in Table 8.

2.3.2 Research biogas plant B (Unterer Lindenhof)

The second experiment was carried out on the full-scale research biogas plant of the University of Hohenheim. The plant is located at Eningen u. Achalm/ Germany. One of two continuous stirred tank reactors (CSTR) with 923 m^3 digester volume was used in this study. The technical design of the biogas plant and the equipment are shown in Figure 13b and Table 8. The solid substrate was supplied by a vertical mixer system in a cross-flow grinder disintegration unit (Bio-QZ, MeWa, Gechingen, Germany) and subsequently fed into the digester. Digester one is equipped with a submersible motor mixer (4670, ITT Flygt AB, Sweden) and a propeller incline shaft agitator (Biogator HPR 1, REMA, Germany) to ensure a uniform distribution of the feed and heat and to enable gas lift from the fermenting substrate [32]. Further details of the plant configuration can be found in [31]. A mixing time of two minutes prior and post feeding was set while continuous mixing was applied during the feeding process using both mixing devices. After the feeding cycle, continuous mixing by using the propeller incline shaft agitator set to 60 % of its maximum power was applied. The substrates fed to the biogas process were weighed by the vertical mixer feeding system or measured with a flow meter.

To minimize overlaying affects in the biogas quantity measurement by pumping, the discharge of digestate was carried out only once a day before the feeding started. Prior to the experiment the plant was operated with liquid cattle manure, maize silage, grass silage and ground wheat grain at an organic loading rate (OLR) of 2.2 $kg_{VS}\ m^{-3}\ d^{-1}$. The substrates chosen for the experimental phase were maize silage (35 %), grass silage (50 %) and ground wheat grain (15 %) because of their different degradation kinetics. The OLR and the composition of the used substrates are given in Table 8. The experiment started after a phase of 75 days of adaptation to substrates and discontinuous feeding (from feeding every two hours throughout the day to compressed feeding of the total daily amount within few hours). This phase was followed by 35 days of testing the

MPC procedure for flexible biogas production. During week 1 and 4 the plant was intensively supervised and sampled.

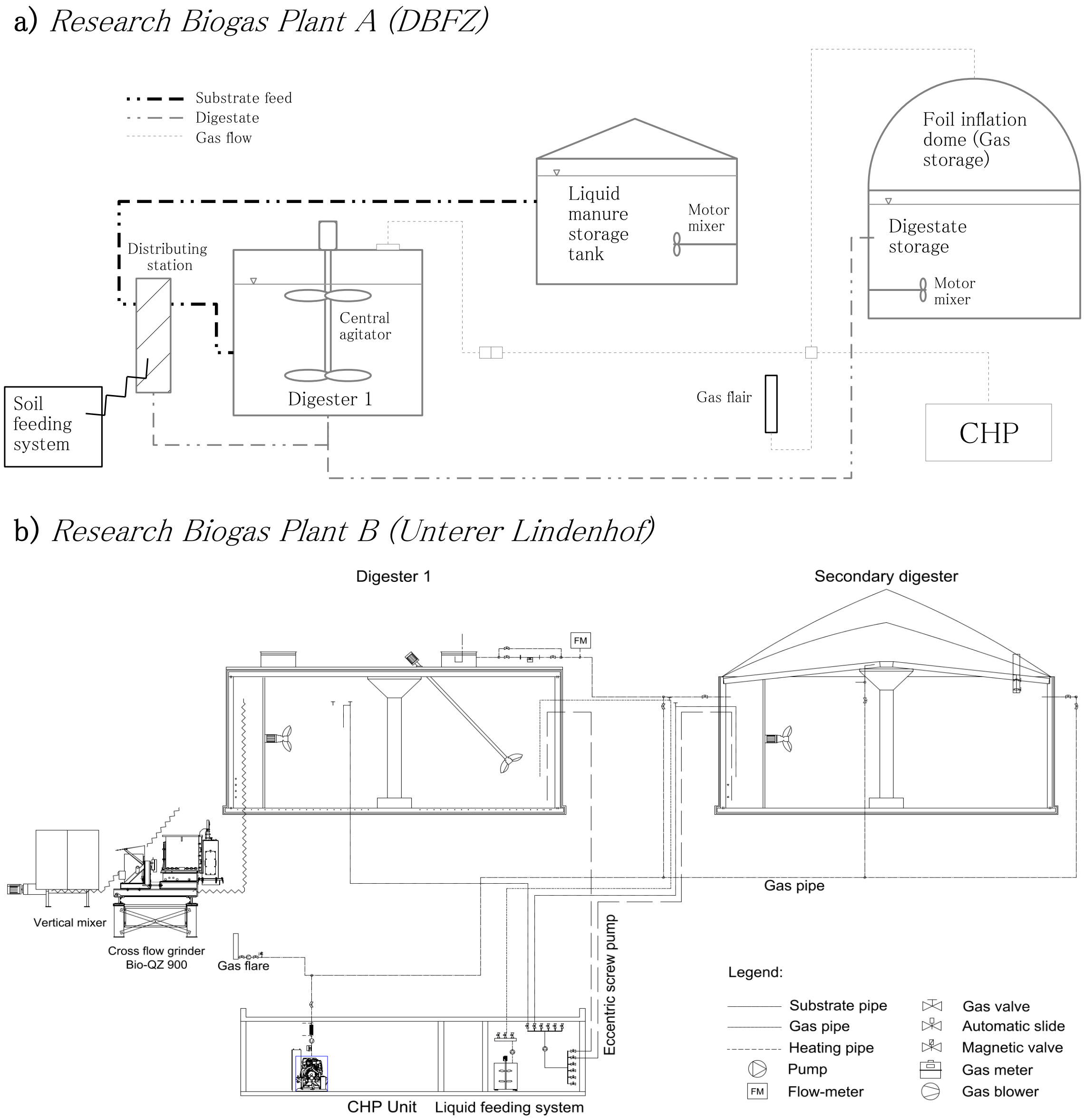

Figure 13: Piping and instrumentation diagram of the investigated research biogas plants (with simplified piping ways and without illustration of other fermenters and feeding systems which were not included in the present investigation) **a)** DBFZ- research biogas plant (Plant A); **b)** Research biogas plant of the University of Hohenheim (Plant B)

Table 8: Overview of the general experimental setup and composition of the used substrates

			Research biogas plant A		Research biogas plant B		
Total digester volume		[m^3]	208		923		
Effectiv net volume	V_{liq}	[m^3]	165		800		
Operating temperature	T	[°C]	38 ± 1		40.5 ± 1		
Organic loading rate		[$kg_{VS}\, m^{-3}\, d^{-1}$]	4.0		2.8 - 3.5		
Substrate composition			Cattle liquid manure	Maize silage	Maize silage	Ground wheat grain	Grass silage
Dry matter	DM	[$g\, kg_{FM}{}^{-1}$]	69	333	395	886	449
Organic dry matter	VS	[$g\, kg_{DM}{}^{-1}$]	721	963	986	975	960
Ash		[$g\, kg_{DM}{}^{-1}$]	279	37	14	25	40
Crude protein		[$g\, kg_{DM}{}^{-1}$]	147	67	35	118	49
Crude lipids		[$g\, kg_{DM}{}^{-1}$]	3	8	15	19	14
Crude fiber		[$g\, kg_{DM}{}^{-1}$]	247	267	67	28	127
Nitrogen free extracts		[$g\, kg_{DM}{}^{-1}$]	324	621	869	810	770
FM: *fresh matter*							
Control parameter							
Weighting coefficient	w_e	[-]	1		1		
Weighting coefficient	w_u	[-]	0.2		0.2		
Assumed gas storage capacity	V_{gas}	[m^3]	296		922		
maximal feeding velocity	$q_{in.max}$	[$kg\, min^{-1}$]	60		60		
Maximal daily substrate amount for:	b, beq						
maize silage		[$kg\, d^{-1}$]	2000		3000		
Cattle liquid manure		[$kg\, d^{-1}$]	1000		-		
Grass silage		[$kg\, d^{-1}$]	-		4000		
Ground wheat grain		[$kg\, d^{-1}$]	-		750		

2.3.3 Analysis at plant A and B

At the research biogas plant A the gas production was measured by a dynamic pressure probe sensor (S.K.I. Schlegel & Kremer GmbH, Germany). The values were corrected to standard temperature and pressure conditions. Several times a day the biogas composition (CH_4, CO_2, H_2S, H_2, O_2) was measured with an AWIFLEX gas analyzer (Awite Bioenergy GmbH, Germany). At the research biogas plant B the biogas production of digester one was recorded continuously with a gas flowmeter (GD 300, Esters Eletronik GmbH, Rodgau, Germany). The gas yields were corrected to standard conditions (0 °C, 1013 hPa and dry gas). The biogas quality (CH_4, CO_2, H_2S, O_2) was determined automatically every hour by a multisensor analyzing system (INCA 4000, Union Instruments GmbH, Karlsruhe, Germany). At both plants the samples of input substrates and digestate were taken twice a week and analyzed both for dry matter (DM) and organic dry matter (VS). The digestate was analyzed in addition for pH, volatile organic acids in relation to carbonate buffer (FOS/TAC), salinity, NH_4-N as well as volatile fatty acids (VFA) content according to standard methods [33]. The composition of substrates was analyzed in both plants by Weender and van Soest method [33].

2.3.4 Reference scenario

For better comparison of the results, a reference scenario for the gas utilization was defined. Therefore, an average week schedule was determined by 2013-data from the EPEX (European Power Exchange SE). Thereby, the daily duration and timing of the combined heat and power unit (CHP) is sorted by price rank to high priced hours. It was assumed that the installed capacity of the CHP was doubled (double of the average amount of gas provided by the biogas plants). The schedule (Table 9) is used replicated in all following experimental procedure as reference.

Table 9: Weekly schedule of the reference scenario used in the experiments

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Utilization times [hh:mm]	7:00 – 15:00	7:00 – 14:00	7:00 – 15:00	7:00 – 14:00	7:00 – 14:00	9:00 – 12:00	11:00 – 12:00
	16:00 – 22:00	15:00 – 22:00	16:00 – 22:00	15:00 – 22:00	16:00 – 23:00	17:00 – 23:00	17:00 – 00:00
						0:00 – 1:00	

3. Results and discussion

3.1 Research biogas plant A

The course of the gas production rate by the flexible feeding is given in Figure 14. The results show that by flexible substrate feeding, the daily gas production rate can be modulated between a min / max ratio of up to 50 % (e.g. day 25 with min/max values of 18 m^3 h^{-1} and 38 m^3 h^{-1}). By specific reduction of feeding amount the gas production rate can be reduced even further compared to the average gas production rate. This results in high intraday flexibility between 30 - 130 % of the average gas production.

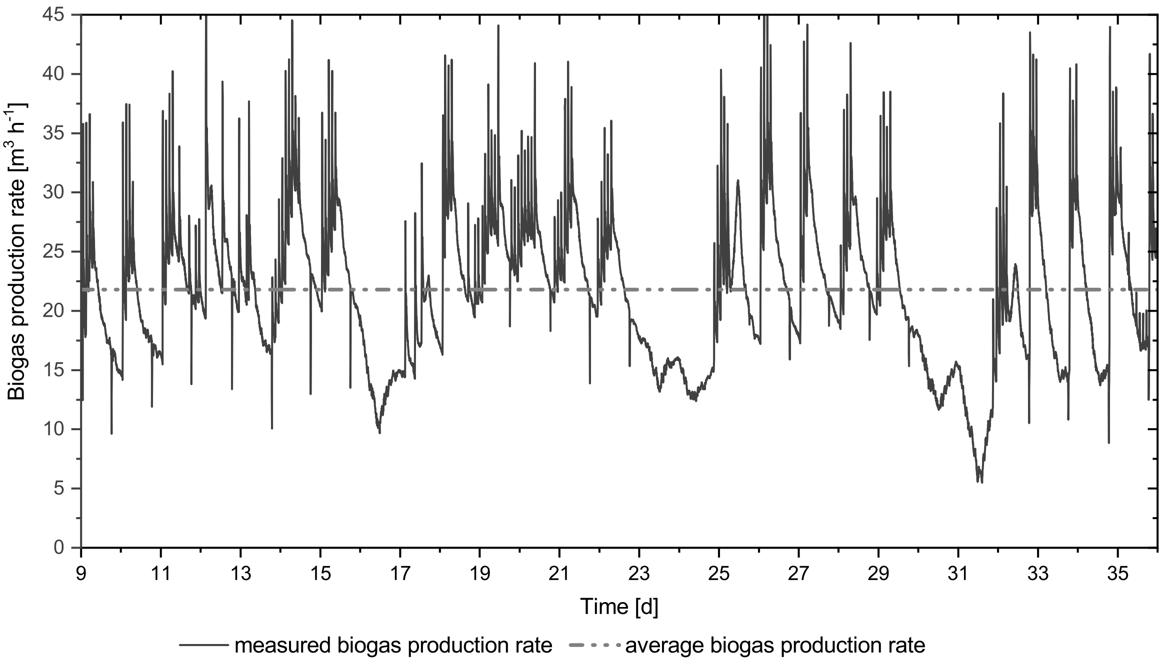

Figure 14: Flexible gas production at the research biogas plant A performed by the model predictive control

Figure 15 illustrates the results of a reference period (day 19 to 29) to demonstrate the model predictive control procedure. Figure 15a shows the results of a prediction run from the 20^{th} day on. The MPC predicted courses of the feeding regime and gas production over the prediction horizon of 7 days are presented.

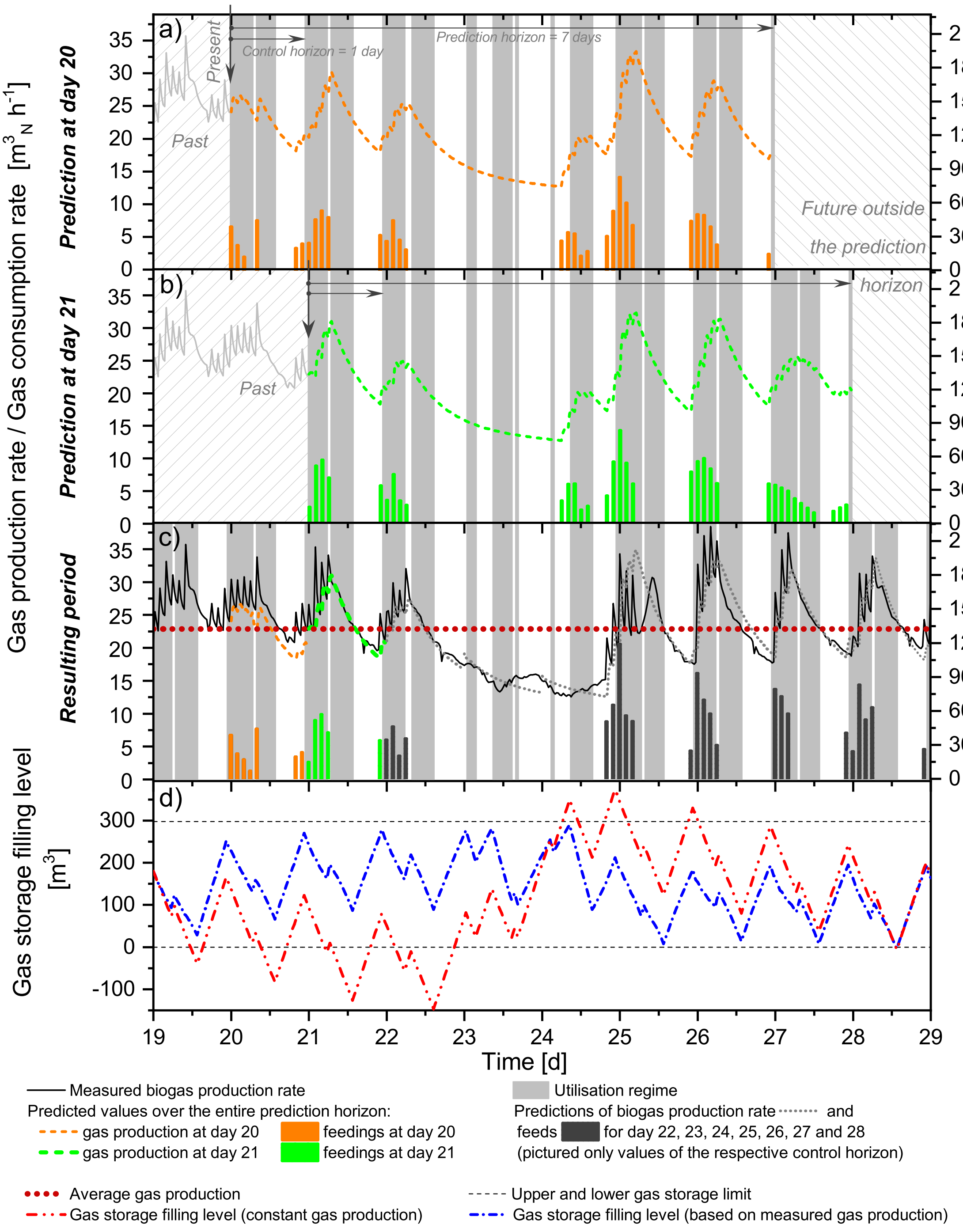

Figure 15: Results of the research biogas plant A.: **a)** Course of the prediction (gas production and feed) beginning at day 20 of the experiment; **b)** Prediction and optimization results (gas production and feed) in the next step 21; **c)** Implemented results compared to the respective predicted course (only the first day of the respective prediction horizon is shown); **d)** course of the theoretical gas storage filling level based on flexible and continuous gas production

The objective was to hold the course within the limits of gas storage filling level and to meet the targeted utilization schedule disclosed in the prediction horizon. Only the feeding regime for the length of the control horizon ($H_c = 1\ day$) is implemented and the algorithms progress one H_c-step forward. The daily optimization took place on the basis of available data from the previous day, according to the procedure of steps 1 - 8 (See chapter 2.1.3). Figure 15b illustrates the results of the prediction at day 21. The comparison of Figure 15a and b shows only little changes in the predicted values. Figure 15c shows the total utilization regime, the measured gas production, the daily, newly predicted gas production and the feeding results. For better clarity only the first steps in the length of $H_c = 1\ day$ of the respective prediction horizon are shown.

The predicted values in Figure 15b in the period between days 27 and 28 differ significantly from the predicted values shown in Figure 15c. In the optimization step (Figure 15b) the limits are being observed and thus the solver is stopped (i.e. from the view of day 21 no further optimization is needed). In the moving optimization progress from day 21 to 27 the deviation is reduced more and more, the closer the day comes. With the progress of the experiment and the daily recalculation of the day, only small changes to the prediction of the following day can be observed. At day 21, 22, 27 and 28 a high correlation of predicted and actually measured gas production are evident (σ_{est} is lower than 10 %). During periods of decreasing OLR and a reduction of the gas production rate (day 23 and 24) the σ_{est} is higher (15 and 17 %). As well, during the phase of increasing OLR at day 25 and 26 the σ_{est} is even higher (20 % and 18 %). Also, after the increasing OLR at day 24 and 31 a delay is observed (Figure 14). Obviously, the predictability of the used first-order model reaches its limits during such dynamic states.

Figure 15d illustrates the course of the resulting gas storage filling level based on the measured gas production (black dotted line). The grey dotted line symbolizes the gas storage filling level of a theoretically continuous gas production. The upper and lower limits (assumed safety limits) of the gas storage are shown by black dashed lines. A gas storage capacity, capable of storing continuously produced biogas for 11 h was presumed. The virtual filling level of the gas storage was calculated by summing up the produced gas according to the measurements from the experiment and subtracting the presumed amounts of gas used during power production periods at half hourly intervals. The average gas production of this week (day 19 – 29) is defined as the theoretical continuous gas production shown in Figure 15c (large light gray dots). Constant gas production requires a much higher gas storage volume, if the same utilization regime is applied. This can be observed in Figure 15c, where the limits of the storage tank are exceeded. It was found that for the investigated scenario the gas storage demand necessary to fulfill the utilization regime can be decreased by more than 45 % by the flexible, controlled gas production with maize silage as compared to continuous gas production.

3.2 Research biogas plant B

Figure 16 shows the course of the measured gas production of four experimental weeks at research biogas plant B. By the intraday shift of feeding and the combination of fast and slowly degradable substrates the gas production rate could be modulated in a range of 65 to 115 m^{-3} d^{-1}. At day 106 the variation in the gas production rate could be lowered to a level of 20 % (35 m^{-3} d^{-1}) of the average rate (80 m^{-3} d^{-1}) by reduced and omitted feedings.

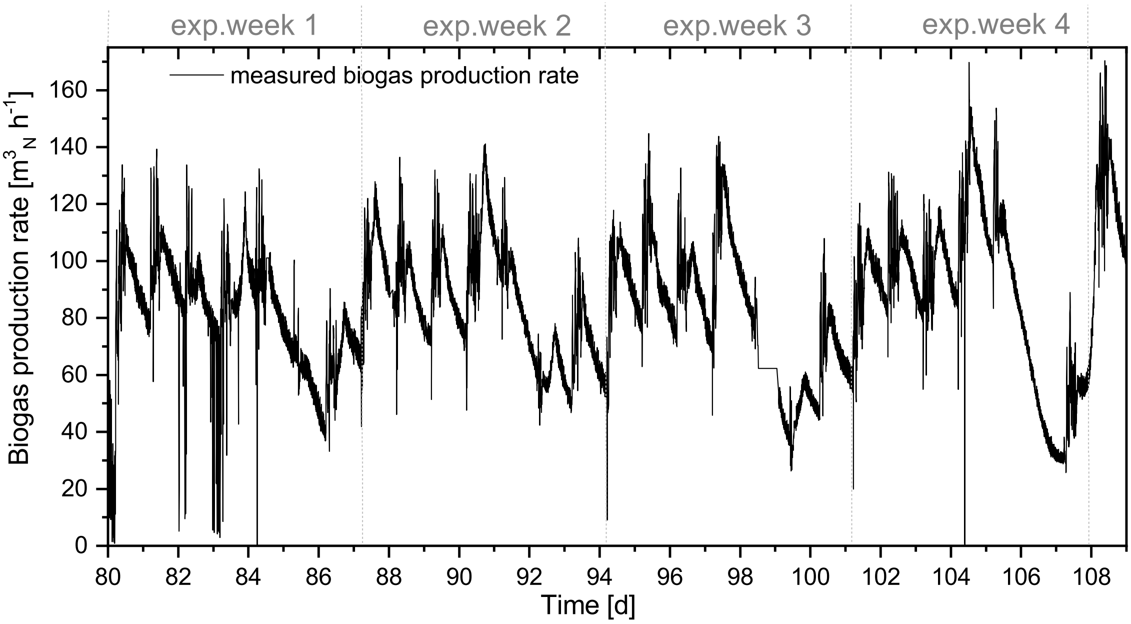

Figure 16: Results of measured gas production rate at research biogas plant B within four experimental weeks

Figure 17a illustrates real measurements compared to the daily predicted gas production rate and the targeted utilization regime (grey bars) for the first experimental week at research biogas plant B. Only the first day of each prognosis is depicted, as the prognosis and the schedule were updated daily. During the first three days a high correlation between predicted and measured gas production rate was observed (R^2 0.71 and 0.64 and σ_{est} = 11 % and 6.3 %). Taking into account that the model prediction does not reflect effects, like pressure fluctuations by feeding or digester mixing, these are high values for the predictability. More important is, though, that the gas storage limits were not exceeded during regular operation.

During day 82 and especially at day 83 a strong delay in gas production is observed. The gas production decreased and differed from the respective prediction. This may be attributed to a disturbance of the biological process reaction that deviated from the prediction by the model.

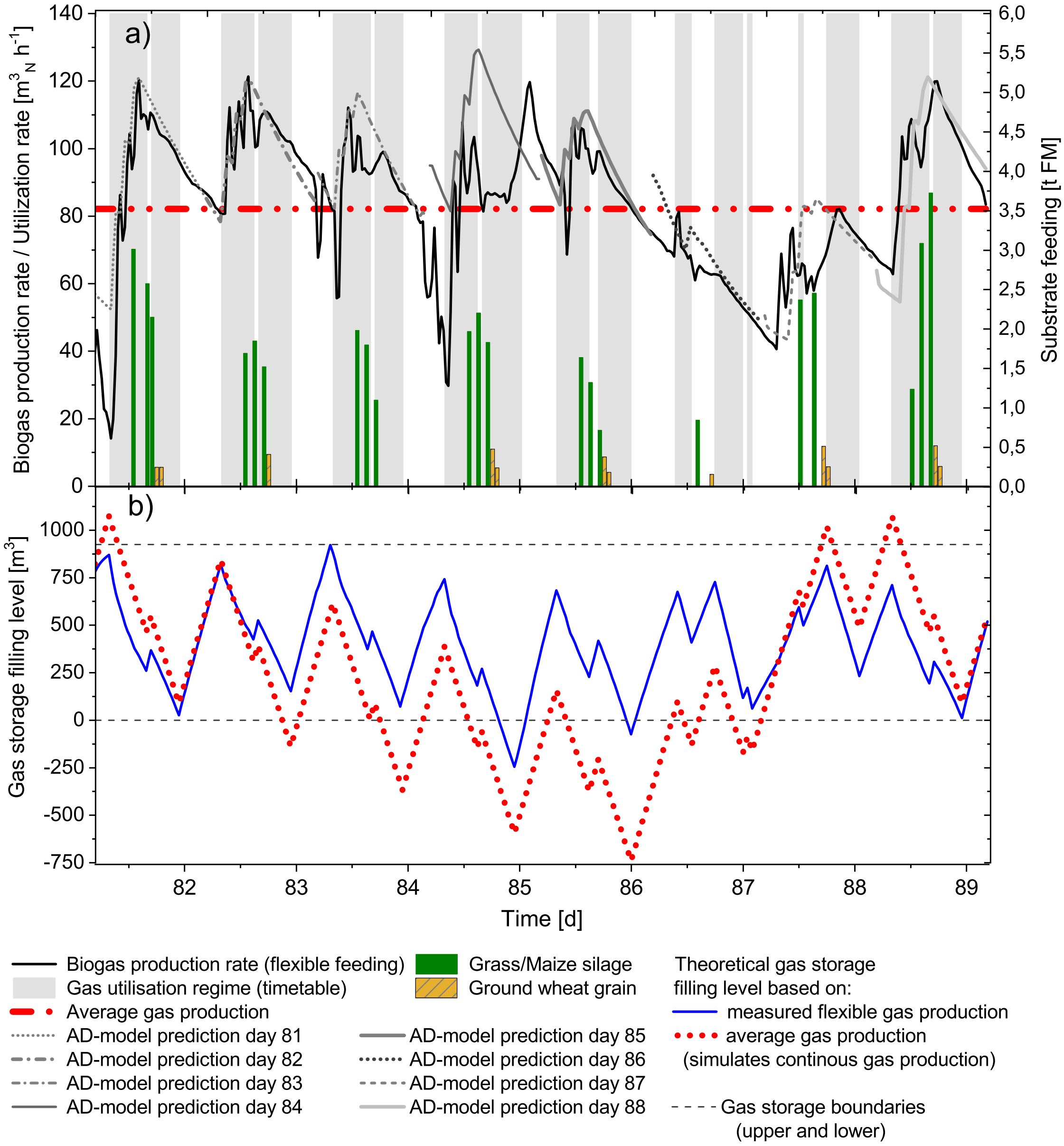

Figure 17: Flexible biogas production at research biogas plant B on experimental week 1. **a)** Measured gas production rate of one week compared with the daily forecasts within the model predictive control of the particular day. **b)** Course of the theoretical gas storage filling level based on flexible and continuous gas production.

Anyway, this assumption could not be confirmed by an increased acid production in the process. The measurements of the VFA at day 82, 83, 84 and 85 show concentrations in a typical range of 1,271; 1,189; 903; 1,082 mg l^{-1} far below a limiting value of $< 2{,}500$ mg l^{-1} [25]. Another assumption is an offset in gas production measurement leading to incorrect values that do not reflect the real biogas volume produced. As a reaction, the MPC tried to compensate this difference by increased feeding amounts. This action has not lead to an expected increased measured gas production. Additionally, a strong noise was additionally observed during the days 82 to 84 with interruptions of the gas measurements (see Figure 17). After sensor maintenance at day 84 the noise and deviation between measured and predicted gas production decreased.

