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Using the mean fuel efficiency to energetically assess agricultural biogas plants

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Biogas plants constitute power plant processes that can be assessed using methods of energy technology. The operating data routinely collected from the biogas plant, and the gross calorific value of the substrate are needed in order to assess the power plant. The four agricultural biogas plants we studied displayed a mean fuel efficiency of up to 40.5 %. By adjusting the energy potential to the anaerobically degradable fraction, we were able to compare plants that ferment poorly degradable substrates with plants that ferment easy-to-degrade substrates. The approach is primarily suited for regular operational checks, for identifying losses, and for assessing plant modification measures.

Keywords
Biogas, energy technology, utilisation ratio, benchmark, calorific value

Numerous empirical studies have looked at optimising biogas plant operations. These studies have identified challenges that include the efficient utilisation of substrates, external heat utilisation, and measures to optimise operational procedures. (Fachagentur Nachwachsende Rohstoffe e.V. 2005, Gehrig 2007, Fachagentur Nachwachsende Rohstoffe e.V. 2009, Winterberg et al. 2012, Wirth and Hartmann 2013). In contrast, biogas engineering uses many established assessment approaches that integrate the biogas plant into a utilisation chain in order to assess it from an energetic and ecological standpoint (Havukainen et al. 2014). A biogas plant, whose primary function is to generate electricity and heat, should be viewed in the same light as a power plant process. There are national and international standards for assessing these processes which enable us to compare plants even beyond technological boundaries (Verein Deutscher Ingenieure 2014).

The operation of biogas plants in Germany is designed to maximise the number of full load hours. Standard gas yield values and the efficiency levels of the conversion units are used to estimate the amount of substrate needed (Mitterleitner o. J., Eder and Schulz 2007, Fachagentur Nachwachsende Rohstoffe e.V. 2013, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. 2013). The necessary amount of substrate m in the nominal period T_N – usually 1 year – can be estimated using Equation 1.

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$$m_{sub,FM} = \frac{P_N \cdot T_N}{Y_{BG} \cdot \varphi_{CH_4} \cdot H_{i,CH_4} \cdot \eta_{el}} \quad \text{(Eq. 1)}$$

m Amount of substrate [t_{FM}/a]

P_N Nominal electrical power of the conversion unit [kW]

T_N Nominal period [h/a]

Y_{BG} Biogas yield [$m^3_{i.N.}/t_{FM}$]

φ_{CH_4} Methane content [Vol.-%]

H_{i,CH_4} Lower heating value of methane [kWh/$m^3_{i.N.}$]

η_{el} Electrical efficiency of the conversion unit [%]

Because electricity feed-in is preferred in Germany, electrical work serves as an indirect design parameter. For biogas plants that supply balancing power, the rated output is customarily taken into consideration during the planning process. For this type of plant no methodology is available to optimise performance parameters in a satisfactory way (Djatkov et al. 2014, Mauky et al. 2015).

A further obstacle is the assumption of standard biogas yields as they do not represent an absolute reference value. The first indication for an absolute value can be found in the stoichiometric Equation 2 proposed by Symons and Buswell (1933). This formula can be used to estimate the specific gas volume and composition of the main components of methane and carbon dioxide. (Symons and Buswell 1933, Reinhold 2005, Linke et al. 2006, Mähnert 2007, Mähnert et al. 2007)

$$C_{38}H_{60}O_{26} + 10\ H_2O \rightarrow 20\ CH_4 + 18\ CO_2 \quad \text{(Eq. 2)}$$

If the stoichiometric composition is applied to a conventional maize silage, the maximum biogas yield is estimated to be 303.6 $m^3\ t_{FM}^{-1}$. The reference value for the biogas yield of maize silage is 216 $m^3\ t_{FM}^{-1}$ (Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. 2013), which is equivalent to a theoretical degradation rate of 71.2 %. The information that the fermentation residue still contains 28.8 % unused biogas potential, is not displayed by standard biogas yields.

Effenberger et al. (2014) recently found that basing the assessment of biogas plants on higher heating value is beneficial as it has a physical basis. Since a detailed analysis of all of the energy fluxes takes effort both in terms of equipment and time, this approach cannot be carried out by the plant operator (Fischer et al. 2015).

We present an approach which can be implemented in the initial step of an operational check in biogas plants. Its key aspect is an energetic cost-benefit ratio, expressed as efficiency of the process based on the utilisation rate. The obtained parameter differentiates between plant output and energy utilisation in the sense that useful energy is decoupled during a nominal time period.

Methodology

In order to assess the quality of the energy conversion process, the biogas plant is assessed on a purely technical basis with the aim of improving operation in order to optimise yields. As a result, energy used in upstream and downstream processes, climate effects, exergetic assessments and the allocation of the chemically bound substrate energy are not used to calculate the targeted energy fluxes. Earlier investigations were carried out in a similar fashion. They assessed different cogeneration and non-cogeneration conversion processes but limited their assessment to the technical pathway used to convert raw biogas (Wegener et al. 2007). In order to take the fuel utilisation factor of the substrates into consideration, all structural and technical facilities which are purely used to generate and convert biogas are included within the system boundaries as depicted in Figure 1.

