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Comparison of process efficiency of biogas plants: Application of Data Envelopment Analysis (DEA)

In view of the large and continuously increasing number of biogas plants in Germany, procedures for evaluating the efficiency of these plants are needed. The operation of a biogas plant is complex and influenced by many parameters. Therefore, it is quite demanding to evaluate biogas plant performance and rank different plants with respect to process efficiency. In this study, it was tried to accomplish this by applying Data Envelopment Analysis (DEA). By means of this method, ten agricultural biogas plants in Bavaria were ranked in terms of their efficiency of converting input materials into electricity and heat.

Keywords
Biogas plant, DEA, electrical energy, process efficiency, heat utilization

Abstract
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The electrical capacity of biogas plants in Germany has quadrupled since 2001, when guaranteed feed-in tariffs for electricity produced from renewable resources were defined in the Renewable Energy Act - EEG. Two amendments of this act in 2004 and 2009 stimulated further rapid growth of biogas technology in Germany. Since biogas production has become an important branch of agriculture, it becomes more and more important to evaluate and compare the efficiency of individual biogas operations.

The complex process chain of biogas production and utilization is defined by manifold parameters. Therefore, in order to compare process efficiency of different biogas plants and to rank these plants, a single measure of process efficiency should be derived.

Material and method

For this study, comprehensive data on process efficiency of ten agricultural biogas plants over a period of one year were used. The ten plants represent some of the diversity of technical concepts and site conditions of biogas installations across Bavaria. The data were derived from automatic data loggers, operators' manual records and chemical analyses of samples of the input materials, digester contents and the digested residues. Some basic technical characteristics of the plants are given in **table 1**.

Data Envelopment Analysis (DEA) was used to compare process efficiency of the ten aforementioned agricultural biogas plants. DEA is a method commonly used to evaluate the relative efficiency of a comparable and homogeneous set of "units" (i.e. biogas plants in this case). It is supposed that these units perform the same function by transforming multiple inputs into multiple outputs. In terms of DEA, inputs (Is) should be decreased and outputs (Os) should be increased to improve the efficiency of the evaluated unit.

Table 1

Technical characteristics of the ten biogas plants assessed in this study

Anlagen-ID ***Plant ID***	**Einheit** ***Unit***	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Jahr der Inbetriebnahme *Year of start-up*	–	2005	2005	2004	2004	2005	2002	2005	2004	2005	2001
Gesamt-Gärraum[1)] *Total digester volume[1)]*	m^3	3,015	2,605	3,676	2,290	2,487	3,740	1,540	1,778	1,095	3,413
BHWK-Motortyp *CHPU engine type*	–	G	G	G	G	G	G	ZS/*PI*	ZS/*PI*	G	G
Installierte elektrische Leistung *Rated electrical capacity*	kW	329	333	630	420	347	526	280	250	324	380
Installierte thermische Leistung *Rated thermal capacity*	kW	447	232	757	472	432	566	300	262	250	486

BHKW = Blockheizkraftwerk/*CHPU = Combined heat-and-power unit;* G = Gas-Otto-Motor/*Gas engine;* ZS = Zündstrahlmotor/*PI = Pilot injection engine*
[1)] Summe der Nutzvolumina aller Gärbehälter der Biogasanlage ohne Gärrestlager.
[1)] Sum of usable volume of digesters not including storage tank.

The measure of efficiency obtained from DEA has the meaning of how efficient an evaluated unit is in transforming inputs into outputs. It takes a value between 0 and 1. The "best" (most efficient) units reach a value of 1 while the "worst" (least efficient) units reach the lowest value which is always larger than zero.

In this study, two DEA models were used: the CCR model (according to Charnes, Cooper, Rodes) and the BCC model (according to Banker, Charnes and Cooper) [1]. Output orientation was chosen which means that in order to improve its own efficiency, an inefficient unit should increase its outputs while keeping the inputs constant. In addition, two variants of these models were used, i.e. super efficiency models which are able to distinguish between efficient units by allowing the measure of relative efficiency to take a value greater than 1. A comprehensive description of DEA methodology and models used in this study is given in [2].

