Greenhouse gas balances and CO_2eq mitigation costs of agricultural biogas plants

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Abstract
Greenhouse gas balances of electricity produced in biogas plants were calculated for four plants of different sizes. Additionally mitigation costs compared to fossil energy provision were assessed for these plants. External utilization of the CHP's waste heat, thus substituting e.g. heating oil, is a prerequisite for saving GHG emissions by electricity production from biogas. Highest greenhouse gas savings compared to fossil electricity (0.76 kg CO_2/kWh_{el}) are obtained when predominantly digesting slurry in a complete gas-tight system, avoiding emissions from otherwise open slurry storage. However, due to the big volume and low gas yields of the manure investment cost are high compared to plants co-digesting energy crops, resulting in high mitigation costs (280 €/t CO2eq; large-scale energy crop plants 150-190 €). On the other hand the use of energy crops is controversially discussed, especially against the background of potential CO_2 emissions from indirect land use change.

Introduction
The sustainability of biogas production, also compared to other renewable energy sources, is subject to controversial discussion, especially when it comes to the digestion of energy crops. Enhanced competition for land with livestock and cash crop farms and the increasing share of maize in crop rotations are two of the main points referred to, but also the possible effect on indirect land use change.
In this study the greenhouse gas (GHG) mitigation potential of agricultural biogas production and the respective mitigation costs are derived for typical German plant types. The most important influencing factors for effective GHG mitigation by biogas production are identified.

Material and Methods
Calculations follow the general LCA approach according to ISO 14040 ff. representing the whole biogas production and conversion process, starting from biomass production, including plant construction and operation and finally application of fermentation residues. Emission data for the various materials and supplies are taken from either the ecoinvent [1] or FEE [2] database. Energy crop production and transport are modeled based on KTBL data on agricultural production processes [3, 4]. Direct as well as indirect emissions from feedstock provision are taken into account, as are leakages or CH_4 emissions from the CHP methane slip. Residue storage tanks are considered to be gas-tight, therefore no emissions occur during storage of fermentation residues.
Emissions of the greenhouse gases CO_2, CH_4, N_2O occurring during the production of one kilowatt hour of electricity from biogas are calculated and counterbalanced with the emissions avoided by a) substitution of heating oil by using CHP waste heat and b) digestion of slurry and gas-tight storage of residue instead of slurry storage in open tanks. The difference between the resulting net emissions of biogas electricity and the emissions for the equivalent amount of fossil electricity is then used as a basis for the calculation of GHG mitigation costs (€/t CO_2eq avoided compared to fossil electricity and heat provision).
The most relevant assumptions for this study are summarized in Table 1.
The model plants (Table 2) reflect the current German legislation on biogas plants (Renewable Energy Sources Act, EEG 2012) and take into account the limit of the share of maize silage in the fresh matter input of 60 % as well as the requirement to use at least 35 % of the CHP waste heat externally (exception: small slurry plants with high demand of process heat for the digester). Additionally, a special feed-in tariff [1] was introduced to enhance slurry digestion in plants up to 75 kW.

[1] 25 Ct/kWh_{el} for plants up to 75 kW with a slurry share of at least 80 FM-%

Table 1. References and assumptions

References	
electricity: fossile power mix	0.72 kg CO_2eq/kWh_{el}; 4.5 Ct/kWh_{el}
heat : heating oil	0.,31 kg CO_2eq/kWh_{th}; 6.5 Ct/kWh_{th}
N_2O emissions during energy cropping [5]	
direct / indirect[1)] emissions	1.0 / 0.37 % of applied N
Diffuse emissions	
leakages	1.0 % of methane production
methane slip CHP	0.5 % of methane production
methane emissions residue storage	none (gas-tight storage tank)
Methane emissions saved by slurry digestion instead of open storage [2)]	
cattle slurry	10 % of potential methane production

1) due to emitted NH_3, surface runoff and leaching
2) based on: KTBL standard methane yields [6] and methane emission factors during open slurry storage according to [5]

Table 2. Main characteristics of the four model biogas plants

Predominant feedstock	75 kW	150 kW	500 kW	1000 kW
Feedstocks (% FM input)				
cattle slurry [1)] (CS)	80 %	20 %		
maize silage (MS)	20 %	60 %		
cereals, total plants silage (CTPS)	0 %	20 %		
transport distance for energy crops and fermentation residues [2)]	3 km			5 km
external heat utilization (% of CHP waste heat)	30 %	40 %		

1) The slurry is digested on-farm, consequently no transport necessary.
2) transport of fermentation residues: Only the share produced from energy crops is taken into account as slurry transport would be necessary anyway and is therefore allocated to livestock husbandry.