This example shows that failures of measurement devices cannot be considered by the control. However, such unexpected differences between predicted and measured values might be used as additional warnings for either technical failures or imbalances of the biological process. For any calculations in times of technical malfunctions and sensor cleanings the average between the last accepted value before and the first measured value after interruption were used. However, the weekly sum of the biogas utilization amounts 14,080 m^3 and the measured gas production with 13,393 m^3 leaves a gap of only 4.9 %. Thus, in the weekly range the deviation could be balanced by the control.

Figure 17b illustrates the effect of flexible compared to constant gas production regarding gas storage demand (average gas production in this week is assumed as a theoretical continuous gas production). It shows the course of the resulting gas storage filling level, when following the same gas utilization regime and depicts the upper and lower limit of the gas storage. The lack of gas production in the utilization phase at day 84 and 85 lead to a calculated drop below the given gas storage limits down to -27 % related to the storage capacity 922 m^3 (Figure 17b). A constant feeding regime (simulated by the average gas production) required a significantly larger gas storage volume, if the same utilization regime would be realized. Accordingly, the gas storage demand could be decreased by the flexible, controlled gas production by over 30 %, despite the disturbance at day 84.

Figure 18a illustrates the real measurements compared to the daily predicted gas production rate and the targeted utilization regime analogous to Figure 17 for the second experimental week. At day 91, a short-term demand adaptation from electricity grid-site was simulated by extending the Friday-demand block (see Table 9) by 3 hours of gas consumption time. The optimization run when the change was introduced to the MPC 12h before the prolonged gas consumption was to take place. The MPC adapted the regime significantly (daily total amount of maize / grass silage from 6,200 kg to 7,600 kg, ground wheat grain was already at maximum daily amount). The discrepancies between predicted and measured gas production ranged from 4 to 9 %. The weekly sum of the gas utilization amounts (14,320 m^3) and the measured gas production (14,482 m^3) corresponds very well (only 1.2 % deviation).

Figure 18b depicts the comparison between the gas storage demands based on measured flexible gas production and the average gas production in this week.

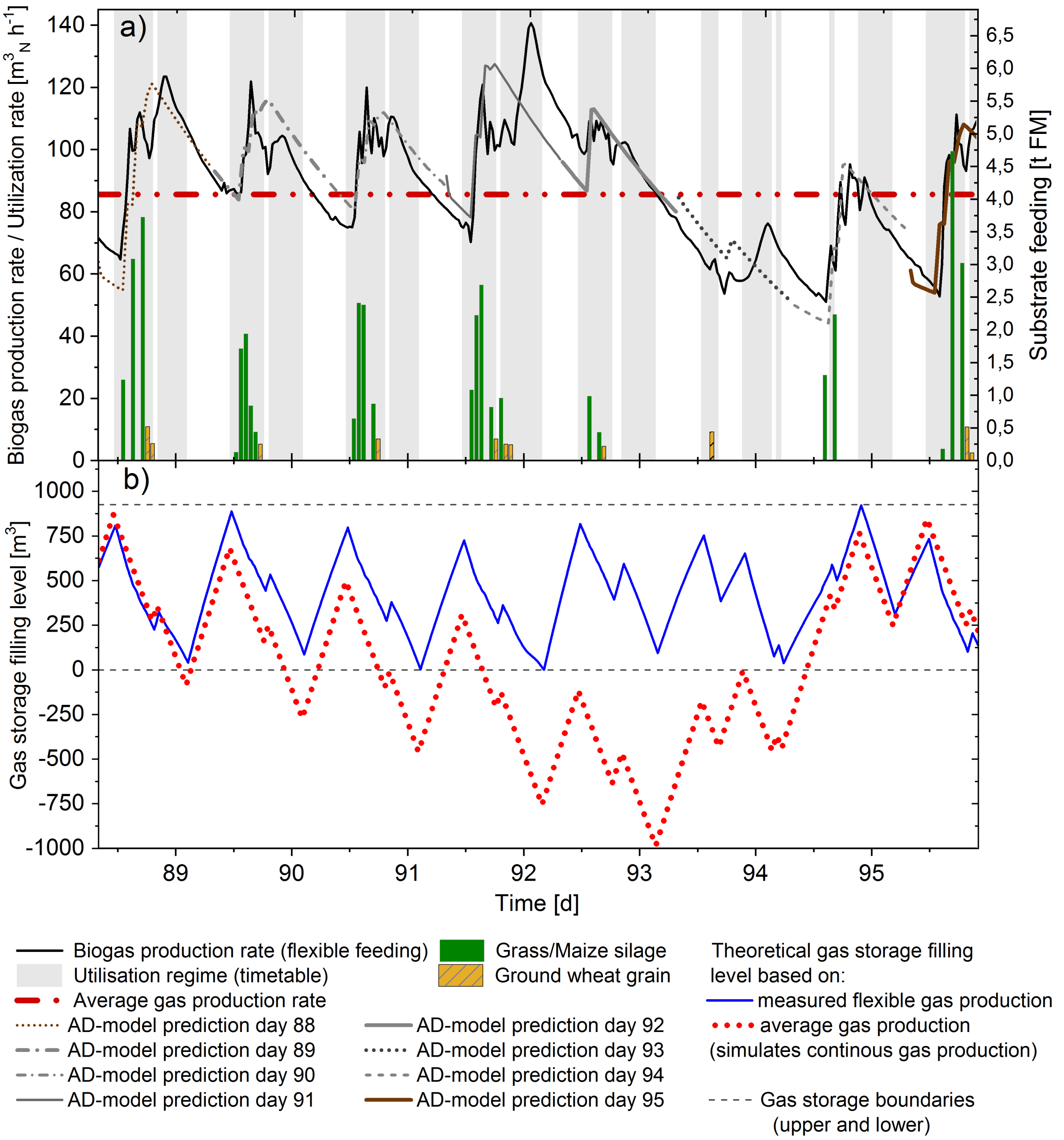

Figure 18: Flexible biogas production at research biogas plant B on experimental week 2. **a)** Measured gas production rate of one week compared with the daily forecasts within the model predictive control of the particular day. **b)** Course of the theoretical gas storage filling level based on flexible and continuous gas production.

In the second experimental week, the gas storage filling level could be held within the given gas storage limits (Figure 18b), despite the delays in the gas production on day 91 and 93. Compared to a constant feeding regime (simulated by the average gas production) the gas storage demand could be decreased by the flexible, controlled gas production by over 42 %, if the same utilization regime would be realized. In general the full-scale experiments at plant A and B showed a high intraday flexibility between 30 - 130 % of the average gas production with at the same time high process stability in reaction to pulse feeding.

The possibility of flexible gas production as observed in laboratory trials [8] could be verified in full scale. However, the delay effects in the gas production rate could not be observed in the laboratory trails for flexible feeding, described in [8]. The different reactions between plant A and B might be attributed to their specific technical setup and volume. The delay in gas production could be caused by the different agitation systems and intensities of mixing (Plant A with a central agitation and Plant B with different paddle mixers). The results point out the importance of scale and hydrodynamics for modeling anaerobic digester performance. Particularly the rheology in practical biogas fermenters is often not optimal. This can lead to slower process dynamics. As there is also a different setup of feeding systems, this may have an influence, too. Therefore, investigations of substrate and intermediate distribution should be carried out at both fermenter types to verify the influence of technical setup on digester performance. All in all, the technical equipment had to ensure a fast and complete distribution of the substrates. These turns out often to be the limiting factor in the flexible production of biogas. Moreover, the expansion of anaerobic models with the effects of mixing and liquid flow processes need to be pursued [34–36], e.g. with computational fluid dynamics (CFD).

In both experiments the process could be predicted sufficiently by the AD-model. Disturbances and measurement errors in the gas production could be mainly counteracted by re-optimization. However, in dynamic phases (i.e. Plant A at day 25 and plant B at day 84 and 91) the predictability of the process by means of the first-order model reaches its limits (non-included effects by intermediates and inhibitions). The biological, hydrodynamic and scale effects in the experiments will be addressed in further research. It has to be stated that the selected step size and model complexity represented a good compromise in terms of forecast accuracy. However, further experiments with shorter MPC iterations (smaller than two hours) need to be carried out and a cascading control (e.g. sub process of mixing, short and long time optimal feed) should be implemented with state estimation (regarding the robustness against disturbances or noise in measured data). Therefore, additional feedback values (e.g. biological or technical parameters), other model complexities and adjusted parameter identification strategies should also being tested. Further research should aim at overall plant models, which include all fermenters and describe the dynamics in gas storage and CHP-unit for new demand-driven operations. This contains multi-objective optimization algorithms for additional control variables, for example, combined electricity and head utilization timetables and efficiency optimization.

4. Conclusion

This paper demonstrates that with a model predictive control, full-scale biogas plants are capable of highly flexible biogas production for demand driven electricity production. Considering the original dimensioning of farm-scale biogas plants, the gas storage savings and the attained process dynamics enable an enormous potential for a demand-driven biogas production (45 % saving of gas storage capacity at research biogas plant A and 42 % at research biogas plant B compared to a constant gas production).

In summary, it can be stated that

- The biogas process could be performed highly flexibly,
- A prediction of biogas production by means of simplified dynamic models was possible,
- Optimization of feeding could be implemented using dynamic models in a model-based control
- A flexibly controlled biogas plant significantly increases the potential savings in required gas storage and provided a much higher flexibility towards a constant gas production rate.

Acknowledgements

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Article 3: Expanding the flexibility of biogas plants - substrate management, schedule synthesis and economic assessment

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Tino Barchmann [a], Eric Mauky [a, b], Martin Dotzauer [a], Mathias Stur [a], Sören Weinrich [a, b], H. Fabian Jacobi [c], Jan Liebetrau [a], Michael Nelles [a, b]

[a] Department of Biochemical Conversion, DBFZ - Deutsches Biomasseforschungszentrum, Torgauer Straße 116, D-04347 Leipzig, Germany

[b] Faculty of Agricultural and Environmental Sciences, Chair of Waste Management, University of Rostock, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany

[c] Hessian State Laboratory, Fachgebiet IV.5.3 renewable energies, Schubertstraße 60, 35392 Gießen

Abstract Since the amendment of the German Renewable Energy Act (EEG) in 2012 as well as in the current version (EEG 2014), the parameters for the expansion of renewable energies aim for their stronger market integration. Here biogas plants represent a promising option to produce demand-driven energy to compensate differences between energy demand and energy supply caused by irregular sources (e. g. wind and solar). The contribution focuses on the economic assessment of the flexible biogas production by specific feeding in comparison to continuous gas production against the background of a flexible conversion of biogas into electrical power. The required additional demand for gas storage capacity of a model biogas plant is determined by combinations of different feeding regimes and by three optimized power generation schedules. Subsequently, a cost-benefit analysis is conducted to assess the substrate management economically. The developed methodology is especially designed for existing plants and is used for assessing a multi-factorial substrate management as flexibility option. The results show that substrate management is increasingly appropriate to reduce the additional demand for gas storage especially for longer-term planning horizons (above 12 h) regarding schedule organization. Moreover, the flexible operation allows generating higher marketing revenues on the European

Power Exchange (EPEX Spot SE) at low additional costs.

Keywords: Biogas, flexibilization, substrate management, feeding management, double membrane gas storage, economic efficiency, demand driven operation

1. Introduction

In an energy system characterized by fluctuating renewable energies, it is becoming increasingly important to balance the fluctuation of supply and demand through flexible options within the electricity system. "Flexibility can generally be defined as using different technologies to balance the divergence of energy supply and energy demand with respect to time and space"[1]. For example, in terms of demand, energy consumption can be controlled and demand can be transferred to times of low load (demand-side management). With respect to supply, additional storage capacities can be created or the operation of power generation plants can be adjusted, i.e. the quantity of the supplied electricity can be tailored to meet demand [1]. Of the available renewable energy technologies, geothermal plants, hydropower stations, bioenergy plants in general, and biogas plants, in particular, currently enable electricity production to be controlled. Biogas plants can sell electricity on the EPEX Spot SE as well as provide system services such as control energy. For example, the German market for control energy (as a system service for the transmission system operators) encompasses P = 833 MW for primary operating reserves, around P = 2,000 MW for positive and negative secondary operating reserves each, and P = 1,700 MW for negative and P = 1,500 MW for positive tertiary operating reserves [2]. The flexibility bonus was implemented only for biogas plants as part of the 2014 Renewable Energy Act in order to incentivise existing plants to provide demand-oriented electricity production. Thus, the question arises as to the flexibilization options that would optimally integrate biogas plants into the evolving energy system in a technical and economical way.

The potential flexibilization of the plant is determined by the properties of a plant's components. Possible flexibilization options along the entire production chain are illustrated in Figure 19. One way to flexibilize existing plants is to specifically influence the biological degradation process through feeding management (Figure 19, A). At the moment, large-scale feeding adjustments are made on a seasonal and monthly basis with the aim of stabilising biogas production and adjusting to seasonal substrate availability and heat sinks [3]. Varying feeding levels and specifically combining different degradable substrates have yet to be used on a large scale. Müller et al. [4] demonstrates in lab scale experiments that a standard load profile (SLP) can be simulated using variable stillage (residual from ethanol production process) feeding. However, stillage is not a very typical substrate for biogas plants. Varying the amount and composition (separating into substrates that degrade quickly, moderately and slowly) in the co-fermentation of sugar beet silage, maize silage and cattle manure was studied at lab-scale by Mauky et al. [5]. This revealed that gas production is a highly dynamic process (minimum to maximum is 1 to 3) while, at the same time, being a stable process. Further experiments were able to verify process stability for flexible substrate feeding on full-scale [6]. There was a considerable reduction in the need for additional gas storage capacity (gross storage volume) up to 45 % when feeding was flexible.

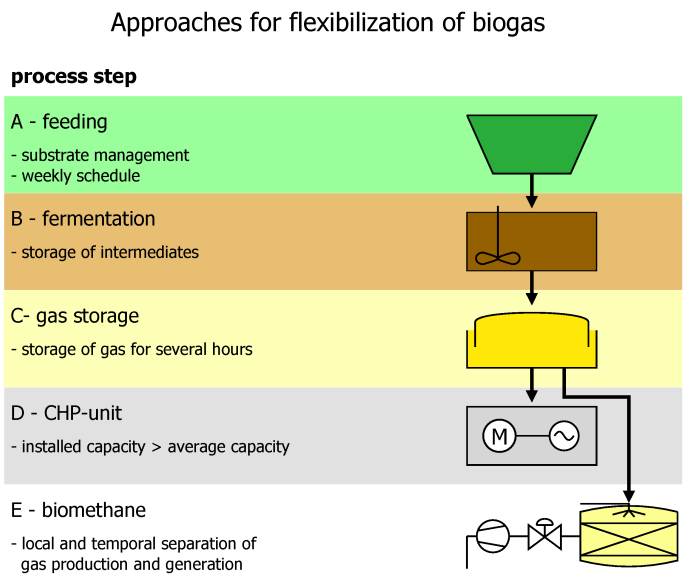

Figure 19: Approaches for flexibilization of biogas

Fermentation/gas production (Figure 19, B) in agricultural biogas plants in Germany is usually done in a continuous stirred-tank reactor (CSTR) followed by a plug-flow reactor (PFR) [7]. The CSTR is considered to be technically straightforward. PFRs have a better utilization rate and operate with much higher organic loadings rates. Other possible methods are two-step configurations (e.g. batch/fixed-bed concept by Gicon [8] ore hydrolysis/CSTR-configuration [9]). Another configuration that has already been tested in lab-scale is described by Wallmann et al [10] and Ganagin et al [11]. It has a continuous upstream hydrolysis step that is followed by methanation in a fixed-bed reactor. The organic acids that form in the separate hydrolysis step are dissolved in a percolate and stored in a buffer tank. From there, the acid-rich percolate is fed to the fixed-bed methane reactor. This enables high load change capabilities and low disturbance vulnerability. One advantage of the two-step fermentation process is that, in the methanation step, biogas production can be disrupted for several days and then started up again in a few hours. It should be noted, however, that this process requires considerable investment and a high technical/equipment outlay. Today gas storage (Figure 19, C) is typically a major component in flexibilizing biogas plants. Different types of gas storage designs are used. Local gas utilization (Figure 19, D) at the site where the biogas is produced is the most frequent form in use. Here, combustion engine-based conversion aggregates are used. The response qualities and the load charge stability of these aggregates play a very crucial role in adjusting power generation to meet demands. Additional combined heat and power units are needed in order to concentrate power generation within short periods of time. Another way to utilize biogas is to purify it into biomethane and to feed this into the natural gas grid (Figure 19, E). This decouples generation and utilization with respect to time and space. The natural gas grid acts as a storage unit which, in the context of flexibilization, achieves a strong time-related decoupling of gas production and gas utilization. These complex ways of flexibilizing plants face a variety of demands made by the energy system. The demands for flexibility differ, for example, depending on the different timescales. Usually the frequently communicated demand for flexibility in the electricity sector focuses on real-time or short-term needs. This corresponds with the control energy, intraday and spot markets. Time-related demands made on energy producers are defined in terms of this window of time if they wish to participate in these markets. Figure 20 lists the mandatory deadlines for participating in reserve markets, and summarizes the ways to optimise the electricity market.

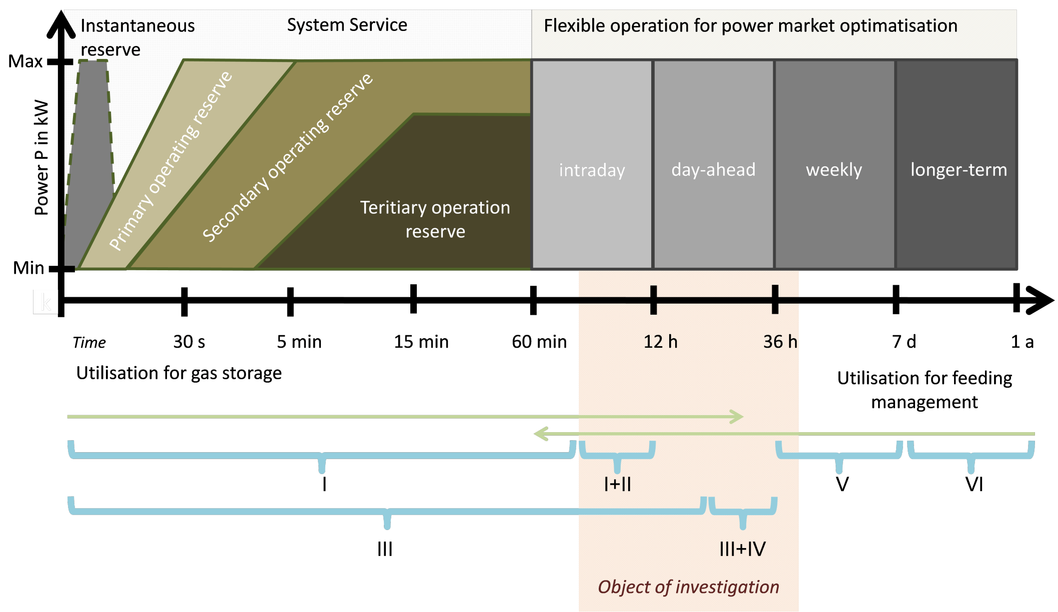

Figure 20: Scheme for classification of multidimensional feeding management concerning temporal use for different types of operating reserve und flexibilization for power market optimization (I: gas storage without extension; I+II: gas storage without extension incl. short-term feeding management (FM); III: gas storage with extension; III+IV: gas storage with extension incl. short-term FM; V: middle-term FM; VI: seasonal FM, Source: own diagram, based on [12]

Medium-term fluctuations within hours are offset by trading on the EPEX Spot SE electricity exchange. Depending on weather patterns, electricity producers and consumers are also exposed to longer-term fluctuations which induce balancing requirements ranging from several days to several weeks, or on a seasonal scale. These demands also have to be borne in the future by renewable energies, following the reduction in the capacities of fossil fuel-based power plants. In order to illustrate the challenges facing biogas plants, different demands for flexibility are schematically listed in Figure 20 with respect to the timeframe of their scope of action. An overlapping of the different areas of use of feeding management and gas storage clearly becomes an instrument of load transfer. The implementation of feeding management enables a range of flexibilization that would otherwise only be satisfied by very large volumes of gas storage (see Figure 20, configuration I versus configurations I + II). At the same time, feeding management also allows the available gas storage to better support the flexibility of the system (see Figure 20, configurations III + IV).

Short-term feeding management for daily and intraday flexibilization is different from medium-term (V) and seasonal feeding management (IV). This paper focuses on short-term feeding management, covering the area in Figure 20 that is shaded red.

The term “flexible feeding”, as used below, will describe a mode of operation in which the anaerobic degradation process is regulated by specifically influencing feeding and in which biogas is produced according to demand. This is contrasted by a mode of operation characterized by continuous feeding with the aim of producing gas on a constant basis. The term multifactorial substrate management has been introduced in the evaluation of flexible feeding with the aim of market-based optimisation. The major factors regulating gas production include:

- Point in time of ration
- Quantity of the ration
- Composition (percentage of substrate) of the ration and its
- Quality and substructure (e.g. through disintegration).

By varying these factors, the biogas process can be influenced to different degrees. This means that very different flexibility needs can be addressed which, in the simplest case, emulate seasonal patterns or which enable short-term adjustments in conversion rates to be made using dynamic process models. The investigations made in this paper are based on a standard existing biogas plant that uses a continuous stirred tank reactor (CSTR), agricultural substrates (e.g. cattle manure, maize silage) and onsite conversion of the biogas into electricity.

The aim is to study the economic effects of flexible feeding on the schedule structuring of such a sample plant, and to work out the potential for saving on gas storage capacities. A number of papers have already been published that discuss the opportunities and benefits of biogas technology on the electricity and control energy market [13–15]. However, the effect of flexible gas production on profitability has yet to be investigated based on EPEX-optimised power generation schedules. The process dynamics of anaerobic degradation is fed back to the schedule synthesis using a simplified simulation model. The model's parameters are based on experimental investigations on the flexibility of the biogas process using conventional substrates on full-scale [6].

The aim of this article is:

- to work out the interplay between schedule structuring and feeding management in the context of flexibilization
- to reveal the cost-benefit ratio by economically assessing flexibilization through flexible feeding.

2. Material und methods

An integrated model consisting of 5 components (Figure 21) was used to assess flexible feeding in terms of the revenue potentials when directly marketed, and to determine the gas storage requirements needed to flexibly generate electricity from biogas.

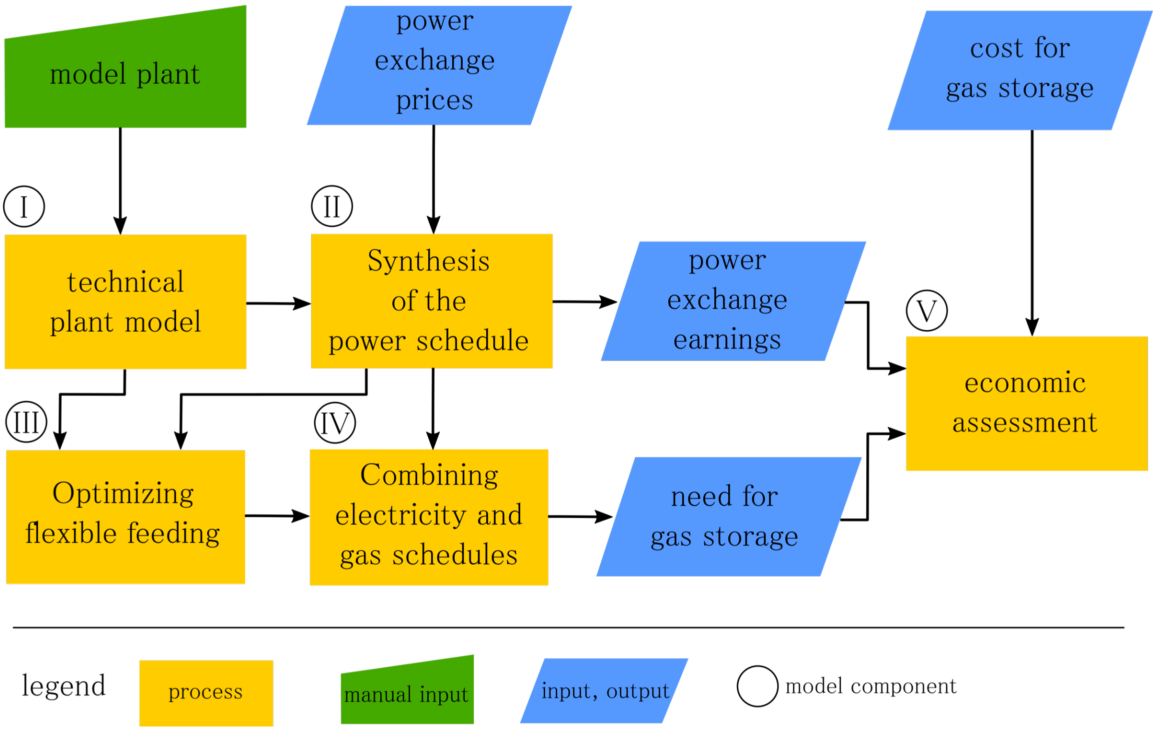

Figure 21: Block diagram of model components (mapped as rectangle processes and mark with roman numerals) for evaluation of flexible feeding

2.1 Model component I - Technical plant model

The first component is a technical plant model in which a biogas plant with 457 kW of electric rated power, corresponding to P_{el} = 500 kW of installed electrical capacity at 8,000 full utilization hours, is represented in a simplified form. This plant produces 4,000,000 kWh of electricity per year. For flexible electricity production it is assumed that the power generation capacity of the model plant is higher than its rated power. The flexibilized model plant has a total electrical power of P_{el} = 1,000 kW consisting of a CHP with P_{el} = 250 kW and an electrical efficiency of η_{el} = 40 %, and a CHP with P_{el} = 750 kW and an electrical efficiency of η_{el} = 42 %. The cascade is assumed to be made up of two fermenters (CSTR), in other words a main fermenter and a post-digester, each with gross volume of 2,168 m^3 and an internal diameter of 25.5 m. The selected substrates are cattle manure and maize silage (30 % to 70 % based on mass). The technically related maximum feeding rate of maize silage is assumed to be 4,500 kg h^{-1}. The biogas plant model in the baseline scenario has a gross storage volume of 2,200 m^3. Both the main fermenter and the post-digester have a gross storage volume for biogas of 1,100 m^3 each. The main technical plant parameters for this analysis are summarized in Table 10 both for reference feeding scenario A and for feeding scenarios B to G.

Table 10: Technical plant parameters, which were used in the different scenarios

Scenarios	**Unit**	**A**	**B to G**
Installed electrical capacity	[kW_{el}]	500	1,000
Full utilization hours	[$h\ a^{-1}$]	8,000	4,000
Electric rated power	[kW]	457	457
Electrical efficiency η_{el}			
CHP I: P_{el} = 500 kW	[%]	40	-
CHP II: P_{el} = 250 kW	[%]	-	40
CHP III: P_{el} = 750 kW	[%]	-	42
Substrate use (based on mass)			
Maize silage	[%]	70	70
Cattle manure	[%]	30	30

The analysis below always refers to the primary energy equivalent of the gas storage volume. The primary energy content of the gas storage is calculated by multiplying the net standard volume with the higher heating value of biogas of 5.19 kWh m^{-3} and deducting 10 % each for the safety margins for the upper and lower filling level limits, and the correction factor to convert operating volumes into standard volumes (1.25). In this example the primary energy equivalent E of the useable gas storage is around 7,300 kWh. The net storage volume therefore refers to the actual gas storage capacity that can be utilized by a biogas plant.

