Energy and Life Cycle Analysis of Co-generation of Biogas from Cattle Manure

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ABSTRACT

This paper presents the results of evaluation of biogas generation from cattle manure, under German conditions, and conversion of biogas to electricity using energetic and life cycle analysis. A range of capacities from about 70 to 250 kW for digester and co-generation set are considered including benefits for heat utilization. It is found that the energy balance without heat benefits would be 40 to 140 times the energy input. Within the LCA selected environmental categories, CO_2-reduction potentials, cost of CO_2-equivalent-reduction, internal and external costs and energetic payback periods are computed and discussed.

1. INTRODUCTION

This paper is part of a research project on different utilization options of biogas (see figure 1), [1, 2]. The system boundaries are also shown in figure 1. The increase of the share of renewable energy within the energy mix is given top priority under the climate protection program in Germany [3]. Big progress has been made in the area of electricity generation from renewable energy sources. The driving force behind this development was the Act on Granting Priority to Renewable Energy Sources dated April 2000.

There exist a few publications on energy balances for biogas production and utilization with different assumptions, and none of them considered a range in generation capacities. System boundaries were compared [4, 5] and modified. Investment in steel and concrete digesters and material consumption was inquired from construction companies and suppliers [6-8]. Prices of co-generation sets, kind and amount of materials invested and operating costs were inquired from suppliers, producers and associations such as KTBL [7]. Energy balances and LCA were prepared according to norms [9] and guidelines [10]. The computer program GEMIS of the Eco Institute was used for computation of environmental categories (EVC) as given below. [11]. GEMIS also computes the cumulated energy demand (CED) [12]. The input energy, in this case biomass, was deducted since biogas is renewable.

2. ENVIRONMENTAL CATEGORIES (EVC)

The following key environmental categories (EVCs) were selected and computed in order to determine environmental impacts on e.g. climate, acidification, area consumption for assessment and comparison with other conversion technologies:

- CO_2-equivalents,
- Cumulated material demand (CMD),
- Cumulated energy demand (CED),

- Ozone-precursor,
- SO_2-equivalents or acidification potential, and
- Area consumption or consumption of natural resources

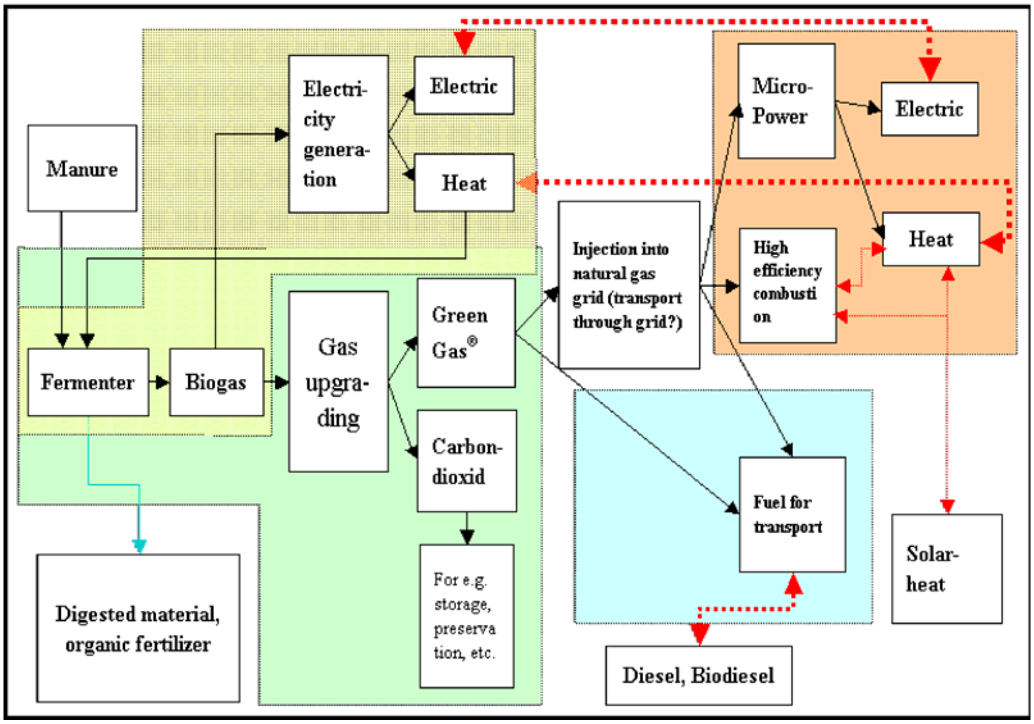

Fig. 1. Utilization options of biogas for co-generation and upgrading to Green Gas.

