TECHNOLOGICAL EVALUATION OF AN AGRICULTURAL BIOGAS CHP PLANT AS WELL AS DEFINITION OF GUIDING VALUES FOR THE IMPROVED DESIGN AND OPERATION

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ABSTRACT: This work, which was funded by "Zukunftsfonds des Landes Steiermark" and "Landesenergieverein Steiermark", focuses on the optimisation of biogas plants and the improved understanding of biogas production processes based on the detailed monitoring and evaluation of a modern biogas plant. Important parameters for the improved operation of biogas plants were measured and characteristic values defined. The project included a one-year monitoring phase for the acquisition and evaluation of relevant operational data and two detailed test runs, which served to examine the substrate streams, the biogas produced, the digestate and the emissions of the gas engine. Moreover, mass and energy balances were performed for the whole plant and for selected components such as the digesters and the gas engine. The paper presented gives a comprehensive survey of the measurements and analyses performed, the methods applied as well as the results of the analyses of the substrates used, the digestate, the biogas, the emissions of the gas engine as well as the condensate and the desulphurisation air. It concludes with a technological evaluation of the plant examined and a summary of relevant guiding values for the improved design and operation of agricultural biogas plants.
Keywords: anaerobic digestion, biogas, methane

1 INTRODUCTION AND OBJECTIVES

In spite of the large number of biogas plants in operation in Europe, focusing on Austria as well as Germany, a comprehensive technological evaluation of agricultural biogas plants was not available so far. However, for an optimised production and an efficient utilisation of biogas as well as for the correct design of biogas CHP plants the understanding of the basic process units is of great relevance. For the understanding of the different effects of single parameters, which are important for the operation of a biogas CHP plant, detailed mass and energy balances are required.

Therefore this work, which was funded by "Zukunftsfonds des Landes Steiermark" and the Styrian Energy Agency, focuses on the optimisation of biogas plants and the improved understanding of biogas production processes based on the detailed monitoring and evaluation of a modern agricultural biogas plant, using a gas engine for the production of heat and power. The biogas CHP plant investigated is representative for a typical modern Austrian agricultural plant (nominal electric output: 500 kW). Important parameters for the improved operation of biogas plants were measured and characteristic values defined. The project included a one-year monitoring phase for the acquisition and monthly evaluation of relevant operation data and two detailed test runs, which served to measure and analyse the substrate streams, the biogas produced, the digestate and the emissions of the gas engine. These data formed the basis for the evaluation of the plant operation, the gas quality and relevant influencing parameters as well as the gas cleaning technology required for specific biogas applications. Moreover, detailed mass and energy balances were performed for the whole plant and for selected components such as the digesters and the gas engine. In a further step characteristic values and benchmarks describing the efficiency of the plant were developed for the improved design and operation of agricultural biogas plants.

2 DEFINITIONS

2.1 Acronyms, abbreviations, symbols and units

a .... ash content
C .... carbon
Ca.................... calcium
Cd .... cadmium
CH_4 .... methane
Cl .... chlorine
CO_2 .... carbon dioxide
Cr .... chrome
Cu .... copper
d .... dry
d.b. .... dry basis
DS .... dry substance
GCV .... gross calorific value [MJ/kg (d.b.)]
H .... hydrogen
H_2O .... water
H_2S................. hydrogen sulphide
HCl .... hydrochloric acid
Hg .... mercury
K .... potassium
Mg................... magnesium
Mo................... molybdenum
N .... nitrogen
Na .... sodium
NCV .... net calorific value [MJ/kg (w.b.)]
NH_3 .... ammonia
Ni .... nickel
NMHC .... non methane hydro carbons
NO_x .... nitrogen oxides
oDS .... organic dry substance
O_2 .... oxygen
P .... phosphor
Pb .... lead
S .... sulphur
Si .... silicon
SO_x.................. sulphur oxides

STDEV........... standard deviation
TOC................ total organic carbon
vol% .... volume percent
w..................... wet
w.b.................. wet basis
WS.................. wet substance
wt% .... weight percent
Zn .... zinc

3 METHODOLOGY

3.1 Description of the biogas CHP plant investigated

For the evaluation and the test runs a typical modern agricultural biogas CHP plant representative for Austria with a nominal electric output of 500 kW (scheme see Figure 1) was selected. The biogas plant consists of a storage (fodder silo) where the solid substrate (maize silage) and a pit were the pig manure can be stored. The solid substrates are mixed and fed into the digester every 2 hours by a screw conveyor, the pig manure is pumped into the digester using the central pumping station, which is also needed to carry the digestate to the filling station. In the digesters the fermentation takes place and the substrates are converted into biogas and digestate. The digestate is stored in a tank from were it is distributed to the farmers. The digestate contains considerable amounts of nutrients and can be used as a fertiliser on agricultural fields which favours a sustainable closed cycle economy within the course of biogas production. The biogas stored in the gas holder is dried and pre-heated (if necessary) after desulphurisation (air injection in the gas holder) before it can be used in the gas engine to produce heat and power.