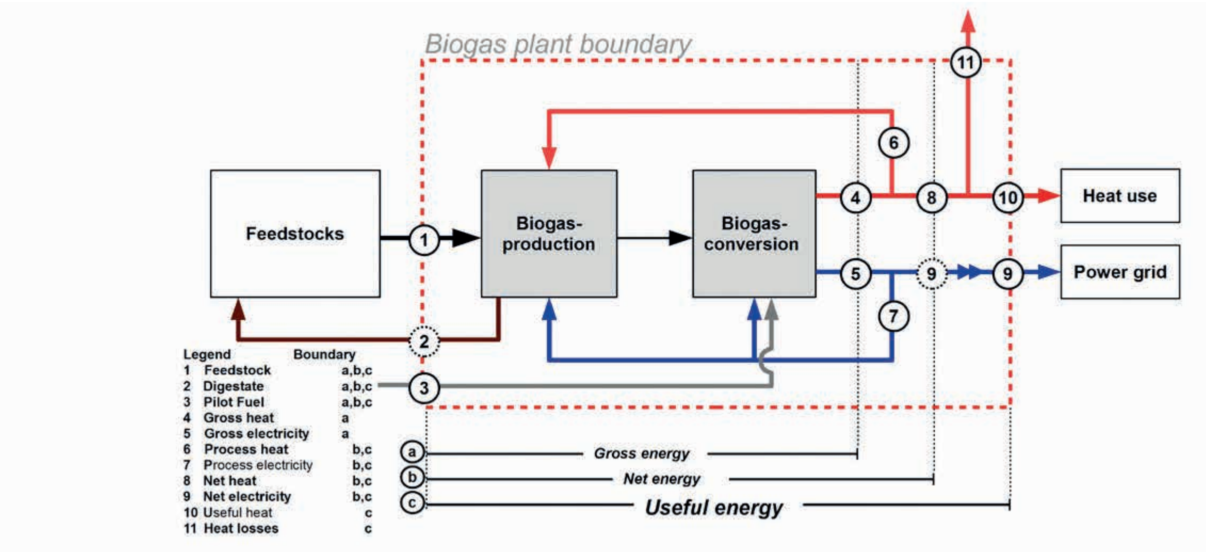

Figure 1: The assessment boundaries of the biogas process for assessing the gross, net and useful energy.

Efficiency factors are used in energy technology as a descriptive index of efficiency (Verein Deutscher Ingenieure 2014). The electrical and thermal work generated in combined heat and power facilities are considered to be the target energies of a conventional biogas plant. The chemical energy bound in the substrate is considered to be an expenditure, which is simplistically assumed to be a continuous energy flux and thus indicates the substrate input P_{sub} (Fischer et al. 2015). Accordingly, the substrate input is the product of the substrate mass flow $\dot{m}$ and the substrate-specific gross calorific value H_S. Here auxiliary materials used in biogas production, such as rapeseed oil, EL heating oil and biodiesel are also taken into consideration. In this sense, substrates and auxiliary materials can be regarded as primary energy carriers and labelled accordingly as fuel. The average overall efficiency rate is referred to as the mean fuel efficiency $\bar{\omega}$, which is defined as the "quotient of the usable target energy output in a particular time period and the total energy input" (Verein Deutscher Ingenieure 2014) (Equation 3). Only the portion of energy that is actually fed into the electrical and heating grid is considered to be usefully emitted. This approach deviates from the usual approach which uses net energies as its basis without taking into account own consumption and the rate of heat utilisation. The observed timeframe includes all breaks, downtimes, idle times, start-up times and shut-down times. While German guideline VDI 4661 generally suggests using the lifetime L of the plant, a more standard reference time period – for example one year – is sufficient. This parameter enables us to assess the efficiency of the energy conversion of the entire plant.

$$\bar{\omega} = \frac{W_{el,net} + Q_{useful}}{\sum m_i \cdot H_{S,i}} \qquad \text{(Eq. 3)}$$

$\bar{\omega}$	Mean fuel efficiency [-]
$W_{el,net}$	Net electricity generation [kWh]
Q_{useful}	Net heat generation (used heat) [kWh]
m_i	Substrate quantities [t_{DM}]
$H_{S,i}$	Specific gross calorific value [kWh/t_{DM}]

The defined figure of the mean fuel efficiency is further differentiated. First, the capacity figure is introduced (Equation 4). It is defined as the ratio between the nominal and the substrate power as a sum of the specific power of the input materials and is accordingly dimensionless.

$$K = \frac{P_N + \dot{Q}_N}{\sum \dot{m}_i \cdot H_{S,i}} \qquad \text{(Eq. 4)}$$

K	Capacity figure [-]
P_N	Nominal electric power [kW]
$\dot{Q}_N$	Nominal thermal power [kW]
$\dot{m}_i$	Mass flow of an input material [t_{DM}/h]
$H_{S,i}$	Specific gross calorific value of an input material [kWh/t_{DM}]