3. MODULES

A module is defined as a process component. There are components like fermenter, CHP-plant, upgrading plant, transport and utilization. To work with modules facilitates considerations, since the results of one module can simply be added up with the result of the other. The combination of modules into system boundaries is shown in figure 2. The complex agricultural module is not considered. In this module growth of energy crops would be considered. Manure is component of this module, however, manure was assumed as a by-product from animal husbandry. Any energetic investment into handling of manure is allocated to animal husbandry and not to the biogas plant. From the various modules generated, only three were utilized in this analysis, as follows:

- Module 1: Fermenter system alone, as shown in figure 3. This study considers: (i) fermenter of constant size but increasing power output (i.e., increasing loading rate, increasing power output per fermenter volume), and (ii) fermenter made of concrete or steel, of varying size but constant power output (i.e., decreasing loading rate, decreasing power output per fermenter volume).
- Module 2: Co-generation set alone.
- Module 3: Fermenter + co-generation set.

CED and EVCs of these three modules were computed. The CED and EVCs of Module 3 were computed as the sum of the other two modules. The individual modules, e.g., (i) a fermenter module made of concrete or steel, of varying size and constant power output, or (ii) a fermenter module of constant size and varying power output could be combined, respectively. Figure 3 shows the modular variations for different process chains. For the modules considered, scenarios may be computed, in which different substrates are being digested in different mixtures, e.g. manures only, or manures with energy crops in co-fermentation. Through the co-generation modules different co-generation sets of varying power output may be combined with the fermenter modules.

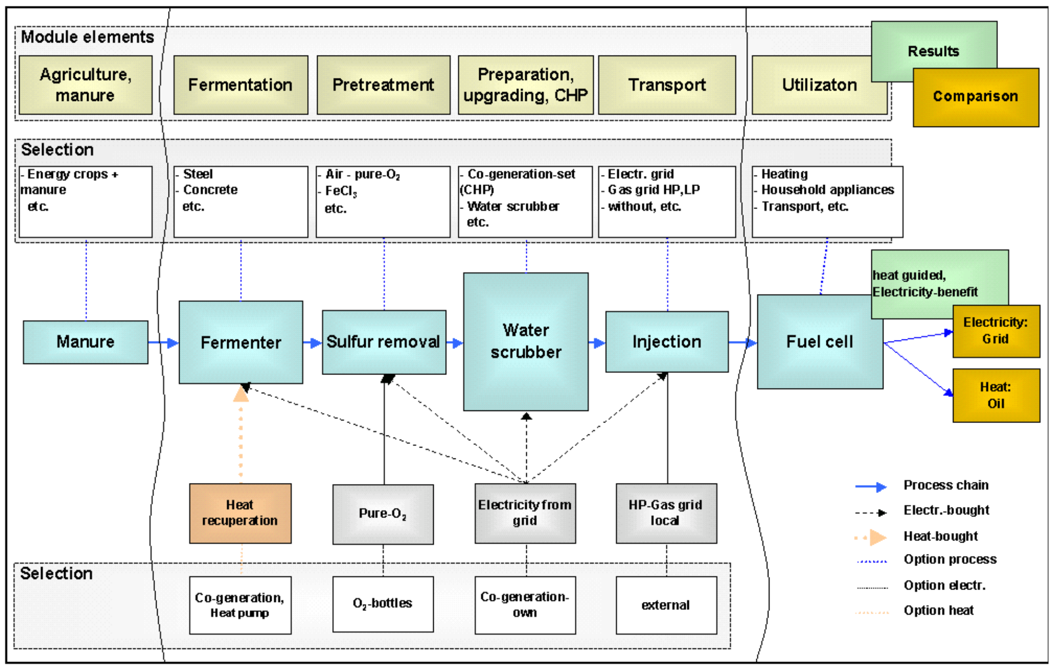

Fig. 2. System boundaries for biogas utilization options.

