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Technical Assessment of Agricultural Biogas plants

Utilization Ratio and Energy Efficiency

Technical indicators of six selected modern agricultural biogas plants were determined to evaluate utilization ratio and energy efficiency. In all of these plants, renewable raw materials were treated in combination with animal manure. At a specific installed electrical capacity between 0.09 and 0.25 kW•m^{-3} usable digester volume, electrical utilization ratios of 88 to 98 % were achieved. The combination of these two characteristic values may be used as a first indicator of process stability and functionality of a BGP. The external utilization ratio for the off-heat from the combined-heat-and-power unit was between 0 and 46 %.

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The studies were sponsored by the Bayerische Staatsministerium für Landwirtschaft und Forsten as well as by the Fachagentur Nachwachsende Rohstoffe e.V..

Keywords

Biogas, efficiency, technology, renewable primary products, animal manure

In the last few years, the market for biogas plants (BGP) in the German agricultural sector has seen a dynamic development. This was driven by the amendment of the Renewable Energy Sources Act (EEG) as of 2004 that brought about a significant increase in compensation for electricity produced from renewable raw materials (RRM). Consequently, in the years 2005 and 2006, 1,450 new biogas plants for biogas production from mainly RRM were erected. In comparison to 2004, this was an increase in the number of BGP of 71 %. In 2007, due to massive rises in prices for grain and maize, the boom came to a sudden end. The second amendment of the EEG this year is supposed to revive the development of the biogas sector and to promote the use of animal manure.

In the past, the focus used to be on the amount of electricity produced from biogas and fed into the grid. However, in order to achieve an economical and environmentally sustainable operation of a BGP, the overall utilization ratio of the biogas fuel value has to be maximized. In this paper, technical indicators of modern BGP in agriculture are presented and the efficiency of biogas production and utilization is analyzed. The data are based on extensive monitoring of full-scale BGP in Bavaria.

Description of Biogas Plants and Methodology

In this paper, selected data from six BGP commissioned between the years 2002 and 2006 are presented. In all of these plants, RRM / energy crops are digested in mixture with animal manure (*Table 1*).

All six BGP are operated in the mesophilic temperature range. The biogas is utilized in combined-heat-and-power units (CHPU), using reciprocating piston engines. Plants A, D and F have upright vertical digesters as first stage; plants B, C and E feature horizontal cuboid primary digesters. If applicable, the secondary stage is designed as an upright vertical digester. The specific installed electrical capacity of the plants ranges between 0.09 and 0.25 kW per m3 of usable digester volume.

In order to properly evaluate and compare the performance of BGP that differ in size and design, a consistent data model and the definition of appropriate indicators are required [1]. *Table 2* provides an overview of some of the measuring data needed for determining relevant indicator values. Depending on the individual plant, the analysis presented here is based on an observation period of between 215 and 455 days. All the reported indicators were calculated as average values over the whole observation period.

The measured biogas and methane yields were compared to prognoses, based on guideline values according to KTBL ([2]; *Table 3*). The "net utilization ratio biogas" refers to the proportion of the total fuel value of the biogas that is supplied to external users in the form of electrical or thermal energy.

Table 1: Characteristics of the investigated biogas plants

Anlagen ID		**A**	**B**	**C**	**D**	**E**	**F**
Jahr der Inbetriebnahme		2005	2005	2002	2004	2006	2004
Anzahl Prozessstufen		2	2	2	2	1	2
Gesamt-Nutzvolumen*	m^3	3600	2800	3200	3800	2100	2100
Gesamt-Lagervolumen	m^3	1200	2400	4800	1500	3000	2300
Mittlere Prozesstemperatur Fermenter	°C	43	42	41	42	42	43
BHKW Motortyp		G	G	G	ZS	G	ZS
Elektrische Nennleistung	kW	329	347	526	580	526	250
Spez. elektr. Nennleistung	kW•m^{-3}	0,09	0,12	0,16	0,15	0,25	0,12
Thermische Nennleistung	kW	447	432	633	600	567	230

*) Summe der Nutzvolumina aller Prozessstufen (ohne Gärrestlager); ZS: Zündstrahl-Motor; G: Gas-Otto-Motor

