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Web-based weak point analysis for agricultural biogas plants

Faulty dimensioning or inefficient operation of biogas plants in agriculture can lead to negative impacts on the environment and poor profitability. In this paper we present a method for weak-point analysis and comparative assessment of biogas plants in agriculture. This method combines fuzzy sets and expert system elements in order to assess biogas plants with respect to different performance criteria. Since these criteria are evaluated on the basis of the state-of-the-art, the assessment results are independent of the individual sample. From this method, we also developed a web based application called "Biogas Doc" which can be used to display and evaluate data on biogas plant configuration and performance in a systematic fashion. Potentially, this application can also be used to simulate the effects of refurbishment or the selection of input materials on main performance figures, and thus allow for more reliable planning.

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Biogas plants are complex bioengineering systems exhibiting various designs and concepts. From surveys it is known that biogas plants are not always dimensioned and operated properly [1]. Such deficits can result in negative environmental impacts and poor profitability of biogas plant operation.

In order to assess the performance of different biogas plants in a reproducible and comparable manner, a system of well-defined characteristic figures and a suitable method for their assessment are required [2]. A couple of web tools that can evaluate a number of characteristic figures are available for biogas plant operators, such as the "Biogas Calculator" of Weltec Biopower GmbH, the "Profitability Calculator Biogas" of KTBL e.V., and the "Biogas Benchmark System" of ARGE Kompost & Biogas Austria (ARGE). KTBL offers its calculator for use without charge and registration. The use of the ARGE system is restricted to members. Weltec Biopower's calculator is offered for acquisition purposes.

The aim of our research was to facilitate a case specific weak-point analysis and comparative assessment of biogas plants and to provide a tool for supporting practitioners in agriculture. In the following we present our assessment method and support tool, and explain their use on the basis of examples from the Bavarian Research Center for Agriculture's biogas monitoring program.

Materials and Methods

Our method combines elements of fuzzy sets and expert systems to assess biogas plants with respect to technical, environmental and economical criteria [3; 4]. This paper deals with the technical aspect which is assessed on the basis of the following four characteristic figures.

Relative Biogas Yield

The ratio of the biogas yield measured at the plant and the potential biogas yield is defined as the relative biogas yield. The potential biogas yield is estimated according to the "feed value model": The amounts of the main organic compounds from "Weender Analysis" in the input to the biogas plant – i. e., raw fiber, nitrogen-free extractive matter, raw protein, and raw fat – with their mean specific biogas yields are multiplied with digestion coefficients from animal feeding experiments [5; 6; 7]. Standard values are used for the calculations if specific chemical analyses of the input materials are not available [8]. Advantages of this procedure are that standard values for potential biogas yield are available for a large variety of input materials, which can be adjusted using actual results from chemical analyses. As a disadvantage of this method, the digestion coefficients from animal feeding experiments appear to be too low for biogas plants which results in a systematic underestimation of potential biogas yields. However, peer reviewed digestion coefficients for specific feedstock in biogas plants have not been published to date.

Methane Productivity

Methane productivity is the methane yield in cubic meters at standard temperature and pressure per cubic meter of net digester volume and day [m^3_N (m^3 d)$^{-1}$].

CHPU Utilization Ratio

CHPU utilization ratio is the ratio of actual electricity production and potential electricity production given full load and 100 % availability.

Net-Utilization Ratio of Methane Fuel Value

The net sum of electricity and heat supplied to external users in relation to the fuel value of the methane yield is the net-utilization ratio of methane fuel value.

Description of Assessment Method

In order to perform a benchmarking of biogas plants, the assessment results for individual plants and the ranking within a comparative assessment have to be independent of the specific sample. To achieve this, we defined four efficiency classes: Excellent, good, acceptable, and unacceptable. These efficiency classes are to be interpreted as follows:

- Excellent: No need for improvement
- Good: Improvement not required, but possible
- Acceptable: Improvement advised
- Unacceptable: Improvement urgently needed

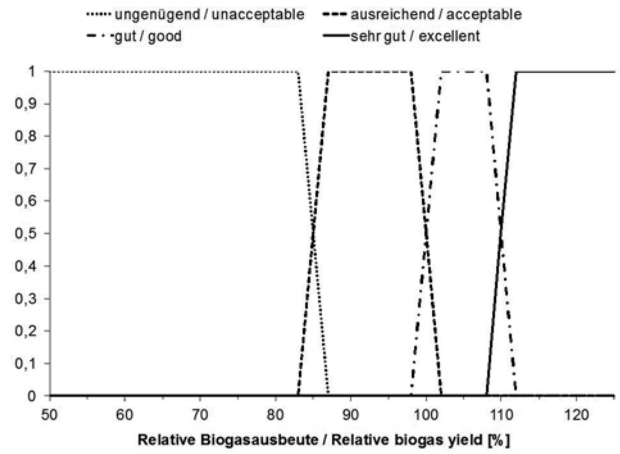
The efficiency classes were defined according to the best available technology based on surveys of real-world biogas plants that were done by FNR e.V. and the Bavarian State Research Center for Agriculture [1; 9; 10; 11; 12].