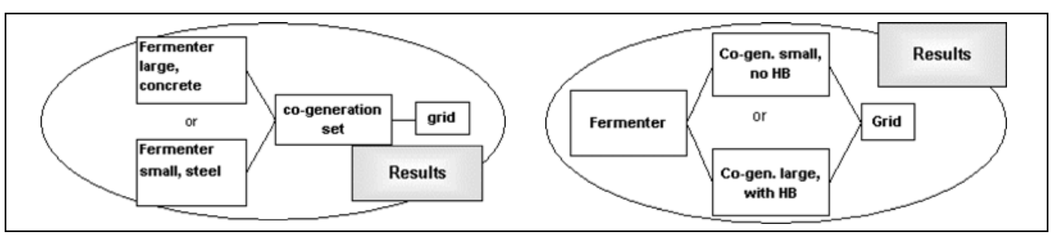

Fig. 3. Examples of combination of modules for computation of different process chains.

4. ASSUMPTIONS

The biogas system consists of a fermenter, receiving tank, and co-generation set. The fermenter module includes the receiving tank and is of varying sizes and at constant power output of 500 kW_{th}. The assumptions for concrete and steel fermenters are given in table 1 and table 2, respectively. Material input in the receiving tank and energy input in construction was considered. The energy inputs are listed in table 3.

Investment and operating costs for co-generation set were taken from ASUE-Statistics (2001) [14], those for the total installation for the full range of capacities from Rau [8] and for small capacities of full installations from KTBL [7]. A heat benefit (HB) was computed in the order of 50% of surplus heat after heating the fermenter.

Table 1. Assumptions for Input for Concrete Fermenter (C-F)

		Ferm. 1 Concrete	Ferm. 2 Concrete	Ferm. 3 Concrete	Ferm. 4 Concrete	Ferm. 5 Concrete	Ferm. 6 Concrete	Ferm. 7 Concrete
Power output	kW_{th}	500						
Required LSU	LSU	540						
Fermentation substrate	-	Cattle manure						
TS-content	%	8						
Lower heating value manure	kWh/kg	0,36						
Specific manure amount	l/(GV*d)	75						
temperature	°C	34						
HRT	d	28						
No. of fermenters	-	1						
Depth of fermenter	m	6						
Wall thickness, concrete	m	0.2						
Wall thickness, steel	mm	7						
Basement thickness	m	0.2						
Digestion at GEMIS	%	30						
Operating time GEMIS	h/a	7.900						
Life time at GEMIS	a	20						
Internal diameter	m	15.5	17.9	21.9	25.3	27.7	29.25	31
Digester volume utilized	m³	1.134	1.512	2.268	3.024	3.623	4032	4.536
Digester volume total	m³	1.281	1.709	2.563	3.417	4.093	4556	5.126
Concrete demand	t	372	465	642	811	942	1030	1138
Heat demand	kWh/d	1057	1399	2078	2755	3290	3656	4105
Electricity demand	kW	14	18	27	36	43	48	54
Area demand	m²	196	261	388	516	617	686	771

Table 2. Assumptions for Input for Steel Fermenters (S-F)

		Ferm. 1 Steel	Ferm. 2 Steel	Ferm. 3 Steel	Ferm. 4 Steel	Ferm. 5 Steel	Ferm. 6 Steel	Ferm. 7 Steel
Diameter internal (H:D=1:1)	m	11.5	12.7	14.4	16	17	17.38	17.9
Digester volume utilized	m³	1.134	1.512	2.268	3.024	3.623	4032	4.536
Digester volume total	m³	1.281	1.709	2.563	3.417	4.093	4556	5.126
Steel demand	t	30.1	36.3	47.8	57.6	65	70.2	76.3
Concrete demand	t	56	69	88	109	122	128	135
Heat demand	kWh/d	1.045	1.378	2.039	2.695	3.211	3564	3.997
Heat demand	kW	14	18	27	36	43	48	54
Area demand	m²	109	132	169	209	234	245	261

Table 3. Consumed Energy for Construction

	Assumption	Energy		Specif. energy
		[MJ]*	[kWh]	[kWh/kWh_{th}]
Soil excavation	120 kW diesel	8.357	30.085	3,81E-04
Transport for excavation- and filling materials	Transport near, Diesel	20.570	74.052	9,37E-04
Transport of concrete, insulation and steel	Transport near, Diesel	1.241	4.468	5,66E-05
*Source: [13]"				

Table 4. Input Data for the Co-generation Set

Co-generation electric		
Power	kW_{el}	165
Electrical efficiency	%	33
Operating time	h/year	7008
Life	year	15
Steel demand	kg	2200
Concrete demand	kg	22000