Table 2: Description of measuring parameters

Messgröße	Einheit	Messintervall	Messvorrichtung
Masse der Einsatzstoffe	t	Tag	Wägezellen; dynamisches Wägesystem
Volumen der Einsatzstoffe	m^3	Tag	magnetisch-induktiver Durchflussmesser; Pumpenlaufzeit
Trockenrückstand der Einsatzstoffe	%	Monat	Waage, Trockenschrank
Glührückstand der Einsatzstoffe	%	Monat	Waage, Muffelofen
Biogas-Volumenstrom	$m^3 \cdot h^{-1}$	kontinuierlich	strömungsmechanischer Durchflussmesser
Biogastemperatur	°C	kontinuierlich	PT100
Biogasdruck	hPa	kontinuierlich	Druckmessumformer
Biogas-Massestrom	$kg \cdot h^{-1}$	kontinuierlich	thermischer Massestrommesser
Biogas-Methangehalt	Vol.-%	1-2 Stunden	IR-Sensor
Biogas-Kohlendioxidgehalt	Vol.-%	1-2 Stunden	IR-Sensor
Biogas-Sauerstoffgehalt	Vol.-%	1-2 Stunden	elektrochemischer Sensor
Brutto-Strom BHKW	kWh	kontinuierlich	Stromzähler Generatorklemmen
Brutto-Wärme BHKW	kWh	kontinuierlich	Wärmemengenzähler
Strombedarf BGA	kWh	kontinuierlich	Stromzähler Gesamtanlage oder Stromaufnahme Einzelaggregate
Wärmeabsatz	kWh	kontinuierlich	Wärmemengenzähler

Results and Discussion

Maize silage is still the predominant input material for biogas plants in the agricultural sector. This is also true for the six BGP analyzed in this work. Other renewable raw materials are whole grain crop silage, grass silage and bruised grain. For those three plants that treat solid poultry manure, the overall dry matter content in the input mixture is significantly higher than for the other three plants using liquid manure. Those plants feature a reclined primary digester which works more reliably with the relatively dry and heterogeneous poultry manure. Plant E with the highest overall organic loading rate is also the only single-stage plant (*Table 3*).

Apart from Plant A, the measured biogas and methane yields exceed the projected values. However, in the case of plant B (and possibly E) the discrepancy is implausible. This is likely due to an erroneous volumetric flow measurement of biogas and a high variability in the composition of the poultry manure. Overall, in comparison to our measurements, the guideline values for biogas yield appear rather conservative.

If larger amounts of liquid manure are used, the biogas yield remains significantly below 200 Nm^3 per ton of fresh matter. The values of biogas and methane yields with respect to fresh matter for the different plants are quite comparable. However, the measured yields from organic dry matter input appear too high, particularly for plants F and E. For plant E the volumetric biogas flow was likely overestimated, since at the same time, the value of electrical efficiency seems too low. Potential errors from biogas flow measurement may be eliminated by determining the electricity yield with respect to the input of fresh matter (*Table 4*).

In this paper we use the term "electrical efficiency factor" for what corresponds approximately to electrical efficiency. However, it is impracticable to measure electrical efficiency according to the respective DIN specifications over such long periods. As mentioned above, the rather low values of the electrical efficiency factor suggest overestimation of the biogas flow rate. Regarding the electrical utilization ratio, all six BGP reach satisfying to excellent values between 90 and over 95 %. This is a good basis for the profitable operation of a biogas plant (*Table 4*).

Regarding the share of parasitic electricity demand, the largest difference is found between plant E with 5.4 % and plant A with 9.1 %. Plant E features only one process stage while in the case of plant A, the six propeller mixers installed at the four tanks exhibit a relatively high electricity demand.

If electrical utilization ratio is plotted over specific installed electrical capacity, it is possible to draw some conclusions with respect to the stability and possible limitations of the anaerobic digestion process. *Figure 1* shows data from the monitoring of 25 BGP including the six plants discussed in this paper. In the diagram, two lines were plotted that may be termed "efficiency border" (horizontal) and "capacity border" (vertical). The "efficiency border" crosses the ordinate at a value of 86 % utilization ratio, corresponding to approximately 7,500 full load hours per year. In fact, given a difficult business environment, the utilization ratio should reach a value of at least 90 %. The "capacity border" crosses the abscissa at a value of 0.25 $kW \cdot m^{-3}$. On the basis of our data from 25 BGP, this value is the current benchmark for the specific installed electrical capacity of biogas plants treating RRM and animal manure. Plants in the bottom left section of the diagram are likely to have a problem with a limitation of the anaerobic digestion process or other deficiencies ("deficiency sector"). Plants to the right of the

