How to measure flexibility – Performance indicators for demand driven power generation from biogas plants

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A B S T R A C T

Flexible power provision from biogas can significantly contribute to energy systems with high shares of renewables. However, the characteristics and demands for this flexibility are not clearly defined or measured. In this paper eight indicators are defined to shape “flexibility” and perform a downstream investigation of eight research projects focusing on flexible energy provision of biogas plants. The indicators are structured in three dimensions (1) velocity (ramps) by which the system can be modulated, (2) power range (bandwidth) and (3) duration for specific load conditions. Based on these indicators bottlenecks for the flexibility potential were identified. One crucial result shows that short-term flexibility of biogas plants is mainly driven by properties of the combined heat and power unit (velocity and bandwidth). The long-term flexibility depends mainly on gas storage, mode of operation and ability for modulation of the target gas production.

1. Introduction and purpose

The transformation from a fossil to a renewable energy system is vital for realizing sustainable development towards global climate protection goals, compliant to the two-degree target according to the Paris Agreement [38]. This requires a redesign and restructuring of production and distribution of energy in the future [18]. Germany has actively been supporting this transition in the power system for over fifteen years especially by introducing and utilizing the Renewable Energy Sources Act (EEG) [13]. Increasing shares of renewable electricity are provided by volatile sources such as wind and solar energy [4]; these are expected to rise in the future [3,8,26,32]. However, these fluctuating energy sources need a flexible counterpart to ensure stable energy supply, where flexible power generation from biomass could be crucial [31,35].

Current and future power supply, demand for various types of flexibility, covering different requirements. The most important ones include residual load balancing and preserving voltage stability [5,34]. Flexibility demand have also a temporal dimension, where control power stands for short-term flexibility and residual load balancing represent mid-term flexibility. Long-term flexibility is an issue of equalizing longer lasting shortfalls or surplus of volatile renewable energy feed in. Of minor relevance, but also essential for reliability of supply and to reduce the need of fossil must-run-units are renewable options for reactive power, support for grid restoration and back-up-capacity [15,17,25]. distinguish between three basic types of flexibility provision with regard to residual load smoothening:

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(1) Downward Flexibility: Compensating the positive residual load with power plants or load shedding
(2) Shifting Flexibility: Shifting surplus feed-in of renewable energy to periods with positive residual load and vice versa
(3) Upward Flexibility: Reducing surplus RES feed-in from renewable energy sources by curtailing the excess amount or increasing the demand

Biogas plants can deliver “Downward Flexibility”. But, to incite these flexibility options in the power system it is necessary to adapt the legal and political framework, design new market instruments and develop new as well as improve the required technologies [9,28,33].

Biogas is a renewable energy source which has a considerable potential to balance fluctuating renewables [12,14,34]. The number of biogas installations has been increased during the last decade in Germany, but mostly still lack on demand-oriented performance [28]. Furthermore, if adapted appropriately biogas plants have a high and easily accessible potential to serve electricity and heat in a highly flexible manner [34].

To provide flexibility based on biogas plants, many different technological concepts are being developed and implemented. They address different service times of flexible power provisions, e.g. minutes to weeks, or seasons, as well as different amplitudes of flexibility [1,1,1,12,14,35,36]. The flexibilization of biogas plants mainly affects the following technological elements: gas production, sensor systems, biogas storage, gas transportation and gas treatment and conversion (usually CHPU) [12]. Hence, the overall flexibility potential of a biogas plant has to consider the performance of every unit in the process chain, including potential bottlenecks. To introduce or increase flexibility options and strategies an operationalization of flexibility is necessary, which can be achieved by measuring flexibility in key figures.

In a future energy system with high shares of fluctuating power provision, flexibility is required to fulfil different demands, such as providing: (i) different qualities of balancing power to stabilize the electricity grid [16], (ii) residual load and thus reducing the demand for non-renewable residual load provision [30], (iii) guaranteed capacities to ensure the reliability of supply [24] (iv) “cold start support” in case of black outs [7].

This paper addresses two research questions: (1) what quality of flexibility could be provided by modifications to elements along the process chain of biogas plants; and (2) which measures are relevant to design and strengthen the effectiveness of flexibilization to unlock flexibility potential for further energy system transformation.

Currently, no consistent approach for assessing the quality of flexibility measures for bioenergy technologies is available. Therefore, we define a set of indicators to systematically describe the quality of flexibility of process elements. Following, an indicator set is exemplarily applied to a number of research projects on flexible biogas provision, which are part of the German research and development program “Biomass energy use” (2009–2021). These projects focus on the current development and perspectives of demand-oriented energy provision from biomass aiming for system integration and greenhouse gas mitigation. Based on these analyses we derive provision chain related potentials and bottlenecks for flexible power from biogas, and provide recommendations for its further role in the future energy system.

2. Materials and methods

2.1. Overview of considered projects

This paper focuses on nine selected research projects of the German research and development (R&D) program “Biomass energy use” funded by the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety and the German Federal Ministry for Economic Affairs and Energy (BMWi). This program, started in 2008, aims at practical-oriented solutions for competitive and climate-friendly technologies from laboratory level to market.

Each of these projects considers different aspects of biogas flexibilization (e.g. substrate/input management, storage of intermediates, output, gas storage and CHP capacities, bio-methane feed into the gas grid) (Fig. 1).

These projects focus on the optimization of plant concepts for demand-driven energy supply, emission reduction, improvement of market revenues, and efficiency enhancement [14,29]. The project results obtained at laboratory scale are implemented in exemplary pilot and demonstration projects with high transfer potential (retrofitting, upgrading).