Co-generation thermal		
Power	kW_{th}	265
Thermal efficiency	%	53
Operating time	h/year	7008
Life	year	15
Steel demand	kg	0
Concrete demand	kg	0

5. RESULTS

5.1 Energy Balance

From the cumulated energy demand (CED) and the energy produced in biogas (e.g., fermenter module) or electricity (e.g. the co-generation module), the energy balance was computed. Computations were done, as describe in section 3, with the individual modules. The results of the energy balances of individual modules, i.e., Module 1 (increasing size, constant power output) and the Module 2 (attached to fermenter with constant size, increasing power output) are presented in figure 4 and figure 5, respectively.

Volumetric biogas production of agricultural biogas plants was in the range of 1 to 2.5 $m^3/(m^3\text{-day})$ or 0.25 to 0.5 kW/m^3. This applied to the fermenter volume of 1000 to 2000 m^3 as shown in Fig. 4. Due to decreasing specific power output of this particular fermenter module, the energy balance decreased from about 700 to 200 $kW\ h_{th\text{-}biogas}/kWh_{th}$. According to these computations, fermenters made of steel showed a slightly lower performance than those made of concrete. For all further computations, fermenters made of concrete were chosen **(for all further computations.)**

The energy balance of Module 2 (co-generation set alone) at constant fermenter volume of 1504 m^3 and increasing power output is shown in figure 5.

If Modules 1 and 2 were combined, the energy balances of the total process chain "manure-fermentation-co-generation" were obtained as shown in figure 6, with and without heat benefits.
The energy balance of the whole process chain at a capacity of 100 kW_{el} was between 40 and 55 kWh_{el}/kWh_{thCED} while that of Module 1 was between 210 and 350 $kWh_{th\text{-}biogas}/kWh_{thCED}$ and that of Module 2 was at 140 kWh_{el}/kWh_{thCED}. With heat benefit of 50% of the surplus co-generation heat, the energy balance increased further as shown in figure 6.

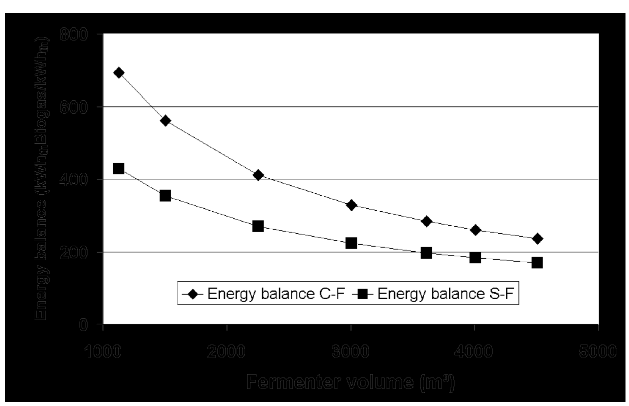

Fig. 4. Energy balance of Module 1, without heat benefit and at constant power output of 500 kW thermal. C-F is concrete fermenter, S-F is steel fermenter.

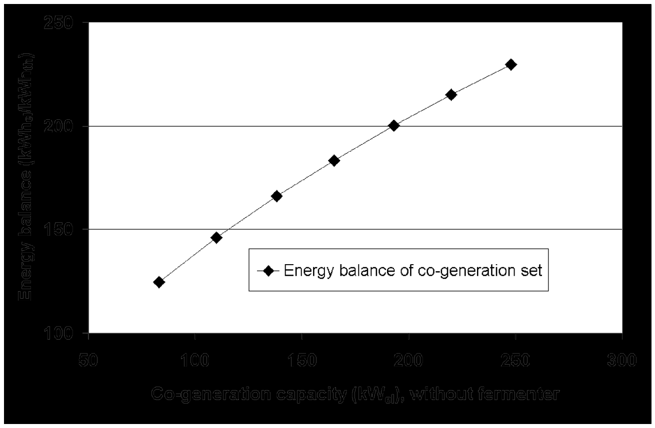

Fig. 5. Energy balance of Module 2 (co-generation module) without heat benefit at increasing power output of the fermenter and constant fermenter volume.