Using these four efficiency classes, seven ratings are determined by the assessment method: For two criteria each within the categories of "Biogas Production" and "Biogas Utilization", plus the summarized rating for the two categories, plus the overall rating for the technical aspect (4 + 2 + 1 = 7). Rules are used to avoid compensation when summarizing individual ratings [13]. Summarizing two criteria with four efficiency classes requires sixteen rules.

For the quantitative assessment, an efficiency score between 0 and 100 is calculated by fuzzyfying the scaled values of the assessment criteria (characteristic figures) and the membership functions of the efficiency classes. Using the fuzzy criteria values, the inaccuracy of the characteristic figures can be represented. For the specific set of rules, the compatibility of the individual fuzzy characteristic values with the four efficiency classes is determined. The fuzzy number for the summarized category rating is calculated as the sum of the fuzzy results from all 16 rules. The resulting efficiency scores can be used to rank any given set of biogas plants.

Trapezoidal membership functions were defined for the efficiency classes. As an example, **Figure 1** shows the membership functions for the criterion "Relative Biogas Yield". Here, we had to account for the significant underestimation of potential biogas yields as mentioned above.

Fig. 1



Membership functions of efficiency classes for criterion relative biogas yield

The efficiency classes for "CHPU Utilization Ratio" are calculated in dependence of nominal power, type, and operating hours of the engine. Further details on efficiency classes can be found in [13]. Adjustments can be made any time, if technological innovations or political action should require this. E. g., the criterion for "CHPU utilization ratio" may be adapted to the framework of demand-driven electricity generation from biogas.

To make this assessment algorithm available for a broader spectrum of users, we developed the web application "BiogasDoc". This app allows for the systematic documentation and display of information and data on the configuration and performance of biogas plants. For access to the app, please contact the corresponding author.

Currently, "BiogasDoc" features two modules, the "plant report" and the "efficiency assessment" (weak-point analysis). In the plant report, the data entered by the user are displayed in a systematic fashion and evaluated on the basis of guideline values and "good professional practice". Beside the criteria used for the efficiency assessment, a number of further characteristic figures are calculated. The efficiency module returns the assessment results for the three categories of "Biogas Production", "Biogas Utilization", and "Technical Aspect" whereby weak points of the plant become obvious.

Applying the method for weak-point analysis

In the following, the application of our method for weak-point analysis of biogas plants is illustrated using three examples from the "Biogas Monitoring" of the Bavarian Research Center for Agriculture. The plants were monitored over longer time periods, during which significant refurbishing was done at plants 7 and 10 (**Table 1**). These two facilities are agricultural

Table 1

Basic characteristics of assessed agricultural biogas plants

Kennung/*ID*	**Einheit/*Unit***	**7-1**	**7-2**	**10-1**	**10-2**	**14**
Inbetriebnahmejahr/*Year of commissioning*		2005	2009	2004	2009	2009
Gesamt-Gärraum/*Overall digester volume*	m^3	3 015	4 020	1 540	1 540	1 600
Anzahl Prozessstufen/*Number of process stages*		2	3	2	2	2
Einsatzstoffe: NawaRo *Input materials: plant biomass*		MS GS GR-GPS CCM	MS GS WKS	MS GS R-GPS WK	MS GS R-GPS WK CCM	GS MS GR-GPS CCM
Einsatzstoffe: tierische Exkremente *Input materials: animal manure*		MVG RM HTK	MVG HTK	SG RM	SG	MVG RM
Installierte elektrische Leistung *Installed electrical power*	kW	329	855	280	350	76
Spezifische installierte elektrische Leistung *Specific electrical power*	kW m^{-3}	0,11	0,21	0,18	0,23	0,048
BHKW (Anzahl, Typ)/*CHPU (Number, type)*		1 GO	2 GO	2 ZS	1 GO, 1 ZS	2 GO