A decisive factor when assessing efficiency is the rate in which the potential contained in the substrate is utilised. This can occur through utilisation factor of maximum capacity, as defined in accordance with VDI 4661, whereby the utilisation period is equal to the theoretical full load hours. Whereas VDI 4661 uses gross energy in its calculations, energy utilisation in the assessment approach developed here represents the ratio between the energy quantities actually emitted for external use and the theoretically producible target energy quantities within a definable time period. This takes into account not only partial load times and downtimes, but also own energy requirements and external heat utilisation which are much more important factors in biogas plant operation. Thus, this approach calculates energy utilisation using Equation 5.

$$n_A = \frac{W_{el,net} + Q_{useful}}{(P_N + \dot{Q}_N) \cdot T_N} \qquad \text{(Eq. 5)}$$

n_A	Utilisation factor of maximum capacity [-]
$W_{el,net}$	Net electricity generation [kWh]
Q_{nutz}	Net heat generation (utilised heat) [kWh]
P_N	Nominal electrical power [kW]
$\dot{Q}_N Q_N$	Nominal thermal power [kW]
T_N	Nominal time (calendar time) [a]

The product of the capacity figure and utilisation factor of maximum capacity results in the mean fuel efficiency (Equation 6).

$$\bar{\omega} = K \cdot n_A \qquad \text{(Eq. 6)}$$

$\bar{\omega}$ Mean fuel efficiency [-]

K Utilisation factor of maximum capacity [-]

n_A Capacity figure [-]

By plotting the capacity figure and utilisation factor of maximum capacity a simple graph can be created. The plant's operational status can be entered in the graph as a dot and the area covered marks the mean fuel efficiency (Figure 2). The highest possible mean value cannot be exceeded, so that utilisation factor of maximum capacity takes on an anti-proportional value when the capacity figure is greater than 1.

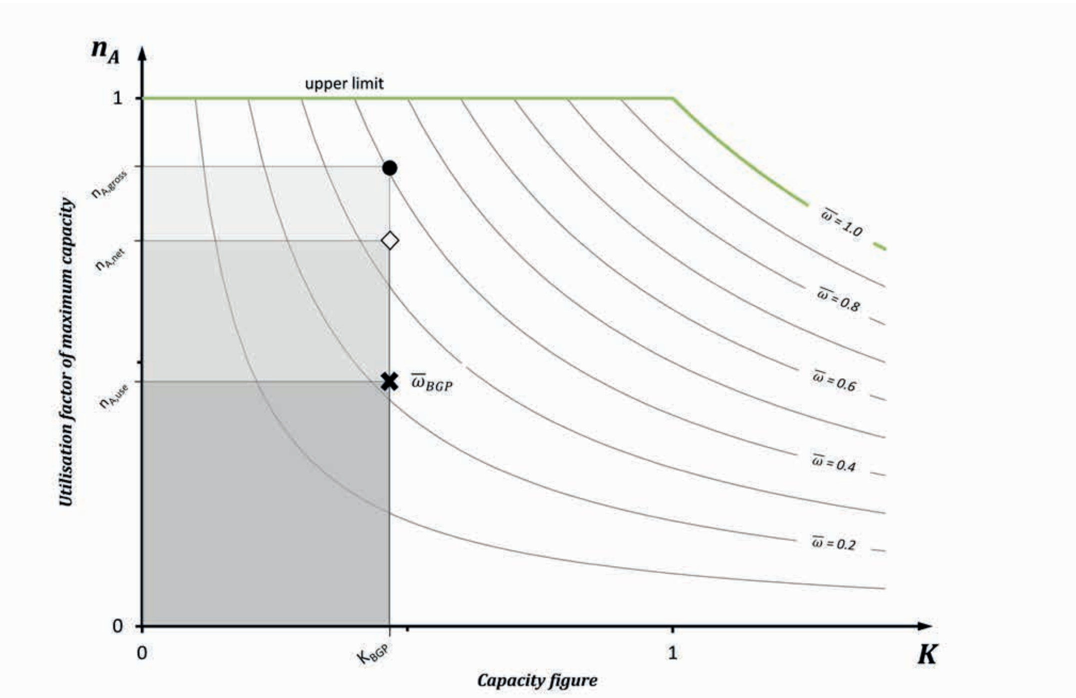

Figure 2: Graph of the mean fuel efficiency and the net and gross energy output

The mean fuel efficiency will get closer to its theoretical maximum as own demands and heat utilisation can be optimised. An examination of the area is helpful when there are differences in capacity figures and utilisation factor of maximum capacity. A larger area always means a higher mean fuel efficiency. According to Figure 3 it can be assumed that $\bar{\omega}_1 < \bar{\omega}_2$ and $\bar{\omega}_3$.