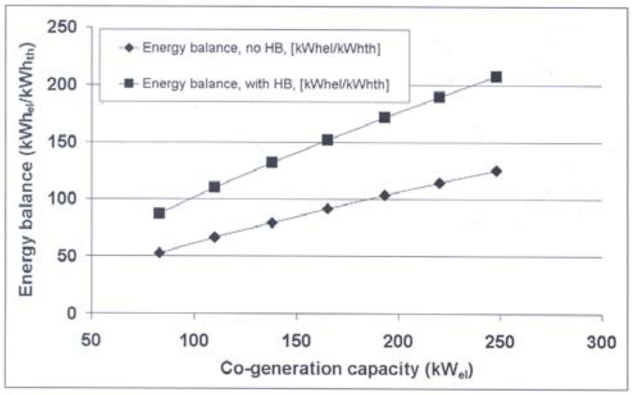

Fig. 6. Energy balance of manure-fermentation-co-generation process chain with and without heat benefit versus co-generation power output for concrete fermenters with constant volume 1504 m³ and varying power output.

5.2 Environmental Categories

The results of environmental categories (EVC) demonstrate low values and thus low negative impact of biogas electricity to the environment. Acidification potential (SO_2-eq), ozone precursors and area demand are very low. The CO_2-equivalents decrease with increasing co-generation capacity from 20 g to 10 g/kWh_{el}. At these low environmental influences the contributions to emission reductions compared to electricity generated with fossil energy sources are very high. The CED in figure 7 contains biomass input. In all other computations, however, biomass input was not included.

5.3 Reduction Potential

Figure 8 shows the reduction of environmental categories (EVC) if electricity from biogas is utilized in comparison to electricity from the grid at a co-generation capacity of 248 kW_{el}. Negative values represent reduction, while positive values represent an increase in EVC when using biogas for electricity as compared to using electricity from the grid. Highest reductions result for cumulated material demand CMD (4,16 kg/kWh_{el}) and cumulated energy demand CED (2,9 kg/kWh_{el}). CO_2-equivalents are being reduced by about 0.65 kg/kWh$_{el}$, the acidification potential and ozone precursor, however, remain almost unchanged. The increase in area consumption is theoretical and does not apply since GEMIS computes wood consumption for buildings or power shed of the biogas plant. Since wood is renewable and regrows, increase in area consumption should be set to zero. One result of the computations showed that the influence of the co-generation capacity on the reduction potential was low.

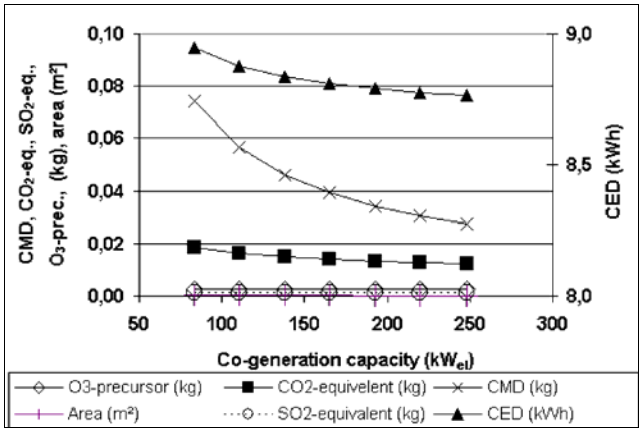

Fig. 7. Influence of co-generation capacity (kW$_{el}$) of the manure-fermentation-co-generation process chain on environmental categories, without heat benefit, constant fermenter volume, and varying power output (Note: Komma on the y-axis denotes decimal points).

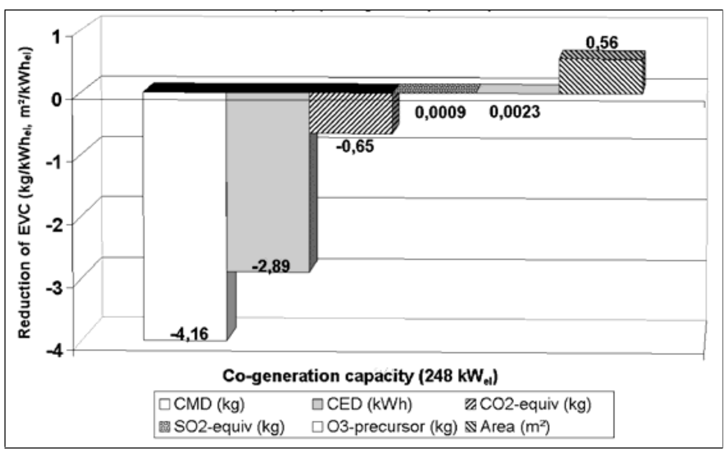

Fig. 8. Reduction of environmental category (EVC) by using electricity from biogas in comparison to electricity from the grid (grid electricity D-Mix 2000), without heat benefit at a co-generation power of 248 kW$_{el}$.