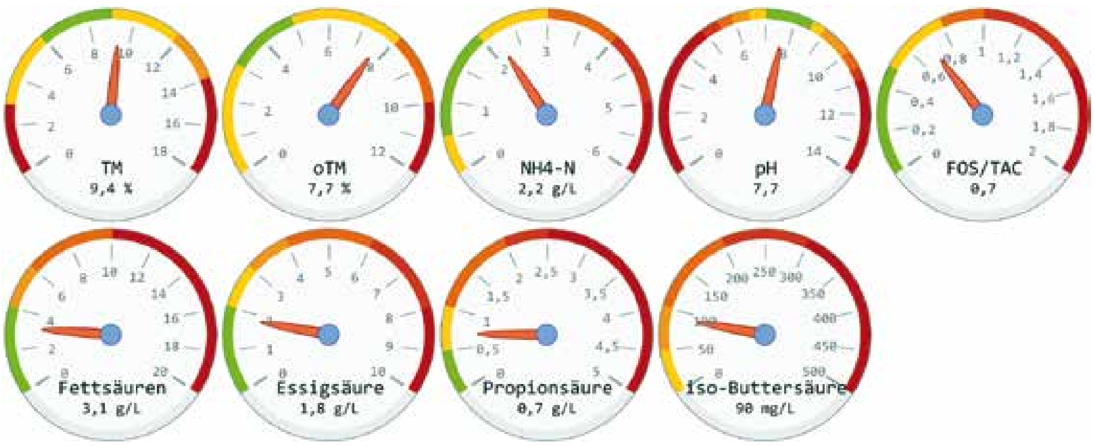
BHKW: Blockheizkraftwerk/*CHPU: combined heat-and-power unit*; CCM: Corn-Cob-Mix; GO: Gas-Otto-Motor/*gas engine*; GPS: Ganzpflanzensilage/*whole crop silage*; GR: Grünroggen/*green rye*; GS: Grassilage/*grass silage*; HTK: Hühnertrockenkot/*chicken manure*; MS: Maissilage/*maize crop silage*; MVG: Milchviehgülle/*liquid dairy cattle manure*; R: Roggen/*rye*; RM: Rindermist/*solid cattle manure*; SG: Schweinegülle/*liquid pig manure*; ZS: Zündstrahlmotor/*pilot-injection engine*; W: Weizen/*wheat*; WK: Weizenkörner/*wheat kernels*; WKS: Weizenkörnerschrot/*ground wheat kernels*

biogas plants using mainly energy crops as input, which was typical for the years after the first amendment of the German “Renewable Energy Act” (EEG). Plant 14 was chosen as an example for a farm-scale biogas plant that uses mainly animal manure from dairy cattle, plus some energy crops from farmland. The data used for this assessment cover time periods between one and a half and two years, over which mean values for the characteristic figures were calculated.

Biogas Plant 7

Mean indicator values in 17 samples from the primary digester of this plant were in the uncritical range (green to yellow color marking) (**Figure 2**). For the first assessment period, plant #7 received an acceptable ranking for the category of biogas production and an inacceptable ranking for the category of biogas utilization (**Table 3**, 7-1). The acceptable rating for biogas production is due to the relatively low methane productivity of the large digestion volume. The inacceptable rating for biogas utilization results from the lack of heat utilization which is given great weight in the respective set of rules. As a consequence, since the method is designed to avoid compensation between different categories, the plant receives an overall unacceptable rating.

Fig. 2



Report on process indicators in samples from primary digester 1 of biogas plant 7 for the first observation period (TM: dry matter, oTM: organic dry matter, NH_4-N: ammoniacal nitrogen, *FOS: volatile organic acids, TAC: total alkalinity, Fettsäuren: volatile fatty acids, Essigsäure: acetic acid, Propionsäure: propionic acid, iso-Buttersäure: iso-butyric acid)*

Table 2

Ausgewählte verfahrenstechnische Kennwerte der untersuchten Biogasanlagen
Table 2: Selected characteristic figures for assessed biogas plants

Kennung / *ID*	**Einheit/*Unit***	**7-1**	**7-2**	**10-1**	**10-2**	**14**
Biogasausbeute/*Biogas yield*	m^3_N t oTM^{-1}	698	523	744	746	637
Methanausbeute/*Methane yield*	m^3_N t oTM^{-1}	380	280	384	385	342
Biogasausbeute/*Biogas yield*	m^3_N t FM^{-1}	188	130	167	162	84
Relative Biogasausbeute/*Relative biogas yield*	%	120	90	129	125	133
Methanproduktivität/*Methane productivity*	m^3_N (m^3 d)$^{-1}$	0,7	0,9	1,0	1,1	0,4
Stromausbeute/*Electricity yield*	kWh t FM^{-1}	346	250	359	345	146
Spezifischer Strombedarf/*Specific electricity demand*	kWh t FM^{-1}	32	21	16	16	15
Elektrischer Nutzungsgrad/*Electrical utilization ratio*	%	33,9	35,9	33,6	35,6	32,4
Thermischer Nutzungsgrad/*Thermal utilization ratio*	%	5,8	32,2	5,5	23,9	43,2
Anteil Eigenstrombedarf/*Own electricity demand*	%	9,1	8,5	4,4	4,5	9,9
Anteil Eigenwärmebedarf/*Own heat demand*	%	8,8	13,3	17,2	11,6	29,5
Netto-Nutzungsgrad Methanenergie *Net utilization ratio of methane heating value*	%	32,5	57,7	47,4	63,7	59,2
Gesamt-Arbeitsausnutzung BHKW *Overall utilization ratio of CHPU*	%	97,8	61,0	89,7	86,0	*100,3*