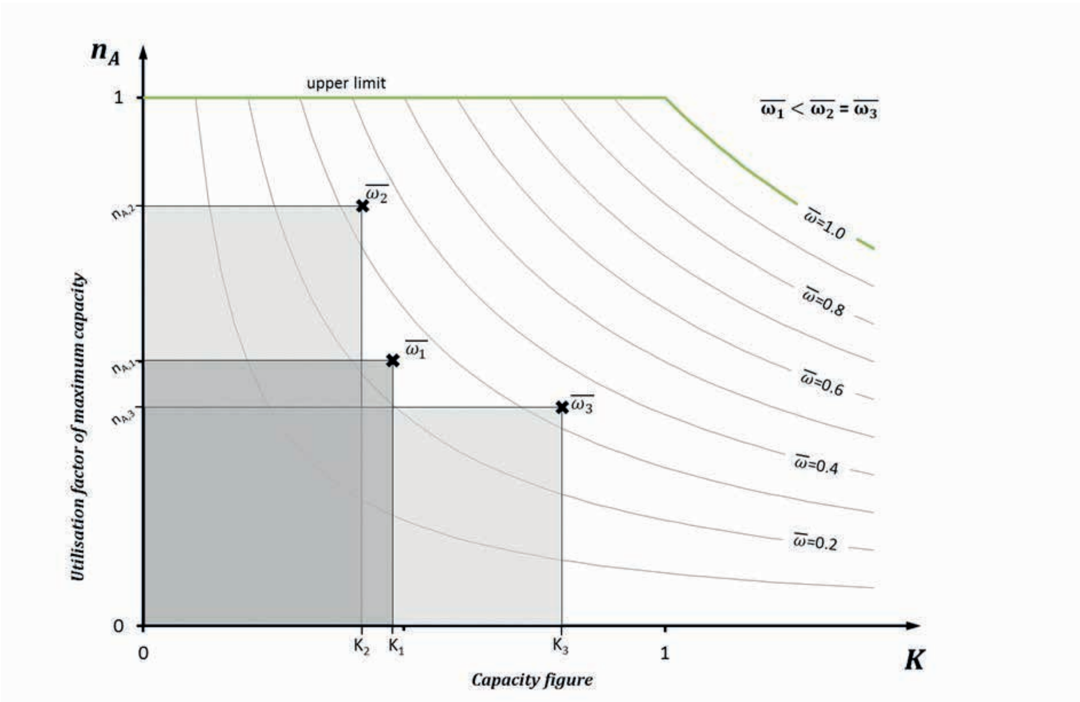

Figure 3: Scheme of the mean fuel efficiency of different plants and/or comparison of one plant over multiple years

The capacity figure can increase, for example, by economising on substrates or as the result of an increase in the CHP performance. If, in practice, one assumes a constant value for K, energy utilisation shows a significant impact on the change in the mean fuel efficiency. It can be raised, for example, by increasing plant availability, and, above all, through a higher waste heat recovery.

Adjusting the capacity figure

Different substrates degrade to different grades. This may lead to allegedly less favourable conditions in BGPs with low-degradable substrates. By applying fermentation ratios in accordance with Weissbach, the mean fuel efficiency can be limited to the fermentable organic matter (FOM, as the anaerobically usable fraction). The fermentation quotient determines the fraction of anaerobically degradable organic matter (Weissbach 2008). The energy potential of the non-degradable organic fraction is subtracted from the specific gross calorific value of the substrate with the help of the adjustment factor f_{an} as per Equation 7.

$$H_{s,adj} = f_{an} \cdot H_{s,OM} \quad \text{(Eq. 7)}$$

$H_{s,adj}$ Adjusted specific gross calorific value [kJ/kg_{FOM}]
f_{an} Adjustment factor [kgFOM/kg_{OM}]
$H_{s,OM}$ Specific gross calorific value [kJ/kg_{OM}]

The adjustment factor is calculated based on the gross calorific value of the organic dry matter minus the non-degradable fraction (unusable organic matter (unOM)) as per Equation 8. The non-degradable fraction is simplistically assumed to be lignin with a maximum calorific value of 25.6 MJ/kg (Raveendran and Ganesh 1996, Kienzle et al. 2001, Sheng and Azevedo 2005).

$$f_{an} = \frac{H_{S,OM} - (1 - \mathrm{FQ}) \cdot \mathrm{H}_{\mathrm{S,unOM}}}{H_{S,OM}} \quad \text{(Eq. 8)}$$

f_{an}	Adjustment factor [kgFOM/kg_{OM}]
FQ	Fermentation quotient [-]
$H_{S,OM}$	Specific gross calorific value [kJ/kg_{OM}]
$H_{S,unOM}$	Specific gross calorific value of lignin [kJ/kg_{DM}]

Determining calorific values

Data on gross calorific values was collected at agricultural biogas plants in western Saxony. All of the plants used manure and renewable raw materials. The primary substrates were cattle manure and maize silage. Other substrates, such as pig manure, horse manure, silo covering material and various silages, were also studied and taken into account when creating the respective material classes. The determination was carried out using a bomb calorimeter in accordance with DIN EN 14918 (Deutsches Institut für Normung 2010). Literature data taken from the Phyllis 2 and BIOBIB biomass databases was available for some substrates (Hofbauer 1997, Energy research Centre of the Netherlands 2012), which enabled the gross calorific value to be calculated using an empirically determined, non-linear model based on elementary analyses (Equation 9). The model is based on the proportion of carbon, hydrogen and nitrogen in the dry matter. (Friedl et al. 2005)

$$HHV = 3.55C^2 - 232C - 2230H + 51.2C \cdot H + 131N + 20{,}600 \quad \text{(Eq. 9)}$$

Similar substrates are summarised and supplemented with data from literature to form standard values. The substrates are placed in the material classes labelled excrements, energy crops and digestates. Individual substrates, such as maize silage, can be selected and separately assessed within the material classes (Table 1).