2.2 Model component II - Synthesis of the power schedule

The model's second component is the synthesis of power generation schedules. Before schedule synthesis can occur, three observable scenarios have to be established. All three scenarios are based on partially flexible operation of the CHP units of the plant model. The smaller CHP unit, with P_{el} = 250 kW of installed electrical capacity, is run on a continuous basis while the larger CHP unit, with P_{el} = 750 kW, functions as a peak load generating unit operated in a start-stop mode. This type of operation is typical for industry; the base-load CHP unit provides control energy and electricity for heat sinks while the peak-load CHP unit markets electricity in line with electricity prices [16]. By dividing the available primary energy, this constellation produces an average daily run-time for the peak-load unit of 11 h per day or 77 h per week. The price rank method is used to place the daily or weekly run-times of the peak-load CHP unit at the most expensive hours of the day. The hours with the highest average stock exchange prices are selected for the three optimisation intervals (see Figure 22).

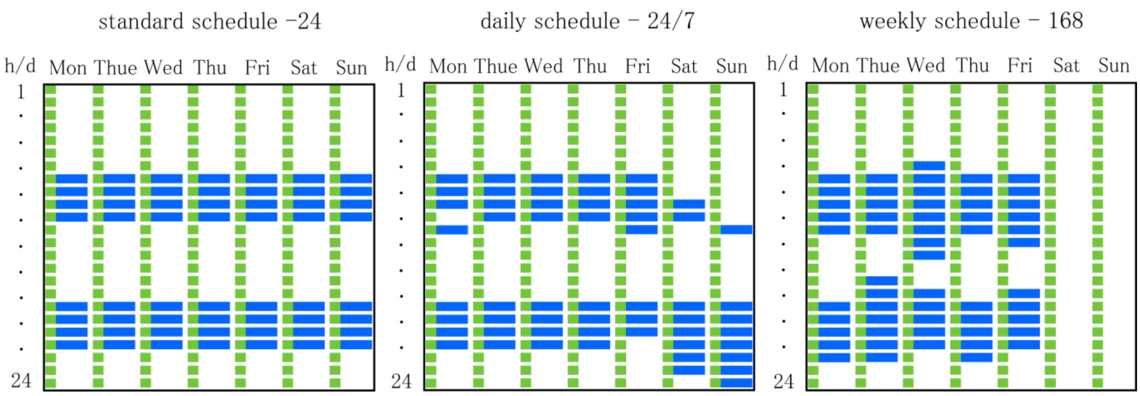

Figure 22: Matrices for one week showing the relative power feed in, 24 rows (h) by 7 columns (d), of 3 schedules (standard schedule, weekly schedule, daily schedule), the shorter green bars representing the continuously running combined heat and power unit (CHP) with 250 kW, the larger bars shows an operating state, where an additional CHP with 750 kW is in operation

The amount of electricity from biogas plants is directly marketed, primarily on the spot market. The input data for the price rank method were therefore the price time series of the European electricity exchange [17]. The reference year was 2013. Even though there was a drop in price volatilities during the observation period up until 2015, an increase in price fluctuations is expected in subsequent years [18]. The "standard 24 schedule" is the most straightforward option. It represents the optimal daily schedule for 24 h (Figure 22) averaged over the year. In the "daily 24/7 schedule", the power generation intervals are optimised for 24 h for seven weekdays averaged over the year. The daily power generation time of the peak-load CHP unit is constant (Figure 22). The “weekly 168 schedule” optimises the use of the plant over the entire average weekly price development for 168 h. Here the daily power generation times of the peak-load CHP unit fluctuate. The weekly schedule exhibits long partial load operation (only the base-load CHP unit runs constantly) as a result of the lower prices on the weekend. These three types of power schedules are then transferred to the model components for flexible feeding for the purpose of varying gas production.

2.3 Model component III - Optimizing feeding and modeling flexible biogas production

The third model component, which is based on the defined substrates (cattle manure and maize silage) and the power generation schedule from Module 2, looks for the optimal feeding regime that fulfils the power generation requirements using the lowest required gas storage capacities. Only the substrate maize silage varies in time and quantity when feeding is optimised. The weekly amount of substrate is determined in advance and can be distributed throughout the week among the days and within the days into 12 slots (feeding interval every 2 hours). The daily allotment of cattle manure is evenly spread out and added every 2 hours due to its slow degradation kinetics and its smaller share in the gas production. Figure 23 schematically shows the model-supported optimization of the feeding regime, consisting of the main components of process model and optimizer.

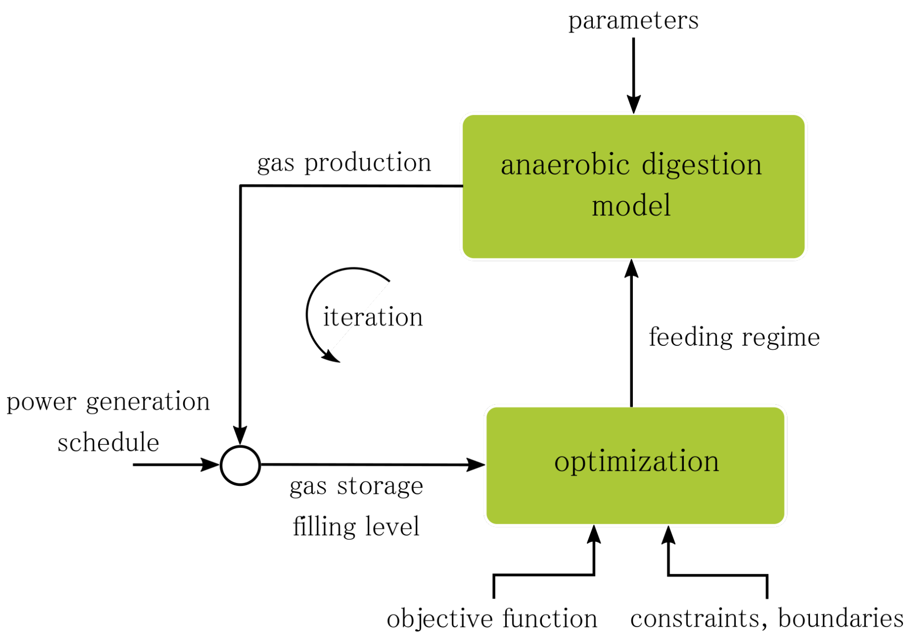

Figure 23: Schematic description of the model-based optimization of gas production according a power generation schedule

The aim is to minimize the necessary gross storage volume by flexibilization of the gas production. Based on the applicable gas utilization schedule the theoretical timely progression of the gas storage filling level is balanced using the modelled gas production process. The process model is based on the Anaerobic Digestion Model No. 1 [19]; however, it has been structurally simplified [6]. The method for simplifying it is described by Weinrich and Nelles [20]. The kinetic parameters used are identified based on full-scale experiments [6]. The resulting maximum gas storage filling level is minimised by iteratively adjusting feeding quantities using an optimisation algorithm. Additional boundary conditions include the feeding rate for each substrate and the quantities of substrate available each week. The application of numerical optimisation was achieved in the software environment Matlab / Simulink R2014a.

2.4 Framework of the investigation – scenario matrix

A total of seven scenarios are produced by comparing continuous feeding with flexible feeding and by taking into account the various power generation schedules and the baseline scenario (standard schedule plant operation without flexibilization) (Table 11).

Table 11: Scenario matrix for evaluation of the flexible feeding

Schedule	**Continuous feeding (CF)**	**Flexible feeding (FF)**
Rated power	A	-
Standard schedule	B	C
Daily schedule	D	E
Weekly schedule	F	G

Scenario A can be seen as the baseline or reference scenario. The biogas plant model consists of a CHP unit with an installed electrical capacity of $P_{el} = 500$ kW. There is no flexibilization in this scenario. Reference scenario A is not considered in more detail below because it only serves as the starting point for the following scenarios in which the model biogas plant is uniformly flexibilized. In scenarios B to G the feeding regime (continuous and flexible feeding) is coupled with the electricity generation schedules of the conversion units (standard schedule, daily schedule and weekly schedule). The economic benefit is determined for flexible feeding in scenarios C, E and G and for continuous feeding in scenarios B, D and F. This benefit is reflected in a reduced need for additional gas storage capacities. In the context of the various power schedules, scenario B is compared with C, D is compared with E and F is compared with G. All of the scenarios can be aligned with the short-term feeding management in Figure 20. The authors focus on configurations I+II and III and IV since the intraday, day-ahead and sometimes even weekly flexibilization opportunities can be utilized in order to better optimize existing biogas plants for the electricity market.

2.5 Model component IV - Combining electricity and gas schedules

The fourth model component combines electricity and gas schedules. It is used to determine the EPEX revenue which the schedules should achieve, and the gross storage capacity needed for the respective power generation schedules. To do so, the CHP schedules for 8,760 annual hours are merged with the gas requirements resulting from this and the gas production for each respective scenario. The EPEX revenue is dependent on the schedule options described above. Only the additional revenues that, as a result of price-optimised operation, are higher than selling electricity at the annual average rate on the spot market are relevant for the economic assessment.

Furthermore, the gross storage requirement varies depending on whether there is continuous gas production through continuous feeding or variable gas production through flexible feeding. The necessary gross storage capacity is determined in the model regardless of the available gas storage capacity in the course of the modelled annual load profile. The difference between the global maximum and minimum in this load profile determines the gross storage volumes needed for the respective model profile. The necessary additional storage volume is calculated by subtracting available storage capacities from the overall storage requirements. If an adjustment is to be made to gas storage in storage vessels (integrated double membrane gas storage (DMGS)), it should be noted that expanding gas storage capacities in existing biogas plants can only be done by replacing the existing storage membrane. A new gas storage unit can be installed on the site of a fermentation residue storage that has not yet been covered with a storage facility, or an external gas storage facility can be installed in addition to and independently from the existing storage system.

2.6 Model component V - Economic assessment

In the fifth model component an economic assessment is conducted based on the identified higher EPEX revenue, the additional gross storage requirements and the ascertained gas storage costs. The following cost considerations are based on integrated and separate/external DMGS units. The terminology is defined by the authors as follows. An integrated DMGS consists of:

- a double-leaf membrane gas storage roof with little gas permeability [21] which has
- an external, non-stretchable weather protection membrane that is pneumatically preloaded with supporting air,
- and a non-stretchable, interior gas storage membrane located above the fermentation area with a retaining system integrated beneath this to store the membrane when the gas storage facility is technically empty.

Stretchable interior gas storage membranes and interior membranes that are mechanically stored using a supporting beam are also sometimes used by industry; however, these storage membranes are not considered in this paper. The potential design of an integrated DMGS unit above a CSTR is illustrated in Figure 24. A separate or external DMGS unit has the same construction as an integrated DMGS unit with the exception that there is no double membrane gas storage roof above the CSTR. Instead it is installed on a separate foundation. The additional external DMGS unit has to be integrated into the already existing gas storage system using the corresponding connections and gas pipelines. In addition to double-leaf gas storage, other ways of storing biogas in biogas plants include single-leaf gas storage or foil cushion storage which are not considered in this paper.

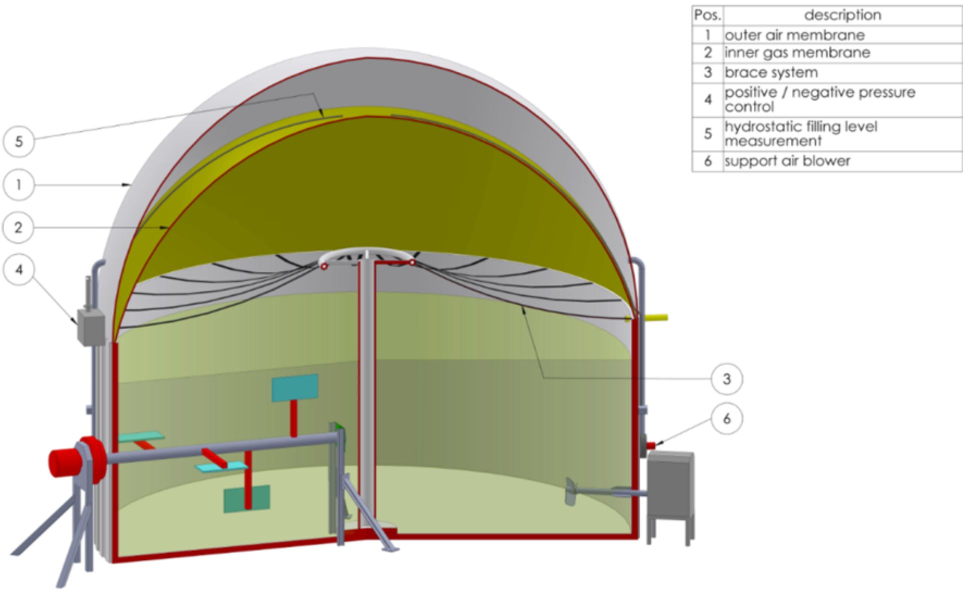

Figure 24: Structure of continuous stirred-tank reactor (CSTR) with integrated double membrane gas storage (adapted from [22])

The costs of integrated and external DMGS units are based on a survey of 5 manufacturers conducted in 2013 and 2015. A total of eleven proposals for integrated DMGS units and four proposals for external DMGS units were received, which serve as the basis for the cost calculation. The specific costs for an integrated DMGS unit (connected to storage vessels) are listed below in Figure 25.

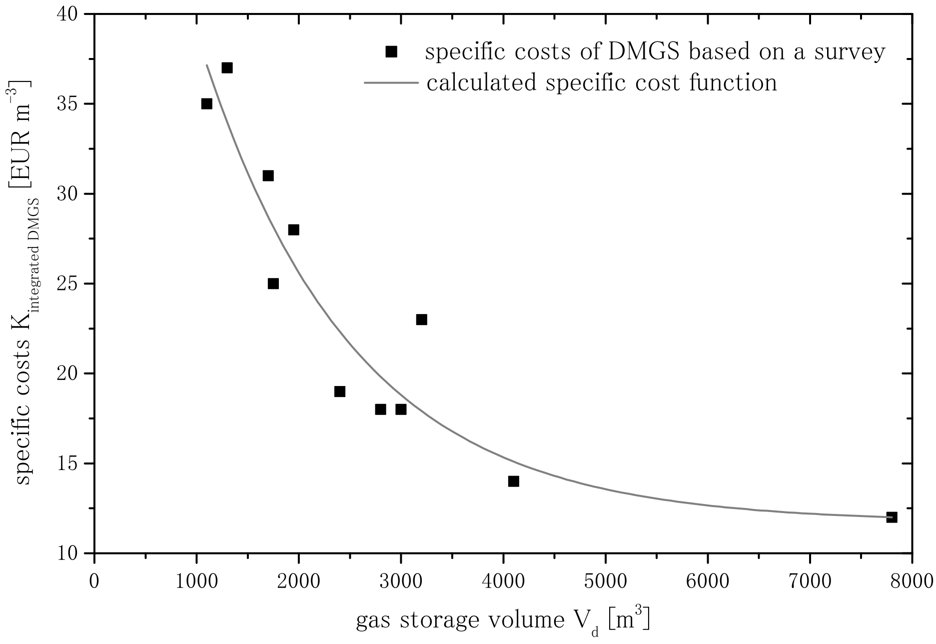

Figure 25: Specific costs of integrated double membrane gas storages based on a manufacturer survey (n=11)

Based on the manufacturer survey, the cost per cubic meter of an integrated DMGS unit can be estimated using the power function in formula (1) below:

$$K_{\text{integrated DMGS}} = 2\,889 \cdot V_d^{-0.624} \quad (1)$$

$K_{integrated\ DMGS}$	Specific costs of an integrated DMGS unit in $EUR\, m^{-3}$
V_d	Gross storage volume of an integrated DMGS unit in m^3

In order to assess the costs of an external DMGS unit, which is also based on a storage membrane system and a maximum of 600 $m^3\ h^{-1}$ for the filling or extraction of gas, proposals were received for storage units with a gross storage volume of 5,000 m^3 to 15,000 m^3. The resulting cost function per cubic meter is reflected in formula (2).

$$K_{\text{external DMGS}} = 456 \cdot V_e^{-0.412} \quad (2)$$

$K_{external\ DMGS}$	Specific costs of an external DMGS unit in $EUR\, m^{-3}$
V_e	Gross storage volume of an external DMGS unit in m^3

Not included in formula (2) are the costs for the footing, construction of the strip foundation, and the pipework for connecting the external DMGS to the existing gas storage system. These are assumed to be a flat rate of 15,000 for an external DMGS unit with a gross storage capacity of 7,300 m^3 (Table 12) Wiedau, H.; Sattler Ceno Biogas GmbH, telephone conversation on 2 December 2015). Other costs, such as transport, crane and installation supervision (installation including cost of labour, installation supervision, leak test and commissioning) are elements of the cost function. Scaffolding construction, supply of construction site electricity and other assembly work can produce slight additional costs. Since these costs are not always incurred, they are not included in the results. All of the prices are net prices and exclude statutory value added tax.

In order to determine the specific investment requirements for an integrated or external DMGS unit, it is necessary to enter V_d or V_e from Table 12 into formula (1) or formula (2) respectively. To determine the absolute investment requirement, formula (1) or formula (2) has to then be multiplied by V_d or V_e respectively. Based on the manufacturer surveys, an average lifetime of 8 years is assumed for integrated and external DMGS units. This means that the observation period of the economic assessment is also 8 years. Thus, the costs for retrofitting or expanding the existing gross storage volume (absolute investment requirement) are only incurred once. Other observation periods based on the remaining term of the existing biogas plant are also possible. Longer lifetimes would mean there would be replacement investments for gas storage membranes and protective membranes for the integrated and external DMGS units. Running costs, for example potential maintenance work and electricity costs for the supporting air blower, are not considered in the economic assessment, since they are difficult to quantify and do not incur necessarily. The costs for retrofitting integrated and external DMGS units are discounted at 8 years and compared to the additional annual EPEX revenue (reference year 2013). Additional costs for the flexibilization of biogas plants (e.g. expanding CHP capacity) and income from flexibility premiums are explicitly not taken into consideration here, since the power generation schedules are based on a uniform plant configuration and the identified factors thus remain constant. Furthermore, the potential optimisation of control energy revenue is also not regarded, since it is outside the object of investigation in Figure 20.

One parameter of assessment is Delta (Δ_{E-K}), formed by subtracting the annual costs for the absolute investment required to achieve additional gross storage volume from the additional annual EPEX revenue (see formula (3)):

$$\Delta_{\mathrm{E-K}} = \mathrm{E}_{\mathrm{additional\ EPEX\ revenue}} - \mathrm{K}_{\mathrm{DMGS\ absolute}} \quad (3)$$

Δ_{E-K}	Delta of additional revenues and additional costs in $EUR\,a^{-1}$
$E_{additional\ EPEX\ revenue}$	additional annual EPEX revenue in $EUR\,a^{-1}$
$K_{DMGS\ absolute}$	annual costs of an integrated/external DMGS unit in $EUR\,a^{-1}$

Thus, only the effect that continuous or flexible feeding has on the investment required to achieve additional gross storage volumes for different power generation schedules is quantified. In the assessment approach used to quantify the benefit of optimising flexible feeding to reduce gross storage capacities, the expenses for adjusting the permitting and safety concepts are not taken into consideration with any of the cost considerations for overbuilding the previous gas storage capacities. Furthermore, the requirements of the Major Incidence Ordinance have to be observed when there are 10,000 kg or more of flammable gas involved (around 7,300 m^3 raw biogas under standard conditions with 0 °C and 1013,25 mbar with 50 % methane) [23]. In addition, disposal costs for old components (membrane, wood construction etc.) as part of retrofitting work may be incurred. These are not considered in the cost consideration; however, under certain circumstances they can be taken into account. Sometimes fixed costs can be expected when retrofitting or expanding the gas storage capacities of existing biogas plants. The same applies when an external instead of an integrated DMGS unit is chosen for structural reasons, e.g. high wind loads.

4. Results and discussion

Only the same types of power generation schedules with different feeding regimes are of interest when comparing the results of the modelling. Figure 26 compares the developments in gas requirements, gas production, and the gas storage filling level in the case of continuous and flexible feeding for scenarios B and C, D and E, and F and G.

In the case of a standard schedule with comparably even distribution of the power generation blocks, the gas storage filling level always fluctuates within the permitted limits both for continuous and for flexible feeding. Flexible feeding only leads to the existing gas storage not being utilized so heavily; utilization is 64 % (scenario C) instead of 74 % (scenario B). In this case, the use of flexible feeding does not provide any notable advantages except for the fact that the operator can reserve more free storage capacity for unscheduled CHP downtimes when necessary. As the result of daily power generation schedule optimisation, there are larger amplitudes for gas storage filling at weekends due to the trend of pushing the power generation blocks to the second half of the week (see Figure 26). When gas production is continuous, the longer break in power generation of peak-load CHP, occurring between Friday afternoon and Saturday morning, leads to a violation of the upper limit for the gas storage filling level (scenario D). When feeding is flexible, this limit violation at weekends can be completely avoided so that, in this case, no additional gas storage is necessary for achieving this power generation schedule (scenario E).

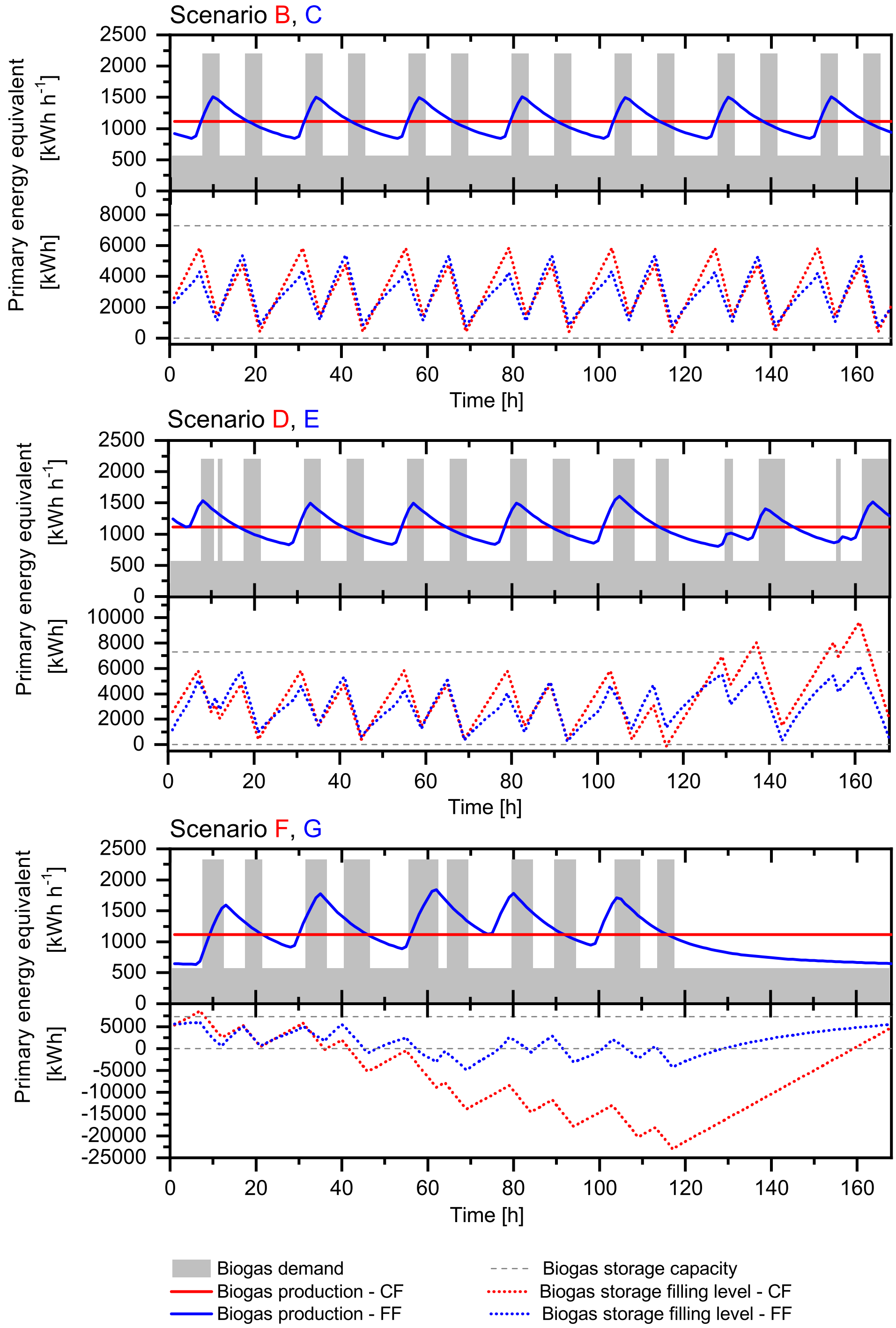

Figure 26: Comparison of continuous and flexible feeding for a period of 7 days for different scenarios. Course for gas demand, gas production and gas storage filling level for scenario B vs. C; Scenario D vs. E and Scenario F vs. G.

In the case of a weekly schedule, there are very long power generation breaks of peak-load CHP due to the generally low prices on the power exchange at the weekend. The utilization patterns on work days are essentially similar to those of daily schedule optimization (daily schedule), whereby longer daily power generation intervals can be observed since the primary energy not used on the weekends can be additionally generated during the week and sold at better conditions. Both effects require strong amplitudes in the timing of the gas storage filling level in the case of continuous gas production, which could considerably exceed the upper and lower limits. In the case of flexible feeding, these extreme values in the gas storage filling level can be considerably reduced so that, instead of 7,300 m^3 (scenario F), only a little more than 1,100 m^3 of additional gross storage capacity is needed to achieve the weekly schedule (scenario G).

In all scenarios, the required amount of storage volume in the DMGS unit can be reduced through flexible feeding. The amount of gross storage required by flexible feeding is, on average, 39 % below what is required for continuous feeding if the power generation times of the peak-load CHP are lowered at the weekend. An overview of the calculation results is summarized in table 12. In terms of the additional revenue, this revenue increases as the degree of freedom in schedule optimisation increases. Thus, compared to reference scenario A, which has a standard schedule, € 17,902 in additional revenue was achieved in 2013 through plant configuration scenarios B and C. In the case of an annual electricity production of 4,000,000 kWh, this corresponds to additional proceeds of € 0.45 cents per kWh^{-1}. When the schedule is optimised daily (daily schedule), as in scenarios D and E, an additional € 19,572 in absolute terms, and € 0.49 cents per kWh^{-1} in specific terms were achieved.

The largest additional revenue was achieved when the schedule was optimised over the entire week (weekly schedule), amounting to € 26,872 in absolute therme or € 0.67 cents per kWh. This means that 50 % higher revenue can be generated than in the case of a standard schedule in which a 24 h schedule repeats on a daily basis. Based on the same plant configuration and using a standard schedule, gross storage requirements can be reduced by a total of 14.1 % from 1,638 m^3 in scenario B to 1,407 m^3 in scenario C through flexible feeding (see Table 12). Since the biogas plant model already has gross gas storage capacities of 2,200 m^3 in the baseline scenario, no additional capacities are needed in either of the scenarios.

More gross storage is needed in scenarios D and E than in scenarios B and C due to the use of a daily schedule. Through flexible feeding (scenario E) gross storage requirements can be reduced from 2,948 m^3 to 1,796 m^3 (39.1 % reduction) compared to continuous feeding (scenario D). While in scenario D a new, larger integrated DMGS unit with a capacity of 1,848 m^3 (see Table 12) has to be built on top of the fermenter (at a cost of € 48,868), this is not necessary for scenario E, since the existing gross storage volume is sufficient. Thus, scenario E that has flexible feeding is preferred over scenario D that has continuous feeding, since both have the same potential to achieve additional revenue, but there are no additional costs for converting to an integrated DMGS unit in scenario E.