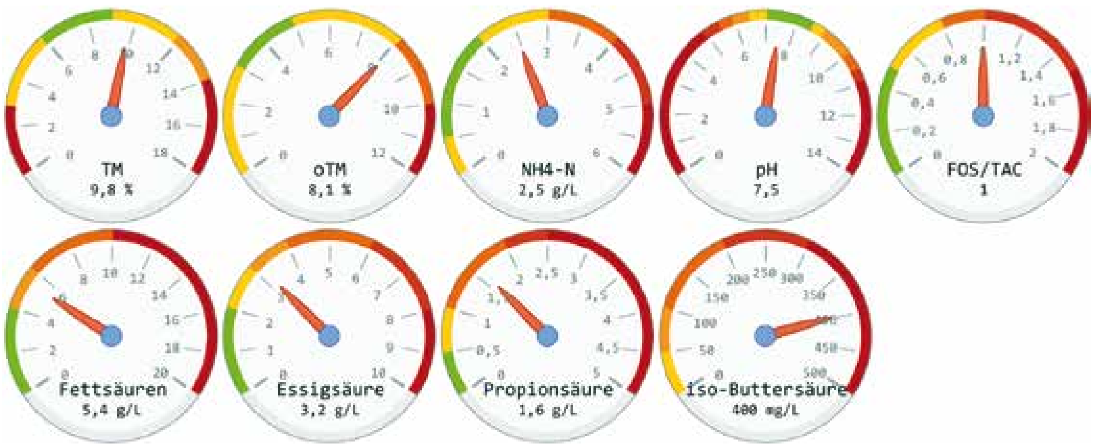
Later, this biogas plant was refurbished which included the following measures (**Table 1**):

- Extending the digestion volume by a third by means of converting the former covered storage tank for digested residues to a tertiary digester;
- Building a new open storage tank for digested residues with a capacity of 2,280 m^3;
- Installing a “satellite CHPU” with 526 kW nominal electrical power on the premises of an industrial customer who purchases the heat output. The CHPU is supplied with biogas via a pipeline. For the biogas facility this translates into an extension of CHPU power by a factor of 2.6 and almost a doubling of specific installed electrical power;
- Raising the share of animal manure in the input from 6 to 32 % in order to receive the special credit for manure digestion according to EEG 2009.

The complete heat output of the satellite CHPU is demanded by the industrial customer. To run the engine at full power, the organic loading rate of the digesters had to be increased, significantly. A loading rate of 4.1 kilograms organic dry matter per cubic meter and day was reached in the two parallel primary digesters which is not particularly high, but still seemed to be close to their limits.

From **Figure 3** it can be seen that in the second observation period, important indicator values in samples from the primary digesters had changed to a critical level. Particularly, the con-

Fig. 3



Report on process indicators in samples from primary digester 1 of biogas plant 7 for the second observation period

Table 3

Assessment results for the selected biogas plants

Kennung/*ID*	**7-1**	**7-2**	**10-1**	**10-2**	**14**
Biogasproduktion *Biogas production*	ausreichend *acceptable*	ungenügend *unacceptable*	sehr gut *excellent*	sehr gut *excellent*	ausreichend *acceptable*
Effizienzwert *Efficiency score*	37,5	13,8	87,4	86,2	37,5
Biogasverwertung *Biogas utilization*	ungenügend *unacceptable*	gut *good*	ausreichend *acceptable*	gut *good*	sehr gut *excellent*
Effizienzwert *Efficiency score*	13,8	51,4	26,3	62,5	75,9
Gesamtbewertung *Overall assessment*	ungenügend *unacceptable*	ungenügend *unacceptable*	ausreichend *acceptable*	gut *good*	ausreichend *acceptable*
Effizienzwert *Efficiency score*	12,7	13,8	27,1	62,5	37,5

centration level of iso-butyric acid indicated a risk for destabilization of the digestion process. As a consequence, despite significant spare capacity of the CHPUs, it was not possible to raise the loading of the digesters any further. While the satellite facility achieved a utilization ratio of around 90 %, a value of only 66 % was reached for the CHPU on site.