Table 1: Compilation of the gross calorific values of the individual substrates and material classes based on several measurements and literature data

Substrate or material class	Number of datasets/ own measurements	Average gross calorific value H_s		Additional sources [3]
	[-]	[kJ/kg$_{DM}$]	[kJ/kg$_{OM}$]	
Maize/maize silage	13/7	18,245 ± 459	18,976 ± 444	1,2,6,7
Grain/Whole plant silage (WPS)	8/4	18,157 ± 322	20,309 ± 800	1
Lawn/grass/grass silage	5/5	18,232 ± 461	20,454 ± 589	1
General energy crops [1]	32/23	18,215 ± 427	19,518 ± 1,016	1,2,6,7
Cattle manure	8/5	17,216 ± 1,382	22,342 ± 1,603	3,4,5
Cow dung	5/5	17,758 ± 560	21,114 ± 1,026	-
General excrement [2]	14/9	17,005 ± 1,638	22,452 ± 1,797	3,4,5
Fermentation substrate	17/15	16,557 ± 1,188	22,478 ± 733	1

[1] includes individual samples of other substrates such as alfalfa silage and various feed residues, excluding sugar beets
[2] also contains values for pig manure
[3] 1 Sutter (2013)
2 Pfeifer and Obernberger (2007)
3 Sweeten et al. (1986)
4 Annamalai et al. (1987)
5 Young and Pian (2003)
6 D'Jesús et al. (2006)
7 Hofbauer (1997)

The material class of energy crops exhibits a very low range of variation in the measurement and literature values. The average gross calorific value of maize silage is 18,245 ± 459 kJ/kg$_{DM}$. Other frequently used substrates, like grass silage and grain/whole crop silage, show similar gross calorific values of 18,157 ± 322 kJ/kg$_{DM}$ and 18,232 ± 461 kJ/kg$_{DM}$ respectively. Figure 4 shows the different averages and ranges of variation. Since the measurements of calorific value do not exhibit a normal distribution for excrement, and the average can be distorted by outliers, the median value should also be considered.

When individual samples of additional substrates, like silo covering material and alfalfa silage, are taken into account, a robust reference value of 18,215 ± 427 kJ/kg$_{DM}$ for general energy crops is achieved. This does not exhibit any notable deviation to individual substrates. The range of fluctuation is larger for cattle manure since the homogeneity of the material class is considerably lower. Solid dung exhibits similar gross calorific values to energy crops; the value ranges overlap considerably due to the enrichment of the dung with straw and feed residues. In order to perform detailed energy flux analyses, digestates from large-scale plants and lab fermenters were also investigated (Fischer et al. 2015). The extensive range of variation can be traced back to the differences in the substrates and the differing ash contents. When the gross calorific value is based on organic dry matter, there is a clear increase in gross calorific value up to and including the fermentation substrates. This observation has already been made by Born and Casaretto (2012) and has been used to determine degradation rates to economically optimise the operation of biogas plants.

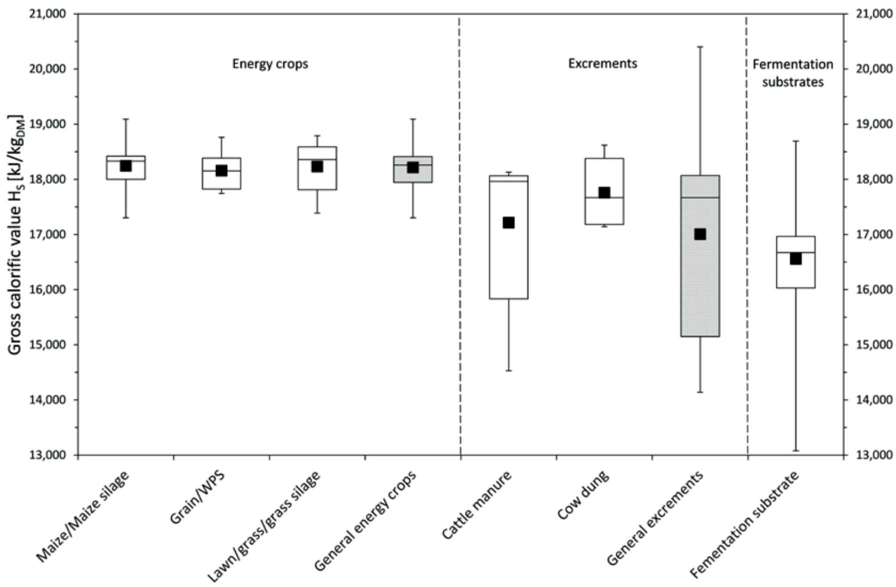

Figure 4: Ranges of variation, median values (line in the box), and averages (black dot) of the gross calorific values of dry matter.