Table 12: Results of model calculations, comparison by pairs of equal schedules for continuous and flexible feeding, specifications concerning gas storage are volumetric and calculations within the model are energetic

Scenarios	**Unit**	**B**	**C**	**D**	**E**	**F**	**G**
Additional EPEX revenues	[€ a^{-1}]	17902	17902	19572	19572	26872	26872
Additional revenues towards reference scenario	[%]	-	-	9.3	9.3	50.1	50.1
Storage demand absolute	[m^3]	1638	1407	2948	1796	9500	3314
Modeled storage utilization towards plant configuration of reference scenario A	[%]	74	64	134	82	432	151
Storage reduction with flexible feeding	[%]	-	-14.1	-	39.1	-	-65.1
Additional gross storage demand	[m^3]	0	0	748	0	7300	1114
Necessary extension gross storage volume of integrated DMGS V_d	[m^3]	-	-	1848	-	-	2214
Necessary extension gross storage volume of external DMGS V_d	[m^3]	-	-	-	-	7300	-
Total available gross storage volume after retrofitting	[m^3]	2200	2200	2948	2200	9500	3314
Maximal length of storage at average biogas production	[h]	10	10	13.6	10	44	15.3
Cost for additional gas storage extension absolute	[€]	-	-	48868	-	100231*	52304
Cost savings DMGS at flexible feeding towards continuous feeding absolute	[€]	-	0	-	48868	-	47927
$E_{additional\ EPEX\ revenues}$	[€ a^{-1}]	17902	17902	19572	19572	26872	26872
$K_{DMGS\ absolute}$ **	[€ a^{-1}]	-	-	6109	-	12529	6538
Δ_{E-K}	[€ a^{-1}]	17902	17902	13463	19572	14343	20334

* *incl. 15000 € for footing, foundation and pipe work*

** *Depreciation DMGS for 8 years*

The utilization of a weekly schedule for generating power from biogas in scenarios F and G has to be assessed in a more differentiated way. There is a high need for storage due to the long period of time in which only the CHP with an installed electrical capacity of $P_{el} = 250\,\text{kW}$ is run at a lower output, and because less biogas is used at weekends. In scenario F this amounts to 9,500 m^3 with continuous feeding (see Table 12). Thus, the absolute gross storage requirement is 4.3 times the existing gas storage capacity. Due to the high absolute gross storage requirement, an external DMGS unit is built in scenario F. The already existing gas storage capacities on the fermenter or post-digester remain and are not changed in terms of construction. Thus, subtracting the existing gas storage capacity of 2,200 m^3, an external gas storage unit measuring 7,300 m^3 is additionally required. When a weekly schedule is used, the gross storage requirements of scenario G can be reduced through flexible feeding by 65.1 % over scenario F, resulting in a gross storage volume of 3,314 m^3. As this corresponds to a considerable investment savings – under the selected assumption of the biogas plant model – flexible feeding (scenario G) is preferred over constant substrate feeding (scenario F). The cost savings by building a new, integrated DMGS unit measuring 2,214 m^3 (see Table 12) on the fermenter in scenario G amount to € 47,927 compared to building a new external DMGS unit in scenario F. Thus, the highest annual Δ_{E-K} is achieved in scenario G, which is only marginally higher than scenario E.

5. Summary and conclusions

Flexibly generating power through biogas plants requires a series of technical components on the biogas plant. Furthermore, not every concept of sustainable flexibilization of existing biogas plants is necessarily economically beneficial compared to the status quo. In terms of the biogas plant's economic results, the technical and conceptual requirements have to be taken into consideration when weighing the costs and benefits of retrofitting. Flexible feeding, or gas production controlled by flexible feeding, proves to be economically more beneficial than continuous feeding as long as there are no additional costs, e.g. through the expansion of the feeding technology. In the case of a scheduled load transfer, focus is placed on gas storage, since the gas storage capacity determines the transfer potential. Flexible feeding exhibits a cost-reducing effect in all scenarios.

From an economic perspective, the choice of gas storage plays a crucial role. Thus, when there is a modification to the operation of power generation plants, it is not expedient to choose an external DMGS unit if the existing biogas plant only needs slightly more gross storage capacity (e.g. less than 1,000 m^3). In such a case step-fixed costs can be incurred that only produce additional revenue on a relatively marginal scale. This statement is tied to the spot market prices (2013 EPEX spot) used in the calculations and the potential for additional revenue connected with it. If the potential for additional revenue changes, the optimum of additional gas storage volumes will also change in the future. The impact of the absolutely necessary gross storage requirements or the additional amount beyond existing gas storage capacities crucially depends on the different power generation schedules and the feeding regime.

It has been shown that, in all scenarios, the need for additional gas storage volumes can be considerably reduced as a result of flexible feeding. The Δ_{E-K} illustrated in Table 12 is influenced, above all, by the additional annual revenue on the EPEX spot. The highest additional costs for adding gas storage capacities are incurred with the weekly schedule and, to a smaller extent, with the daily schedule. The standard schedule does not require an expansion of the existing gas storage capacities in the modeling and thus produces no additional costs. When a daily or weekly schedule is used to generate power from biogas using CHP technology, the Δ_{E-K} is lower for continuous feeding than for flexible feeding. The largest Δ_{E-K} is achieved in the modeling when a weekly schedule is used in combination with flexible feeding.

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Article 4: Demand-driven biogas production by flexible feeding in full-scale - process stability and flexibility potentials

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Mauky E. [a,b], Weinrich S. [a,b], Jacobi H.F. [c], Nägele H.J. [d], Liebetrau J. [a], Nelles M. [a,b]

[a] Department of Biochemical Conversion, DBFZ - Deutsches Biomasseforschungszentrum, Torgauer Straße 116, D-04347 Leipzig, Germany

[b] Faculty of Agricultural and Environmental Sciences, Chair of Waste Management, University of Rostock, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany

[c] Hessian State Laboratory, Fachgebiet IV.5.3 renewable energies, Schubertstraße 60, 35392 Gießen

[d] State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim, Garbenstraße 9, Stuttgart 70599, Germany

Abstract For future energy supply systems with high proportions from renewable energy sources, biogas plants are a promising option to supply demand-driven electricity to compensate the divergence between energy demand and energy supply by uncontrolled sources like wind and solar. Apart from expanding gas storage capacity, a demand-oriented feeding with the aim of flexible gas production can be an effective alternative. The presented study demonstrated a high degree of intraday flexibility (up to 50 % compared to the average) and a potential for an electricity shutdown of up to 3 days (decreasing gas production by more than 60 %) by flexible feeding in full-scale. Furthermore, the long-term process stability was not affected negatively due to the flexible feeding. The flexible feeding resulted in a variable rate of gas production and a dynamic progression of individual acids and the respective pH-value. In consequence, a demand-driven biogas production may enable significant savings in terms of the required gas storage volume (up to 65 %) and permit far greater plant flexibility compared to constant gas production.

Keywords: demand-oriented feeding; monitoring; gas storage; sugar beet silage; bioenergy; balancing power

1 Introduction

The share of energy - especially electricity - produced from renewable energy is constantly increasing [1]. The major challenge for the next decades is to further expand the amount of renewable energies in the grid and to efficiently integrate them into energy system. Due to the fluctuation within production of solar and wind energy, it is essential to also evolve the potential of capacity utilization management, powerful transmission networks, as well as new storage technologies [2]. Bioenergy and especially the biogas technology can play a significant role in such smart energy grids [3–5]. The strong political support for biogas production by the German Renewable Energy Act (RESA, German "EEG") over the past decade has greatly affected agricultural sectors in Germany, which led to a boost in biogas production [6]. Particularly between 2006 and 2011, the total number of plants doubled and the total capacity increased by more than 150 %. In 2015, more than 8800 biogas plants with a total capacity of 4000 MW produced renewable energy in Germany [7]. This immense and decentral potential could be used to stabilize the grid.

Agricultural biogas plants in Germany are mainly based on continuous stirred tank reactor (CSTR) systems and have originally been designed for a constant energy output (base load energy). Up until today the substrate is usually fed semi-continuously in intervals between 15 minutes and three hours (based on a DBFZ operator survey). However, the requirements for bioenergy are currently changing and the cost pressure is increasing (i.e. decreasing remuneration and increasing substrate prices). A promising economically feasible and sustainable perspective for biogas is a flexible and demand-oriented energy production [8,9]. Therefore, bioenergy has to supply demand-driven electricity to compensate the divergence between energy demand and energy supply by uncontrolled sources like wind and solar power, because the energy conversion from biomass is – in opposite to wind and solar power – weather independent.

In general, there are different options for increasing flexibility along the biogas production chain, e.g., substrate management, storage of intermediates (i.e. acids), heat and/or gas use within a further expansion of gas storage and CHP capacities and upgrading the generated biogas to bio-methane and its subsequent feed into the gas grid [10]. However, the possible extent of flexibilization depends on the design and the dimensions of plants for example, in additional CHP capacity and available gas storage. One example in [11] shows an integrated double membrane gas storage on top of the fermenter which costs about 51,000 Euro for a capacity of 3000 m^3.

Besides the extension of gas storage capacity, a promising part of the solution to improve the flexibility of biogas plants is the direct regulation of the biological process, e.g. by individual feeding management. Barchmann et al. [11] and Grim et al. [12] showed that flexible biogas production also benefits economically from a reduced gas storage demand by a demand-oriented feed management. Different lab-scale studies by Lv et al., Mauky et al. and Mulat et al. [13–15] demonstrated that flexible feeding resulted in high dynamic biogas production and does not have a negative impact on the stability of the process. Although these promising results are achieved under controlled lab scale conditions, the question remains, if these results can be repeated and transferred at full-scale. Only a few studies [8,16,17] developed methods to operate biogas plants demand-driven by flexible feeding in full-scale. According to Gaida et al. [18], the main challenges for upscaling advanced control procedures into practice are a lack of robust and reliable process monitoring tools as well as the difficulty of convincing a conservative industry of the benefits of monitoring and feed control. Reservations of plant operators in flexible biogas production are largely due to fear of process disturbances caused by changing feeding regimes. And obviously, a lot of questions are still open about possibilities and limitations of plant flexibility by demand-oriented feeding.

The scope of this work is to investigate the flexibility of a full-scale biogas production and to compare the results with lab-scale studies. The focus is on the achieved dynamics of gas production rates intraday and for longer periods up to 3 days. The effect of flexible feeding on daily and longtime process stability will be assessed. Furthermore, the saving effect on gas storage demand based on the achieved flexible biogas production versus a constant production will be discussed and compared with literature values.

2 Materials and Methods

2.1 Experimental Setup and Substrates

2.1.1 Research Biogas Plant A

The two main CSTR-digesters at research biogas plant A have each an active volume of 165 m^3 (208 m^3 total). The digesters were equipped with central agitators (Centromix; 7.5 kW, Karl Buschmann Maschinenbau GmbH, Germany). To ensure a constant gas space volume for accurate gas quality measurement, they had a fixed flat ceiling. For piping and instrumentation diagrams and further setup information, see Mauky et al. [17]. The digester temperatures were maintained at mesophilic conditions (38 ± 1 °C). The feeding substrates were cattle slurry and maize silage at the primary digester and sugar beet silage at the secondary digester (results of Weender analysis given in Table 14). The digestate from the primary digester was pumped to the secondary digester once a day prior to the first feeding of the primary digester. Before feeding of the secondary digester, the digestate from the secondary digester was transferred to the digestate storage tank. Table 13 shows the different experimental phases with the respective operation time, used substrates and organic loading rates (OLR).

2.1.2 Research Biogas Plant B

The CSTR-digester at research biogas plant B had a volume of 923 m^3 with an active volume of 800 m^3. The digester was equipped with a submersible motor mixer (4670, 13 KW, ITT Flygt AB, Sweden) and a propeller incline shaft agitator (Biogator HPR 1, 15 kW, Ellzee-Hausen, Germany). A fixed flat ceiling ensured a constant gas space volume for accurate gas quality and volume measurement. For additional information for piping and instrumentation, see Mauky et al. [17]. The digester temperatures were maintained at mesophilic conditions at 40.5 ± 1 °C. At full-scale plant B maize silage, grass silage and ground wheat grain were used as feedstock (results of Weender analysis given in Table 14). Table 13 summarizes the experimental phases with the respective operation time, used substrates and OLR. The total flexible operation time was 10 months for experiments A, and 7 months for experiments B. The course of the gas production rate of both full-scale plants is already published partly in [17].

Table 13: Overview of the experiments performed during the study (acronyms: MS-maize silage; SBS-sugar beet silage; CS-cattle slurry; DP-digestate primary; GS-grass silage; GWG-ground wheat grist; $V_{R,liq}$: active liquid volume; VS: volatile solids)

Experiment	**Period**	**Days** [d]	**Digester**	$V_{R,liq}$ $[m^3]$	**OLR** $[kg_{VS} m^{-3} d^{-1}]$	**Substrates** [1]
Full-scale experiment A	I	70	Primary	165	4	MS II + CS II
	II	70	Secondary	165	2	DP + SBS III
Full-scale experiment B		190	Primary	800	2.8 - 3.5	GS + MS III + GWG

[1] *maximal feeding velocity at both plants is 60 kg min^{-1} fresh matter*

2.1.3 Referential Laboratory Experiments

To evaluate the full-scale experiments, additional data of already published lab-scale experiments were used. Table 15 gives an overview of information characterizing these experiments. The total flexible operation time was 8 and 5 months of lab-scale experiment A and B. Further information on the experiments can be found in Mauky et al. [14]. Table 14 shows additional the results of the Weender analysis for the used feedstock in the laboratory experiments.

Table 14: Composition of feedstocks (Maize silage, Grass silage, Cattle slurry, Sugar beet silage and Ground wheat grain) based on Weender analysis; Acronyms: fresh matter (FM)

Component	**Unit**	**Maize silage**			**Grass silage**	**Cattle slurry**		**Sugar beet silage**			**Ground wheat grain**
		MS I	MS II	MS III	GS	CS I	CS II	SBS I	SBS II	SBS III	GWG
Dry matter (DM)	[% FM]	28.4	33.3	39.5	44.9	5.9	6.9	19.4	20.3	14.1	88.6
Organic dry matter (VS)	[% DM]	96.4	96.3	98.6	96.0	77.9	72.1	82.2	86.2	71.4	97.5
Nitrogen free Extracts (NFE)	[$g\ kg_{DM}^{-1}$]	595.3	621.0	869.0	770.0	343.8	324	707.2	753.7	617.0	810.0
Crude protein	[$g\ kg_{DM}^{-1}$]	77.4	67.0	35.0	49.0	190.4	147	46.1	42.3	63.9	118.0
Crude lipids	[$g\ kg_{DM}^{-1}$]	11.5	8.0	15.0	14.0	5.3	3	4,5	2.9	4.5	19.0
Crude fiber	[$g\ kg_{DM}^{-1}$]	280.1	267.0	67.0	127.0	239.3	247	64.6	63.3	136.6	28.0
Ash	[$g\ kg_{DM}^{-1}$]	35.7	37.0	14.0	40.0	221.2	279	177.6	137.8	178.0	25.0

Table 15: Overview of already published laboratory experiments for comparison based on Mauky et al. [14] (Acronyms: MS-maize silage; SBS-sugar beet silage; CS-cattle slurry; DP-digestate primary)

Experiment	**Period**	**Days**	**Digester**	$V_{R,liq}$	**OLR**	**Substrates**
		[d]		$[m^3]$	$[kg_{VS} m^{-3} d^{-1}]$	
Laboratory-scale experiment A	I	107	Primary	0.01	3.0 – 4.0	MS I + CS I
	II	109	Secondary		3.0 – 4.0	DP + SBS II
Laboratory-scale experiment B		122	Primary	0.035	2.0 – 5.0	SBS I

2.2 Analytical Methods

At the research biogas plant A the gas production was measured by a dynamic pressure probe sensor (S.K.I. Schlegel & Kremer GmbH, Germany). The biogas composition (CH_4, CO_2, H_2S, H_2, O_2) at research biogas plant A was measured with an AWIFLEX gas analyzer (Awite Bioenergy GmbH, Germany). At the research biogas plant B the biogas production was recorded continuously with a gas flowmeter (GD 300, Esters Electronik GmbH, Rodgau, Germany). The biogas quality (CH_4, CO_2, H_2S, O_2) at the research biogas plant B was measured by a multisensor analyzing system (INCA 4000, Union Instruments GmbH, Karlsruhe, Germany). The gas yields at both plants were corrected to standard conditions (0 °C, 1013 hPa). The preparation and measurement of the sum parameter of volatile organic acids (VOA) by means of titration (Kapp method, Mettler Toledo Typ Rondo 60/T90), ammonia nitrogen (photometric by Nessler method with Hach DR3900), and pH (WTW Typ pH 3310 SenTix 41) are described in [19]. At research biogas plant A the redox potential was measured by an online sensor (Hach Lange, type DRD2P5.99).

At both plants the samples of input substrates and digestate were taken twice a week and analyzed both for dry matter (DM) and organic dry matter (VS). The composition of the individual feedstocks was analyzed by Weender method [19]. For evaluation of the process stability, the relationship of VOA and the reactor buffer capacity relative to calcium carbonate (FOS/TAC according to [19]) was used. In general, reactor samples were taken and prepared for further measurement prior to the first feeding. Additionally, at particular days the course of the acids was monitored by frequent sampling throughout the day. The samples at research biogas plant B were immediately frozen for transportation and further analyzation at DBFZ. The concentration of individual volatile fatty acids (VFA) was determined by using an Agilent 7980A gas chromatograph (Agilent, USA) equipped with a Turbo Matrix 110 automatic headspace sampler (Perkin Elmer, USA) and an Agilent HP-FFAP column (30 m x 0.32 mm x 0.25 mm) for chromatographic separation. Sample preparation for VFA analysis (1 ml H_3PO_4 and 1 ml internal standard) was performed according to [19].

2.3 Data Processing

For illustrating the intraday distribution of the gas production (chapter 3.2), the experimental data was split into two periods every day. Figure 27 shows the subdivision of an exemplary daily gas production course to get the flexibility potential.

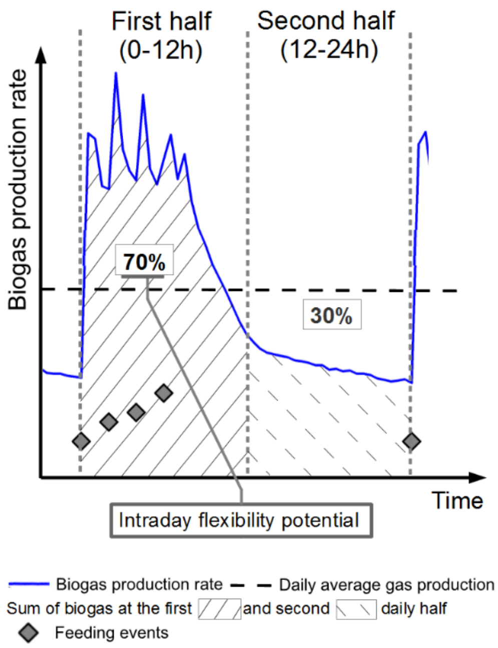

Figure 27: Schematic illustration of determining the flexibility potential by comparing the gas production generated within the first half of the day (0-12 h) related to the total daily biogas volume (0-24 h); In this example 70 % of the daily total biogas production was produced in the first half of the day. In result the cumulative intraday flexibility potential is 70 %. In the second half of the day only 30 % of the total daily sum of biogas was produced; every day's calculation is beginning with the first feeding event

In a practical context, the first half (0 – 12 h) can be understood as a utilization phase in which biogas is consumed and electrical current is produced. The second half (12 – 24 h) represents the storage phase when no biogas is utilized. The real daily time sequence of the experiments can be slightly different. However, the starting point for calculation (0 h) is set by the first feeding event of a day.

To assess the temporal degradation characteristics and the dynamics of biogas production in different experimental scales, a model-based evaluation was performed. The utilized model is based on the stoichiometric structure of the Anaerobic Digestion Model No.1 (ADM1, [20]). Furthermore, the complex model structure of the ADM1 is simplified to simulate the complete anaerobic digestion of particulate carbohydrates, proteins and lipids to biogas by the superposition of three brutto reactions. Detailed information on the model derivation procedure or the simplified model structure, as well as the implemented kinetic and physico-chemical model parameters can be obtained in Weinrich et al. 2015 [21] and Mauky et al. 2016 [17].

For each experimental setup the model parameters were manually adjusted to simulate the measured biogas production rate in a semi-stationary process state, see Figure 28.

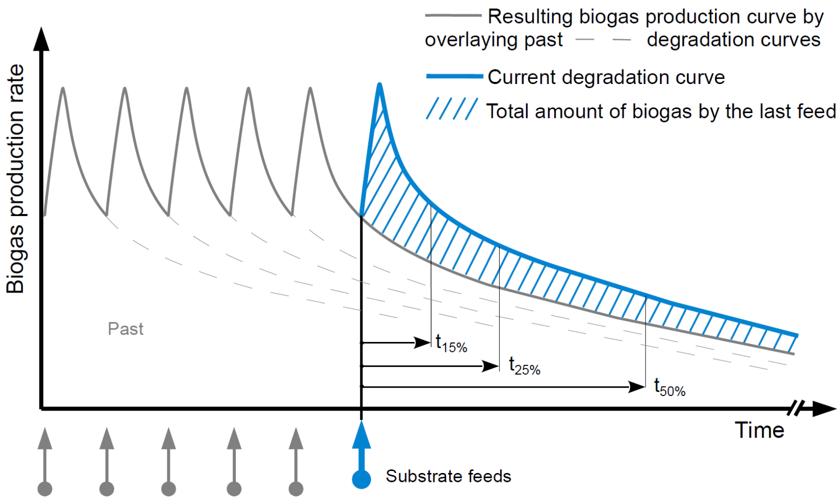

Figure 28: Illustration of determining the duration from feeding event to the point where 15, 25 and 50 % of cumulated total biogas is produced; The total amount of biogas produced by the last feeding is calculated by subtracting the current (blue line) from the previous degradation curves (gray overlaid lines)

Then the modelled feed was suspended and the simulated gas production rate subsides. The total amount of biogas produced by the last feed is determined by subtracting the current from the previous degradation curves (dashed area in Figure 28). On this basis, the time periods were calculated when 15, 25 and 50 % of the total amount of biogas is produced by the last feed. The calculated area can be assumed to be the biogas potential of each substrate at infinite retention time. Compared to the practical semi-continuous process, there is a small difference because of the effect of the hydraulic retention time (partial substrate washout at each feeding event in the CSTR).

In order to evaluate the theoretical effect of flexible compared to constant feeding on the necessary gas storage demand (chapter 3.3 in this article), a third method was introduced. The comparison was done by four gas utilization scenarios. Scenarios A, B and C assumes gas utilization phases of 8, 12 and 16 h a day. The storage phase thus stretched over 16, 12 and 8 h per day, respectively. Finally, a scenario with a feeding break of 72 h was assumed to simulate a low demand at the weekend or high electricity production by i.e. wind power [22]. The flexible gas production for calculating the utilization scenarios was based on the measured gas production dynamics of the laboratory-scale experiment B and full-scale experiment B. The comparison of the scenarios was extrapolated up to gas production rates of 1400 m^3 h^{-1}. Therefore the necessary gas storage demand was calculated for the gas production rate of the respective experiment and was furthermore extrapolated to gas production rates of up to 1400 m^3 h^{-1}. In order to broaden the spectrum of experiments and reactor technologies, literature results for an 8 h and a 72 h scenario implemented with alternative hydrolysis/fixed bed configuration (called ReBi) [22] were integrated in the comparison. Another result found in literature bases on flexible feeding of comparable anaerobic filter concepts. As Lemmer and Krümpel [23] described, high gradients in the gas production were affirmed. Both approaches realizes a highly dynamic gas production rate (up to factor 8 between minimal and maximal rate) by addition of energy rich hydrolysate into a methanization reactor.

Based on regulations of the German Federal Pollutant Control Act (BImSchV), an upper limit for on-farm biogas storage capacity was specified for evaluation. This act defines limits for on-farm biogas storage capacity as a threshold for the type of permission of operation. Exceeding 50 tons on-farm biogas storage capacity, the plant needs to deal with stronger safety regulations and expensive permit procedures with high administrative effort. Calculating with a density of raw biogas of approximately 1.3 kg m^{-3} the limit of 50 tons corresponds to a gas volume of 38,000 m^3. In consequence, plant operators will try to operate below this biogas storage capacity limit.

3 Results and Discussion

3.1 Process Dynamics and Stability

3.1.1 Full-scale Biogas Plant A

Figure 29a shows the gas production rate and gas quality achieved with flexible feeding at full-scale plant A (full-scale experiment A) between day 9 and 36. The results indicate that by flexible substrate feeding, the daily gas production rate can be modulated up to ± 50 % of the daily average gas production rate (e.g. day 33 with min/max values of 13 m^3 h^{-1} and 36 m^3 h^{-1}).

By targeted reduction of the feeding quantity at the weekend, the gas production could be reduced even below 12 m^3 h^{-1}. The results show the effects of flexible substrate feeding on the gas production rate and thus on the flexibility of the process itself. The process reacts to the feeding event within several minutes with a significant jump in the gas production rate. Thereby, presumably the volatile components in the substrate are initially degraded; CO_2-content is released due to the prevalence of hydrolytic activity and a slight pH drop within the digestate is measured. A considerable increase in the gas production rate can be observed within an hour. After a feeding event, the CH_4 concentration drops below 50 % and the CO_2-content rises up. But in the further progress, the methane content increases again, exceeding 55 % and returns to the initial percentage in the course of the day.

Figure 29c shows the biogas and the methane production rate normalized to the respective average gas production rate and the deviation to each other. Thus, the effect of CO_2 can be separated and the metabolic activity can be better described. It can be seen that the methane potential slightly shifts into the second half of the day. This behavior can be explained by the immediate onset of hydrolysis with the feeding event, where organic acids and CO_2 are produced. Once these intermediates are available, the downstream processes and finally methanogenesis follow, leading all measured values back to the initial levels. It is assumed that processes fed in a flexible manner, as presented, alternate between phases with both increased hydrolysis / acido- / acetogenesis and methanogenesis processes throughout the course of roughly 24 h after a feeding event. The anaerobic system reacts, buffers the disturbance and gains stability again. Phases with higher gas production after feeding events yielded poorer gas qualities regarding the methane content.

At full-scale experiment A, a fixed roof with a relatively small gas volume, similar to laboratory-scaled digesters, was used. However, in conventional full-scale plants the gas is collected in larger gas storages holding capacity for several hours. Thus, different qualities are mixed, leading to lower variations in the gas quality. Furthermore, modern combined heat and power (CHP) units with combustion control can process gas of varying quality within the observed margin of 45 % methane. However, the engine needs more gas at low CH_4 contents to generate the wanted output, may start worsening and the exhaust gas values qualities might also deteriorate (NO_x can increases). A reduction of gas production rate over several days was tested three times (day 16, 23, 30) in this experimental period (day 9 to 36) to simulate a period of lower demand. The ability to reduce the gas production rate over several days is considered equally important in the context of the requirements from the energy system as the short term “on/off” flexibility of intraday gas production [11]. Findings indicate that the biogas production can be highly varied and ramp up and down within a few hours.