Results

Greenhouse gas emissions and greenhouse gas balance of agricultural biogas plants

Total GHG emissions of electricity produced from biogas in the model plants add up to 0.29-0.34 kg CO_2/kWh_{el} (Figure 1 A). While plant construction and transport of feedstock or contribute only little to the overall emissions, the production of energy crops is the most relevant source of GHG. This is even the case for the small slurry plant where only 20 % of the fresh matter input are energy crops. Both process energy (electricity, pilot fuel for 75 and 150 kW) and diffuse emissions on the plant have a significant share in the GHG emissions of electricity produced from biogas. The plant size has only little influence on emissions; decreasing emissions with size are due to the higher electric efficiency of bigger CHPs.

When counterbalancing emissions from electricity produced from biogas with GHG savings due to slurry digestion and CHP waste heat utilization (Figure 1 B) the small slurry plant can produce electricity without net GHG emissions. The model plants with significant shares of energy crops have a positive GHG balance (0.17 kg CO_2/kWh_{el}); however net emissions are still significantly lower than the German fossil power mix (0.72 kg CO_2/kWh_{el}; [1]). GHG mitigation costs are on the one hand determined by the extent of savings compared to fossil electricity, but even more by production costs. These show a clear degression with plant size (data not shown), resulting in highest mitigation costs for the small slurry plant despite highest GHG savings per kWh_{el}. Even the 1 MW energy crop plant cannot reach the threshold of 100 €/t CO_2 which is regarded as economically sensible for industrial processes or energy efficiency measures. This threshold can however not be directly applied to agricultural biogas production for energy provision.

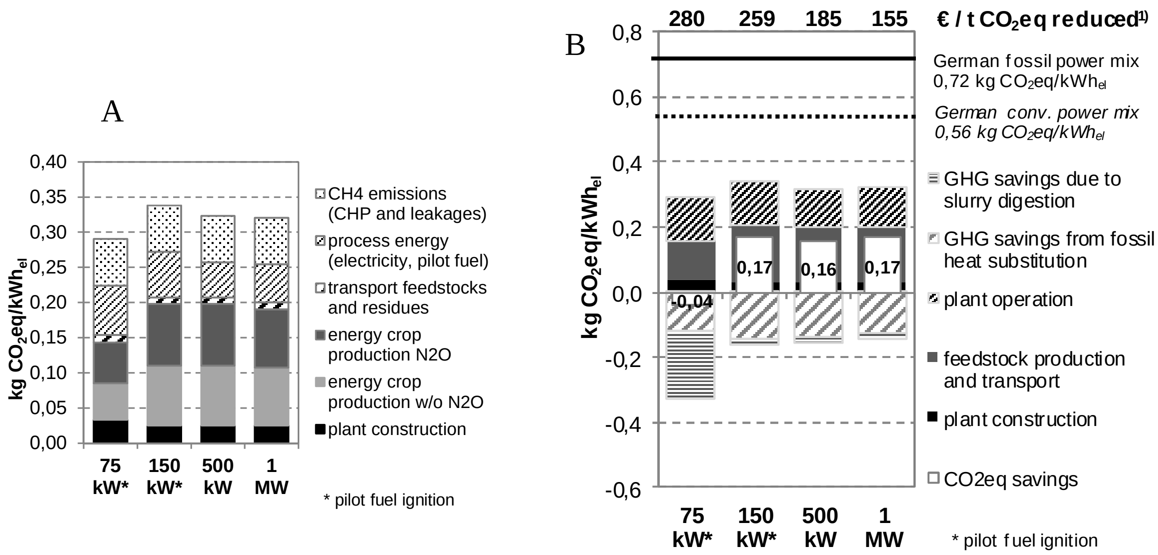

Figure 1. Greenhouse gas emissions (A) and balances (B) of agricultural biogas plants (on-site electricity production); 1) mitigation costs compared to fossil electricity