In the following, an overview of the projects with respect to aspects of measuring optimization of flexible power generation from biogas plants and information on the considered

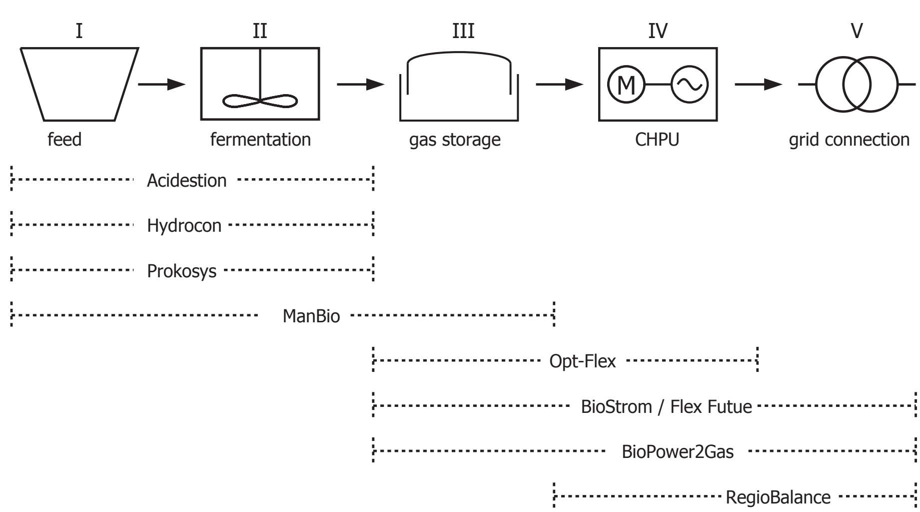

Fig. 1. Options for flexibilization along the process chain (process steps I-V) of biogas plants and the categorization of the considered projects in the R&D program “Biomass energy use”.

technological elements is provided. Furthermore, the general focus, the project goal as well as the methods of the projects are described (Table 1).

2.2. Considered systems and sample plants of the projects

The considered projects follow various approaches to demonstrate the results of simulations, laboratory and experimental tests and the functionality of the flexibility measures. The developed concepts are tested under real conditions at pilot- and practical-scale. As a result, plant-specific solutions are designed, developed and implemented within the projects. In particular, the constructional and/or process modifications implemented in the projects provide the basis to investigate the flexible production of gas in response to changing demand. An overview of the considered projects along the process chain is given in Table 1.

2.3. Indicator set for measuring flexible power generation

The aim of this study is to identify, define and (if possible) quantify the main indicators for effectiveness of demand-oriented power supply at the biogas plant level. Within the scientific community, only few definitions for the concept of flexibility exist [2,27,37,11]. describe flexibility as a derivative of power; consequently, flexibility is the change rate of power (generation as well as demand). Opposed to this, we define flexibility as the ability to fulfil varying requirements, associated with demand-oriented power supply. Thus, flexibility means a source of electrical energy, here a biogas plant, can deliver power in line with temporal structured demand patterns. Consequently, flexible biogas plants are able to react to demand changes through the temporal shift of power generation. The potential of plant flexibility therefore depends on their technological configuration. Thus, the question “which factors influence the ability to react on changing power demands” lead to the basic indicator set based on plant specific technical parameters (Fig. 2 a). The indicators refer to the requirements of flexibility given by the energy system and define to what extend a certain plant can met these requirements. To describe this flexibility potential, indicators are divided in three dimensions: (1) velocity (ramps) to change the power output, (2) power range (bandwidth) and (3) duration for specific load conditions. Within these dimensions, we propose a set of eight indicators. Depending on the scope of the considered projects, not all indicators can be provided for each project; hence, focus lies on specific aspects alongside the process chain. In some cases, projects provided additional systemic indicators describing the impact of expected load balancing or grid stabilization. To ensure a clear focus of this paper, these indicators are excluded from this study.

The following indicators are categorized and defined:

2.3.1. Velocity ramps

Velocity ramps, including the positive (m_{P+}) and negative load ramp (m_{P-}), can be interpreted as ramps for the biogas plant as a whole. The velocity ramps of biogas plants characterized by CHPU power generation are limited to the properties of the CHPU, as the CHPU is the final conversion step to electricity generation from biogas.

Even though the process of fermentation has velocity ramps, the gas storage smooths these load fluctuations concerning power generation. The positive ramp ranges between minimum and maximum load. In case of start up after standstill of the CHPU, the start duration, described later in this chapter, needs to be considered.

Velocity (ramps)

Table 1
Overview of the considered flexibilized systems in the considered projects.

Project	Main focus of the flexibilization project
Acidestion (Project ID 03KB084)	- Controlling demand-oriented biogas production by modified alternatively ensiled silage (fatty acid-ensiling) - Tests in operational plant - Feeding/feedstock: corn silage and modified silage
Hydrocon (Project ID 03KB082)	- Flexibilization of biogas plants by influencing the gas production through the integration of a newly developed hydrolysis container (including reactors, stirring and heating system, as well as pumps and pipes) in an existing pilot plant - Tests in real plant - Feeding/feedstock: corn silage, grain, manure, landscape management material, biowaste
Prokosys (Project ID 03KB072)	- Development of processes, components and systems for the flexible operation of biogas plants using organic waste material - Tests in real plant - Feeding/feedstock: corn silage, manure, grass silage, green waste, material from landscape management
ManBio (Project ID 03KB094)	- Technical improvement of gas holder systems and implementation of a model in order to ensure an improved flexible operation at low emissions - Tests in real plant and simulations - Feeding/feedstock: demand-driven feeding of corn silage, food waste, biowaste, grease trap residues
Optflex (Project ID 03KB073)	- Analysis of several scenarios to investigate the impact on varying flexibilization approaches and power generation schedules of existing biogas plants - Analysis of possible flexible modes of operation from an economic and environmental point of view - Tests in real plant and modelled - Feeding/feedstock: neglected
RegioBalance (Project ID 03KB087)	- Analysis and evaluation of the performance and the costs of bio-energy plants as an option to stabilize the regional grid in defined model regions - Tests in simulated plant inventory - Feeding/feedstock: not in the focus
BioStrom + FlexFuture (Project ID 03KB061 + 102)	- Identification of control instruments for controllable power generation (BioStrom) - Development and demonstration of a system for demand-orientated gas provision by gas storage as well as flexible biogas utilization and heat provision in case of demand-orientated power generation - Integration of biogas plants in electricity grids characterized by a high share of intermittent power producers - Tests in real plant and modelled - Feeding/feedstock: not in the focus
BioPower2Gas (Project ID 03KB089)	- Analysis of different concepts for the flexibilization of biogas, biomethane and BioPower2Gas plants; flexible operations were simulated, tested in practice and evaluated - Tests in real plant and modelled - Feeding/feedstock: not in the focus