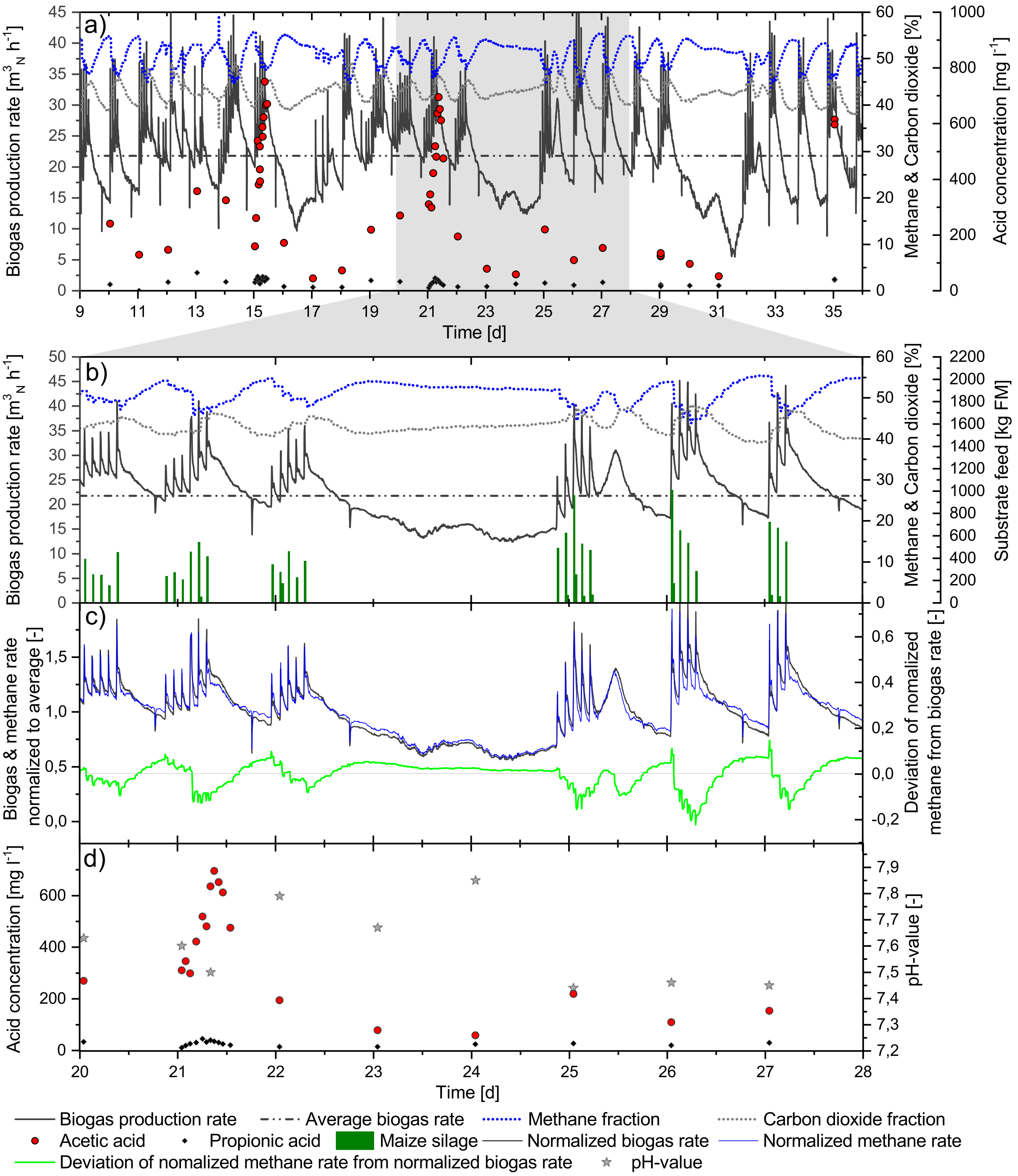

Figure 29: Experimental results at full-scale plant A – period I: **a)** (experimental day 9 to 36) biogas production, methane and carbon dioxide concentration and acid concentration **b)** biogas production, methane, carbon dioxide concentration and feeding events from experimental day 20 to 28 **c)** normalized biogas and methane rate and deviation of normalized methane rate from normalized biogas rate d) acid concentration and pH-value from experimental day 20 to 28

With a view to process stability, the courses of acetic and propionic acid concentrations are also presented in Figure 29a. The samples for analyses were usually taken prior to the first daily feeding event, and the results show no significant long term accumulation of VFAs. In laboratory experiments [14], a highly dynamic behavior and stability at the same time was detected in a CSTR-system. In the full-scale experiments on days 15 and 21, the course of the acids was monitored by frequent sampling throughout the day. Figure 29b gives a detailed segment from day 20 to 28 with gas production rate, gas quality (CH_4 and CO_2) and the course of the feeding rate. Additionally, in Figure 29d the courses of the acetic and propionic acid concentration and the pH-value are indicated. A parallel rise in acid concentrations and gas production rate can be seen. Any increased acid concentration should lead to an increased gas production as long as the risen concentration does not lead to an inhibition. During the day (see day 21), the acetic acid concentration reaches a maximum of 800 mg l^{-1} and then decreases until below 200 mg l^{-1}. In the course of the day, the propionic acid does not rise above 50 mg l^{-1}. The fluctuations of the acid concentration in the indicated ranges are not critical for the process [24]. The FOS/TAC ratio varies between uncritical values of 0.17 and 0.29 (not shown). This also corresponds to the observations made in laboratory-scale [14]. Feeding pauses (see day 23 – 25) lead to a substantial reduction of the acids. The subsequent accumulation of acids which is often feared could not be observed. Other analyzed acids, (butyric-, valeric- and hexanoic acid) also remained below a level of 50 mg l^{-1} (not shown). The pH-value corresponds inversely proportional to the acid concentrations. Hence, the pH can be suitable for an easy-to-measure indicator, as already recommended by [25].

The experiments show that the stop of substrate addition for 2 days does not harm the general responsiveness of biogas production. However, after longer periods (from 2 days) without feeding, a delay in the previous rise of the gas production rate could be observed (e.g. 8h delay after feeding on day 25 in Figure 29b and day 32 in Figure 29a). In consequence, only 50 % of daily gas production can be found in the first half of the day. In comparison, on day 26 the proportion of daily gas production within the first 12 h is 65 %. The CO_2-fraction on day 25 (see Figure 29b) rises in a typical way during the first feeding events. But after the fourth feeding the CO_2-fraction begins to decrease, followed by a second peak, which is untypical.

On one hand, the delayed CO_2 formation could be due to the degradation process itself (i.e. hydrolysis gas from a fraction with a delayed degradation). Furthermore, only small changes in the hydrogen measurement (gas phase between 100 and 150 ppm) and a constant low redox potential (< -300 mV) were observed. These are not typical signs of inhibition [26]. In the considered time period, no online-measured values were available for pH-value and acids which could confirm this hypothesis. Nevertheless, a slight inhibition or metabolic state change caused by the high feed after this long hunger phase is possible. The feeds were calculated by a model predictive control (already published description in [17]) in order to fulfill a gas demand timetable. In doing so, the model possibly overestimated the responsiveness of the process directly after a longer pause, which leads to a daily overfeed. However, on the next day (day 26), the analysis of the acids, pH value and the course of the gas production and quality showed no long-term inhibition.

On the other hand, the second peak in the CO_2-content could have led to a dissociation shift in the direction to CO_2. In consequence, more CO_2 is set free in the liquid phase, which leads to an increased contribution to the gas phase. With the presumed acid formation the pH value might be reduced, which leads to the dissociation shift and CO_2 is ejected from the liquid phase. In this case, the second peak can be explained with the delayed degradation of the acids. Further reasons for these behaviors may be found also in rheological-induced local disturbances which still have to be investigated. The described behavior was not observed in previous laboratory experiments (10 and 35 Liter volume) [14]. Therefore, it should be investigated whether similar situations can be reproduced in a laboratory fermenter, if possible in larger scale.

3.1.2 Full-scale Biogas Plant B

Figure 30a shows the course of gas production rate and gas quality (CH_4 and CO_2) at full-scale experiment B during a period of 11 weeks. The results evince that by flexible substrate feeding, the intraday gas production rate can be modulated between min/max values of 75 $m^3\ h^{-1}$ and 140 $m^3\ h^{-1}$ (e.g. day 53). This daily spread of 65 $m^3\ h^{-1}$ (± 30 % variation of gas production rate based on the daily average) is lower than the intraday dynamic observed in full-scale experiment A (full-scale Exp. A gives an example variation of ± 50 %). Causes of this observation may be found in the different substrates, geometrical, rheological and procedural conditions. In general, the gas production rate rises within 2 hours after feeding by a rate of change of 10 $m^3\ h^{-2}$ to a significantly higher level. Shea et al. [27] suggests a comparable 2-hour lead-time for feeding of grass silage in advanced of required electricity production. Figure 30b and c show a single week in detail. The gas production rate as well as the CH_4 and CO_2 percentage show a highly dynamic behavior as already observed in full-scale experiment A and lab-scale [14]. Between day 79 and 85 as well as between 100 and 107 samples were taken several times a day in order to analyze the dynamics of intermediate formation (Figure 30a and c shows the course of the acetic and propionic acid concentrations). During this period, a parallel progression of the individual acid concentrations and the gas production rate can again be observed. The basic level in the acid concentrations at full-scale experiment B is higher than in full-scale experiment A. Acetic acid concentrations peaks of over 1500 mg l^{-1} were measured. During the feeding pauses (i.e. day 85 and 105), the acid concentration decreased significantly. The FOS/TAC ratio varies between 0.18 and 0.30 throughout the experiment. However, the values are below a potentially process jeopardizing limit of 2500 mg l^{-1} for acetic acid and FOS/TAC ratio of < 0.4 [24]. Therefore, a stable anaerobic digestion process can be stated with no long-term inhibitions.

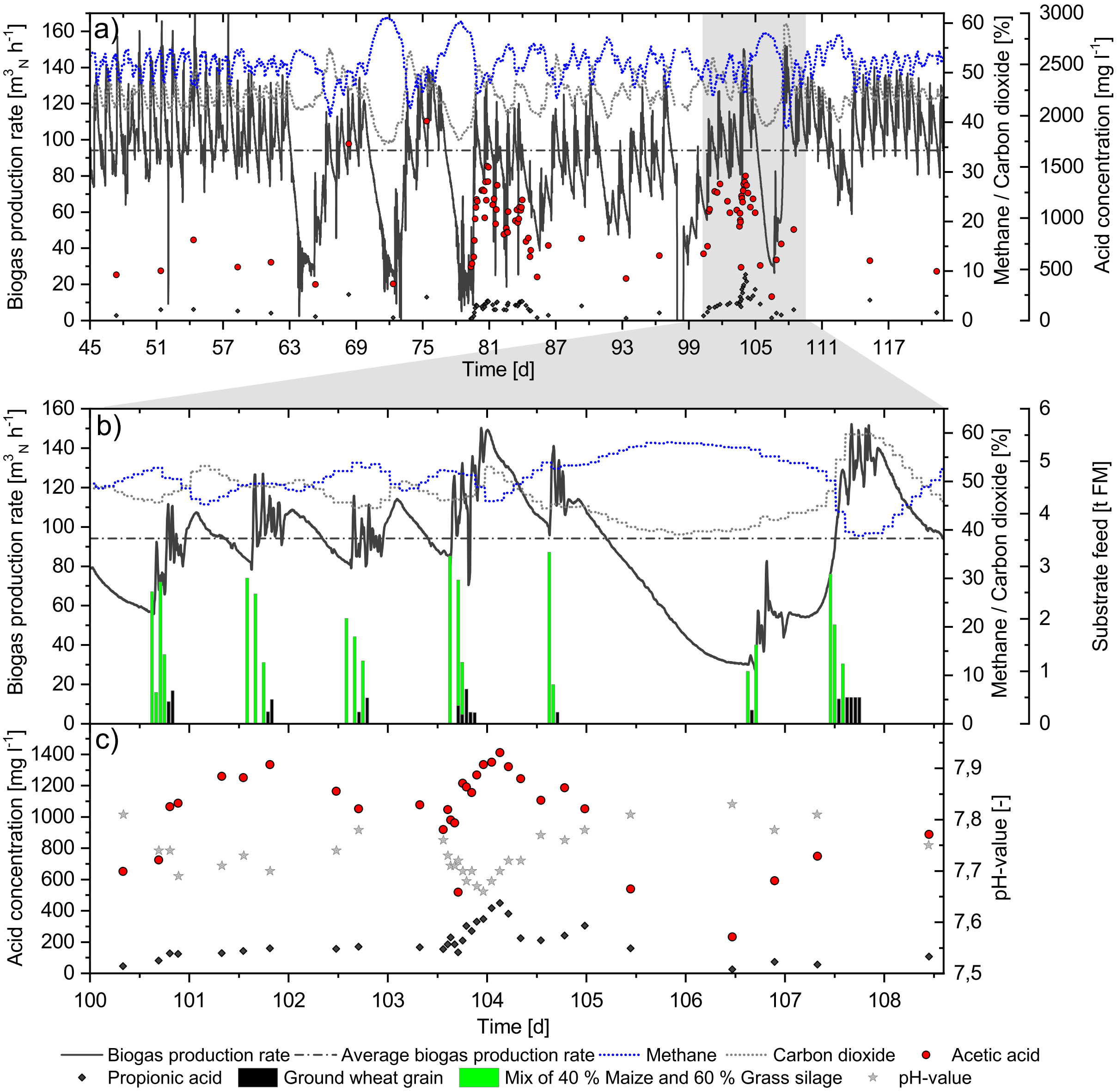

Figure 30: Experimental results at full-scale plant B: **a)** (experimental day 45 - 122) biogas production rate, average biogas production rate, methane and carbon dioxide concentration, acid concentration, **b)** biogas production rate, average biogas production rate methane, carbon dioxide concentration and feeding events at experimental day 100 - 109 **c)** acid concentration and pH- value at experimental day 100 – 109

Furthermore, pH and acids concentration show the same inversely proportional behavior as in full-scale experiment A and laboratory. However, the pH-value should nevertheless be considered critically, since the accuracy related to the measured alterations is low. Furthermore, the pH-value depends on the plant-specific buffer capacity affected e.g. from substrates and procedural conditions. Therefore it should be used only in combination with other parameters (i.e. according to Bensmann et al. [25] with gas composition measurement) for monitoring short term changes of process stability at biogas plants.

During feeding pauses of 2 days (day 63 - 65; 70 - 72; 77 - 80) it was possible to reduce gas production rate by more than 70 % compared to the average over a time of up to 72 h based on the used substrates and their proportional variation. In comparison to the full-scale experiment A, a similar delayed gas production (maxima 5 to 7 h later than expected) is observed on days 101, 102 and 103. The same causes can be stated as already discussed in the previous section 3.1.1. Thus, a minor inhibition or acidification could cause the delay. Furthermore, rheologically induced effects and general activity changes in the microbial community are possible. This delay effect should be reproduced and investigated in more detail.

It is thus also apparent in full-scale that the anaerobic process can be operated with stability even in the case of flexible feeding including high short-term organic loads. The pH and acids concentrations show an inverse behavior, as already seen in laboratory-scale in Mauky et al.[14]. However, different levels of acid concentrations (i.e. average acetic acid concentration of around 200 mg l^{-1} in full-scale experiment A and 1000 mg l^{-1} in full-scale experiment B) could be observed. In comparable laboratory experiments, only an average of 55 mg l^{-1} acetic acid was measured. However, during the entire period no process conditions were observed which endangered the long-term stability of the biogas process.

3.2 Effect of Demand-Oriented Feeding at Different Scales

Figure 31 illustrates the intraday flexibility potential compared for different scales and substrates. According to the methodology in chapter 2.3 in the present article, the percentage of the cumulated daily gas production (0-24 h) is shown, which is produced in the first half (0-12 h after first feed).

Figure 31a compares the gas production rate from experiments at different scales where maize silage was the main substrate. The impact on process dynamics of the co-substrate cattle slurry can be neglected, since it contributes to the OLR with less than 5 %. Grass silage (GS) shows a nearly similar behavior as maize silage regarding kinetic behavior [28]. In laboratory-scale experiment A in the first daily half a spread in the flexibility of biogas production between 58 and 66 % was observed. The median is at 62 % gas production in the first half of the day in percentage of the cumulated daily gas production. In both full-scale experiments (A and B) nearly the same level (median at 56 and 55 % of cumulated percentage in the first daily half) can be observed. The comparison shows a reduction of the intraday flexibility potential from laboratory to full-scale. Explanations for that different behavior could be found in the rheology and fermenter dimensions as well as in the general process conditions in practice against laboratory conditions. Here, full-scale lower mixing times and outgassing are reached compared to laboratory-scale. The full-scale system responds more slowly to changes in process conditions and thus a reaction to feedings will take longer.

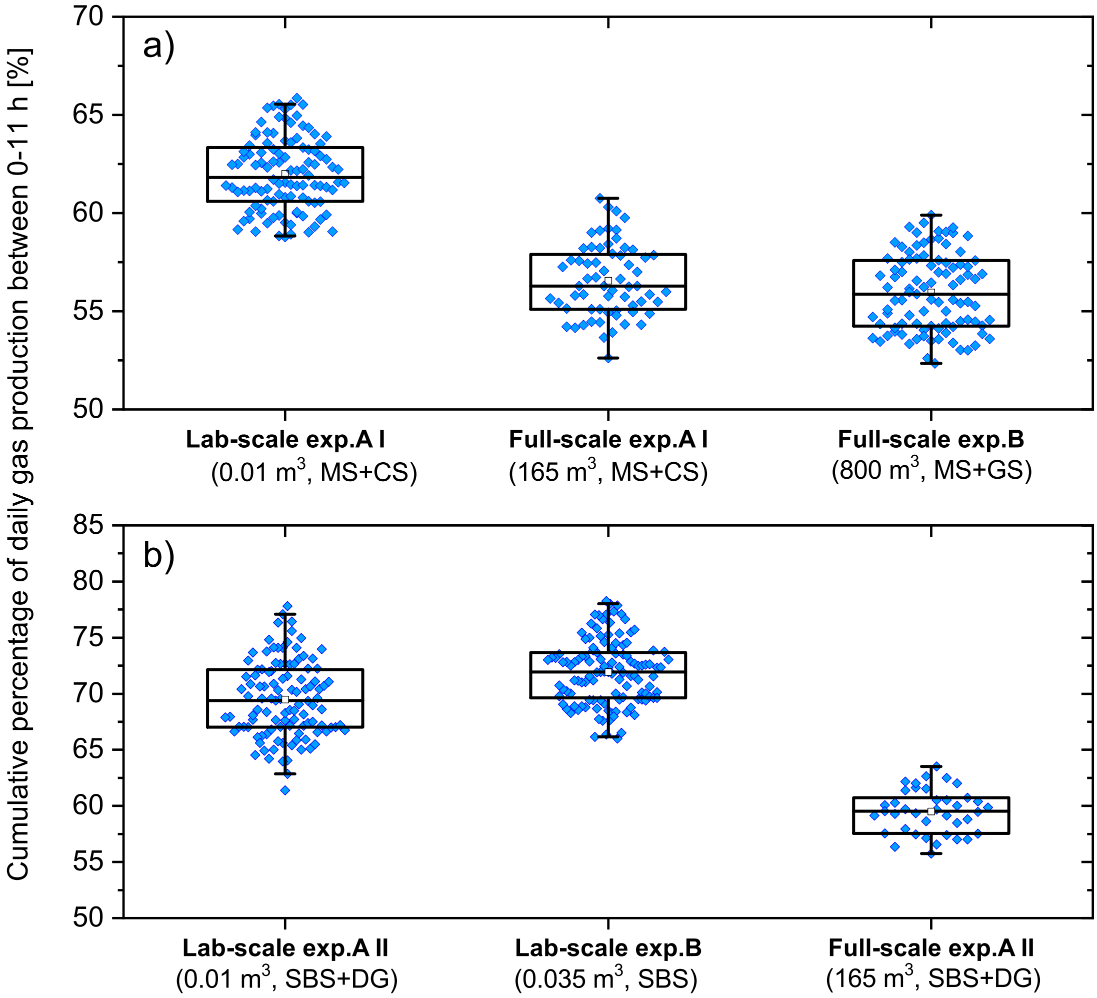

Figure 31: Flexibility potential as percentage of daily gas production (0–24 h) cumulated in the first half of the day after first feeding (0–12 h) at different scales and substrates; **a)** Comparison of experiments based mainly on maize silage; **b)** Comparison of experiments based mainly on sugar beet silage; Abbreviations: MS = maize silage; CS = cattle slurry; GS = grass silage; SBS = sugar beet silage; DG = digestate from a primary digester; The box's give the upper and lower quantile (25 % and 75 % range), the median line, the whiskers give the 99 % and 1 % quantile; the white square stands for the arithmetic average

In Figure 31b, a comparison of intraday flexibility potential based on the sugar beet experiments is given. In laboratory-scale experiment A II a high percentage of 69 % biogas with a spread between 62 and 77 % could be produced in the first half of the day. In laboratory-scale experiment B with an exclusive digestion of sugar beet silage the highest flexibility potential with a median of 72 % and a spread between 66 % and 77 % was reached. In full-scale only a flexibility of 59 % (median) was measured, but the spread was the smallest of all experiments. The results confirm the expectations that with sugar beet silage a higher flexibility is possible as this substrate has a high content of quickly degradable components and thus faster kinetics. In all experiments, the percentages for intraday methane production for this consideration are lowered the values by 2.5 % compared to biogas.

In Table 16 the simulated degradation time, which is needed to produce 15, 25 and 50 % of the expected biogas yield of each substrate is shown. For each scale, differences in the dynamics of biogas production can be observed. Within the first few hours after the substrate addition, large proportions of the substrates are already degraded (e.g. 15 % after 2 h and 25 % after 4 h using sugar beet silage in laboratory scale experiment B).

Table 16: Comparison of the duration from feeding event to the point when 15 %, 25 % and 50 % of biogas were produced from a substrate portion (acronyms: MS - Maize silage; SBS - Sugar beet silage; GS - Grass silage; GWG - Ground wheat grain); Information's about the Experiments and Substrate batches see Table 14, 13 and 15

		Lab-scale exp. A	**Lab-scale exp. B**	**Full-scale A**		**Full-scale B**	
Duration from feeding event to:		MS I	SBS I	MS II	SBS III	Mix of MS III and GS	GWG
15 % of cumulated total biogas production from a substrate portion ($t_{15\%}$)	[h]	2.5	2	6	4.5	7.5	5
25 % of cumulated total biogas production from a substrate portion ($t_{25\%}$)	[h]	5	4	11.5	8	15.5	8
50 % of cumulated total biogas production from a substrate portion ($t_{50\%}$)	[h]	15	13.5	36	20.5	51.5	20

In full-scale experiment, it takes more than twice as long for a comparable degradation of sugar beet silage (4.5 and 8 h for 15 %, respective 25 %). However, due to the different substrate qualities and process conditions, the results can only be compared with each other to a limited extent and should only give an orientation. The shorter this time span, the larger is the possibility to substantially shift the daily gas production into the periods of demand. A substrate degradation of 50 % within one day is reached (besides the general results in laboratory scale) only with the fast degradable sugar beet silage (20.5 h) and ground wheat grain (20 h). In the first 30 minutes of all experiments a peak in the measured biogas production rate can be observed. This can probably be explained by the proportion of volatile acids in the respective ensiled substrates and the content of fast degradable components. This behavior can already be comprehended within the model.

In general, the full-scale experiments could confirm the practical possibilities of flexible biogas production, albeit at a lower level. Therefore, in particular the transferability to even larger plants, the degradation process itself and higher OLRs should be further investigated.

3.3 Theoretical Saving of Gas storage Capacity Based on Flexible Feeding

Figure 32 compares the theoretical savings of gas storage capacity caused by flexible versus continuous biogas production based on laboratory and full scale experiment B. Scenario A, B, C (Figure 32 a, b, c) assumed a gas utilization phases of 8, 12 and 16 h a day, and storage phases of 16, 12 and 8 h (see methodology in chapter 2.3 in the present article). The thin gray line describes the respective basis of a continuous biogas production. The dashed line and bolt line give the demands of gas storage capacity based on the laboratory and full-scale flexible potentials at CSTR experiments. The resulting savings in storage capacity were described by the differences to the gray line (continuous biogas production).

In scenario A (8 h utilization, 16 h storage) a high reduction of the necessary storage demand was possible by 35 % in laboratory-scale and 11 % in full-scale was possible with flexible feeding. However, with the high dynamics of a fixed-bed reactor [22] (dotted line), a further decrease of more than 35 % could be achieved. In scenario B (12 h utilization, 12 h storage) the necessary storage demand could be reduced by 45 % and 15 % at laboratory respective full-scale (Figure 32b). The necessary storage demand, assuming the scenario C (16 h utilization, 8 h storage) could be reduced by 15 % (full-scale) and 17 % (laboratory-scale) with a flexible feeding of CSTR-systems. For the scenarios B and C (12 h and 16 h utilization), no additional data for hydrolysis/fixed-bed configuration could be found in the literature.

At last - in scenario D, in Figure 32d - a period without biogas consumption during 72 hours (i.e. weekend from Friday noon to Monday noon) was assumed. Biogas plants can have an economic benefit in times of low demand, if they can reduce the feed-in energy into the grid for longer periods. Furthermore, the limiting factor of 50 tons on-site biogas storing capacity (see methodology in chapter 2.3) is pictured as bolt dashed/dotted line. With the ReBi-configuration, a high decrease of the necessary gas storage demand until below the 50-ton-limit is possible for much larger biogas plants, i.e. higher average biogas production rates than with constant biogas production (see Figure 32d). The ReBi concept generally shows a lower storage demand and additionally benefits at higher gas production rates over 1400 m^3 h^{-1} in these scenarios and undercuts the on-farm biogas storage requirement. However, the ReBi-results need to be validated at larger scale, taking into account that these results are based on laboratory-scale experiments. With a full-scale CSTR-system, a substantial reduction of the necessary gas storage demand by over 65 % can also be reached in scenario D.

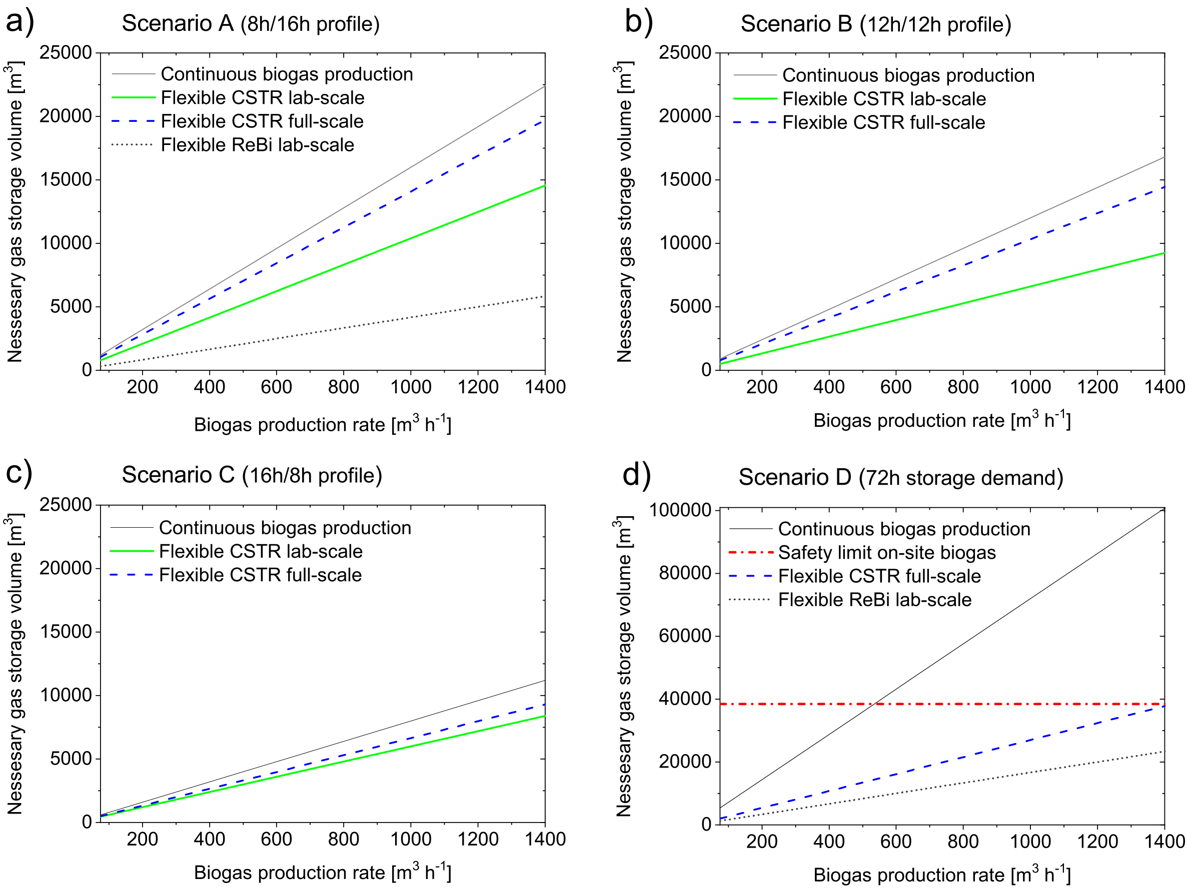

Figure 32: Comparison of necessary gas storage volume based on continuous and flexible biogas production by CSTR system and hydrolysis/fixed bed configuration; **a)** Scenario A with 8 h utilization /16 h storing profile; **b)** Scenario B with 12 h utilization /12 h storing profile; **c)** Scenario C with 16 h utilization /8 h storing profile; **d)** Scenario D with a 72 h storing phase; (ReBi: alternative hydrolysis/fixed bed configuration. Description and values of ReBi-configuration adapted from [22])

Here the 50-tons-limit can be undercut up to an average biogas production rate of 1400 m^3 h^{-1}. This allows a considerably expanded range of flexibility options to be offered without the need for an additional high investment for complex structural changes. The calculation is based on the dynamic seen in the full-scale experiment B (experimental day 60 to 80 in Figure 30a). Besides the intraday flexibilization, the possibility to reduce gas production within CSTR-systems over several days shows a large potential to substitute necessary gas storage volume. The investigation demonstrates a significant contribution of flexible feeding to a demand-driven energy production at full-scale biogas plants.