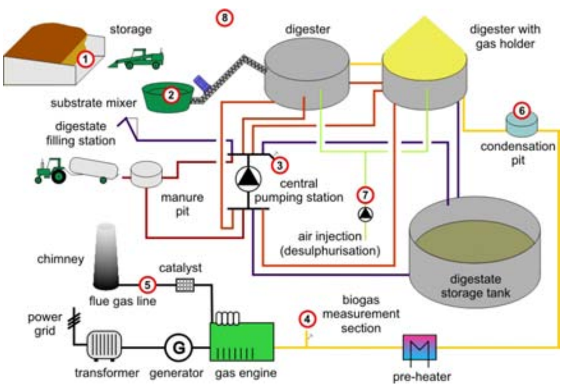

Figure 1: Scheme of the agricultural biogas CHP plant investigated
Explanations: measurement and sampling points marked with numbers (1-8)

Number 1 to 8 in Figure 1 mark the measurement and sampling points used during the test runs. The sampling of the input materials (maize silage and pig manure) and of the digestate for subsequent analyses was performed at sampling point 1, 2 and 3.

The random samples from the storage (1) were taken such that the top layer of the silage was removed to get representative samples. The samples from the mixer were taken directly after the mixing phase. To achieve representative samples of the pig manure and the digestate the samples were taken from the manure flow while the pump was in operation

The biogas measurements concerning CH_4, CO_2, H_2S, NH_3, H_2O and O_2 as well as trace components like CO, siloxanes, Hg and HCl took place at measurement point 4. At measurement point 5 the flue gas downstream the gas engine was analysed concerning its contents of CO, CO_2, TOC, HCl, H_2O, O_2, NO_x, SO_x and Hg. The amounts of condensate from the gas cooling (the condensate was collected and measured in the condensation pit) and the air injected into the digesters for the desulphurisation of the biogas (by reading the meter) were investigated at measurement point 6 and 7. The ambient temperature was measured nearby the biogas plant (measurement point 8).

As mentioned before within the two test runs analyses of the substrates (maize silage, pig manure) and the digestate concerning C, H, N, S, Cl, Na, Mg, Si, P, K, Ca, Cr, Ni, Cu, Zn, Mo, Cd, Pb, dry substance and ash content as well as calorific value and pH value were performed. Based on the results of these analyses and the biogas and flue gas streams measured, total as well as elemental mass and energy balances were performed. The following flows were taken into consideration for these investigations:

- substrate streams
- biogas produced
- digestate
- emissions of the gas engine
- desulphurisation air
- condensate from gas cooling

4 RESULTS

The results of the analyses of the substrates and the digestate as well as the measurements of the biogas and the flue gas are shown in Table I to Table III.

Table I: Chemical composition of the substrates and the digestate
Explanations: MS…maize silage, PM…pig manure, DG…digestate, STDEV…standard deviation

explanation		MS	STDEV	PM	STDEV	DG	STDEV
No. of samples		10		10		8	
GCV	[MJ/kg d.b.]	18.04	0.21	16.34	0.23	15.91	1.58
C	[wt% d.b.]	45.45	0.84	33.71	2.68	35.34	5.20
H	[wt% d.b.]	6.28	0.11	4.47	0.32	4.53	0.48
N	[wt% d.b.]	1.13	0.11	11.16	3.66	5.35	1.39
O	[wt% d.b.]	42.37	0.81	16.86	2.82	24.36	2.69
a	[wt% d.b.]	4.76	1.45	33.80	2.40	30.38	6.62
oDS	[wt% d.b.]	95.24	1.45	66.20	2.40	69.62	6.62
DS	[wt% w.b.]	32.07	2.00	2.11	0.53	4.66	0.97
S	[mg/kg d.b.]	917	183	7,604	2,535	6,224	950
Cl	[mg/kg d.b.]	1,789	563	22,163	2,026	14,990	1,288
P	[mg/kg d.b.]	2,209	437	24,939	3,216	17,384	648
K	[mg/kg d.b.]	9,171	2,640	72,660	18,106	55,065	3,356

The results in Table I present the low contribution concerning gas yield of the pig manure used due to the low organic dry substance content. On the other hand the pig manure is very important concerning the nutrients it contains, which are needed for the growth of the bacteria and therefore an essential contribution to a stable process (e.g. C/N ratio).