Factors influencing the GHG balance of agricultural biogas plants

Additional calculations were made for small-scale plants with shares of slurry exceeding 80 % (Figure 2). Exclusive slurry digestion would lead to mitigation costs lower than those of the bigger plants co-digesting energy crop due to high GHG savings. However, production costs on small slurry plants are in a range (20-28 Ct/kWh_{el}) which might put in question the profitability even despite the high feed-in tariff. Results from a practice plant digesting slurry and feeding residues of a large dairy installation (1880 dairy cows, 1.4 MW) show that, when realized at large scale without long transport distances, slurry biogas plants might operate profitably with consequently low mitigation costs [7].

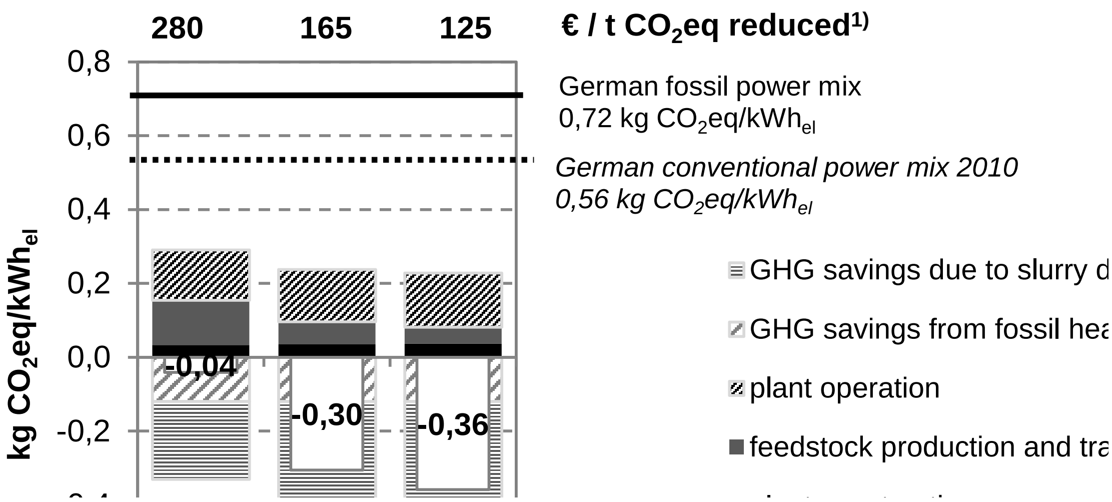

Figure 2. Influence of manure share on the greenhouse gas balance of agricultural biogas plants (on-site electricity production); 1) mitigation costs compared to fossil electricity

In practice external utilization of the CHP waste heat can be achieved which exceed the legislative minimum of 35 % of the produced heat. Site-specific and well adapted concepts might allow using excess heat all year round. The use of 75 % of the CHP heat (assuming 25 % to be necessary for process heat) would lead to an very low GHG balance also for energy crop plants, with mitigation costs significantly lower than those in Figure 1 B (data not shown).

As already the moderate emissions from CH_4 leakages assumed in this study significantly contribute to the GHG load of biogas electricity (Figure 1 A), methane losses on the plant, although not completely avoidable (Table 2) should be minimized as far as possible. Leakage detection should therefore be part

of good operational practice and fermentation residue storage tanks should be gas-tight in order to recover residual methane emissions.
The issue of indirect land-use change (iLUC) due to biomass production for energy provision is controversially discussed in Europe. However its relevance for the biogas sector is not clear yet. So far no method to derive an iLUC factor for energetic biomass has been agreed on. However, with the continuing increase of bioenergy this factor will have to be taken into account in the future. Therefore model calculation were made for a small slurry plant with only 5 % energy crops and the 500 kW energy crop plant (80 % energy crops) using an iLUC factor of 3.5 t CO_2/(ha*a) that is regarded to be at the lower range [8;]. Already an energy crop share of only 5 % leads to about 20 % higher emissions due to iLUC, while in case of predominant energy crop use consideration of iLUC results in 45 % higher GHG emissions and thus almost doubling the net balance (Figure 3).