4 Conclusion

This study showed that by dynamic substrate feeding flexible biogas production can be achieved in full-scale biogas plants. Flexible feeding in anaerobic digestion results in an accordingly variable rate of gas production (up to 50 % of daily average). At the same time alterations of methane, carbon dioxide and acid concentrations occur within acceptable ranges. Also, the pH-value corresponds to the flexible feeding. However, the long-term process stability was not negatively affected by flexible feeding. As a result, a flexible biogas production can enable significant savings regarding the required gas storage volume (in intraday context up to 45 %) and thus allows a far greater flexibility in power production than at a constant gas production rate. Particularly the decrease of gas production during periods without any feeding of up to 3 days, the investigated processes, showed great savings potentials (of up to 65 %) regarding necessary gas storage volume.

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Part C – SUMMARIZING DISCUSSION, CONCLUSION AND OUTLOOK

5 Summarizing discussion

In the following part of this thesis, the specific objectives and questions (see objectives in section 2, page 14) are discussed in detail, taking into account the results of the four present articles.

5.1 Flexibility potentials in biogas production by flexible feeding (objective A)

Substrate characterization as a basis for evaluating the flexibility potential of substrates

The degradation of complex organic material is assumed to pass multi-stages starting from complex organic materials to monomers to gaseous compounds [59]. The degradability of an organic substance is mainly due to its biochemical composition. From a biochemical point of view, the essential organic substances can be subdivided into characteristically groups of substances, such as more or less structural carbohydrates, proteins, lipids (fats) and lignin. These groups of substances have different anaerobic degradabilities under anaerobic conditions and consequently require different degradation times. In effect, first statements on dynamic behavior of substrates can already be derived by an analysis of substrate ingredients.

Figure 33 shows the classification of the dry matter based on Weender and extended Weender analysis by van Soest. With the Van Soest extension, the components of dry matter can be further distinguished into the two groups, cell wall and intracellular components. While organic intracellular components, such as crude protein or sugar, can be degraded quite readily, cellular wall structures, such as cellulose, are quite less readily fermentable [74], [75].

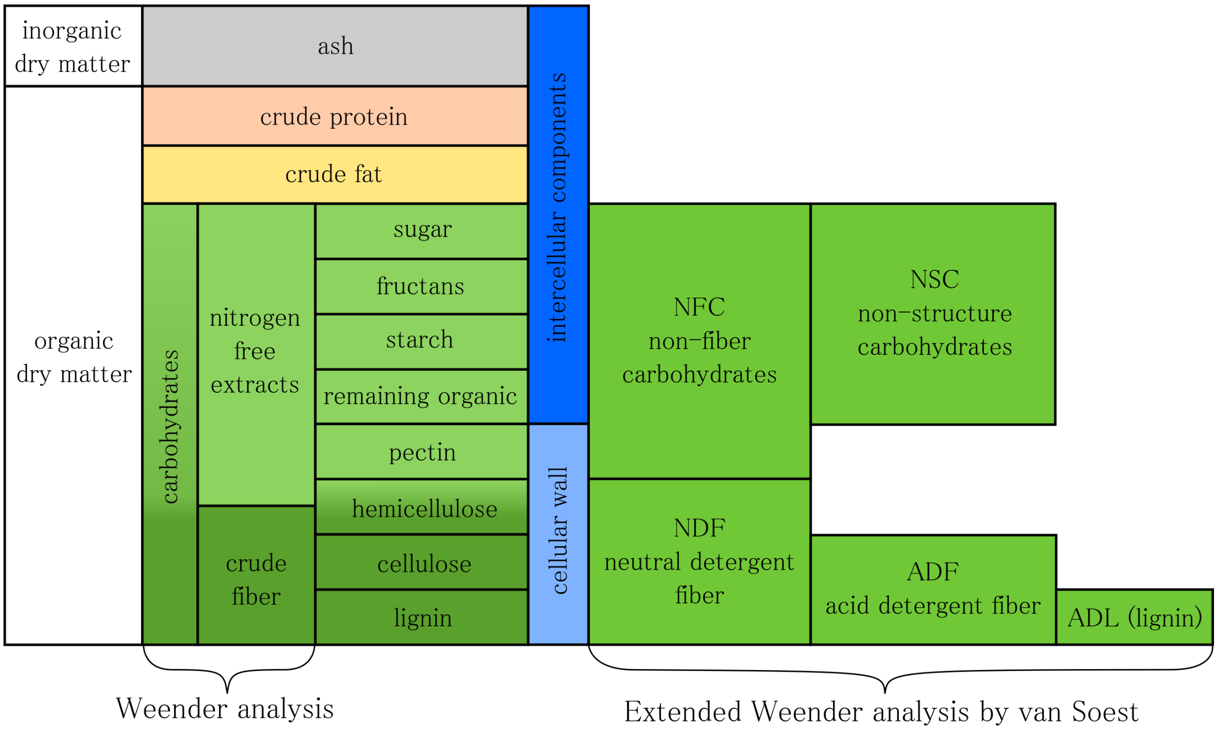

Figure 33: Classification of feedstock into characteristic components based on the analysis method *Weender* and *extended Weender by van Soest*

Figure 34 characterizes the individual groups of basic substances according to their degradability. The anaerobic degradability - and also the kinetic behavior - of a substrate can thus be estimated as the sum of the degradation of each of the available substance groups of this substrate, considering the contents of each group.

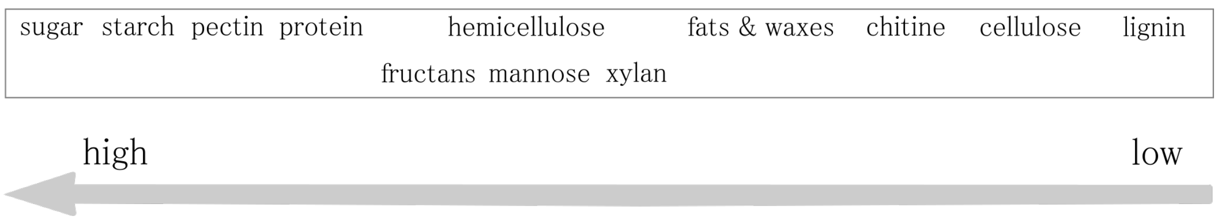

Figure 34: Schematic classification of the degradability for different biochemical components (adapted from [75])

Due to the high amounts of structural-rich carbohydrates of most of the agricultural substrates, the hydrolysis has especially shown to be a rate-limiting step for digestion [76]. Nevertheless, in this approach uncertainties remain. Additional aspects, such as organic material size, shape, surface area, biomass concentration, enzyme production and adsorption, seem to influence the digestibility, too [76]. Exemplary results of feedstock compositions of cattle slurry, maize silage and sugar beet silage are compared in Figure 35, illustrating distinct fractional differences.

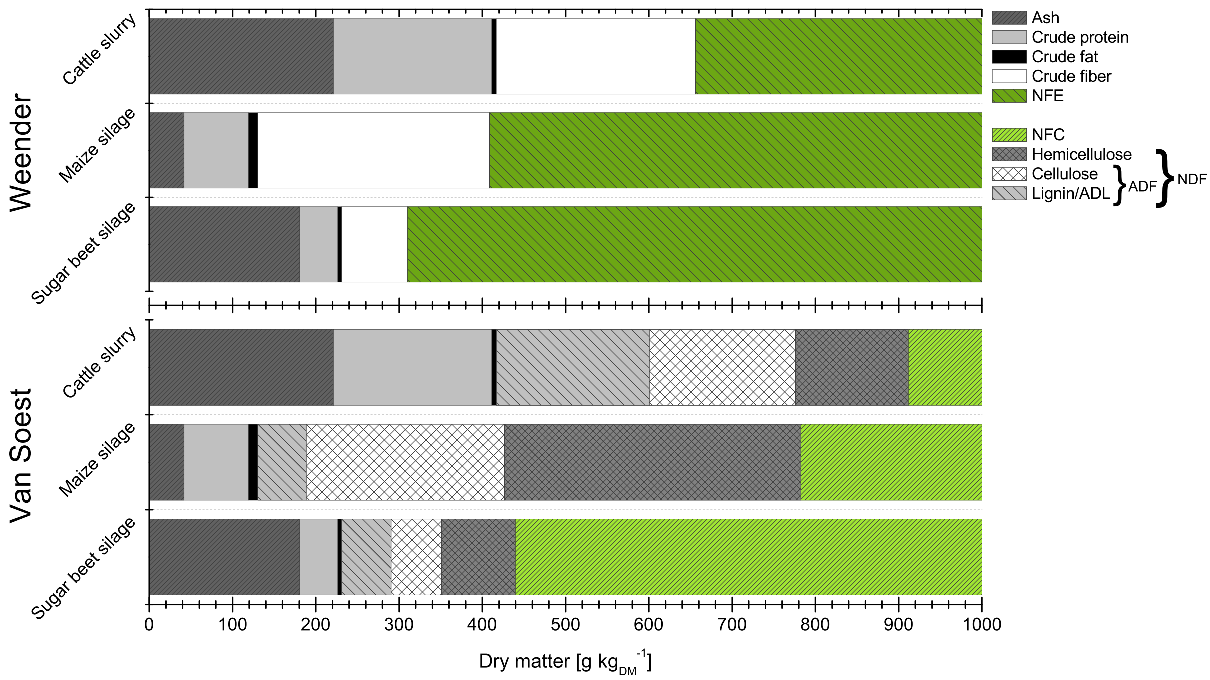

Figure 35: Comparison of feedstock composition (Weender with the extensions by Van Soest) of cattle slurry, maize silage and sugar beet silage used in the lab-scale experiments (Article 1); Fast degradable carbohydrate fractions marked in green

It is evident that carbohydrates are the main substance in all investigated substrates. However, the differences can be seen mainly in the crude fiber and nitrogen free extracts (NFE) content and in the proportions of non-fiber carbohydrates (NFC), cellulose and hemicellulose. These components have different degradation properties (see Figure 34) which lead to different degradation characteristics.

In the experimental work of this thesis, it could be demonstrated that the addition of sugar beet silage leads to a very rapid gas production directly after feeding (**Article 1,** Figure 9), due to the higher proportions of easy degradable carbohydrates (sugar) as well as acids and alcohols. In cattle slurry, the rapidly degradable fractions have already been largely degraded by the animal. These differences also derived from the summated specific gas production curves of batch assays (see Figure 36). Irrespective of the different gas yields of the substrates, the different degradation kinetics can be clearly deduced from the gradient of gas production curves (1^{st} order kinetical factors given in **Article 1, Table 4**). Cattle slurry, for instance, has a very slow gas production rate deduced from the flatter curve. In contrast, maize silage and especially sugar beet silage has a steeper gradient and thus a significantly higher production rate, especially with regard to the first hours after the substrate addition.

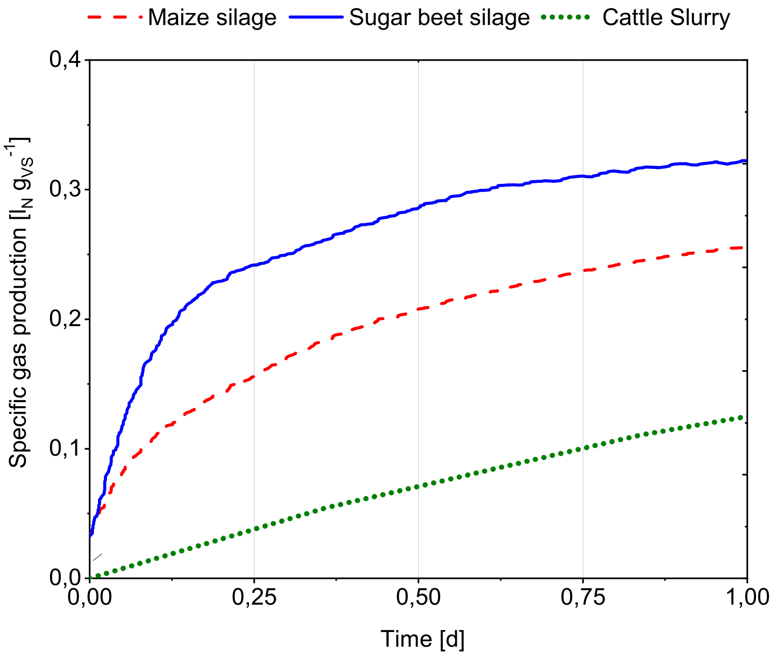

Figure 36: Results from batch assays testing cattle slurry, maize silage and sugar beet silage

Characteristics of flexible biogas production in continuous processes

Beside the estimation of statements on the flexibility potential via substrate characterization and batch assays, characteristic parameters could be also found in continuous anaerobic digestion processes. In general, the following four parameters (illustration in Figure 37) were developed (**Article 1** and **4)**, assessing the individual flexibility of a gas production course:

A: increase rate of gas production after first feeding event (time span t_a between feeding and reaching the maximal productions plateau $\dot{V}_{max}$),

B: the possibility of holding a plateau for a specific time (t_b),

C: 1^{st} order kinetic constant (corresponds to the reduction rate within a certain time t_c) and

D: positive ($\dot{V}_{max}$)) and negative ($\dot{V}_{min}$) dynamic in relation to rated power or average gas production rate.

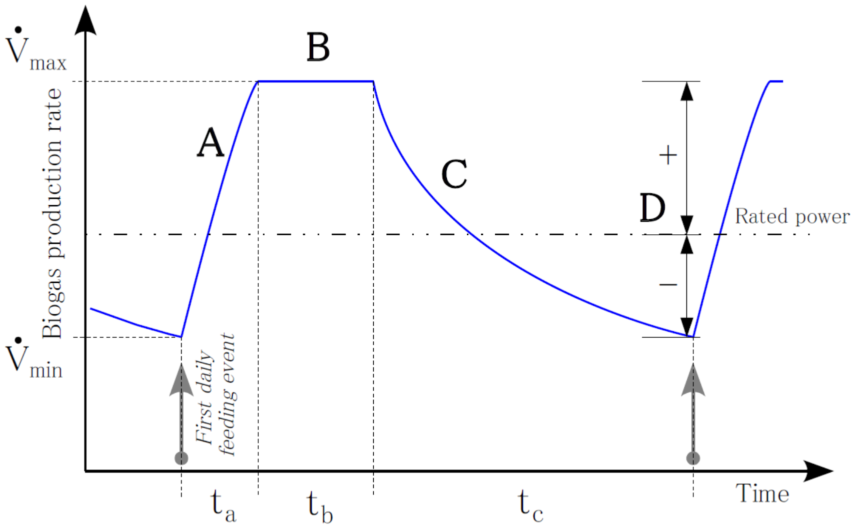

Figure 37: Characteristic parameters for the assessment of flexible biogas production courses; **A:** phase of increasing gas production; **B:** plateau phase; **C:** reduction phase; **D:** min/max ratio compared to rated power or average gas production rate (dashed/dotted line)

Table 17 gives a comparison of the presented parameters A, B, C and D based on exemplary daily courses from the performed laboratory (**Article 1**) and full-scale experiments (**Article 2** and **4**). For practical implementation of flexible gas production the DBFZ- research biogas plant and the research biogas plant of the University of Hohenheim were used.

However, the parameters should be considered in the interaction to each other and interpreted as one unit in context to process descriptive parameters. Derived statements and correlations based on the comparison are:

- Parameter A (increasing rate, normalized to digester volume) and Parameter C (k-value of decreasing phase) depend on the substrate (see composition of maize silage compared to sugar beet silage in Figure 35) and digester scale (e.g. digestion of maize silage in lab- compared to full-scale plant A)

- A longer plateau (parameter B) within a constant OLR-level can be achieved by splitting the daily feed into more portions; however, this would reduce the spread of parameter D (positive and negative dynamic in relation to rated power). Another possibility of extending a plateau in the gas production rate is a temporal overloading (increased daily

OLR compared to the rated OLR level). Limit is the maximal safe OLR, which have to be determined individually for each process and state. For this purpose, other stability characteristics, such as VFA trends, have to be monitored more intensively.

Table 17: Comparison of parameters assessing the flexibility potential (given results are examples and not the respective maximal values of each parameter) acronyms: MS –Maize silage, SBS – Sugar beet silage, GS – Grass silage, GWG – Ground wheat grain, DG – Digestate from a maize silage fed process, CS –Cattle slurry

	Unit	**Lab-scale-exp 2A**	**Lab-scale-exp 1B**	**Full-scale A**	**Full-scale A**	**Full-scale B**
Substrate		MS, CS	SBS	MS, CS	SBS, DG	MS, GS, GWG
Experimental day	[d]	65	199	34	101	108
Digester volume (V_{liq})	[m^3]	0.01	0.035	165	165	800
OLR	[kg_{VS} m^{-3} d^{-1}]	4.8	3.3	4.0	2.0	3.5
HRT	[d]	62.5	63	75	71.7	114
Daily fed portions	[-]	3	4	4	5	6
Parameter **A** *(increasing rate, normalized to digester volume)*	[m^3_{biogas} h^{-2} $m^{-3}_{V.liq}$]	0.7	0.9	0.59	0.74	0.36
Parameter **B** *(plateau length)*	[h]	6	8	6	7.5	12
Parameter **C** (*k*-value of decreasing phase)	[d^{-1}]	0.9	1.5	0.6	0.9	0.6
Parameter **D** *(positive and negative dynamic in relation to rated power)*	[%]	+119 / -38	+203 / -39	+65 / -39	+73 / -45	+47 / -21
Spread of parameter D	[%]	156	242	102	118	68

- Very sharp responses in the gas production rate after feeding could be observed in laboratory scale with the easily degradable sugar beet silage (parameter A: 1.5 d^{-1} and parameter D with a variation of +203 % in relation to the rated power)

- A higher degradation rate results in a larger spread between the positive and negative amplitude of parameter D. This is also characterized by steep ramps (parameter A und C) in the process and a low minimal gas production base level (V_{min}). This was also proven within a model-based evaluation in **Article 4**. The temporal degradation characteristics in different experimental scales were calculated by an anaerobic model. On this basis, the time periods were calculated when 15, 25 and 50 % of the total amount of biogas is produced by a specific feed. Thus, regarding the results in Table 17, the higher the rate of degradation in the process, the more biogas can be provided from the daily feeds within a day.

Another possibility to rate the intraday distribution is the split of daily gas production into two periods[1] with a subsequent comparison of the respective shares. With the applied flexible feeding regimes in laboratory scale (**Article 1**), the gas production – produced during the first half – could be raised up to 80 % of the daily gas production. Accordingly, in the storage phase, the production could be reduced to a minimum of 20 %. The comparison of these values from laboratory with the results in full-scale (**Article 4**) shows an almost halved intraday flexibility in full-scale. Here again, the full-scale system responds obviously more slowly to changes in process conditions and thus a reaction to feedings will take longer. As already discussed before, explanations for that different behavior were assumed to be caused by the rheology and fermenter dimensions as well as differences in the general process conditions between full-scale and laboratory scales.

Beside the evaluation of intraday flexibility, the ability to reduce the gas production in a longer phase of low demand is also of practical interest. This potential for an electricity shutdown could be demonstrated in the lab- and full-scale experiments. At such a shutdown of up to 3 days, the gas production rate decreases by more than 60 % in the full-scale experiment B (**Article 4, Figure 30a**, from day 77 to 80). Also, the previously described idea of separating the feeding between primary and secondary digester to generate a higher overall dynamic (**Article 1**) was picked up and could be reproduced successfully at the DBFZ- research biogas plant (see **Article 4**).

Evaluation of flexible biogas production based on gas storage demand

Another way to assess the process dynamic is the performance of theoretical gas utilization scenarios. The resulting gas storage savings towards an assumed constant production (simulated

[1] In a practical context the first half (0 – 12 h after the first daily feed) can be understood as a utilization phase in which biogas is consumed and electrical current is produced. The second half (12 – 24 h) represents the storage phase when no biogas is utilized. Usually, evenly distributed, consecutive feeding of a biogas plant would lead to 50 % of the daily gas production to be produced in each half of the day.

by the average gas production in the respective period) can serve as a flexibility score. In these scenarios, the gas utilization was varied within the day, assuming gas utilization phases of 8, 12 and 16 h a day, and storage phases of 16, 12 and 8 h. The laboratory results in Article 1 illustrate that up to 45 % of gas storage capacity can be saved based on a 12/12 scenario (12 h utilization and 12 h storing phase). The data from both full-scale experiments were also evaluated according to the same procedure (see Article 4, Figure 32 for an overview of results). In full-scale, only 33 % of the gas storage saving possibilities from laboratory scale could be achieved. In order to broaden the spectrum of experiments and reactor technologies, literature results for an 8 h and a 72 h scenario implemented with alternative hydrolysis/fixed bed configuration (called ReBi) [22] were integrated in the comparison (see Article 4). With the high dynamics of the fixed-bed reactor, a further decrease of another 35 % could be achieved compared to the own experiments in CSTRs. However, these results from fixed-bed reactor were only available from lab-scale experiments.

Alternatively to the intraday flexibility evaluation, in full-scale experiments (**Article 2**), a weekly schedule was chosen which, in addition to the daily fluctuations in demand, also includes a two-day demand reduction. Figure 38 shows an example week from the full-scale experiment at the DBFZ –research biogas plant (**Article 2**). In Figure 38a the measured gas production (black line) as well as the feeding regime (green bars) are illustrated. The aim was the fulfilling of schedule A (consumption as gray bars in Figure 38b) and, not exceed the limits of the gas storage (small blue line in Figure 38b). Details to the procedure of optimizing the feeding are in Article 2 and in the following discussion about flexible feed control. Figure 38b shows the course of the theoretical gas storage level with flexible and assumed constant gas production (simulated by the average gas production of the observation period as a dash-dot line in Figure 38a).

The results show that the required gas storage capacity can be almost halved (43 %) in the case of flexible (blue dotted) to constant gas production (orange spotted). In hours[2], this means that where average (continuous) production requires 22.7 h of gas storage capacity to meet the gas requirement schedule A, only 12.9 h are required with flexible biogas production. Depending on the specific schedule and availability of CHP-capacity, further savings are possible. In combination with scheduling methods of **Article 3**, an alternative schedule B was developed in order to use the specific process dynamic of the example process. The schedule B in Figure 38c assumes that 40 % of the energy is supplied by a continuous operated CHP and 60 % by an additional flexible CHP. If this schedule is applied to the initial process data of schedule A and the corresponding curves of the gas storage filling levels are compared an even greater reduction in the gas storage requirement from 23.8 h with continuous to 7.7 h with flexible gas production results. This corresponds to a 68 % reduction in the required gas storage capacity, based on this optimized schedule.

[2] An hour of gas storage capacity corresponds to the intake of the gas, accumulated in an hour at average production rate

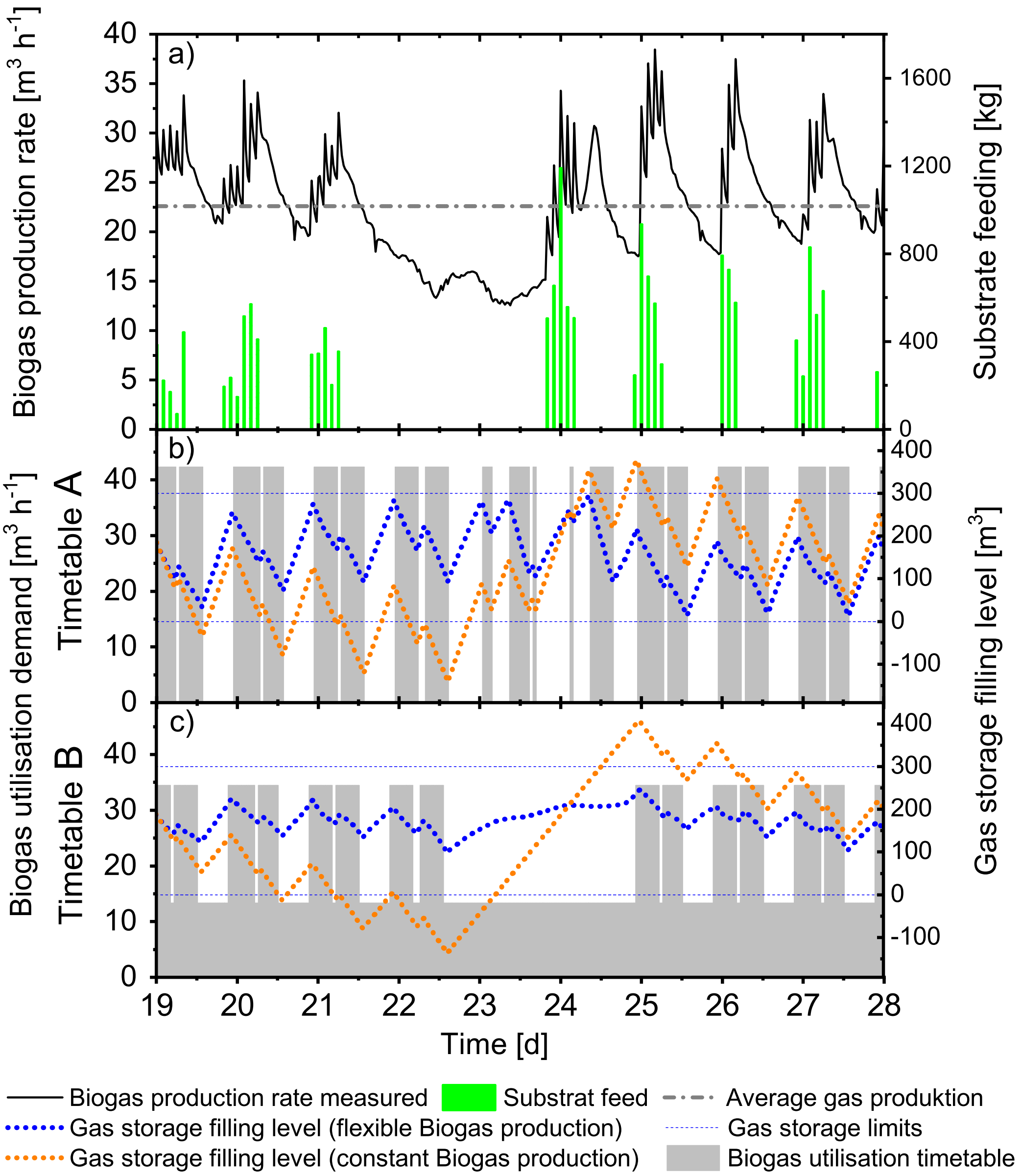

Figure 38: Course of gas production rate optimized to fulfill a gas utilization schedule based on energy exchange data with resulting courses of the gas storage filling level with constant and flexible gas production at the DBFZ research biogas plant (based on Article 2, full-scale experiment A)

Evaluation of flexible biogas production in an economical point of view

In **Article 3** the potentials of flexible feeding were investigated economically based on three different utilization schedules. Within a model-based optimization (internal model and identified kinetics from **Article 2**) the optimal feeding regime and the necessary gas storage requirements of a representative model biogas plant (digester volume: 2100 m^3) were determined. Subsequently, an economic cost-benefit analysis was carried out. As general result, flexible feeding exhibits a cost-reducing effect in all developed scenarios. The impact of the gas storage requirements absolutely necessary or the additional amount beyond existing gas storage capacities crucially depends on the different power generation schedules and the feeding regime. The results show that flexible operation allows a **doubling of the revenues** at the European Power Exchange compared to constant gas production, with low additional costs. However, if the potential for additional revenue in the market changes, the optimum of additional gas storage volumes will also change in the future.