A comparison of the facilities

The mean fuel efficiency model was applied to four biogas plants in western Saxony. All of the plants are directly affiliated with agricultural farms and use cattle manure as their main substrate. Another output-defining substrate is maize silage and other energy crops in modifiable proportions are also fermented. Three of the four plants have fundamentally identical structures. Biogas is generated using a main fermenter, secondary fermenter and digestate storage. The plants differ mainly in the number and type of conversion units. In terms of production, the fourth plant consists only of a main fermenter and the digestate storage is an open basin. BGP 1 and 2 each have a gas engine powered CHP, while BGP 3 and 4 operate a combination of a pilot injection and gas engine CHP. The ignition oil used (EL heating oil) is attributed to the substrate input. The long-term average percentage of ignition oil in the electricity production of one of the examined plants (BGP 4) is approximately 3.5 %. The calculation model is used exemplarily for a complete operating year. Maintenance intervals, downtimes, seasonal substrate adjustments, and changes to heat consumption influence the capacity figure and utilisation factor of maximum capacity accordingly. The calculation of the mean fuel efficiency is done on the basis of the useful energies emitted. Net and gross energy yields are also calculated (Table 2).

Table 2: Biogas plant specifications, as well as gross, net and useful energy decoupling in the reference period T_N = 1a

	Unit	BGP 1	BGP 2	BGP 3	BGP 4
P_N	[kW]	360	537	550	530
$\dot{Q}_N$	[kW]	427	452	556	550
P_{sub}	[kW]	2,225	2,098	2,048[1)]	2,248[1)]
$\sum m_{corps}$	[t]	3,600	8,883	7,172	7,363
$\sum m_{excreta}$	[t]	35,552	8,460	15,425	10,400
$(P_N + \dot{Q}_N) \cdot T_N$	[kWh]	6,889,930	8,662,465	9,668,560	9,460,800
$W_{el,gross}$	[kWh]	2,653,853	4,459,743	4,341,640	4,390,713
$W_{el,net}$	[kWh]	2,343,086	4,137,953	3,977,647	4,039,456
Q_{gross}	[kWh]	3,122,180	3,747,683	4,377,120	4,556,400
Q_{net}	[kWh]	2,520,235	2,863,484	3,549,502	3,417,300
Q_{useful}	[kWh]	1,161,945	37,872	3,291,181	640,634
Gross energy yield					
K	[-]	0.35	0.47	0.54	0.48
$n_{A,gross}$	[-]	0.84	0.95	0.90	0.95
$\bar{\omega}_{gross}$	[-]	0.296	0.447	0.486	0.454
Net energy yield					
K	[-]	0.35	0.47	0.54	0.48
$n_{A,net}$	[-]	0.71	0.81	0.78	0.79
$\bar{\omega}_{net}$	[-]	0.249	0.381	0.420	0.379
Useful energy – mean fuel efficiency					
K	[-]	0.35	0.47	0.54	0.48
n_A	[-]	0.51	0.48	0.75	0.49
$\bar{\omega}_{BGP}$	[-]	0.180	0.227	0.405	0.238

[1)] Use of ignition oil taken into account.

The four plants exhibit average gross energy yields of 0.296 to 0.486. In other words, a maximum of nearly half of the fed-in primary energy potential can be transferred to the target energies of electricity and heat. This clearly demonstrates that BGP 1, with the highest proportion of liquid manure, achieves the lowest capacity figure. There is an obvious correlation between the substrate-dependent biogas yield and the low capacity figure, which ultimately puts the use of high amounts of liquid manure in biogas plants at a systematic disadvantage. The practical comparison of BGP 3 and 4 shows, however, that no clear rule can be derived from this when looking at gross energy yield rates. Both BGPs demonstrate how the rate of heat utilisation can influence the mean fuel efficiency. Since BGP 3 emits nearly all of the available heat, the difference between the net energy yield and the mean fuel efficiency is very low. In order to classify the operating results of the plants, a total of 12 BGPs with similar substrate spectrums from German biogas measuring programmes (BMP) were equally assessed. Selection criteria included the availability of the required data, the highest possible percentage of cattle manure and the use of renewable raw materials. The plants' nominal electrical power reveals values between 48 and 806 kW. No useful heat was documented for the plants from BMP 1

(Fachagentur Nachwachsende Rohstoffe e.V. 2005, 2009). This impacts the average fuel utilisation rate accordingly. The results of the comparison are shown in Figure 5.