The fermented digestate contains a high amount of nutrients which are easily available for plants after fermentation and low trajectory application, thus reducing the amounts of artificial fertiliser required and practically closing the nutrient cycle. The remaining dry substance is not readily accessible to bacteria and therefore will not decompose without further treatment.

Table II: Chemical composition of the biogas
Explanations: MV…mean value of two test runs, STDEV…standard deviation

component	unit	MV	STDEV
NCV	[MJ/Nm³]	17.52	0.25
CH_4	[vol%$_w$]	49.24	0.65
CO_2	[vol%$_w$]	47.04	0.62
O_2	[vol%$_w$]	0.04	0.06
N_2	[vol%$_w$]	1.44	0.02
H_2O	[vol%$_w$]	2.18	0.20
CO	[vppm$_w$]	383.67	17.57
NH_3	[vppm$_w$]	63.50	30.24
H_2S	[vppm$_w$]	167.84	15.32
HCl	[mg/Nm^3_d]	1.69	0.65
T	[°C]	31.49	1.05

Table III: Chemical composition of the flue gas of the gas engine
Explanations: *) limiting value given for NMHC, results for the first of two test runs

component	unit	average	STDEV	limit
N_2	vol%$_w$	68.82		-
CO_2	vol%$_w$	11.71	0.10	-
H_2O	vol%$_w$	13.54		-
O_2	vol%$_w$	5.88	0.04	-
CO	mg/Nm³$_d$ (5% O_2)	533.20	5.85	650
NO_x	mg/Nm³$_d$ (5% O_2)	518.09	25.22	400
C_xH_y	mg/Nm³$_d$ (5% O_2)	257.08	1.52	150 *)
HCl	mg/Nm³$_d$ (5% O_2)	1.81	0.97	
SO_x	mg/Nm³$_d$ (5% O_2)	39.94	6.48	
Hg	mg/Nm³$_d$ (5% O_2)	-	-	

In Table II the chemical composition of the biogas is presented. In the determined agricultural biogas plants comparatively low methane contents can be achieved with the substrates used. For higher methane contents other substrates with higher methane yields like corn-cob-mix have to be used. The low O_2 and H_2S contents indicate a well working, well adjusted desulphuration by air injection. The amount of NH_3 is very low, typical values for agricultural biogas plants are below 1,000 vppm. For CO and HCl no literature data are available. The Hg content in the biogas as well as in the flue gas was under the detection limit.

For the most important emissions in the flue gas of the gas engine (CO, NO_x and TOC) the limits are given by the guideline for stationary engines from the Austrian Federal Ministry of Economics and Labour. As shown in Table III the emissions of CO were below the limiting value throughout the test run. The NO_x emissions, which were exceeding the limiting value during the test run, could be reduced after adjusting the compression of the turbo charger. After the adjustment of the air ratio NO_x emissions below the limiting value could be achieved. Table III also shows the limit for NMHC. Due to the measurement of the TOC content, which includes the measurement of methane from leakage and incomplete combustion, it is not possible to compare the achieved data with the given limiting value. Anyway, within the second test run even the TOC content was below the limiting value. As a conclusion and recommendation of these results the necessity of a detailed maintenance for the reduction of emissions and a regular operation of the gas engine can be mentioned.

The measured amounts of condensate reached 1 to 3 l/hour, depending on the ambient temperature which influences the temperature of the biogas in the gas holder. If this water is not separated it could cause corrosion and malfunctions of the gas engine. Following, a reduction of the moisture content in the biogas is of relevance.

Available optimisation potential is given by the adjustment of the substrate mixture (increase of the methane content) and the utilisation of agricultural residues instead of energy crops (multi-stage utilisation).