Influencing factors and limits of the provided evaluation criteria for flexible biogas production

The different response between full and laboratory-scale could be attributed to the kinetical degradation characteristics of the substrates in the specific process and as well as to their specific technical setup and scale. Additionally, the results show a delay in gas production after feeding breaks (discussed in **Article 4**) in the full-scale experiments. However, the delay effects in the gas production rate could not be observed in the laboratory experiments described in **Article 1.** Possible reasons for these inconsistent results are different agitation, feeding systems and intensities of mixing, as the laboratory digester and DBFZ-research biogas plant (Plant A) has a central agitation and the research biogas plant in Hohenheim (Plant B) has different paddle mixers. Inadequate mixing limits the gas transport. Lindmark et al. point out the large effects of mixing on the performance of anaerobic digestion [77]. In addition to the design of the agitation system itself [78], mixing also depends on the particle size distribution, which is related to the substrate behavior [64]. Unfortunately, these mixing effects could not be investigated in the thesis, but should be kept in mind for further experiments. For this, flow profiles as well as the analysis of the particle size distribution should be brought in the context to degradation characteristics.

Another importance for comparative analysis is the provision of equal conditions. However, for logistical reasons, it was not possible to provide exactly the same substrates batches and start-inocula for full and laboratory-scale experiments. Consequently, the microbiological community could be different [33], [79], [80]. However, this possibility could not be investigated in this thesis. Finally, the experiments showed that it was necessary to pay attention to the use of defoaming agents, trace elements and extra nitrogen supply, especially for the use of sugar beet silage. However, the exact mechanisms and the optimal need are still in research.

Résumé to objective A

A highly dynamic gas production can be achieved by targeted temporal distribution of substrate feeds. Furthermore, a combination of substrates, according to their composition (fast / slow degradable carbohydrates, fats and proteins) with a temporally shifted distribution allows a further flexibilization of the anaerobic process. The biogas production rate in full-scale can be varied intraday, under the selected conditions, by up to 50 % based on the rated power. In addition, the experiments demonstrated the possibility of a feeding brakes of up to 3 days with an decreasing gas production rate by more than 60 % in full-scale. In consequence, a demand-driven biogas production may enable significant savings in terms of the required gas storage volume (up to 68 %). With regard to the initial situation (constant gas production rate), this dynamic has both technological feasibility and economical worthiness.

5.2 Process stability at flexible operated process in short and long-term context (objective B)

A common assumption in literature is that a flexible feeding imposes alternating stress levels on the biocoenosis, which leads to an instable process (e.g. accumulation of acids) and in long-term perspective to a breakdown of the process. In order to investigate this hypothesis and the underlying mechanisms more closely, an intensive monitoring (in addition to the usual measuring program at biogas plants, see page 23) was done at laboratory (see **Article 1**) and also at the two full-scale processes (see **Article 4**). Corresponding to the already discussed dynamic gas production, the diurnal feed variation leads to alternations of the methane, carbon dioxide and individual acid concentrations as well as the pH-value. After a feeding event, the proportion of CH_4 and CO_2 changes towards low CH_4 and higher CO_2. In further progress, the CH_4 content rises again, exceeding 55 % whereas CO_2-content lowers accordingly. This behavior can be observed in different intensities in laboratory (**Article 1, Figure 10**) as well as in the full-scale experiments (**Article 4, Figure 29 and Figure 30**). This margin corresponds to observations by Lv et al. [33] and Mulat et al. [80], which focus on microbiological community changes by different feeding patterns. In all experiments in this thesis, phases with higher gas production after feeding events yielded poorer gas qualities regarding the methane content. At full-scale experiment, a fixed roof with a relatively small gas volume, similar to the relation at laboratory-scaled digesters, was used. However, in conventional full-scale plants the gas is collected in larger gas storage holding capacities for several hours. Thus different qualities are mixed, leading to lower variations in the gas quality. In addition, modern combined heat and power (CHP) units with combustion control can process gas of varying quality within the observed margin of 45 % methane. The daily average CH_4 content in all experiments is higher than 50 %, which is an indication of sufficient degradation of agricultural substrates. The measurements of H_2 and H_2S show uncritical reactions ($H_2 < 150$ ppm, $H_2S < 3$ ppm) in all experiments.

The course of the individual acid concentrations shows a corresponding behavior to the feeding events (see **Figure 29 and Figure 30** in **Article 4**). The acetic and propionic acid concentration increase after feedings and throughout the day, and the concentrations decrease to the initial level (maximal and minimal measured values in Table 18). Butyric-, valeric- and hexanoic acid remained in sum in all experiments below 50 mg l^{-1}. Moreover, in all experiments a ratio between acetic and propionic acid concentrations > 3 and a FOS/TAC ratio lower 0.3 $g_{FOS}\ g_{CaCO3}{}^{-1}$ was observed, which is considered as uncritical [42], [81]. However, the overall level of the acid concentrations increased within increasing fermenter volume from laboratory to full-scale. At full-scale experiment B partially (e.g. up to 1500 mg l^{-1} acetic acid in daily course) higher values as the defined limits for stability (page 24) could be measured. However, no long-term accumulation could be detected. Furthermore, the pH value also follows inversely to the concentration changes of the acetic acid (see exemplary Figure 30 in Article 4). Due to fact that the produced acetic acid was consumed by methanogens, the range of pH values was very narrow (up to 0.35 units in full-scale experiment B), and a relatively balanced pH level was maintained. The observed behavior of pH value, acid and gas concentrations could be explained by the immediate onset of hydrolysis step, where organic acids, H_2, and CO_2 are produced. Once these intermediates are available, the downstream processes and finally the methanogenesis follow. A shift in the solubility system throughout a changed pH-value is also a proportional cause of increasing CO_2 after feeding events.

Table 18: Comparison of characteristic values for stability evaluation, based on intensive daily course measurements at exemplary laboratory and full-scale experiments

	Units	**Lab-scale B1**	**Full-scale A**	**Full-scale B**
Digester liquid volume	[m^3]	0.035	165	800
OLR	[kg_{VS} m^3 d^{-1}]	4.0	4.0	3.5
HRT	[d]	50	75	114
Acetic acid *(min – max value in daily course)*	[mg l^{-1}]	100 – 300	200 – 800	1000 – 1500
Propionic acid *(min – max value)*	[mg l^{-1}]	30 – 100	< 50	200 – 500
Ratio acetic to propionic acid	[-]	> 3	> 4	> 3
Sum of Butyric-, valeric- and hexanoic acid	[mg l^{-1}]	< 50	< 50	< 50
FOS/TAC	[g_{FOS} g_{CaCO3} $^{-1}$]	< 0.3	0.22 – 0.27	0.21 – 0.28
pH	[-]	7.2 – 7.7	7.4 – 7.9	7.6 – 7.9
NH_4-N	[mg l^{-1}]	1000 – 1500	1400 – 2300	3000 – 4200

It could be seen that processes which are fed in a flexible manner alternate between phases with increased hydrolysis / acido- / acetogenesis and methanogenesis processes over time. Investigations by De Vrieze et al. [34] suggest that especially this application of a limited pulse feed and/or a variation in the substrate composition might promote a divers microbial community and hence a higher functional stability in anaerobic digestion.

In summary, the results show that the **long-term process stability** (related to experimental times between 70 and 300 days) **was not negatively affected by the flexible feeding**. In particular, no uncontrolled accumulation of acids, only small daily changes in pH-value (maximal 0.35 units), CH_4 concentration in daily basis over 50 %, could be observed.

Furthermore, the following points were considered:

- balanced trace elements supply (monitored based on [66], [67]),
- distinct buffer system [3] (FOS/TAC ratio in all experiments lower 0.3 g_{FOS} $g_{CaCO3}{}^{-1}$),
- known contaminants and inhibitions not ascertainable and
- moderate overall OLR level (in full-scale up to 4.0 kg_{VS} m^3 d^{-1}) with moderate protein input.

Based on the results, it could be stated that the investigated anaerobic digestion processes are able to buffer the alternating imbalances by means of a flexible operation.

Résumé to objective B

An intermittent high load, which occurs during a demand-driven feeding, was not followed by an unstable process state in any of the experiments (Based on stability criteria, defined in chapter 4.4, page 24). A short-term increase in acid concentrations does not negatively affect the overall process as long as the metabolic activity increases and the acids are reduced again. In any experiments, the increase in metabolic activity after feeding is sufficient to degrade the substrates and to prevent a long-term accumulation of intermediates. The pH value has not left the optimal range and an Inhibition due to low or high pH was not evident. Other indicators, like FOS/TAC, were also in uncritical ranges.

The results indicate that online gas production rate and quality measurements in combination with easy-to-measure parameters on site such as FOS, FOS/TAC by titration and pH are sufficient to monitor the long-term stability[4] of a flexibly operated anaerobic digestion process under the described specific conditions of low inhibited process. The stability criteria based on individual acids (absolute concentrations and the ratio between acetic and propionic acid) are not required. In consequence, the stability criteria can be further reduced for a practical-oriented process monitoring in a control concept.

[3] The main buffer systems in anaerobic digestion are carbonic acid/hydrogen carbonate and ammonium/ammonia. However, in agricultural biogas plants often the carbonate buffer system is primarily active. With nitrogen-rich substrates, also an effective ammonium/ammonia buffer system could be established

[4] A monitoring of trace element supply is generally recommended and will be preconditioned.

5.3 Control concept for flexible feeding (objective C)

General control structure and measurement basis

A literature study was performed about control methods (see introduction section of this thesis and Article 2), which revealed the model predictive control (MPC) concept as a promising method. Especially the characteristic of prediction and targeting operation to future set points [53], [54] was crucial for the use of this basic concept. MPC uses an internal model of the process, a history of past control moves and an optimization objective function over the receding prediction horizon to calculate the optimal control moves. In contrast to many other modern control methods, MPCs are able to consider explicit limitations and keep future timeslots into account (in the present aim e.g. electricity demand schedules or the substrate availability).

As a result of the limitations in available measuring technologies at practical biogas plants (see Introduction section), a reduced measuring scenario (measuring scenario II at page 23) was defined and serves as basis for the development of the control concept. These minimum requirements are a characterization of substrates and process (dry matter (DM), volatile solids (VS) with a quantitative analysis of feedstock composition) and on-line measurements for biogas quantity and quality. The selected measuring concept was presumed for a low-inhibited anaerobic process (i.e. low inhibitions by NH_3 or H_2S). Furthermore, offline measurements of FOS, FOS/TAC by titration and pH are used for manual monitoring of long-term stability.

The investigations of flexible gas production dynamic and stability in the former discussion section (section 5.2) indicates two general process states related to the defined stability criteria (page 24) for flexible operation:

1. **The process is stable:** A flexible gas production with long-term stability is possible. Only short-term alternating fluctuations in diverse process values could be measured.

2. **The process is unstable:** long-term stability is not ensured – i.e. accumulations of intermediates and consequently potential process failure ahead. Flexible gas production is not recommended at the present OLR level, with the current substrate mix or process conditions.

Based on this classification, the control tasks were separated into two subtasks:

- **Subtask A (flexible feeding MPC) -** Shifting substrates (quantity and type in a given OLR range) optimally in feeding slots, to fulfill the gas demand of a given schedule (fluctuating demands and lead times). In this process, technical and operational aspects (limits of gas storage, available substrates and individual degradation characteristics and technical-limited of biogas plants like feeding rates) were considered. Figure 39 shows the overall structure of the control concept. The developed flexible feeding MPC controller for Subtask A is marked in green (detailed scheme of MPC find in Figure 12 in **Article 2**).

- **Subtask B (monitoring and main control)** - Regulation of general OLR levels, introduction of new substrates to the process (changing the operational point of the anaerobic process), definition of the constraints for the lower-level MPC (Subtask A) and prevention of disturbances. The Subtask B (general monitoring & control of rated power and long-term process stability) was taken in that case manually by supervision. This procedure simulates the common state of the art at biogas plants in the field of monitoring and feed planning based on reference stability criteria (mentioned in section 4.4 and simplified, based on the own investigation described in discussion section 5.2).

Subtask B could be in a practical context also - as usual until now - executed by a qualified plant operator or/and with supporting monitoring and control tools. There are already tools and concepts for the automation of these higher-level control tasks, such as in the works of Löffler [81] and Gaida [82]. This approach is based on complex ADM1 models and online - measurements of individual acids. The automated classification of the process state based on the mentioned stability criteria could be performed with fuzzy logic approaches or state estimation approaches like moving horizon estimation or extended kalman filters [83], [84].

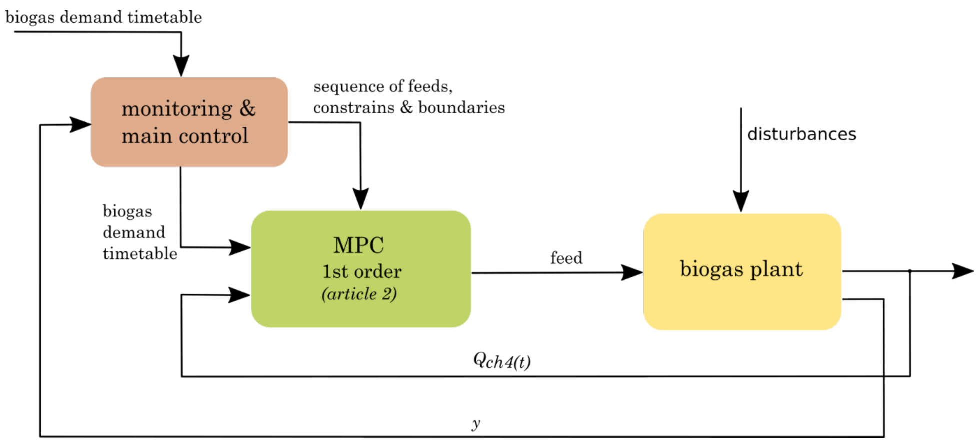

Figure 39: Overall control structure of the model predictive feed control; (**yellow component**): controlled biogas process; (**green component**): model predictive control for flexible gas production by feeding (Subtask A); (**red component**): monitoring and main control tasks (Subtask B) fulfilled by manual supervision

However, massive changes in the OLR or the regulations of inhibited processes require still a higher effort in measuring and monitoring, which are not an objective in this thesis. Primary objective are a robust control concept for flexible biogas production at the condition of low-inhibited agricultural biogas processes with limited changes in measuring equipment.

The needed constraints with maximal weekly and daily available substrate amounts for optimization were calculated in Subtask B based on the specific OLR-target of the respective experiment and transfer to the lower-level MPC-controller (Subtask A).

Internal anaerobic digestion model

The utilized model in the flexible feeding MPC (Subtask A) is based on the Anaerobic Digestion Model No.1 (ADM1, [59]). In contrast to the original ADM1, the complex model structure is simplified to simulate the complete anaerobic digestion of particulate carbohydrates, proteins and lipids to biogas by the superposition of three brutto reactions [62]. Attempts were made to find a compromise regarding the few online measurements available in practice, easy adaptability of the model and rapid calculation. The reduction of model orders is employed in few applications of model predictive controls to balancing stability and prohibitive computational complexity [56]. A modification of the model approached was performed in order to optimize the simulation results particular to flexible biogas production (higher correlation during the intraday gas production curves) by means of separating the carbohydrate fraction in a fast and a slowly degradable fraction. This results in a fourth brutto reaction with an extra kinetic parameter. An additional parameter represents the relation between fast and slowly degradable carbohydrate fraction (see Table 6 in Article 2 for parameter range). The model parameters were identified on every MPC-step on basis of a set of real measured past process data (measuring scenario II) in a receding identification horizon (an appropriate horizon was 20 days).

Optimization procedure, objective function and constraints

The optimization procedure consists of an objective function, constraint equations and a solver (see **Article 2**). The research on algorithms for solving optimization problems revealed the Matlab-solver *fmincon* [85] as suitable to minimize the developed constrained multivariable function.

In order to take into account the dependencies between gas production, storage and gas utilization in a comprehensive approach, the course of the gas storage filling level was used as command variable. The manipulated variable is the profile of the feeding rates and substrate types in a specific horizon. The implementation of the gas storage filling level in the optimization requires a precise measurement of gas storage filling level. In this thesis it was achieved by precise gas flow rate measurements from the headspace of the fermenters (used fermenters had fixed flat ceilings and little headspace volume) to the gas storage in the post digestion system. The gas storage filling level was calculated based on these flow rates and was not fed back with real measurements.

The control results shows that the developed approach of using an indirect control variable was functionally capable. This indirect control variable was based on the course of the gas storage filling level along the predicted horizon which was rated stepwise by a weighing function. The weighing function penalized here low and high gas storage filling levels in boundary regions.

The considerable linear equalities and inequalities were used to control the feeding process and substrate utilization. Functions and dependencies which were taken into account in the present optimization are:

- capacity and filling level of a gas storage,
- interconnection of several fermenters (i.e. primary and secondary digester configuration),
- maximum substrate amount allowed per fermenter within a defined time range,
- regulation which substrates have been fed explicit (i.e. cattle slurry) and which substrates can be fed only if necessary and
- the maximal feeding rate for each substrate.

The optimization time until convergence was smaller than one hour to find the appropriate feeding sequences minimizing the necessary gas storage volume.

Proof of concept and demonstration

The control concept was tested at two different full-scale biogas plants (Article 2). The results show that with flexible feeding in a stable OLR range there was no uncontrolled accumulation of acids. This supports the hypothesis that with sufficient robustness of the anaerobic process (see former chapter about stability), a control approach based on a simplified model (without modeling intermediates) and minimal measurement technology (substrate characterization, biogas production rate and quality) is sufficient to adequately control the feed quantity and type according to the requirements of electricity demand schedule and gas storage. A manual monitoring based on common offline measurements of intermediates characterizing the process stability is sufficient.

For evaluating the accuracy of prediction, different statistical values (Predicted Residual Error Sum of Squares ($PRESS$), Coefficient of determination (R^2) and the standard error of the estimation (σ_{est}) were used (see Article 2, page 51).

The discrepancies – expressed by standard error of the estimation (σ_{est}) - between daily predicted and measured gas production courses ranged in all experiments from 4 % to 10 %. Considering the various uncertainties (e.g. measurements, model simplification and variations in the substrates), these results should be classified as sufficiently precise. However, only in dynamic phases does the predictability of the first-order model reach its limits (i.e. Plant A at day 25 and plant B at day

84 and 91) with much higher discrepancies (σ_{est} up to 20 %). Nevertheless, by re-optimization the difference between simulated and measured gas production rate could be mainly counteracted. The weekly comparison of the biogas utilization amounts and the measured gas production leaves a gap of only 4.9 % and 1.2 % (first and second experimental week at full-scale plant B). This shows that the MPC was able to compensate short-term differences and realize the planned weekly production. One way to increase the accuracy in gas production prediction is to increase the frequency of calculating the MPC procedure. However, for technical and safety reasons, the MPC system could not be integrated directly into the plant control system (complete established procedure and transfer routine see **Article 2, chapter 2.1.3**).

As a result, the optimization in this study could generally only be performed once a day. However, shorter intervals show higher accuracy by the shorter feedback, which could be confirmed in a preliminary theoretical simulation (un-shown data). The internal step size of *48/day* represented a good compromise in terms of forecast accuracy. However, the control results indicate that especially the measurement of the gas production rate in the full-scale experiments is further influenced by different effects (i.e. pressure fluctuations by feeding and digester mixing and variations in substrate quality), which are not included in the used simplified model and also not in the established original ADM1. Statistical methods could be used for a data correction.

Especially the observed delay effect after pausing feeding (described in the former section) could not be modeled adequately by the simplified model approach (delays of up to 6 h expected production and high daily derivation up to 20 %). The investigation of the causes by repetition of the experiments is still pending. Since there was no excessive accumulation of (analyzed) acids in these phases, a reduction in hydrolytic activity could also be a cause, which could then be counteracted also in the simplified model by a phased adjusting the hydrolysis rates.

If further replicating studies show that the cause is an accumulation of acids with a phased inhibition, then a slight extended model structure, which additionally models one sum-parameter of VFA in combination with the pH value, could result in increased reliability.

Procedural and measurement recommendation for practical implementation of the developed concept

Based on the present experiments and results, the following recommendation for the operation of flexible feeding MPC at practical biogas plants was proposed.

(0) low-inhibited process in an agricultural biogas plant[5]

(1) Definition of operating range: Intensive measuring concept for minimal 1 Month (twice a week FOS, FOS/TAC, pH and concentration of acetic and propionic acid), one feedstock characterization of substrate and process by extended Weender by Van Soest, higher interval according to changes in substrate batches). This phase is necessary to generate a basis for the model adaptation and to estimate the operating point of the process.

(2) Transition phase, with option:

> **A - Start-up phase of flexible feeding:** Gradual transition from continuous to flexible feeding over a phase of minimally 8 weeks. The overall OLR is constant, only the substrate amounts and types change within days. This transition phase serves as a minimum period for the parameter adjustment of the used models (internal model of the MPC). Start of the feeding optimization by the MPC at the end of this phase.
> **B - Transition of operating point:** If flexible operation was already introduced, this transition phase serves as a monitoring period for changes in operation. This could be an adjustment the OLR level or an introduction of a new substrate. This phase is needed to assess the impact of changes on the process and adjust the control concept to the new operational point. Feeding optimization by the MPC is continuing, but the constraints for feeding optimization were restricted.
>
> *Both options need to be supported by operator experience or simulations studies.*

(3) Reduced monitoring of long-term stability criteria (see below) after transition phase (2 A and B).

In the case of pending changes according to point **(2B)** the procedure has to be repeated.

The minimal measurement requirement for the procedure (according to current practical equipment) can be defined for the MPC for flexible feeding (lower-level control for subtask A):

[5] Decision based on the assessment of the general process conditions (e.g. low OLR, substrates with low protein content) and / or on the basis of a test period.

- Substrate characterization for every used substrates and process (DM, VS with a quantitative analysis of feedstuff composition; frequency: DM and VS weekly, feedstuff composition monthly, higher interval according to changes in substrate batches),

- Gas production rate measuring with high density of measuring points for quantity (frequency of measuring < 15 min) and quality measurements (frequency of measuring < 6 hours); Both measurements should be carried out directly at every fermenter and not only as sum before the CHP unit

- Measurements of the gas storage filling level (frequency of measuring < 1 hour).

For the simultaneous monitoring and control of overall operation (higher-level control for Subtask B) - additional to requirements of flexible feed MPC - the following measurements of the process are recommended minimal (with minimal measuring frequency twice a week):

- FOS and FOS/TAC by offline titration and

- pH-values (offline pH-meter).

Résumé to objective C

The aims of the developed process control were on one side the demand-driven controlling of the gas production rate and on the other side the ensuring of a stabile overall anaerobic process. Due to the practical constraints (e.g. few measurements available) and based on preliminary investigation of process stability, a distinction between model-predictive feeding control and overall process monitoring and control was forced. A simplified anaerobic digestion model was used to find a compromise regarding few online measurements available in practice, easy adaptability of the model and rapid calculation. Practically relevant functions and dependencies (e.g. gas storage capacity and filling level) could be integrated. In the validation experiments, it could be demonstrated that the controller is capable to control the course of the gas production demand-driven and follow a given schedule. The developed control concept was able to ensure the defined process objectives. Based on the results, a procedural and measurement recommendation for practical implementation of the developed concept was given.

6 Conclusion

A full-regenerative energy system is one of the major challenges for the next decades. Therefore, a further expansion of solar and wind energy is necessary. However, this requires new ways to guarantee grid stability and supply security. In particular, biogas could be a key technology supporting the transition towards a regenerative energy system. One possibility for a demand-driven energy output is the adaptation of the anaerobic process itself by flexible feeding.

The objectives of the present thesis were:

A) to investigate general possibilities, underlying mechanisms and dependencies establishing a flexible biogas production in full-scale by means of a demand-driven feeding,

B) investigate the behavior of characteristic measurements under the conditions of flexible feeding and deriving recommendations for the valuation of process stability and

C) develop and demonstrate a robust control concept under practical requirements and limitations.

For this purpose, firstly criteria were developed, describing the characteristic of flexible operated processes (objective A). A highly dynamic gas production can be achieved by targeted temporal distribution of substrate feeds. Furthermore, a combination of substrates, according to their composition (fast / slow degradable carbohydrates, fats and proteins) with a temporally shifted distribution allows a further flexibilization of the gas production rate. The biogas production rate in full-scale (CSTR-digesters at average OLRs of up to 4 $kg_{VS}\ m^{-3}\ d^{-1}$) can be varied intraday, under the selected conditions, by up to 50 % based on the rated power. Laboratory-scale results show even higher intraday flexibility of more than 200 % based on average gas production rate (at OLRs of up to 6 $kg_{VS}\ m^{-3}\ d^{-1}$).

Additionally, the experiments demonstrated the potential for a shutdown of electricity production of up to 3 days (decreasing gas production by more than 60 %) by flexible feeding in full-scale. In consequence, a demand-driven biogas production may enable significant savings in terms of the required gas storage volume (up to 68 % based on the gas production dynamic, archived in this work) and permit far greater plant flexibility compared to constant gas production rate.

Beyond that, an economic investigation shows that flexible biogas production by feeding management allows a doubling of the revenues (based on data from the European Power Exchange) compared to constant gas production with low additional costs.

The investigations of process stability (objective B) under the conditions of flexible feeding shows that an intermittent high load, which occurs during a demand-driven feeding, was not followed by an unstable process state in any of the experiments. The flexible feeding resulted in a variable rate of gas production and a dynamic fluctuation of individual acids, gas quality parameters and the respective pH-value. The amplitude of the changes differs between the scales, but remains below critical values. A short-term increase in acid concentrations does not negatively affect the overall process as long as the metabolic activity increases and the acids are reduced again. In any experiments, the increase in metabolic activity after feeding is sufficient to degrade the substrates and to prevent a long-term accumulation of intermediates. The long-term process stability was not affected negatively due to the flexible feeding.

The results showed that under the specific conditions (e.g. agricultural substrates and low inhibited process) online measurements of gas production rate and quality in combination with easy-to-measure parameter on site such as FOS, FOS/TAC by titration and pH) are sufficient to monitor the long-term stability in a practical-oriented control concept.

The aim of the developed process control (objective C) was on one side the demand-driven controlling of gas production and on the other side ensuring a stabile process. The concept of model predictive control was selected. Due to the practical requirements and constraint (e.g. few available measurements, integration of gas storage), it was payed attention to the robust control structure and an appropriate model complexity. Based on preliminary investigation, a distinction between the control task of model-predictive feeding control and overall process monitoring and control was forced.

A simplified anaerobic digestion model was used in the model-predictive feed control to find a compromise regarding few online measurements available in practice, easy adaptability of the model and rapid calculation. The model was able to predict the course of the flexible gas production with a sufficient accuracy and operate the process in full-scale according to a given demand schedule. The developed control concept fulfilled the imposed requirements. The selected measuring concept for the control is feasible under the chosen conditions (e.g. agricultural substrates and low-inhibited process). Finally, a recommendation for implementation of the developed control concept at practical biogas plants was proposed.