The set of 10 biogas plants evaluated in this study was assumed to form a homogeneous group, since all units represent agricultural biogas plants with the same goal of producing electricity and heat from anaerobic digestion of agricultural residues and raw materials within a limited capacity range. The parameters used for the assessment are described in **table 2**.

Table 2

Parameters used for evaluation of biogas plants with DEA

Parameter ***Parameter***	**Einheit** ***Unit***	**DEA-Kriterium** ***DEA-criterion***
Masse an oTS *Amount of oDM*	kg	I_1
Strombedarf der Biogasanlage *Electricity for own demand*	kWh	I_2
Brutto-Stromproduktion *Electricity production*	kWh	O_1
Externe Wärmeverwertung *External heat use*	kWh	O_2

oTS = organische Trockensubstanz/*oDM = organic dry matter*; I = Input (Eingangsgröße); O = Output (Ausgangsgröße)

The biogas plants were described as systems for energy conversion. By anaerobic digestion of the organic dry matter that is contained in the input materials (I_1), biogas is produced and subsequently converted into electricity (O_1) and heat (O_2). A certain amount of electricity (I_2) is consumed to run the biogas plant with its various devices. The matrix with normalized criteria values for the ten biogas plants is presented in **table 3**.

Table 3

Standardized criteria values for the ten biogas plants

Anlagen-ID ***Plant ID***	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
I_1	0.3004	0.2744	0.3858	0.2839	0.3294	0.5300	0.2187	0.1785	0.1678	0.3278
I_2	0.2541	0.5247	0.3390	0.2358	0.3059	0.4242	0.1784	0.2805	0.2252	0.2338
O_1	0.3061	0.2515	0.4512	0.3034	0.3183	0.4699	0.2357	0.1986	0.1788	0.3132
O_2	0.0000	0.0000	0.7090	0.1714	0.3492	0.5377	0.0744	0.1456	0.1214	0.1230

Results and discussion

The results from CCR and BCC models for the relative efficiencies and ranking of the biogas plants are presented in **figure 1**. In both models, plants C and J were rated most efficient. The reasons for this are a relatively low own electricity demand, large electricity production and high external heat use (C). In the BCC model, another 4 biogas plants (G, F, I and H) were recognized as efficient. This is due to the flexible shape of the efficiency frontier in the BCC model [1].

Plants G and H were given lower ranks in the CCR model, because of lower external heat utilization (around 16 % share of available heat) and higher own electricity demand. Plant G consumed only about 6 % of its total electricity output and therefore was ranked before H.

The ranking of plants A and B was strongly influenced by the lack of external heat use at these plants. Plants E and F showed a low amount of produced electricity compared to the amount of ODM input, due to considerable shares of relatively dry solid chicken manure with limited digestibility. DEA "recognized" these shortcomings resulting in lower ranks for these plants.

The results from CCR and BCC super-efficiency models are presented in **figure 2**. Using these models, it was possible to differentiate efficient biogas plants. The extremely high relative efficiency of plant C was mainly due to the excellent external heat use.