The reduction potential of the cumulated energy demand CED in comparison to the conventional electricity generation in Germany is shown in figure 9, with and without heat benefit for manure-fermentation-co-generation process chain. A biogas plant with a generator capacity of 83 kW$_{el}$ may, at full load during 7000 operating hours per year, reduce the CED by 1.62 GWh per year, while a benefit through co-generation heat may increase this contribution by about 23% to 2 GWh per year. A biogas plant with a 250-kW generator may reduce the CED by about 5 to 6 GWh per year.

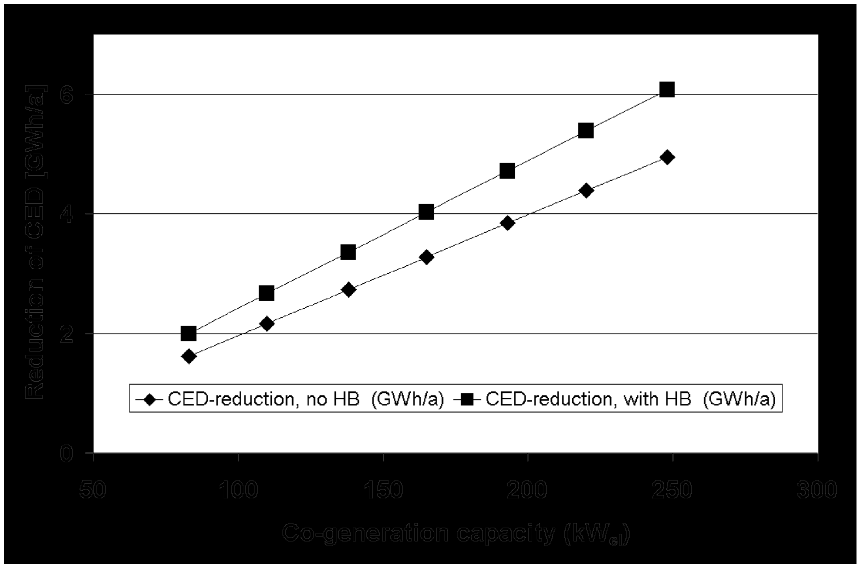

Fig. 9. Reduction potential of cumulated energy demand CED per year for the manure-fermentation-co-generation process chain through electricity generation with biogas compared to grid electricity with and without heat benefit.

The reduction potential of CO_2 – equivalents compared to grid electricity in Germany is shown in figure 10, with and without heat benefit for the manure-fermentation-co-generation process chain. A biogas plant with an installed power of 83 kW-generator may at full load and during 7000 operating hours per year reduce the CO_2-emissions by 363 tons per year. A heat benefit increases this result by about 22% to 444 tons per year.

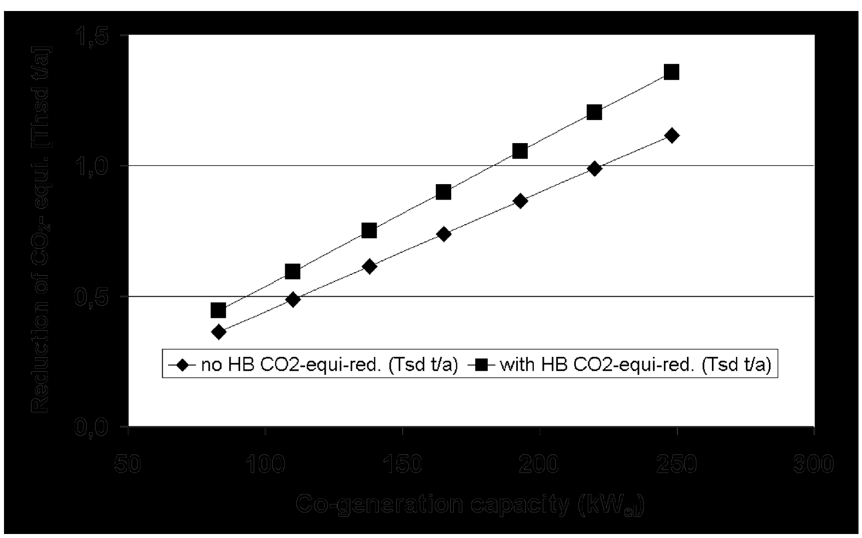

Fig. 10. Reduction potential of CO_2-equivalents per year for manure-fermentation-co-generation process chain through co-generation of biogas in comparison to electricity from the grid (D-MIX 2000), with and without heat benefit. (Note: Komma on the y-axis denotes decimal point).