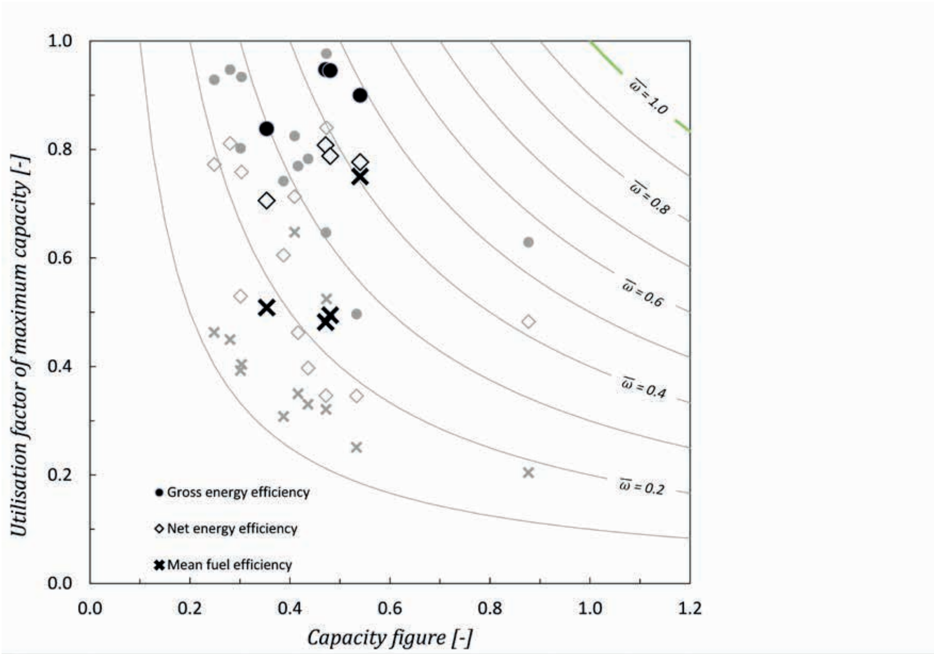

Figure 5: Mean fuel efficiencies of the four agricultural biogas plants studied (black) compared to similar biogas plants from Biogas Measuring Programmes 1 and 2 (grey) (Fachagentur Nachwachsende Rohstoffe e.V. 2005, 2009).

The mean fuel efficiency for the biogas plants in our study was between 0.180 and 0.405, compared to 0.119 to 0.265 for similar plants in the two biogas measurement programmes. The BGPs in the first BMP, which tended to be older and more simply constructed, exhibited a mean fuel efficiency throughout of less than 0.2, even though the gross energy utilisation had, in part, very high values of up to 0.977. This can mainly be traced to a lack of heat utilisation. The plants in the second measuring programme, with a portion of liquid manure, demonstrate average figures of mean fuel efficiencies of up to 0.265. Plants running purely on energy crops achieve values of between 0.232 and 0.348 based on the data from 7 biogas plants in the second measuring programme. Their gross energy yield can reach values of 0.598 (BMP 2/plant 51). Thus, the BGPs we looked at are within the range we expected in terms of mean fuel efficiency – with the exception of BGP 3. This is also confirmed for capacity figures which were between 0.25 and 0.53, with only one exception. The high value of 0.88 (BMP 1/plant 26) for one BGP is an indication of a considerable technical and biological reserve capacity in combination with low energy utilisation. This assumption is supported by the highest gross energy yield of 0.553 for all the BGPs (Fachagentur Nachwachsende Rohstoffe e.V. 2005, 2009).

Anaerobically useful energy potential

To determine the adjustment factor, fermentation quotients have to be used for the input materials displayed (Table 3).

Table 3: Fermentation quotients according to (Weissbach 2008) and an estimated adjustment of the gross calorific value for the anaerobically degradable fraction. In terms of value ranges for the fermentation quotients of maize, whole plant silage and grass, the adjustment was made based on the upper values (minimum values in brackets)

Substrate/ Material Class	FQ [-]	$H_{s,DM}$ [kJ/kg$_{DM}$]	$H_{s,OM}$ [kJ/kg$_{OM}$]	f_{an} [-]	$H_{s,adj}$ [kJ/kg$_{FOM}$]
Maize silage	(0.78) 0.8	18,245	18,976	0.730	13,322
Whole plant silage	(0.68) 0.86	18,157	20,309	0.824	14,953
Lawn/grass	(0.56) 0.86	18,232	20,454	0.825	15,037
General energy plants[1)]	0.77	18,215	19,518	0.698	12,720
Cattle manure	0.5	17,216	22,342	0.427	7,353
Cattle dung	0.595	17,758	21,114	0.509	9,038
General excrements	0.55	17,005	22,452	0.487	8,280
non-degradable organic dry matter	-	-	25,600		

1) also includes sugar beet, alfalfa and straw (barley, wheat).

Adjusting the gross calorific values means that the energy potential of the animal excrement can be adjusted for the methane potential so that substrates with different degradability are on an equal footing. This effect is shown in Figure 6.