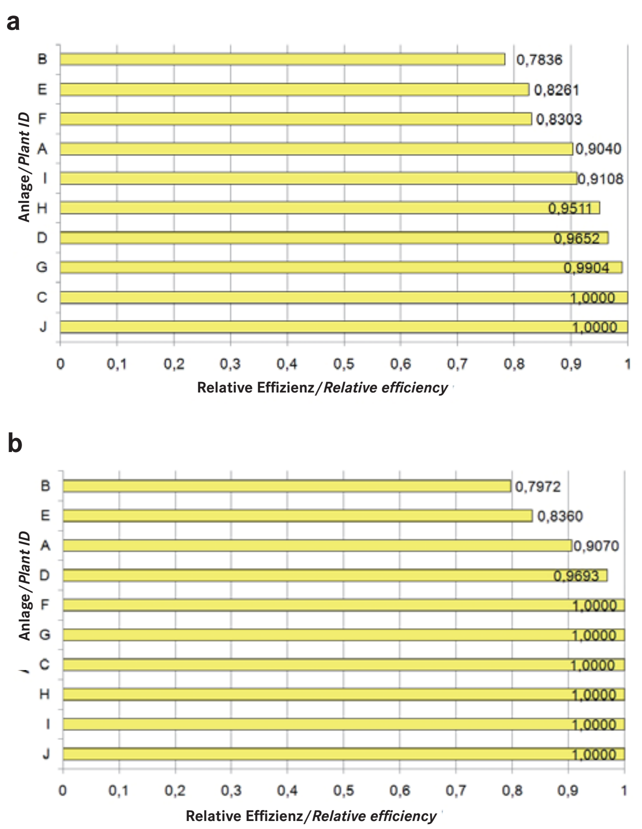
Relative efficiency values from DEA are not on a cardinal scale. For example, an efficiency value in the super-efficiency CCR model of 1.7633 for plant C, compared to a value of 1.0000 for plant J does not mean that plant C is approximately 1.8 times more efficient than plant J.

Conclusions

In this analysis, biogas plants were described as systems for energy conversion using absolute values of two inputs (ODM and electricity) and two outputs (electricity and heat). The method of DEA was suitable to rank biogas plants based on a single measure of relative efficiency. The achieved efficiency values were not directly comparable, but the ranking of the plants could be verified by expert knowledge.

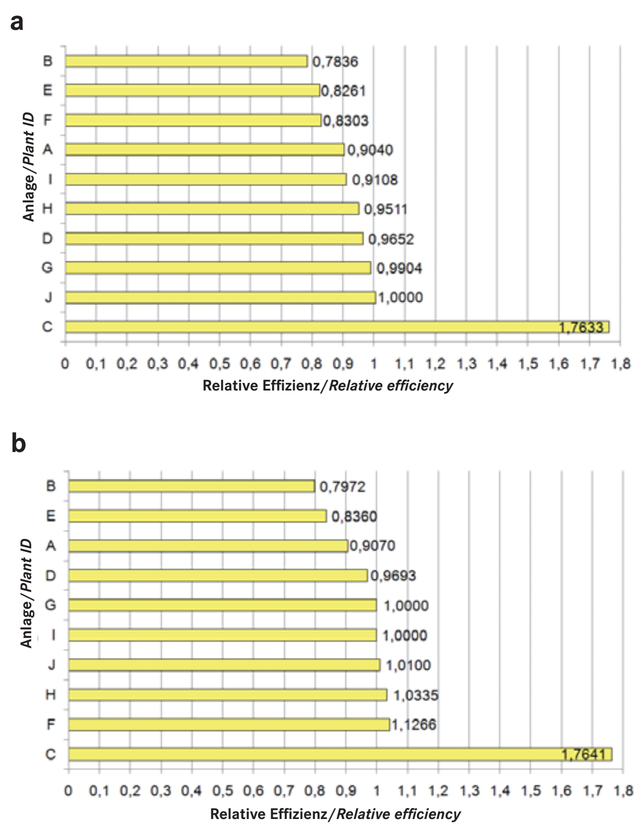
In terms of the DEA method, the number of parameters used in this study is insufficient in order to fully describe the process efficiency of biogas production and utilization. Additionally, if biogas plants differ fundamentally, i. e. they do not form a homogeneous group, it is more appropriate to use specific characteristic figures for evaluation. Further research is needed to apply such specific figures in DEA or other suitable methods.

Fig. 1



Relative efficiency of biogas plants from two DEA models: (a) CCR and (b) BCC

Fig. 2



Relative efficiency of biogas plants from two DEA models: (a) Super-efficiency CCR and (b) Super-efficiency BCC

Literature
Books are signed with ●

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