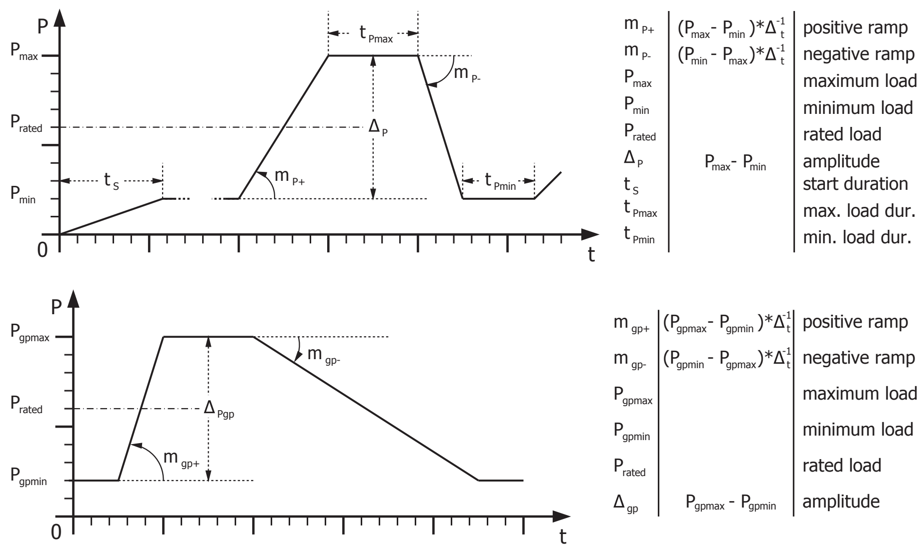

Fig. 2. a) Illustration of direct measurable indicators for flexible power generation by biogas plants (power quotient and baseload ratio is not shown, but calculated based on P_{max}, P_{rated} and P_{min}). b) Indicators for flexibility of biogas production (P_{rated} here is no indicator, and just shown for illustration purposes).

$$\text{Positive ramp } m_{P+} = (\mathrm{P_{max}} - \mathrm{P_{min}})*\mathrm{P_{max}}^{-1}*\Delta_t^{\ -1} \ \left[\%\mathrm{min}^{-1}\right] \quad (1)$$

$$\text{Negative ramp } m_{P-}+ = (\mathrm{P_{max}} - \mathrm{P_{min}})*\mathrm{P_{max}}^{-1}*\Delta_t^{\ -1} \ \left[\%\mathrm{min}^{-1}\right] \quad (2)$$

2.3.2. Power range

The power range depends primarily on the operation of the biogas plant as a whole (technological issues are subordinated). For flexible biogas plants with more than one CHPU, two modes of operation can be distinguish [19]. First: if all CHPU run synchronously they act as a solely generation unit resulting in fully flexible mode of operation (*ffo*). Second: partial flexible mode of operation (*pfo*), means that some of the CHPU runs constantly and the other units produce flexible. Comparing these two modes of operation, different degrees of flexibilization can be achieved for the same plant configuration. Under *pfo* bandwidth is lower and the minimum load is higher; compared to a setup where the full CHP capacity is flexible. For *pfo* configurations, the baseload-ratio (*blr*) is defined as ratio of minimum load to rated capacity ($P_{min} * P_{rated}^{-1}$). *blr* describe the amount of electrical work that is already linked to the base load CHPU. Therefore, it indicates the relative share of inflexible quantity of electricity, independent of the installed capacity of the biogas plant.

The amplitude (Δ_P) results from subtracting the maximum load from the minimum load and can be interpreted as the bandwidth available for power regulation; based on the specifications of the CHPU.

Power-quotient (Q_P) depends on the ratio of installed and rated capacity [19]. However, an uncertainty of defining an accurate power quotient for a plant in practice remains. Reason is that the installed capacity is a technically defined parameter, but rated capacity depends on power generation over a defined period (one year). Furthermore, power generation in a given interval can differ from time to time; for example, the reduction of the power generation caused by maintenance or curtailment during network congestion. Consequently, the power quotient is an estimated value for a set of assumptions under defined conditions. If other conditions remain constant, the manipulation of gas production by controlled feeding-management leads to short-term variations of the power-quotient. Thus, feeding management is interpreted as a manipulation of the power-quotient. The variation of daily gas production affects the ratio between installed to (daily) rated capacity. A special subset of indicators for flexible gas production is described in Section 2.4.

Power range (bandwidth)

$$\text{Base load ratio } blr = \mathrm{P_{min}}*\mathrm{P_{Bem}}^{-1} \ [-] \quad (3)$$

$$\text{Amplitude } \Delta\mathrm{P} = (\mathrm{P_{max}} - \mathrm{P_{min}})*\mathrm{P_{max}^{-1}}*[\%] \quad (4)$$

$$\text{Power quotient } Q_P = \mathrm{P_{inst}}*\mathrm{P_{rat}}^{-1}[-] \quad (5)$$

2.3.3. Load duration

The first temporal indicator represents the duration for the start-up duration, beginning with standstill (t_S). This indicator simplifies the multilevel character of the starting process. In case of a start from standstill, the CHP-unit has to complete several phases (lubrication/pre warming, machine start/ignition, nominal speed, grid synchronization) before the positive load ramp (m_{P+}) follows (Fig. 3.). Hence, t_S covers the time from the start signal to the beginning of the load ramp. In the case of turning off a CHPU, we assume that, by lowering the load with m_{P-} below the level of P_{min}, the electrical power generation drops to zero and there is no need to define a shut of delay.

The duration of continuous maximum and minimum load depends on various factors. The most important are the amount of biogas production rate, the gas demand of the CHPU and the capacity of the gas storage.

The duration of maximum load conditions is defined by the quotient of the gas storage capacity to the differential gas demand which is given by the demand of all CHPUs under full load operation minus the constant gas delivery. If the fermentation process can be controlled in short term, the duration can be extended

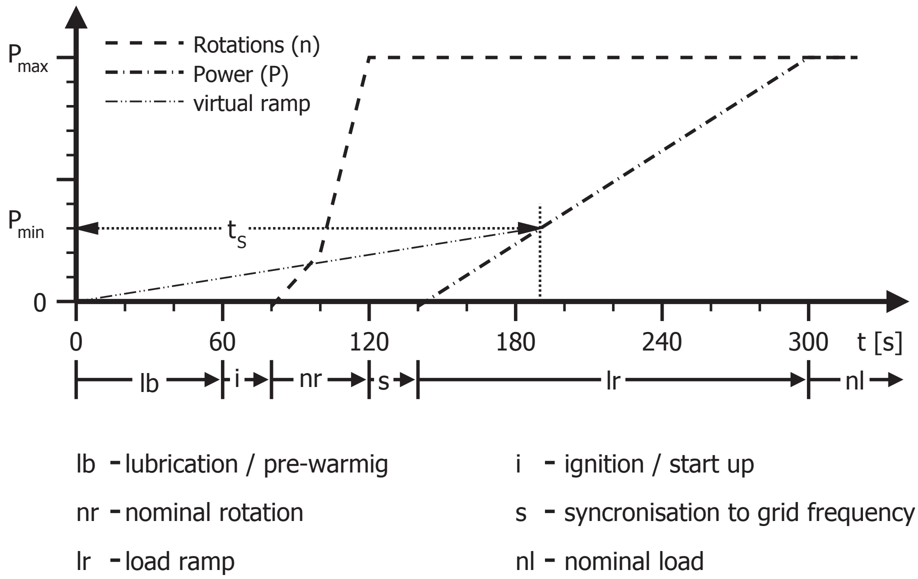

Fig. 3. Phases of CHPU start up, based on data of [6,10].

depending on the amount of control range of the feeding-management and the potential to increase the gas production (see also Section 2.4).