Table 3: Characteristic values of biogas production

Anlagen ID		A	B	C	D	E	F
Auswertungszeitraum	d	215	385	455	365	378	406
Einsatzstoffe (Massenanteile)		R-Gülle (30 %) MS (42 %) GS (16 %) GPS (10 %) sonstige (2 %)	H-Mist (16 %) MS (49 %) Wasser (35 %)	H-Mist (20 %) MS (55 %) GPS (11 %) Schrot (13 %) sonstige (1 %)	R-Gülle/ S-Gülle (47 %) MS (44 %) GS (1 %) GPS (3 %) Schrot (4 %)	P-Mist (5 %) MS (83%) GPS (6 %) LKS (3 %) Schrot (2 %)	R-Gülle (26 %) MS (64%) GS (1 %) GPS (9 %)
Gesamtmasse der Einsatzstoffe (ohne Wasser)	t	6.403	6.614	12.444	17.937	10.238	6.141
Durchschnittlicher TS-Gehalt der Einsatzstoffe	%	21	40	41	19	31	21
Ges.Raumbelast.	$kg\ oTS \cdot (m^3 \cdot d)^{-1}$	2,1	2,4	3,0	2,7	4,0	1,6
Projektion Biogasertrag*	Nm^3	908.706	1.218.910	2.144.376	2.297.018	2.036.885	902.401
Gemessener Biogasertrag	Nm^3	865.933	1.751.726	2.446.904	2.457.369	2.416.193	964.163
Abweichung	%	-4,7	43,7	14,1	7,0	18,6	6,8
Projektion Methanertrag*	Nm^3	478.054	631.132	1.122.005	1.204.906	1.060.644	470.671
Gemessener Methanertrag	Nm^3	454.500	915.909	1.226.226	1.253.796	1.249.049	521.999
Abweichung	%	-4,9	45,1	9,3	4,1	17,8	10,9
Biogasausbeute	$Nm^3 \cdot t^{-1}$	135	265	197	137	236	157
	$Nl \cdot kg\ oTS^{-1}$	624	664	464	716	780	753
Methanausbeute	$Nm^3 \cdot t^{-1}$	71	138	99	69,9	122	85
	$Nl \cdot kg\ oTS^{-1}$	328	347	232	366	405	408
Methanproduktivität	$Nm^3 \cdot (m^3 \cdot d)^{-1}$	0,70	0,85	0,69	0,90	1,57	0,60
Stromausbeute	$kWh \cdot t^{-1}$	448	443	339	280	441	317

*) basierend auf Richtwerten gemäß [2]; R-Gülle: Rindergülle; S-Gülle: Schweinegülle; H-Mist: Hähnchenmist; P-Mist: Putenmist; MS: Maissilage; LKS: Lieschkolbensilage; GS: Grassilage; GPS: Getreide-Ganzpflanzensilage

"capacity border" and below the "efficiency border" are under-dimensioned with respect to the current state of the technology ("development sector"). The top right section of the diagram represents the "innovation sector". According to this simple categorization scheme, all six plants discussed in this paper are within the "efficiency sector".

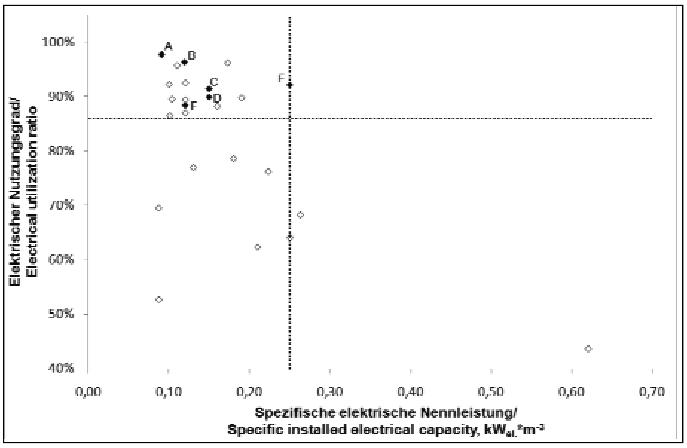
Data about the utilization of the off-heat at the BGP are incomplete, since it was not possible to install heat meters in all cases (*Table 4*). However, external heat use was measured for all plants so that external heat utilization could be calculated. In those cases where the average thermal energy output was not available, it was estimated from the nominal output and the electrical utilization ratio of the engine. The ratio of external heat utilization showed a wide range of 0 to 46 % with respect to the available off-heat. For the 25 BGP that had been monitored, the parasitic heat demand reached a maximum of 30 % and was clearly below 25 % in most cases. This means that on biogas plants a considerable potential of thermal energy is currently wasted. The monitoring indicated that over the whole year, a high ratio of heat utilization can only be achieved with a combination of community heating and drying of agricultural goods. So far, the off-heat from biogas plants is very seldom used to supply process heat to small and medium-sized businesses although this would be an option that is more or less independent of season.