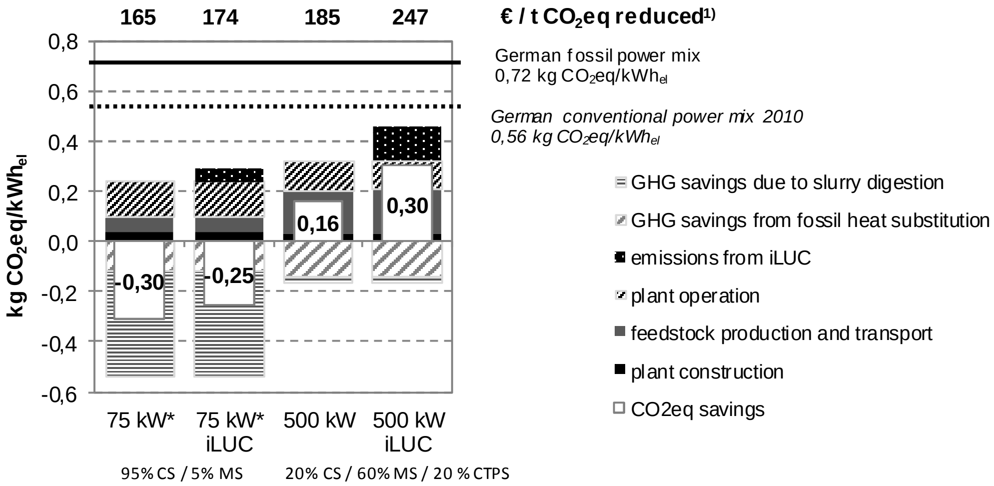

Figure 3. Possible effects of indirect land use change on the greenhouse gas balance of agricultural biogas plants (on-site electricity production); 1) mitigation costs compared to fossil electricity

Conclusion and perspectives

Electricity from biogas can be an effective measure for reducing GHG emissions compared to electricity production from fossil resources, if

- livestock manure and/or residual materials are used;
- excess CHP heat is used;
- methane losses on the plant are minimized and
- energy crop production and conversion process are optimized.

CO_2eq mitigation costs vary according to the set-up of the plant and usually exceed 100 €/t CO_2eq. Consideration of effects from indirect land use change due to energy crop production strongly influences the balance as well as mitigation costs.

References

[1] ecoinvent (Swiss Centre for Life Cycle Inventories, 2004-2008): The ecoinvent data v2.0
[2] FEE (2005): Ergebnisse zur Ganzheitlichen Bilanzierung. www.ffe.de:
[3] KTBL (2007): MaKost Maschinendatenbank (machine costs database). https://sec.ktbl-shop.de/
[4] KTBL (2011): Feldarbeitsrechner (field work calculator). http://www.ktbl.de/index.php?id=806
[5] IPCC (2006): Guidelines for national greenhouse gas inventories; Chapter 4, Agriculture, Forestry and other land use.
[6] KTBL (2010): Gasausbeute in landwirtschaftlichen Biogasanlagen, Darmstadt.
[7] Roth, U.; Döhler, H.; Hartmann, S.; Wulf, S. (2011): Treibhausgasbilanzen und CO_2eq-Vermeidungskosten landwirtschaftlicher Biogasanlagen. In: Biogas in der Landwirtschaft – Stand und Perspektiven. FNR/KTBL-Kongress 20.-21. September 2011. KTBL-Schrift 488, S. 196-208
[8] Fritsche, U.; Hennenberg, K.; Hermann, A.; Hünecke, K.; Herrera,, R; Fehrenbach H.; Roth, E.; Hennecke, A.; Giegrich, J. (2010): Entwicklung von Strategien und Nachhaltigkeitsstandards zur Zertifizierung von Biomasse für den internationalen Handel. Hrsg. Umweltbundesamt, Dessau-Roßlau