Hereby, the duration under minimum load conditions relates to the biogas production rate, the gas demand of the CHPU (partial flexibilization concept), and the volume of the gas storage. The duration under minimum load condition is characterized by the quotient of the biogas production rate minus the gas demand of (where appropriate) permanent running CHPU, divided by gas storage capacity. If the biogas production will be reduced during intervals of a lower power generation (see also Section 2.4), the duration time can be extended.

Duration

1. Start duration t_S [min]
2. Continuous maximum load duration t_{Pmax} [h]
3. Continuous minimum load duration t_{Pmin} [h]

2.4. Indicator set for flexible gas production

Flexible biogas production can be realized by adjusting the feeding rate for the fermenter and therefore the amount of biogas produced. Alterations to the feeding are already carried out in practice for various reasons, including achieving a constant gas production and/or adapting to a changing (e.g. seasonal) availability of feedstock. Also, through the variation of the feeding amount (extent by the time, amount and composition of the feedstock), the gas production can be adapted to the requirements of the utilization unit. Consequently, the gas storage capacity can be minimized [21–23]. This potential can be increased by the combination of feeding management, gas storage capacity and adapted utilization. On the one hand, based on feeding management, the flexibilization of biogas plants can be increased, a flexibility which otherwise would be unlocked by additional gas storage capacities (Barchmann et al., 2016). On the other hand, the feeding management enables the existing gas reservoir to contribute to the provision of flexibility [22].

For the first conversion step in a biogas plant, the subset of indicators shown in Fig. 2b was created analogically to the general indicator set. Due to the dependence of the modulation capacity on gas production rate, indicators can be used to determine the quality of different flexible gas production approaches in a simplified manner.

The indicators can be defined as follows:

Velocity (ramps)

Positive ramp for gas production m_{gp+}

$$= (P_{gpmax} - P_{gpmin})*P_{gpmax}^{-1}*\Delta_t{}^{-1}\ \left[\%\ \mathrm{min}^{-1}\right] \tag{6}$$

Negative ramp for gas production m_{gp-}

$$= (P_{gpmin} - P_{gpmax})*P_{gpmax}^{-1}*\Delta_t{}^{-1}\ \left[\%\ \mathrm{min}^{-1}\right] \tag{7}$$

Power range (bandwidth)

$$\text{Maximum load } P_{gpmax} = P_{gpmax}*P_{rated}^{-1}[\%] \tag{8}$$

$$\text{Minimum load } P_{gpmin} = P_{gpmin}*P_{rated}^{-1}[\%] \tag{9}$$

Rated Load (heating value) P_{rated}[kW]

$$\text{Amplitude } \Delta P = (P_{max} - P_{min})*P_{max}{}^{-1}*[\%] \tag{10}$$

As all indicators are applied to the concepts of the considered projects, the term “plant” has to be defined: According to the EEG (revised in 2016), a biogas plant is defined as the sum of the installed CHPU at a production site, within a common commissioning. For the purpose of this study, the term “plant” is considered from a technological point of view: biogas plants are defined as the whole conversion plant, including the sum of all CHPU.

2.5. Calculation of indicators for flexible power generation within projects focusing on flexible gas production

The flexibility indicators are calculated using the above methodology. For projects, whose research focus does not cover the final energy generation but concentrates on dynamics of gas production, the calculation of flexibility indicators is done by a simulated reference plant. The simulated reference plant is chosen based on a standardized basis of design to achieve comparable results. Altogether, eight calculations for the virtual plant were carried out: two for each of the four projects with a focus on variable gas production. We distinguish between the above-mentioned two modes of operation, namely partial and full flexibilization.

2.6. Sensitivity analysis of main process factors for the indicators for flexible power generation

A sensitivity analysis is carried out to establish the impact of flexibility factors on flexibility indicators and partly the interaction of. For the indicators m_{P+}, m_{P-}, Δ_P, blr and Q_P in Section 2.6 certain values were predefined (Table 2b). To understand the influence of various process factors along the process chain on the quality of final power generation, we carry out a sensitivity analysis. The general interrelation of the process parameters is visualized in Fig. 4. The following relevant variables were identified: (a) gas production, b) gas storage, c) CHPU-properties. These variables are divided into:

- Factors influenced by gas production (a.1 − a.5)
- Factors influenced by gas storage capacity (b.1)
- Factors influenced by CHPU properties (c.3, c.4)

The safety margin (b.2) and the load ramps (c.1, c.2) of the CHPU are not considered. Therefore, the safety margin (b.2) is characterized by a linear and direct impact on the available gas storage capacity. In addition, the load ramps of the CHPU define the power generation of the biogas plant and, consequently, do not interact with other factors.

Within this analysis, each considered variable is varied separately, while keeping all other variables constant. Considering the mode of operation of the CHPU (c.3), all factors can be varied continuously within their given range. The sensitivity calculations are made for a multiplier range from 0 to 2 in 21 discrete steps of 0.1. An exception is made for the multiplier of the power quotient (c.4: QP); this factor is varied between 0.5 and 1.5 or rather 1 to 3 in absolute measures. All calculations are based on the simulated reference biogas plant, described below. The basic parameters for the reference biogas plant were show in Table 2a. The variable parameters (flexibility factors) of the reference plant are listed in Table 2b. All sensitivity analyses are carried out using parameters of the reference plant specified in Table 2a for a pre-defined period of 168 h (h) and an additional foresight period of 24 h to calculate the indicators for load duration in case of gas production manipulation. For example, the calculation runs for 192 h (24 h foresight + 168 h investigation) for the considered biogas plant. In the first period (−24 h − ~-18 h), the CHPU is running in defined partial load (CHPU #1 is under operation) and the gas production is ramped up with m_{gp+} until P_{gpmax} is reached. When the level of gas storage reaches its maximum in the second phase (~-18 h−0 h), the CHPU power generation shifts to the level of the given gas production. Hence, the storage level remains constant. At the beginning of the analyzed period (third phase 0 h−12 h), the CHPU is set to maximum load until the gas storage is empty or the maximum period of 168 h is reached. This run determines both load duration parameters (t_{Pmax}, t_{Pmin}) and is repeated for each variation step of the appropriate parameter within the sensitivity analysis.