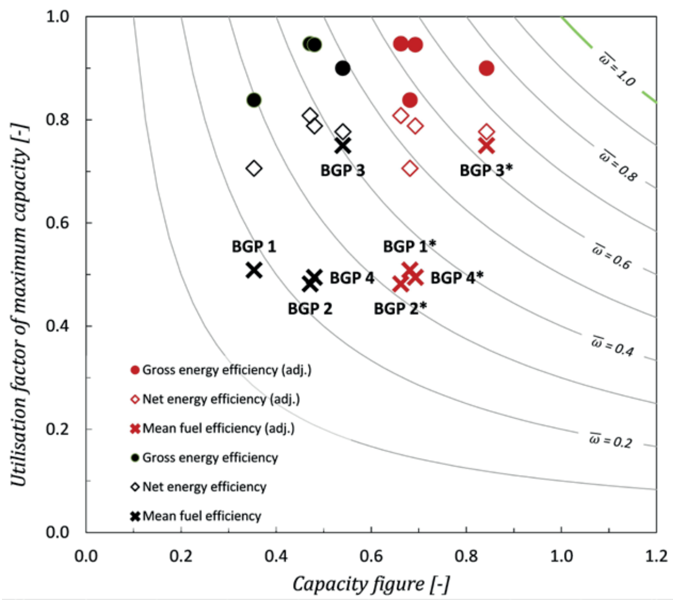

Figure 6: Mean fuel efficiencies of the four plants in our study without (black) and with (red) adjustment of the gross calorific value for the fermentable organic matter (FOM)

The adjustment solely affects the capacity figure, with adjusted values between 0.67 and 0.84. The mean fuel efficiency of BGP 1 shows above-average improvement, from 0.180 to 0.347, compared to the other plants that have a lower proportion of liquid manure. No direct comparison with the plants in the biogas measuring programme can be made since there is no information on the substrate specific dry matter content.

Discussion

We take a fundamental look at the assessment of biogas plant operation from an energy technology perspective, similar to the examination on thermochemical biomass conversion processes (Wiese 2007). Biogas plants tend to be at a disadvantage over other power plant technologies when it comes to the achievable fuel efficiency because biological conversion processes are relatively slow, microorganisms require energy for their metabolism, and a higher number of fuels are being used that contain water. Accordingly, low mean fuel efficiencies for certain substrate concepts are not a deficiency of the technology and are of subordinate interest.

The gross calorific value of the biogas feedstock presents an easily accessible and objective basis for the assessment of agricultural biogas plants. In addition to the technical significance, a reference to the thermodynamic processes in the fermenter can be easily established. In contrast to the conventional standard gas yield values that are well suited to designing a plant, the calorific value provides the opportunity to identify global losses in operation.

Should a biogas plant be technically modified, the success of the project can easily be checked and quantified through a change in the mean fuel efficiency. Plants that provide balanced power have a special status in this regard; the capacity figures of such plants will theoretically increase by the corresponding amount of the over-construction, while energy utilisation sinks. Therefore, in contrast to the utilisation factor of maximum capacity, capacity figures can take on values that are much higher than 1. The mean fuel efficiency remains unchanged as long as no losses occur as a result of irregular plant operation.

Determining gross calorific values for agricultural substrates has created orientation values that determine energy potential with high precision and reproducibility. The standard deviation for renewable raw materials is 2.34 % and for animal excrement it is 8.13 % overall. Because there is a higher deviation and a smaller basic population for animal excrement, it is fundamentally recommended to determine gross calorific value on an individual basis, as it is done for residual materials and waste.

Limiting gross calorific values to the anaerobically useful part presents a novel way to compare different substrate concepts with one another. Weißbach's division of organic matter into anaerobically useful and non-useful fractions is transferred here to energy potential. The adjustment of the gross calorific value only impacts the capacity figure, which is why substrate-related differences in terms of energy requirements are not offset.

The mean fuel efficiency model presented here enables to check the running operation of a plant and compare plants. This differs from an assessment previously based on agricultural technology. The maximum potential and tendencies can be clearly seen. Based on two separate parameters derived from production and conversion aspects, a global figure for the optimisation of biogas plants is generated. Other models that separately analyse fermentation and conversion by distinctive biological and technical parameters are of advantage if in-depth information about the process is needed. Our approach delivers a first step outline as part of a systematic procedure integrating technical, socio-econonomic and/or ecological aspects affecting biogas plant operation (Berglund and Börjesson 2006, Gerin et al. 2008, Madlener et al. 2009, Pöschl et al. 2010, Born and Casaretto 2012, Djatkov et al. 2014, Effenberger et al. 2014).

Conclusions

Our investigation of the mean fuel efficiency of biogas plants introduces a concept which simplifies the assessment of biogas plant operation by foregoing biogas-specific standard values and using robust parameters. The plants evaluated as part of the biogas measuring programmes achieve fuel utilisation rates of up to 34.8 % in the case of pure energy crop fermentation, compared to 18.0 to 40.5 % in our own investigations. In order to assess very different plants, an adjustment of the gross calorific value can be made with the help of fermentation quotients following Weißbach. In the case of retrofitting actions the three-stage basis allows a funded before-after comparison. The concept that has been developed based on on-site conversion to electricity is future-proof and equally suitable for plants supplying biomethane and for flexible plant operation.

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