The rating for biogas production declined to unacceptable due to a significant decrease in "Relative Biogas Yield" which reflects the problems with digestion process stability (**Table 3**, 7-2). On the contrary, a good rating was achieved for biogas utilization due to the complete use of the heat output from the satellite CHPU. Overall, this resulted in a marginally better rating for plant 7 during the second observation period.

Biogas Plant 10

For the first observation period, this plant received an excellent rating for biogas production and an acceptable rating for biogas utilization (**Table 3**, 10-1). "Relative Biogas Yield" was high while "Methane Productivity" was on a satisfactory level. There were no signs of unstable biological conditions. Concerning the rating for biogas utilization, the excellent value of "CHPU Utilization Ratio" and a very low electricity demand could not make up for the low heat utilization ratio. Overall, the technical aspect of the plant was rated acceptable.

Later on, based on economical considerations, the owner of the plant took the following "repowering measures" (**Table 1**):

- Replacing the older and smaller one of the two CHPUs with a new gas engine with 150 kW nominal electrical power;
- Installing an ultrasonic treatment unit for digester content;
- Plugging on a number of heat users whereby the heat utilization ratio was raised from 14 to 49 %;
- Using corn-cob-mix as additional input.

While the increase in organic loading rate was noticeable in terms of the respective process indicators, critical values did not occur. The excellent rating for biogas production declined only marginally due to a small decrease in "Relative Biogas Yield" (**Table 3**, 10-2). The decline in CHPU Utilization Ratio during the second observation period was mainly caused by an interruption of digester operation which had become necessary to remove deposits. Nevertheless, the significant increase in heat utilization ratio resulted in a good rating for biogas utilization.

The specific electricity demand per ton of input did not change with the repowering measures, likely due to a higher share of liquid animal manure in the input. Although this cannot be proven based on the available data, there appeared to be a positive impact of the ultrasonic treatment on digestion kinetics. While the hydraulic retention time in the digesters was decreased by 14 %, the biogas and methane yields from the organic dry matter input remained unchanged (**Table 2**). Overall, for the second observation period, plant 10 received a good rating und thus a significant improvement compared to the first period. This was also the best rating among the three examples presented here.

Biogas plant 14

With 75 % (m/m) animal manure in the input, this facility is significantly different from the other two biogas plants. Even for such a high share of animal manure, the organic loading rate was at a very low level of around 1 kg oDM $(m^3\ d)^{-1}$. Relative Biogas Yield was rated excellent, while Methane Productivity was very low, resulting in an acceptable rating for biogas production (**Table 3**). Of course, this is not really a critical point for this operation, since the input materials are produced on the farm at relatively low cost and the investment for the plant was also comparably low.

Since most of the heat output was utilized, biogas utilization was rated excellent. The calculated value of 100.3 % for CHPU Utilization indicates that the nominal electrical power output of the engines was not rated correctly. Overall, an acceptable rating was achieved for this plant.

Conclusions

With the method described here it is possible to perform an absolute and comparative assessment of the process efficiency of biogas plants, based on expert knowledge and without compensation effects. Using the corresponding web application, plant operators and consultants can evaluate important characteristic figures of biogas plants in a systematic fashion. In the “plant report”, additional information is given for interpreting characteristic figures and process indicators. With the “efficiency analysis”, weak points of the plant are identified and different biogas plants can be compared and ranked. A current methodological drawback is the underestimation of the potential biogas yield for determining the efficiency parameter Relative Biogas Yield. As an alternative, the calorific values of the input materials could be used, but this has been very uncommon in the biogas sector, so far.

Our application does not replace an experienced professional consultant. Rather it aims to streamline the consulting process by providing operators with a better, systematic understanding of the status and weak points of their biogas plants. As a precondition for making use of the application, sufficient and valid data from the plant have to be available.

With the rule based approach in the efficiency assessment, we introduce a subjective component. For interpreting the assessment results, it is also important to take into account the individual preferences of the user. Thus, a possible advancement of the method could be to enable the user to somewhat adapt the rules to his personal priorities. On the other hand, then the assessment results for different plants would not be comparable anymore.

In principle, the application could also be used to simulate the effects of repowering measures or changes in the selection of input materials on important performance figures of a biogas plant, thereby supporting the planning process. As a further module of the web application, we aim to implement a method for analyzing improvement measures. Based on additional characteristic figures and specifications of a biogas plant, this method derives the most probable reasons for weak points and suggestions for improvement measures.

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