Figure 2 und 3 show the results of the detailed mass and energy balances calculated for the overall plant, based on the data gained from the first test run and the long term monitoring. Under consideration of the dry substance content of the substrate mixture (17 wt% w.b.) and the digestate (5 wt% w.b.), Figure 2 illustrates the huge amounts of water, necessary for the fermentation process. The energy balance in Figure 3 shows the good conversion rate of the substrates used. Over 80% of the input material (based on the content of organic dry substance) is converted to biogas (methane content ~49 vol%$_w$). This clearly indicates that the fermentation process conditions are set up well and the process is stable.

The energy balance shows the good electric annual utilisation rate (annual useful electric energy produced divided by the annual fuel energy input based on the net calorific value) of ~29% and it also identifies the insufficient utilisation of the excess heat as the main weak point of the plant investigated.

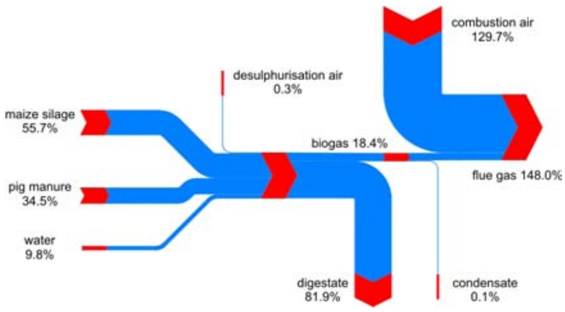

Figure 2: Overall mass balance of the investigated biogas CHP plant
Explanations: all data are related to the input mass flow rate (maize silage, pig manure and water =100% w.b.)

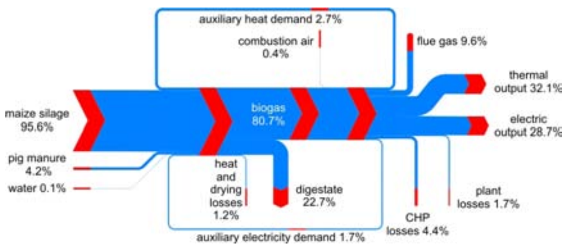

Figure 3: Overall energy balance of the investigated biogas CHP plant
Explanations: all data are related to the net calorific value and the enthalpy of the input streams (maize silage, pig manure and water) at 0°C and 1013 mbar; plant losses include friction losses of the agitators, conveyors, fans and measuring and control devices

Table IV: Important characteristic values and benchmarks derived for the evaluation of agricultural biogas plants
Explanations: measured values include all data from the plant investigated, benchmarks show the values that should be achieved

description	unit	measured value	benchmark	comment
dry substance content (input)	wt% w.b.	19.25		related to the DS content, should be below 12% (in the digester)
organic dry substance content (oDS)	wt% d.b.	94.76	>90	only the oDS is degradable, the higher the oDS content the more substance is available for bacteria, upper limit depending on ash content
digester temperature (first / second digester)	°C	38 / 35	38-40 / 38-40	38-40°C for mesophile operation, 55-60°C for thermophile operation
pH-value first / second digester	-	7.6 / 7.8	6 – 8 / 6 - 8	depending on the type of digestion, single-level: (6-8), multi-level: (5.2-6.3 hydrolysis , 6.7-7.5 methanogenesis)
gas yield	$Nm^3{}_d$/kg oDS	0.73	0.5 – 0.8	depending on the substrates 0.30-0.46 for pig manure 0.60-0.80 for maize silage
CH_4 content of biogas (before gas engine)	$vol\%_w$	50	> 50	depending on the substrates and the digester volume load
H_2S content of biogas (before gas engine)	$vol\%_w$	0.02	as small as possible < 0.03	depending on the substrates and the desulphurisation as well as on the further biogas utilisation
H_2O content of biogas (before gas engine)	$vol\%_w$	2.18	as small as possible < 6%	a low water content provides a stable operation of the gas engine
carbon conversion rate	%	83.29	> 80	depending on the substrates and their pre-treatment as well as on the type of fermentation
organic dry substance conversion rate	%	81.86	> 70	depending on the substrates and its pre-treatment and plant design
C/N-ratio input	kmol/kmol	36.50	10-40	depending on the type of digestion, single-level: (10-30), multi-level: (10-45 hydrolysis, 20-30 methanogenesis)
digester volume load (total)	(kg oDS/d)/m³	2.29	2-3	the lower the load the more stable the microbiological conversion process
digester volume load (first digester)	(kg oDS/d)/m³	4.58	3-8	the lower the load the more stable the microbiological conversion process
hydraulic retention time (total)	d	81.69	50-90	depending on the plant technology and the substrates
auxiliary electricity demand	%	5.6	3-9	primarily depending on the number of agitators and their operation time
auxiliary heat demand	%	8.7	2-40	depending on the plant design
full load operating hours	h/a	8,380	7,900	important benchmark for the economic performance of a biogas plant
thermal annual utilisation rate	%	3.9	> 35	the utilisation of the excess heat is strongly recommended
electric annual utilisation rate	%	28.7	> 25	depending on the size of the gas engine
overall annual utilisation rate	%	32.6	> 60	important benchmark for the economic performance of a biogas plant
plant availability (related to 8,760 hours per year)	%	96.96	> 90	important benchmark for the economic performance of a biogas plant