The thesis indicates that with slight modifications common agricultural CSTR-based biogas plants can be operated much more flexibly than usual.

7 Outlook and future research directions

In forthcoming studies various research directions, which may affect the possible degree of flexibilization of biogas plants, should be investigated.

Overall plant modeling and control:

First, the technical, biological and economic effects and dependencies in the context of a flexible plant operation should be combined to a comprehensive concept. That includes the close linking of technical and biological process optimization as well as the predictive synthesis of operation timetables for the best possible economic and energetic utilization of the provided electricity and heat output. In order to predict the different processes adequately, a dynamic model-oriented description of the different processes is necessary. This means an expansion of system boundaries - from substrate pretreatment through the fermentation process to the entire gas system (gas conduction, storage and use). Particularly in the case of the strong influence of the ambient conditions on the available gas storage volume, it is apparent how necessary the involved description of such processes is. In Mauky et al. 2017 [86] it could be shown, for example, that a temperature difference of 30 K results in a 20 % lower gas storing capacity. Such high temperature differences within one day have already been measured inside the gas storage of a biogas plant [86].

Within all these possibilities, one major shortcoming is the equipment of measurements at practical biogas plants. A review of Jimenez et al. [49] shows that a large number of online measurement techniques have been developed in the last decades, but have rarely found their way into broad practice. Especially a prompt and reliable substrate characterization, particularly in the case of more fluctuating proportions and qualities, is a key factor for an advanced plant operation. However, the current optimization pressure forced rethinking and will support the establishment of advanced monitoring, diagnosis and control tools in the future.

Influence of demand-driven operation on technical components:

The behavior of the technical components in the case of more flexible use is increasingly under investigation and optimization e.g. the effects of varying composition of biogas on performance and emission characteristics of CHPs [87] or the gas storage measurements [88]. In general, the present experiments for flexible biogas production should be repeated for evaluation at higher OLRs, larger scale and an additional focus on the behavior of the technical components. Obviously, as also shown by the present investigations, fermenter types and technical setups have a great influence on the flexible digester performance. In consequence, methodological advancements describing these relationships have to be made regarding the transfer of the methods to other conditions with a focus on the gas production dynamics, process stability and reproducibility. This includes the investigation of other fermenter types, such as Pfefferkorn or plug-flow digesters and of interactions between mixing performance and degradation conditions. Coupling of biochemical with spatially resolved modeling could help to find a better agitation characteristic in order to create substrate-specific optimal degradation conditions. In this context, disintegration effects should also be considered, which can influence the rheological conditions and thereby the degradation characteristics. The integration of large heat storage is also conceivable. This would result in a larger leeway for flexible feeding, since the heat supply is decoupled from the electricity production and thus longer periods of the CHP-shutdowns are possible. To accomplish the suggested plant-overarching approach, the efficiency assessment and optimization should be carried out in a comprehensive way, using biological, technical and also economic / ecological performance indicators. This approach will help to identify the specific bottlenecks and limits for a higher overall flexibilization.

Progress to anaerobic digestion model, state estimation and control:

For a more focused modeling and prediction of anaerobic digestion, further methodological advancements have to be made regarding the optimal model complexity. In the last years, the benefits of robust model approaches have been discussed also in scientific literature (see [62], [89]–[91]). This would not only save computing time during model-based optimization of operation strategies, but also allow straightforward and explicit parameter identifications. Within an increasing availability of cheap online measurements (like acid concentrations [92]) in practice, more complex modeling approaches would be conceivable. On this basis, the monitoring of process stability can be done by a higher-level ADM1 (according to Gaida [82]) in combination with an integrated flexible-feed-MPC. Unfortunately, many states of the original ADM1 cannot be or are still not measured at full-scale biogas plants. Therefore a state estimator could be used, which estimates the states on basis of past and present measured data. Besides improving the used models, future work should be done in enhancing the required optimization procedures. Especially regarding the suggested overarching task with more than one objective function, a robust and fast finding of optima is crucial. These different objectives could range from revenue optimization, to efficiency enhancement to minimal ecological footprints. A range of multi-objective optimization strategies is discussed in the field of the electricity market, which considers for example environmental aspects and physical constraints of energy generation ([93]–[96]).

Investigation and combination of demand-driven processes and operation modes:

The ongoing research should also be followed by investigations in the field of multi-stage fermentation systems [22]–[24], [97], but also in power2gas/power2heat technology [98], [25]) and its combination with existing infrastructures. A further possibility to increase the process flexibility of existing plants could be the transition to thermophilic conditions (increasing degradation kinetics, heat sink etc.). However, considering this would also require higher degrees of process monitoring.

Effects of demand-driven operation on the biocenosis and its stimulation:

Improved online measurements in practice also allow a deeper investigation of biochemical processes and phenomena. Particularly for flexible use, the research on the optimal use of fast degradable substrates as process boost as well as the prevention of foam formation during the use can be mentioned as important [99], [100]. To accomplish this investigation, detailed analyses have to be done which influence specific feeding patterns on process performance. This should include further substrate categories, especially residual potentials (such as from oilseed and grain milling, foodstuff industry or bio-wastes). Finally, a test procedure should be developed, which determines the individual limit of an anaerobic process (e.g. short-term overfeed, optimal OLR, buffer system boundaries and substrate ratios). An interesting question to be answered in that context is the possibility of making the anaerobic community more resilient against process fluctuations because of the more flexible operation mode. Investigations of [33], [34], [80], [101] suggest this correlation and possibility of influence. Moreover, studies about biological augmentation describe possibilities for shifting the digester community to increase the performance and to help to prevent disturbances [102], [103].

Investigations in energy system transition and economic / social effects:

Beside technological and operational possibilities, of course, the economic and ecological feasibility should be kept in mind. In particular, with regard to life cycle assessment, some studies have been published [16], [104], which show the benefit of the demand-driven power supply based on biogas plants [105]. However, these studies do not yet include all the site advantages of a supervised, forward-looking plant operation, among others:

- Saving of gas storage capacity and larger operation gaps (priority high-demand periods, etc.)

- Forward-looking gas management can reduce overproduction and thus gas losses through flaring or overpressure release events,

- Optimized shutdown and start-up during maintenance results in less idle times

Additionally, the question of whether a further expansion of the grid is fully necessary in the course of a further increase in renewables, or whether it can be compensated partly by flexible biogas plants is also discussed [106]. Also, the cost efficiency of flexible biogas plants depends significantly on the renewable portfolio and its transition [107]. However, it is becoming increasingly clear in scientific discussions [108] that it is purposeful not only to carry out purely economic considerations, but also to allow overall ecological and public service oriented perspectives. Less centralized structures of common energy systems are also discussed [109] and practically tested, for example in the form of bioenergy regions and places [110]–[112].

In summary, all these broached development fields - from technological, biological, procedural to energy systemic level - should also be reflected in optimization strategies - in plant-wide optimization strategies, but also in cross-sectoral strategies. Advanced control and monitoring technologies could support this progress.

The present research tries to expand the utilization limits of available biogas technology, connect technological possibilities with systemic requirements from the grid and may help to establish a sustainable bioenergy provision, being socially useful, economically viable and ecologically friendly.

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Conferences attended and additional publications

During my PhD study I have participated in the following relevant conferences:

- **13th IWA World Congress on Anaerobic Digestion**, Santiago de Compostella, Spain, June, 2013

  Oral Presentation: *Optimized restart of a full scale biogas plant after disturbances by means of an anaerobic simulation model*

  Poster presentation: *Simulation and investigation of procedural effects of a high rate anaerobic digestion of grain stillage*

- **3th Progress in Biogas Conference**, Stuttgart, Germany , September 2014

  Oral Presentation: *Flexible BioGAS production for flexible energy provision*

- **3th Conference on Monitoring & Process control of anaerobic digestion plants**, Leipzig, March 2015

  Oral Presentation: *Model predictive control for demand-driven biogas production*

- **8th Biogas Innovations Congress**, Osnabrück, Germany, June 2015

  Oral Presentation: *Bedarfsgerechte Biogasproduktion durch modellprädiktive Fütterungsregelung im Praxismaßstab*

- **14th IWA World Congress on Anaerobic Digestion**, Viña del Mar, Chile, November 2015

  Oral Presentation: *Demand-driven biogas production in full-scale by model predictive control*

- **25th European Biomass Conference and Exhibition**, Stockholm, Sweden, June 2017

  Oral Presentation: *Demand-driven biogas production in full-scale by model predictive feed control*

The following non-reviewed papers on relevant topics were published as main- or co-author:

- DEMAND-DRIVEN BIOGAS PRODUCTION IN FULL-SCALE BY MODEL PREDICTIVE FEED CONTROL, Conference paper, proceedings of European Biomass Conference and Exhibition (EUBCE), 2017, Stockholm, Sweden
- Flexibilisierung von Biogasanlagen als Beitrag zur Reduzierung des notwendigen Netzausbaus In: Tagungsband zum FNR/KTBL-Kongress „Biogas in der Landwirtschaft – Stand und Perspektiven", Sept. 2017, Bayreuth
- Flexibel füttern - bedarfsgerecht Biogasstrom produzieren, BIOGAS Journal, 6_2016
- Simulationsgestütztes Anfahren von Biogasanlagen nach einer Störung, BIOGAS Journal, 5_2012
- Bedarfsgerechte Biogasproduktion - Option für die Flexibilisierung erneuerbarer Energien; ew; Jg.112 (2013), Heft 1-2
- Flexibilisierung von Biogasanlagen in Deutschland - Ein Überblick zu technischen Ansätzen, rechtlichem Rahmen und Bedeutung für das Energiesystem / Flexibilization des unités de méthanisation en Allemagne - Tour d'horizon des approches techniques, du cadre réglementaire et de l'importance pour le système énergétique; Deutsch-französisches Büro für Erneuerbare Energien (DFBEE), Background- Paper, March 2016

Additional oral presentations and posters:

- Process simulation - a key step for efficient biogas production, oral presentation, Dechema/ 1th European Congress of Applied Biotechnology, 2011, Berlin
- Investigation of the stoichiometric conversion processes during the anaerobic digestion, oral presentation, 1^{st} International Conference on Biogas Microbiology, 2011, Leipzig
- Flexible BioGAS produktion als Beitrag zur bedarfsgerechten Energiebereitstellung, Poster, FVEE-JAHRESTAGUNG and DBFZ-Jahrestagung (2014)
- Flexible Biogasproduktion mittels modellprädiktiver Regelung im Praxismaßstab, oral presentation on 8. AgrosNet- PhD student day, 2015, Berlin
- Möglicher Betrag einer variablen Fütterungsstrategie zur Flexibilisierung der Stromerzeugung aus Biogas, oral presentation, Biogas-Fachgespräch, 2015, Nossen
- Empfehlungen zur optimalen Flexibilisierung von Biogasanlagen in der Praxis; oral presentation, BioFit-seminar, 2015, Hannover
- Entwicklung eines simulationsgestützten Regelungsverfahrens unter Berücksichtigung einer bedarfsgerechten Biogasproduktion; oral presentation, DGAW-Wissenschaftskongress „Abfall- und Ressourcenwirtschaft", 2017, Aachen

The Articles, Posters and presentations produced for these conferences are not presented in this dissertation since the main results presented there are included in the scientific articles or in the background and discussion section.

Proof of individual contribution

Manuscript included in the thesis	**Author (E. Mauky)**	**Co-authors**
Eric Mauky, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles *Flexible biogas production for demand-driven energy supply – feeding strategies and types of substrates* Bioresource Technology 178 (2015) 262–269	Idea, experimental planning, realization and interpretation, writing the article	**Jacobi H.F.:** experimental planning, realization and interpretations, writing and corrections of the article **Liebetrau J., Nelles M.:** Article corrections
Eric Mauky, Sören Weinrich, Hans-Joachim Nägele, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles *Model predictive control for demand-driven biogas production in full-scale* Chem. Eng. Technol. 39(4), (2016) 652–664	Idea, control method, experimental planning and realization, statistical calculations, interpretation, writing the article	**Weinrich S.:** providing the used model and parameter identification procedure, experimental planning and realization, Article corrections **Nägele H.J.:** experimental realization and interpretations, Article corrections **Jacobi H.F.:** experimental planning and interpretations, Article corrections **Liebetrau J., Nelles M.:** Article corrections

Manuscript included in the thesis	**Author (E. Mauky)**	**Co-authors**
Tino Barchmann, Eric Mauky, Martin Dotzauer, Mathias Stur, Sören Weinrich, H. Fabian Jacobi, Jan Liebetrau, Michael Nelles *Expanding the flexibility of biogas plants - substrate management, schedule synthesis and economic assessment* Agricultural Engineering / Landtechnik 2016, 71(6), 233–251	Optimization procedure for flexible feeding management, modeling, interpretation, writing the article	**Barchmann T.:** idea, economical calculations, interpretations, writing the article **Dotzauer M.:** Method for synthesis of demand schedules from electricity exchange data, calculations, interpretations, writing the article **Mathias Stur:** Writing parts about gas storage technology **Weinrich S.:** Providing the used model, article corrections **Jacobi H.F., Liebetrau J., Nelles M.:** article corrections
Eric Mauky, Sören Weinrich, H. Fabian Jacobi, Hans-Joachim Nägele, Jan Liebetrau, Michael Nelles *Demand-driven biogas production by flexible feeding in full-scale – Process stability and potentials* Anaerobe 46, (2017), 86–95	Idea, experimental planning and realization, interpretation, statistical calculations, modeling, writing the article	**Weinrich S.:** Providing the used model, experimental planning and realization, article corrections **Jacobi H.F.:** experimental planning and interpretations, article corrections **Nägele H.J.:** experimental realization, interpretations, article corrections **Liebetrau J., Nelles M.:** article corrections

Thesen

A - Hintergrund und Zielstellung

Die Lösung des globalen Energieproblems gilt als eine zentrale Herausforderung des 21. Jahrhunderts. So sollen die durch die Nutzung von konventionellen Energieträgern verursachten ökologischen, gesellschaftlichen und gesundheitlichen Probleme minimiert werden. Gleichzeitig stellen die Endlichkeit der fossilen Energieträger sowie die Gefahren der Kernenergie wichtige Gründe für eine Beendigung der Nutzung von fossilen Energieträgern dar. Um der zunehmenden Umweltbelastung langfristig vorzubeugen, sind als direkte Reaktion ein sparsamer Energieverbrauch sowie eine Umstellung auf erneuerbare Energiequellen notwendig. 2015 wurden durch erneuerbare Energien in den OECD Ländern 2,471 TWh elektrische Energie erzeugt, was 23 % der gesamten Produktion entspricht[1]. Mit dem in den letzten Jahren verstärkten Ausbau von hochgradig fluktuierenden erneuerbaren Energien (Windkraft, Photovoltaik) und dem voraussichtlichen Weiterschreiten dieser Entwicklung wird die intelligente Integration dieser neuen Energiequellen in das Energieversorgungssystem zur weiteren Herausforderung.

Biogasanlagen besitzen dabei eine Schlüsselrolle, denn bei Biogas gestaltet sich die Kontrollierbarkeit der Energiebereitstellung anders als bei Wind- und Sonnenenergie. Dort können Laufzeit und Auslastungsgrad des Blockheizkraftwerks (BHKW) und damit Zeit und Menge der Einspeisung elektrischer Energie technisch einfach kontrolliert und schnell geändert werden. Weiterhin besitzt die Biogastechnologie allein durch die Anzahl und installierte Leistung (rund 8000 großtechnischen Anlagen mit einer installierten elektrischen Leistung von rund 4000 MW_{el} in Deutschland im Jahr 2016[2]) ein bedeutendes Potenzial für eine nachhaltige und versorgungssichere Energiebereitstellung.

Landwirtschaftliche Biogasanlagen in Deutschland basieren in der überwiegenden Zahl auf dem Prinzip des kontinuierlichen volldurchmischten Rührkesselfermenters (engl. CSTR) und sind ursprünglich für einen gleichmäßig konstanten Energieoutput ausgelegt worden. Für eine bedarfs-

[1] 'Key Renewables Trends - Excerpt from Renewables information', INTERNATIONAL ENERGY AGENCY, EXCERPT FROM RENEWABLES INFORMATION 2016 edition, 2016.

[2] Liebetrau, J., Daniel-Gromke, J., Denysenko, V., Rensberg, N., Scheftelowitz, M., and Nelles, M., 'Aktuelle Entwicklungen bei der Erzeugung und Nutzung von Biogas', in Biogas Innovationskongress 2016, Osnabrück, 2016, pp. 15–27.

gerechte Verstromung ist allerdings das dafür nötige Biogas entweder in Gasspeichern vorzuhalten oder bedarfsgerecht zu produzieren. Neben einem erheblichen Gasspeicherzubau oder dem Umbau in mehrstufige Konzepte, welche die Betreiber vor große Investitionen stellen, ist die gezielte Einflussnahme auf den anaeroben Abbauprozess an Bestandsanlagen eine vielversprechende Alternative.

Zielstellung der vorliegenden Arbeit ist daher, die Möglichkeiten und Grenzen der flexiblen Biogasproduktion durch bedarfsgerechtes Substratmanagement zu untersuchen und ein geeignetes Regelungsverfahren zu entwickeln.

Folgende inhaltliche Schwerpunkte sind dafür zu bearbeiten:

- A.1 Auf Basis von Analysen zur Substratcharakterisierung sind erste Klassifizierungen für die Eignung der Substrate zur flexiblen Biogasproduktion zu eruieren.
- A.2 Anhand von Laborversuchen sind verschiedene Fütterungsstrategien und Substratkombinationen hinsichtlich der zu erreichenden Gasproduktionsdynamik zu untersuchen. Darüber hinaus sind die Auswirkungen der dynamischen Prozessführung auf die prozessbiologische Stabilität zu bewerten.
- A.3 Für die vorausschauende Prozessführung in Abhängigkeit des Energiebedarfs sind geeignete Regelungsmethoden, sowie Optimierungsstrategien zu entwickeln, welche die Mechanismen der flexiblen Biogasbildung ausreichend abbilden und gleichzeitig die Anforderungen eines praktischen Anlagenbetriebs landwirtschaftlicher Biogasanlagen einbeziehen.
- A.4 Die entwickelte Regelungsstrategie ist anhand repräsentativer Versuche im Praxismaßstab zu validieren und hinsichtlich ihrer Aussagekraft und Grenzen zu bewerten.
- A.5 Mithilfe eines Simulationsmodells sind verschiedene Fütterungsstrategien anhand von charakteristischen Stromfahrplänen (aus realen Börsenpreiszeitreihen der EPEX identifiziert) hinsichtlich wirtschaftlicher Kenngrößen zu bewerten.
- A.6 Abschließend sind die durchgeführten Versuche sowohl bezogen auf die Prozessstabilität als auch hinsichtlich der Prozessdynamik vom Labor- bis zum Praxismaßstab zu vergleichen und anhand charakteristischer Prozess- und Zustandsgrößen zu bewerten.

B - Hauptaussagen der Arbeit

Im Rahmen der in dieser Arbeit beschriebenen Untersuchungen wurden die Möglichkeiten und Grenzen der bedarfsgerechten Biogasproduktion mit verschiedenen Versuchen im Labor- und Praxismaßstab betrachtet. Die durchgeführten Versuche belegen, dass in einer zeitlichen und in ihrer Zusammensetzung optimierten Substratzugabe ein erhebliches Potenzial zur Flexibilisierung der Gasproduktion liegt, bei gleichzeitig stabilem Prozess. Das entwickelte modellprädiktive Regelungskonzept konnte den Biogasbildungsprozess hinreichend genau führen und die gestellten Anforderungen (u.a. Erfüllung eines Gasbedarfsfahrplans bei gleichzeitigem Gewährleisten eines Gasspeicherfüllstandes in definierten Grenzen) erfüllen. Weiterhin konnte gezeigt werden, dass die verwendete vereinfachte Modellstruktur durch die geringe Anzahl an benötigten Eingangsgrößen sowie Modellparametern und das robuste Systemverhalten für den praxisnahen Einsatz geeignet ist.

Die Hauptaussagen und zentralen Forschungsergebnisse der Arbeit werden im Folgenden zusammengefasst:

B.1 Durch die gezielte zeitliche Verteilung der Substratbeschickung kann der Biogasbildungsprozess dynamisiert werden. Weiterhin kann durch die gezielte Substratkombination, entsprechend der Zusammensetzung (schnell/langsam abbaubare Kohlenhydrate, Fette, Eiweiße) bzw. durch zeitliche Verteilung unterschiedlich schnell abbaubarer Substrate eine weitere Dynamisierung der Gasproduktion erreicht werden.

B.2 Die Biogasproduktionsrate kann – unter den gewählten Versuchsbedingungen - im täglichen Verlauf, je nach Substrat und Raumbelastung um bis zu 50 %, bezogen auf die Bemessungsleistung im großtechnischen Maßstab, variiert werden.

B.3 Neben einer flexiblen Biogasproduktion zeigt sich unter den Versuchsbedingungen auch in den individuellen Säurekonzentrationen, der Gaszusammensetzung sowie dem pH-Wert eine alternierende Prozessreaktion gemäß der Substratbeschickung. Bei Gewährleistung eines ausreichenden Puffersystems führen diese Prozessreaktionen allerdings nicht zu einer langfristigen Prozessstörung.

B.4 Der Biogasprozess kann unter Verwendung einer modellprädiktiven Regelung vorausschauend anhand eines Bedarfsfahrplanes und unter Berücksichtigung technologischer Grenzen (z.B. Gasspeicherkapazität) dynamisch mit Substrat beschickt werden. Auf Grund der geringen messtechnischen Ausstattung von großtechnischen Biogasanlagen wurde ein vereinfachtes Modell des Biogasprozesses verwendet, welches den Verlauf der Gasproduktionsrate bei ungehemmtem Prozess mit ausreichender Genauigkeit vorausberechnet.

B.5 Im großtechnischen Versuch konnte die Substratbeschickung bis zu 3 Tage pausiert werden, wodurch eine Reduktion der Gasproduktionsrate um mehr als 60 % möglich wurde. Es zeigten sich bei Wiederanfahren des Prozesses keine negativen Auswirkungen auf die langfristige Prozessstabilität (u.a. FOS und FOS/TAC nicht über kritischem Wert).

B.6 Durch einen bedarfsgerechten Betrieb einer Biogasanlage mittels Fütterungsmanagement können die Erträge an der Europäischen Strombörse unter aktuellen Bedingungen gegenüber einer konstanten Gasproduktion verdoppelt werden. Es zeigte sich, dass im Vergleich zu einem Gasspeicherzubau oder aufwändigen mehrstufigen Fermenterkonzepten nur geringe Zusatzkosten nötig sind.

B.7 Der benötigte Gasspeicher kann unter Annahme der in dieser Arbeit ermittelten Prozessdynamik um bis zu 68 % gegenüber einer konstanten Gasproduktionsrate reduziert werden.

C - Wissenschaftliche Wertung der Ergebnisse

Die bisherige Forschung im Bereich der bedarfsgerechten Energiebereitstellung mittels Biogasanlagen befasste sich vorwiegend mit der bedarfsgerechten Verstromungsoptimierung sowie speziellen mehrstufigen Reaktorkonzepten und Betriebsstrategien. Die vorliegende Arbeit hingegen widmet sich der Untersuchung von Möglichkeiten und Grenzen der direkten Beeinflussung des anaeroben Prozesses durch den bedarfsgerechten Substrateinsatz. Folgende Wertungen können vorgenommen werden:

C.1 Es konnte erstmals gezeigt werden, dass auch in volldurchmischten Rührkesselreaktoren einer großtechnischen Biogasanlage bedarfsgerecht Biogas produziert werden kann, ohne die Prozessstabilität negativ zu beeinflussen.

C.2 Insbesondere die Demonstration und Untersuchung der flexiblen Biogasproduktion im großtechnischen Maßstab erlaubte neue Erkenntnisse hinsichtlich Wechselwirkungen und Grenzen im anaeroben Abbauprozess infolge alternierender Prozessbedingungen. Ein noch zu untersuchender Aspekt ist allerdings die gezielte Beeinflussung der mikrobiellen Gemeinschaft („Bioaugmentation") durch eine dynamische Prozessführung und eine einhergehende Steigerung der Resilienz gegenüber Prozessschwankungen.

C.3 Es zeigte sich, dass insbesondere die verknüpfte (ganzheitliche) Betrachtung von Prozessen der anaeroben Vergärung, der Gasspeicherung und Verstromung zur Findung von optimalen Betriebsstrategien notwendig ist. In weiteren Untersuchungen sollte der Fokus auf der modelltechnischen Abbildung weiterer Teilprozesse liegen, um in der Zusammenführung dieser Teilmodelle Biogasanlagen sowohl hinsichtlich einer effizienten Substratnutzung, als auch hinsichtlich einer optimalen Bereitstellung von Strom und Wärme entsprechend externer und interner Bedarfe zu beschreiben und zu regeln.

C.4 Durch die geringe messtechnische Ausstattung an Praxisanlagen mussten in der Arbeit Kompromisse hinsichtlich der Modell- und Regelungskomplexität eingegangen werden. Die entwickelten Methoden zur modellprädiktiven Regelung und der dafür benutzten vereinfachten Modellstruktur erscheinen angesichts des Standes der Wissenschaft und der vorliegenden Erfahrungen zur messtechnischen Ausstattung an Biogasanlagen sachgerecht. Insbesondere das gewählte Messkonzept zur Regelung war den gestellten Anforderungen entsprechend geeignet. Durch eine umfangreichere messtechnische Ausstattung von Biogasanlagen können auch komplexere Prozessmodelle in Regelungen eingesetzt werden, um auch bei Nutzung von störstoffbelasteten Substraten (mit hohen Stickstoff-, Schwefelgehalten) den Prozess bedarfsgerecht zu führen.

D - Allgemeine Bedeutung der Ergebnisse

In der vorliegenden Arbeit konnte gezeigt werden, dass CSTR-basierte Biogasanlagen mit leichten Modifikationen im Betriebsregime deutlich flexibler betrieben werden können, als es Stand der Technik ist. Damit ergeben sich folgenden Möglichkeiten im praktischen Kontext:

D.1 Ein vorausschauendes Substrat- und Gasmanagement ermöglicht eine, entsprechend dem tatsächlichen Energiebedarf, bedarfsgerechtere Nutzung der verfügbaren Substrate.

D.2 Hinsichtlich einer bedarfsgerechten und flexiblen Energiebereitstellung von Biogasanlagen lassen sich vereinfachte anaerobe Modelle als belastbare Grundlage für eine Vorhersage oder Optimierung möglicher Betriebsvarianten und profitabler Fahrpläne nutzen.

D.3 Die flexible Fütterung kann als Alternative oder als Ergänzung zum Speicherzubau betrachtet werden, da sie das benötigte Gasspeichervolumen bei gleicher Verstromung deutlich reduzieren kann.

D.4 Weiterhin zeigen die Ergebnisse, dass die Erträge an der Europäischen Strombörse unter aktuellen Bedingungen gegenüber einer konstanten Gasproduktion verdoppelt werden können, bei nur geringen Zusatzkosten. Somit können die Ergebnisse auch als Grundlage für die Weiterentwicklung und Ertüchtigung (Repowering) bestehender Biogasanlagen genutzt werden.

D.5 Ein flexibler Biogasanlagenbetrieb, insbesondere eine flexible Gasproduktion, beeinflusst die Anforderungen, die an technische Komponenten einer Biogasanlage gestellt werden. So sind Beispielsweise Substrateintragssysteme hinsichtlich höherer Volumenströme zu modifizieren und auch Messbereiche von Gasvolumenstrommesstechnik zu erweitern. Weiterhin sind Infolge schwankender Gaszusammensetzungen oder häufiger Start/Stopp-Phasen die Verbrennungscharakteristiken am BHKW anzupassen, oder auch die Messkonzepte an Gasspeichern zu optimieren.