5.4 CO_2-reduction cost

The reduction costs for CO_2 – equivalents with and without heat benefit are presented in figure 11. At an installed power of 83 kW_{el} the costs amounted to about 236 €/t CO_2–equivalent, which may be further reduced through heat benefit by about 27% to 172 €/t CO_2 –reduction. At 250 kW_{el} the reduction costs amounted to about 100 €/t CO_2–equivalent.

5.5 Internal and external costs

The internal and external costs were determined for the different modules, with and without heat benefit. The internal costs (or production costs) per kWh decreased with increasing installed co-generation capacity, while the external costs nearly remained constant. The external costs for the modules, without heat benefit amounted to about 0.005 Euro/kWh_{el} .

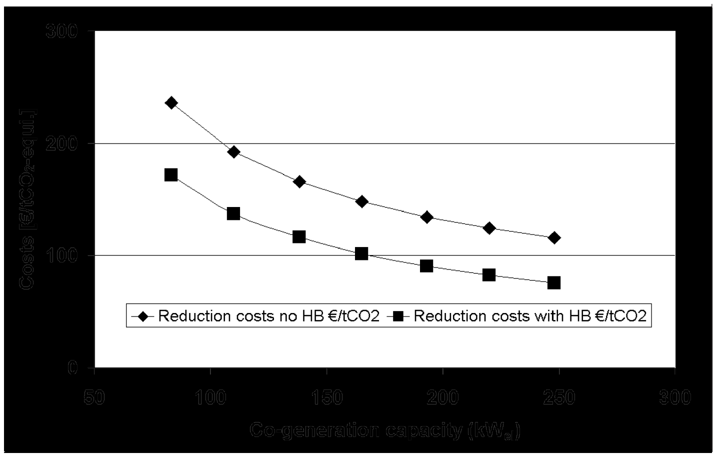

Fig. 11. Costs per ton of reduced CO_2-equivalent for the process chain manure-fermentation-co-generation through electricity from biogas with and without heat benefit compared to electricity from the grid in Germany.

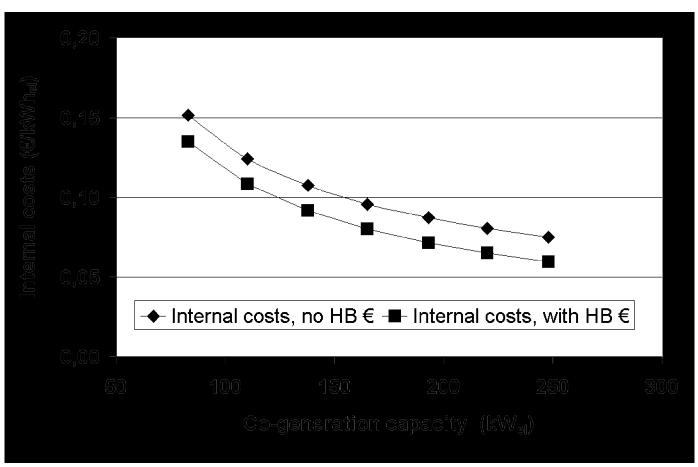

Fig. 12. Internal costs for the manure-fermentation-co-generation process chain depending on installed co-generation capacity, with and without heat benefit (note: Komma on the y-axis denotes decimal points).

Internal costs (as shown in figure 12) are important for the consideration of economic feasibility. At 83 kW installed co-generation capacity the operating costs of the biogas plant amounted to about 15 €Cent/kWh_{el}, which may be reduced by a heat benefit by about 11% to about 13 €Cent/kWh_{el}. At 100 kW_{el} installed electrical power the internal cost of the manure-fermentation-co-generation process chain are at 0.13 Euro/kWh_{el}. At 250 kW-co-generation capacity the internal costs amounted to 7.5 €Cent/kWh_{el}, without heat benefit, and about 6 €Cent/kWh_{el}., with heat benefit.