In some of the sensitivity analyses, the variation of only one parameter solely is not possible, based on the interconnection between rated load, power quotient and baseload ratio. Consequently, for the variation of rated load, the installed capacity of the baseload CHPU is set to 50% of the rated load. Thus, to keep the total installed capacity constant, the base load CHPU is reduced and the baseload ratio decreases directly proportional to rated load. Simultaneously, the power quotient (Q_P) is reciprocally proportional to the rated load and increases. To vary Q_P, the baseload CHPU is set to be constant (50% of rated load), but reduces, if the flexible CHPU capacity is increasing.

3. Results and discussion

First, we present the indicators for flexible biogas production separately according to their rank in the process chain, starting with the feeding and the fermentation process. Second, the results for the general flexibility indicators are discussed.

3.1. Determination of the indicators for flexible gas production based on research projects

For each of the four (out of the total of nine) projects focusing on flexible gas production, indicators are determined regarding two different approaches. The first one is named “24 h − scope”, which means that indicators are considered in a 24 h time scope.

The second one is named “7 h − scope”, which consequently represents the 7 h time scope referring to a standardized load schedule of 7 days (which is equal to 168 h). An overview of the plant specific flexibility indicators referring to flexible gas production within the considered projects is given in Table 3. The focus of the process steps is on the sub processes feeding and fermentation.

Table 2a
List of basic parameters for the reference biogas plant.

Parameter	Symbol	Unit	Initial Value
Installed capacity	P_{inst}	[kW]	1000
Capacity CHPU#1	P_{CPHU1}	[kW]	250
Capacity CHPU#2	P_{CHPU2}	[kW]	750
Annual power generation	W_{el}	[kWh]	4,200,000
Gas storage volume	V_{gs}	[m^3]	2037

Table 2b
List of variable parameters (flexibility factors) for the reference biogas plant.

Parameter	Factor	Symbol	Unit	Initial Value
Rated load	a.1	P_{rated}	[kW]	479
Positive ramp - gas production	a.2	m_{gp+}	[%* h^{-1}]	12
Negative ramp - gas production	a.3	m_{gp-}	[%* h^{-1}]	3
Minimum load - gas production	a.4	P_{gpmin}	[%]	75
Maximum load - gas production	a.5	P_{gpmax}	[%]	135
Gas storage capacity (electrical equivalent)	b.1	C_{gs}	[kWh]	6500
Gas storage safety margin	b.2	M_s	[%]	20
Base load ratio	c.3	bls	–	0.25
Power quotient	c.4	Q_P	–	2.1

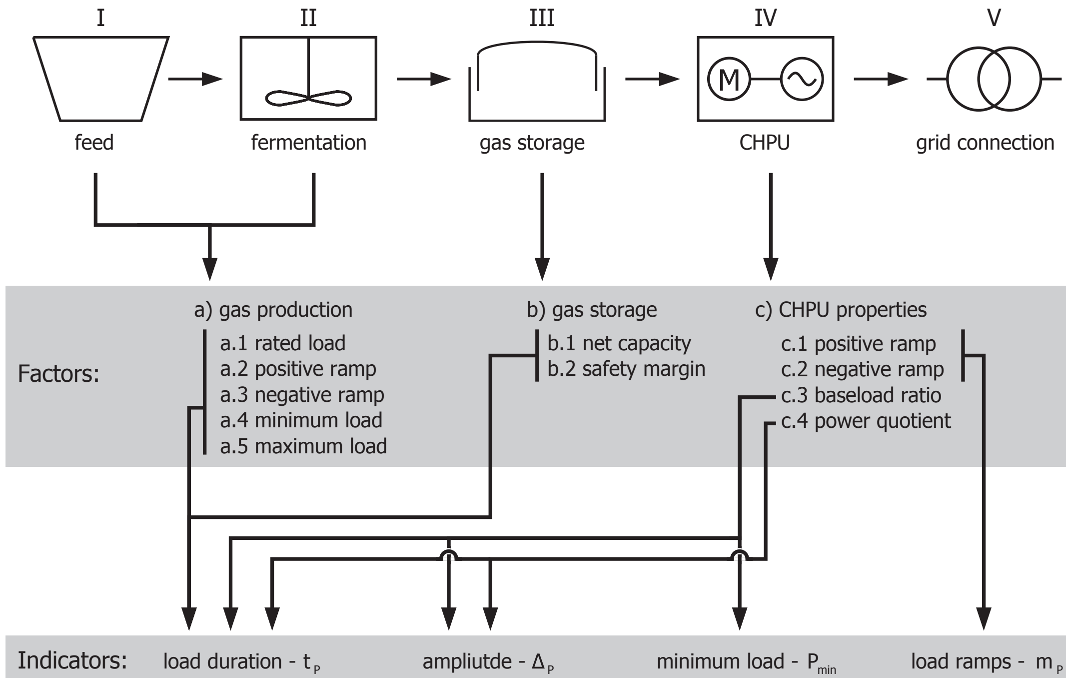

Fig. 4. General impacts of process parameters on influenced flexibility indicators.

Table 3
Overview of the comparison of the plant specific flexibility indicators referring to flexible gas production within the considered studies. Focus on the sub processes feeding and fermentation.

Indicator [unit] Project sample plant	Scope of process steps	m_{gp+} [%*h^{-1}][a]	m_{gp-} [%*h^{-1}] [a]	P_{gpmin} [%][a]	P_{gpmax} [%][a]	Δ_{gp} [%][a]
Acidestion 24 h - scope	I-II	11	3	74	140	66
Acidestion 7 d - scope	I-II	11	2	54	156	102
Hydrocon I 24 h – scope	I-II	28	14	60	218	159
Hydrocon II 24 h – scope	I-II	18	11	48	139	91
Prokosys 7 d - scope, scrap	I-II	10	2	36	155	120
Prokosys 7 d – scope, silage	I-II	39	5	24	219	195
ManBio 24 h - scope	I-II	10	3	72	144	72
ManBio 7 d - scope	I-II	11	3	57	165	108

[a] All relative measures refer to the rated capacity in terms of the projected gas production.