The thermal output of the gas engine corresponds to 568 kW from which 43 kW are used for own demand. Only 66 kW of the remaining 525 kW available are used for district heating at present. The rest of the available heat has to be cooled and thus released to the environment. The poor utilisation of the useful heat available results in a low overall efficiency of about 33%. If the total heat available could be used, an overall annual utilisation rate between 65 und 70% could be achieved. Following, new biogas CHP plants should be located at sites where an efficient heat utilisation is also possible. This recommendation is of importance from an efficiency as well as economic and ecological point of view.

Furthermore, the results of the long term monitoring show a low auxiliary electric energy demand of ~5.6 % (of the nominal electric capacity of the gas engine), over 8,300 full load operating hours and a plant availability higher than 96% as well as a good performance of the biological desulphurisation and the gas drying.

Based on the results achieved important characteristic values and benchmarks for the evaluation of biogas CHP plants were developed (see Table IV).

These data can be divided into parameters relevant for the design of biogas plants, parameters needed for the control of a biogas plant as well as important parameters for the operation of a biogas plant. The category dealing with the design of plants considers the evaluation of the dry substance and the organic dry substance content, the digester temperatures, the pH-value, the gas yield, the volume load and the retention time. Each of these parameters should be discussed during the concept phase to prevent mistakes concerning plant design. The operational parameters include the composition of the biogas concerning (at least) CH_4, H_2S, and H_2O, the carbon conversion rate, the organic dry substance conversion rate and the C/N-ratio. Beside the concentration of the different volatile fatty acids and the pH-value of the digester these data are indicators for a stable fermentation process which should be evaluated for the control of the plant. From the economic point of view the auxiliary electricity and heat demand, the full load operating hours, the thermal, electric and overall annual utilisation rate and the plant availability are important parameters. These data provide an overview of the plants performance (annual utilisation rates) and are indicators for the operation of a biogas plant (plant availability).

As an objective for future plants further guiding values are mentioned, to ensure a high efficiency, a stable fermentation process and a meaningful decision concerning plant location, plant type and plant size.

5 CONCLUSIONS AND RECOMMENDATIONS

The results and conclusions achieved in this project form a relevant and valuable basis for the improved design and the optimised operation of biogas CHP plants. Within the technological evaluation the following major conclusions and recommendations could be found:

It is shown that agricultural biogas plants can achieve high conversion rates of the organic dry substance (> 80%), even with high amounts of water needed for the fermentation, if the substrate mix and the fermentation conditions are carefully monitored. The production of biogas and its utilisation in a gas engine is state-of-the-art.

The utilisation of the digestate on agricultural fields can substitute fertilisers and almost closes the nutrient cycle. Also from an economic point of view a meaningful digestate utilisation is of great importance.

For agricultural biogas plants a biological desulphurisation followed by a drying step is sufficient for the utilisation of the biogas in a gas engine.

A comprehensive maintenance of the gas engine and the whole biogas plant is recommended to achieve high full load operating hours (> 8,000 h/a), a high availability of the plant (> 95%) and a regular operation of the gas engine (keeping the emission limits given).

As the main outcome of the technological evaluation the meaningful selection of a suitable location for biogas plants with heat consumers available was found. Only with the utilisation of the heat produced high overall annual utilisation rates (> 60%, related to NCV substrates) can be achieved.

Beside the performance of a multi-stage utilisation of substrates by using residues instead of energy crops and an optimised mixture of substrates for high methane contents, the increase of the electric efficiency of the gas engine is mentioned as a possible improvement for future agricultural biogas plants. Further a periodically monitoring of the most relevant parameters for a stable fermentation process and a steady operation of the plant should be performed.