External costs in GEMIS are the monetarized environmental costs of emissions and by-products [11]. These costs represent the monetarized value of damages or the efforts to avoid damages, which result from emissions or by-products. External costs are not a component of the conventional economic feasibility computation, in which only private costs are being taken into account. Public costs of emissions and by-products are external, i.e., not inside the parameters of private economic decision making. The GEMIS – basic data offer the possibility of computing external costs for emissions and greenhouse gases, which are based on the economic effort of emission avoidance. For nuclear risks, a value of 1.5 €Cent/kWh electricity from an atomic power plant was considered.

5.6 Energetic Payback Period

The energetic payback period was computed. Figure 13 shows the payback period at three different heat benefits of the manure-fermentation-co-generation process chain. The payback period of a biogas plant with 83 kW installed co-generation capacity without heat benefit would be 40 days. With 50% heat benefit, the payback period would be about 30 days and with full heat benefit, about 24 days. At 250 kW_{el} installed co-generation capacity, the payback period of the biogas plant may be reduced to 9, 11 and 14 days, for the process chain with 100%, 50% and 0% heat benefit, respectively.

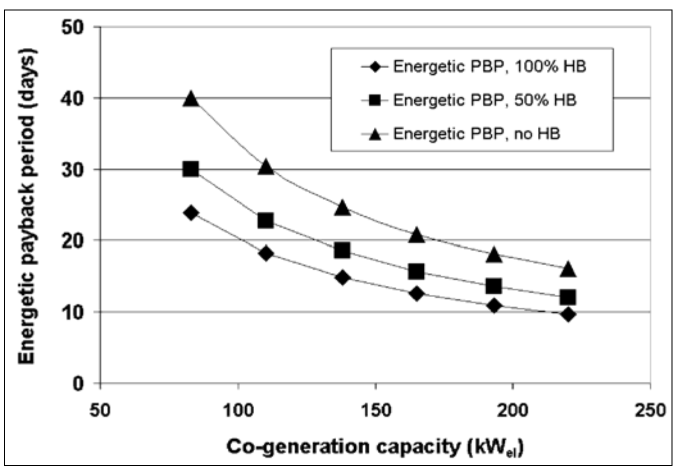

Fig. 13. Energetic payback period at three different heat benefits 0%, 50% and 100% based on primary energy of the manure-fermentation-co-generation process chain compared to electricity from the grid.

6. CONCLUSION

Co-generation of biogas, as conversion process at the farm site, is applied in all farms in Germany which own a biogas plant. This conversion process proves to achieve high energy balances and a high reduction potential of CO_2-equivalents. Annually, a biogas plant with 250 kW installed co-generation capacity may reduce GHG-emissions by about 1200 t CO_2-equivalents, if manure is digested, the generator is fully loaded and operates 7000 hours per year. The CO_2-reduction costs are about 100 to 400 times higher than actual prices for CO_2-certificates, so that such certificates, should they be realized at all, are only a small component within the benefit-cost computation. The internal costs or operating costs were computed for smaller biogas plants (about 80 kW_{el}) at about 15 €Cent/kWh_{el}. Thus, these costs are higher than the cost of electricity supplied into the grid according to the Act on Granting Priority to Renewable Energy Sources of April 2000 and should, according to these assumptions, not be feasible. The energetic payback period is between 11 and 40 days, respectively and depends on the degree of utilization of co-generation heat.

The computations in this study may only give an example for the specific applications used in the study. Individual projects may perform differently. It is recommended to compute individual projects by taking into account all site specific variables and assumptions. Such individual project- and site-specific computations allow a detailed consideration of all energetic and LCA parameters. This also applies for agricultural scenarios of cultivation of energy, food and feed crops.

7. ACKNOWLEDGEMENT

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8. GLOSSARY

CED	=	Cumulated energy demand
CMD	=	Cumulated material demand
EB	=	Energy balance: energy gain (output) in renewable energy over cumulated energy demand CED (input in fossil energy sources)
EPP	=	Energetic payback period: that period in which the energy input is amortized by energy output in renewable energy
EVC	=	Environmental categories
GEMIS	=	Global Emissions Model of Integrated Systems, computer package available under www.oeko.de
GHG	=	Greenhouse gas
HB	=	Heat benefit: fossil energy replaced by CHP-heat
HRT	=	Hydraulic retention time
LCA	=	Life cycle assessment
LSU	=	Livestock unit
1 US$	=	1 EURO

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