3.2. Determining of the indicators for flexible power production

To compare the different approaches of the projects, a uniform indicator set is created (Section 2.3). An overview of the plant specific flexibility indicators within the considered studies for power generation is given in Table 4.

3.3. Results of sensitivity analysis

The results of the sensitivity analysis for partial flexible operation are presented in Fig. 5 a. and in Fig. 5 b. for fully flexible operation. The effects of variations of the factors a.2 and a.3 (representing the load ramps for gas production) show for the investigated range in both cases, a slightly negative impact. If they drop below relative values of 0.4 for negative load ramp (a.2: m_{gp-}) and 0.2 for positive load ramp (a.3: m_{gp+}) of gas production.

The variation of the boundaries of gas production (factors a.4, a.5) shows a significant effect on load durations, both, for maximum and minimum load. The duration under minimal load (t_{Pmin}) tends to slightly decrease if minimum gas production (a.4: P_{gpmin}) increases and converges towards infinity, while P_{gpmin} decreases to values below 1.0. Vice versa, the impact of varying maximum gas production level (a.5: P_{gpmax}), can influence the load duration under maximum load, whereby, the load duration values can be increased significantly above 1.0. Load duration under maximum load converge to infinity, while P_{gpmax} comes close to the equivalent of the installed capacity.

The effect of a variation of the rated load (a.1: P_{rated}), which can be interpreted as average primary energy production (respectively biogas production) within the fermentation process, is very complex and influences all targeting indicators. The most obvious effect is impacted by the relation of Q_P, Δ_P and *blr* (for pfo) which is directly modified by the given assumptions of the calculation (share of base load capacity, relation between P_{rated}, P_{max} and P_{min}). The impact on load duration times differs between maximum and minimum load operation. Even if they do not follow the same course, load duration under P_{max} decreases slightly if values of P_{rated} drop below 1.0 and increases exponentially above the initial value.

The load duration for P_{min} shows a nonlinear course that decreases for values above 1.0. It describes a hump for values between 0.0 and 1.0 with a peak around 0.6. In this context, it is very important to note that for the variation of P_{rated} at the lower end of

Table 4
Overview of the comparison of the plant specific flexibility indicators within the considered studies for power generation.

Indicator [unit] Project sample plant	scope of process steps	m_{P+} [% min^{-1}]	m_{P-} [% min^{-1}]	Δ_P [%]	blr [−]	t_{Pmax} [h]	t_{Pmin} [h]	Q_P [−]
Acidestion pfo[a]	I-II	20%[c]	33%[c]	75%[c]	0.5[c]	29.8[d]	168+[d,e]	2[c]
Acidestion ffo[a]	I-II	20%[c]	33%[c]	75%[c]	0	29.8[d]	24.3[d]	2[c]
Hydrocon pfo[a]	I-II	20%[c]	33%[c]	75%[c]	0.5[c]	21.7[d]	168+[d,e]	2[c]
Hydrocon ffo[a]	I-II	20%[c]	33%[c]	75%[c]	0	21.7[d]	27.2[d]	2[c]
Prokosys pfo[a]	I-II	20%[c]	33%[c]	75%[c]	0.5[c]	28.9[d]	168+[d,e]	2[c]
Prokosys ffo[a]	I-II	20%[c]	33%[c]	75%[c]	0	28.9[d]	36.2[d]	2[c]
ManBio pfo[a]	I-III	20%[c]	33%[c]	75%[c]	0.5[c]	37.8[d]	168+[d,e]	2[c]
ManBio ffo[a]	I-III	20%[c]	33%[c]	75%[c]	0	37.8[d]	22.2[d]	2[c]
OptFlex pfo[a]	III-IV	20%	33%	69%	0.74	5.3	32.4	2.4
OptFlex ffo[a]	III-IV	20%	33%	100%	0%	5.7	8.4	2.4
BioStrom/FlexFuture pfo[a]	III-V	13%	21%	62%	0.68	9	27	1.8
BioStrom/FlexFuture ffo[a]	III-V	20%	34%	100%	0	9	7	1.8
BioPower2Gas xfo[a]	III-V	13%	20%	100%	0	6.75	10.5	2.6
RegioBalance pfo[a]	IV-V	–[b]	–[b]	75%	0.5	4.9	11.7	2

[a] – distinction of partial flexible mode of operation (pfo) and fully flexible mode of operation (ffo).
[b] – not explicitly considered.
[c] – pre-set values for the reference plant.
[d] – calculated values, based on flexibility indicators for variable gas production within the modelled reference plant.
[e] – values of "168+" means, that load duration last the calculated time frame of 168 h or longer.

the scale, *blr* cannot be higher than 1.0. This leads to the fact that lowering P_{rated}, *blr* is 1.0 and P_{rated} is equal to P_{min}. For a further reduction of P_{rated} P_{min} should also be lowered in the same way to comply with the constraint that the maximum limit for *blr* is 1.0. This exception of the general assumption to modify one parameter, should be considered when evaluating Fig. 5 a. for a.1 for relative scale of P_{rated} smaller then 0.5.

The influence of the gas storage capacity (C_{net}) on load duration for P_{max} as well as for P_{min} can be described as direct proportional.

The variation of the base load ratio (*blr*) is relevant for the partial flexible operation and influences the Δ_P, while the *blr* is indirectly linked to P_{min}. In addition, the load duration under minimum load shows a significant inverse correlation to *blr*.

Q_P is highly sensitive to all of the investigated indicators; however, t_{Pmin} shows a slight decrease for very low values of Q_P. Δ_P shows a direct linear correlation to Q_P and *blr* decreases with larger Q_P-values. This trend results from the constant size of the baseload CHPU, which decreases relatively to the increase in flexible CHPU. The load duration time under maximum load shows an inverse correlation. This seems reasonable, as a larger installed capacity leads to a faster drain of the gas storage.

3.4. Discussion

Within the discussion of the used methodology and the created results, three fundamental aspects were focused. Firstly, it has to be considered, whether the used methodology and the described indicators are suitable for describing flexibility of biogas plants. Secondly, the fundamental difference between the regulation of gas production and the flexible provision of energy and their interdependency needs to be highlighted. Thirdly, the results of the examined projects and the sensitivity analysis are discussed to identify the determining indicators for a well-directed adaption of biogas plants to reach higher flexibility under the existing constraints.