The positive result of high electrical utilization ratios is overshadowed once the net utilization ratio of the biogas fuel value is examined (*Table 4*). Here, only two out of six plants reach a value of more than 50 %. Naturally, in the BGP without any external heat use, two thirds of the biogas energy is wasted. The energy balance becomes worse if the energy input for producing the RRM is also considered.

Conclusions and Outlook

In this paper, results from a comprehensive monitoring program at agricultural BGP were presented. Data on methane yield, utilization ratio of the combined-heat-and-power unit and the net utilization ratio of the biogas fuel value were discussed. In most cases, the values of biogas and methane yields that were measured at the BGP exceeded the respective guideline values. However, besides the weighing of the input materials the measurement of biogas volume is considered the most frequent source of systematic error during the monitoring of BGP in practice.

Fig. 1: Specific rated electrical capacity and electrical utilization ratio of 25 agricultural biogas plants in Bavaria



All of the plants presented in this paper exhibited a satisfactory to excellent electrical utilization ratio. This indicates a stable anaerobic digestion process and a sound operational management. Up to a level of approximately 0.25 kW•m^{-3} the electrical utilization ratio was independent of overall reactor volume but somehow dependent on reactor design. The combination of utilization ratio and specific installed electrical capacity can therefore be used as a first indicator of process stability and functionality of a biogas plant. Currently, BGP with a significantly smaller specific reactor volume are not state-of-the-art for the anaerobic treatment of agricultural raw materials and residues. More technical development is needed to improve the specific power output of agricultural BGP. At the same time, there is still a high demand for improving the process stability in BGP with conventional dimensioning.

The results for the net utilization ratio of biogas fuel value indicate a considerable potential for improvement. Achieving a net utilization of more than 50 % the whole year round requires a well thought-out concept for the utilization of the off-heat.

Finally, the methods of evaluating the performance of biogas plants that were presented here do not cover all relevant aspects. There are other technical as well as economical and ecological criteria that have to be taken into consideration.

Literature

Books are marked by •

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[2] • KTBL : Gasausbeuten in landwirtschaftlichen Biogasanlagen. KTBL , Darmstadt, 2005

Table 4: Characteristic values of biogas utilization

Anlagen ID		**A**	**B**	**C**	**D**	**E**	**F**
Auswertungszeitraum	d	215	385	455	365	378	0
Elektrischer Nutzungsgrad	%	37,3	33,8	43,7	37,5	35,2	39,2
Mittl. elektr. Leistungsabgabe	kW	327	335	481	573	515	222
Spez. elektr. Leistungsabgabe	kW•m^3	0,09	0,12	0,15	0,13	0,23	0,11
Elektrischer Ausnutzungsgrad	%	97,7	96,4	91,5	89,9	92,2	88,4
Anteil Stromeigenverbrauch	%	9,1	7,0	7,2	7,5	5,4	6,7
Mittl. therm. Leistungsabgabe	kW	415	416	518	n.v.	n.v.	n.v.
Externe verwertete therm. Leistung	kW	0	143	222	285	186	47
Wärmeeigenbedarf Fermenterheizung	%	12,3	n.v.	10,7	n.v.	n.v.	n.v.
Anteil externer Wärmenutzung	%	0	34,4	42,9	45,6	32,8	20,2
Abwärmeanteil	%	87,7	n.v.	41,2	n.v.	n.v.	n.v.
Netto-Nutzungsgrad Biogasenergie	%	33,9	46,0	60,8	57,6	48,8	49,8

n.v.: nicht verfügbar