3.4.1. Limitation of the methodology

The methodology to predefine a set of indicators is based on a deductive approach by deriving the indicators with regard to the needs of the energy system. However, the need to establish a universal assessment scheme is acknowledged. One discussion worthy aspect is the appropriate degree of simplification of the flexibility properties. Considering the aim - to develop an indicator set that should be applicable to preferably all flexible bioenergy concepts in the power sector the degree of simplification is regarded reasonable. The level of detail is average in comparison to studies which focus on specific aspects of flexible biogas production. Therefore the assessment probably lack of some specific issues. For example, the nonlinear behavior of the methanation process related to given substrates, especially the decay curve after exposing feed in of substrates, is here simplified to a linear course.

Nevertheless, we assume that the proposed seven flexibility indicators cover all fundamental properties of flexibility which are related to the initial needs of the power sector. In this context, flexibility predominantly arises from the ability of load variation by an increase/decrease in power generation, a certain speed of this load variation and its possible duration. From this perspective, the indicators cover the most important properties, even though the indicator Q_P is not necessarily required. We include Q_P to acknowledge the commonly used but vague term of "surplus capacity" (analogous translation) [20], which is typically used in the German biogas community to describe the degree of flexibilization. This term is not precise enough, as it is often not specified if it means a relation referred to the whole (additional) installed capacity. So in this paper, we use to describe the degree of flexibilization considering the power range with Q_P as a more precise concept.

The methods for calculating the indicators within the projects are as simple as possible, considering the application to a broad range of projects. Especially the indicators for flexible gas production are sensitive to the certain conditions for different flexibility approaches (kind of fermenter, types of feedstock, process parameters like temperature, volumetric loading). Process flexibility can differ heavily by modifying some of those preconditions for the same technical layout.

3.4.2. Interaction between modulated gas production and flexible power provision

The power generation for biogas plants with an onsite CHPU is not directly influenced by the gas generation patterns, as the gas storage decouples fermentation and power generation to some extent.

Thus, the short-term behavior of the power generation is mainly independent from the gas production management. But

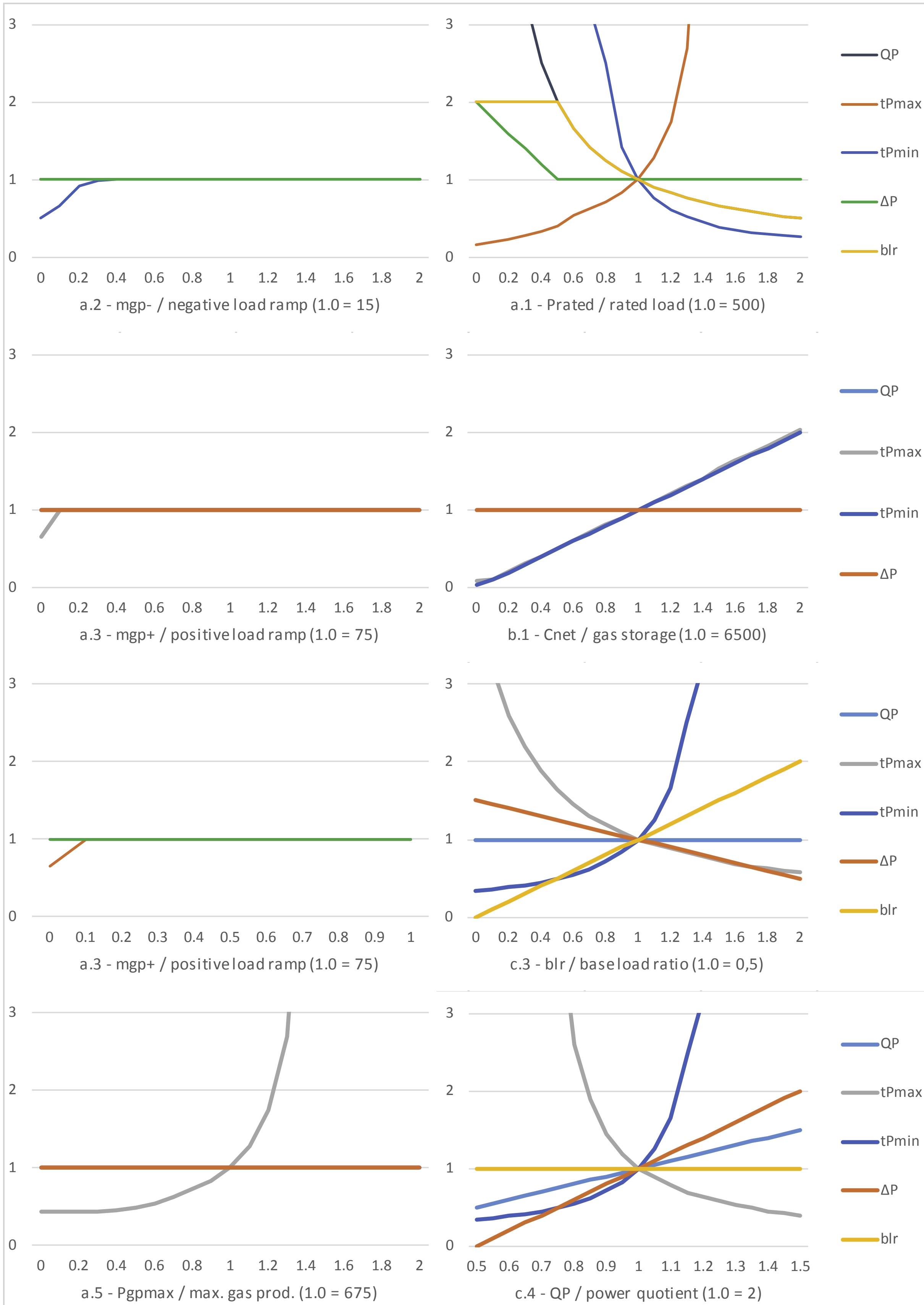

Fig. 5. a) Diagram array of sensitivity analysis for flexibility determining parameters of flexible biogas plants under partial flexible operation (pfo); *blr* - base load ratio, C_{net} – gas storage capacity in electrical equivalents, Δ_P – amplitude, m_{gp+} - positive ramp of gas production rate, m_{gp-} - negative ramp of gas production rate, P_{gpmin} – maximal biogas production level, P_{gpmax} - minimal biogas production level, P_{rated} – rated Power generation, Q_P – power quotient, t_{Pmax} – load duration for maximum load, t_{Pmin} – load duration for minimum load, all values normalized to percent of the initial value for the model plant *(colored figure)*. b) Diagram array of sensitivity analysis for flexibility determining parameters of flexible biogas plants under fully flexible operation (ffo); *blr* - base load ratio, C_{net} – gas storage capacity in electrical equivalents, Δ_P – amplitude, m_{gp+} - positive ramp of gas production rate, m_{gp-} - negative ramp of gas production rate, P_{gpmin} – maximal biogas production level, P_{gpmax} - minimal biogas production level, P_{rated} – rated Power generation, Q_P – power quotient, t_{Pmax} – load duration for maximum load, t_{Pmin} – load duration for minimum load, all values normalized to percent of the initial value for the model plant *(colored figure)*.

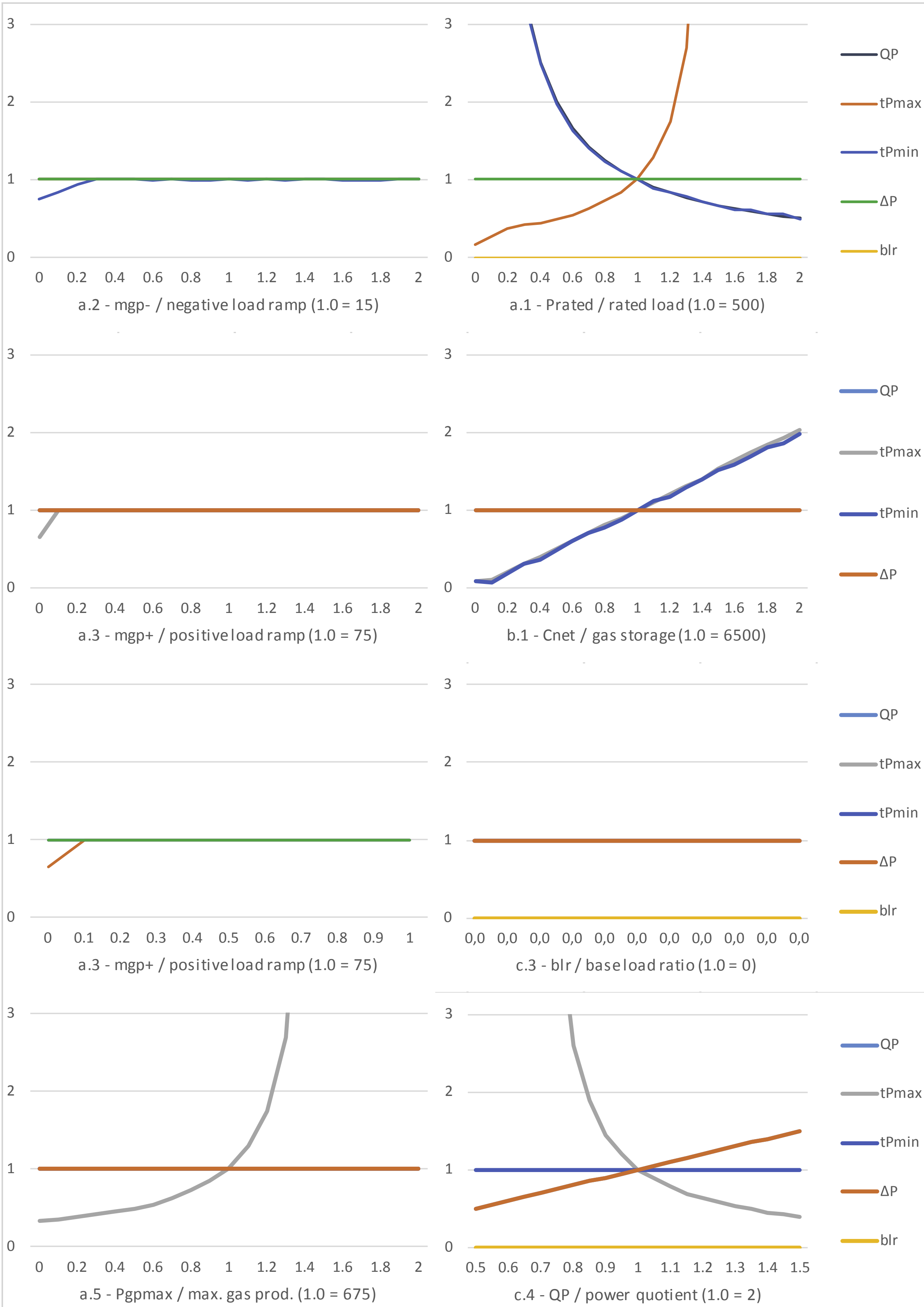

Fig. 5. (*continued*).

manipulation of gas production influences the long-term aspects of flexibility, in particularly the possibility to elongate operational states where the power generation is lowered or raised relatively to the rated capacity. This approach is therefore a key factor for gaining long term flexibility to compensate critical meteorological situations with longer lasting deficits ("dark doldrum") or surplus power ("Christmas storm"). This way flexible biogas plants can compete less with existing short-term flexibility options like batteries or pumped hydro storage, but with more expensive options like Power-to-Gas.

3.4.3. Comparison of projects and sensitivity analysis

The comparison of the different research projects as well as the results of the sensitivity analysis lead to the conclusion, that short-term-flexibility (m_{P-}, m_{P+}) is defined by technological parameters of the particular CHPU. In contrast, the mid- or the long term flexibility is affected or rather defined by the gas storage capacity and if possible by control of the raw gas production.

Furthermore, it is important to highlight, that the simplification of the gas production dynamics is suitable for systemic approaches, but not sufficient for detailed process simulation. Therefore, we recommend for further investigations to describe how the gas production is influenced by process parameters and how to derive a suitable and generally applicable concept of flexible gas production.

4. Conclusions

The flexibility of biogas plants can sufficiently be described with a set of eight indicators. These indicators allow a comparison of different approaches for flexible biogas plants with regard to velocity (ramps), power range (bandwidth) and duration for specific load conditions. Hence, the results can be used to modify influencing factors to gain different aspects/modes of flexibility and to identify targets for further research. The detected interaction among factors and indicators highlights possible trade-offs. Summarizing, the further improvement of flexible biogas plants can be adjusted more precisely based on the particular requirements of the energy system.

Declaration of interest

None

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