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Greenhouse Gas Balance of Bio-methane – which Substrates are Suitable?

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Abstract: Biogas and bio-methane that are based on energy crops are renewable energy carriers and therefore potentially contribute to climate protection. However, significant greenhouse gas emissions resulting from agricultural production processes must be considered, mainly resulting from agricultural production processes, as fertilizer use, pesticide etc.

This paper provides an integrated life cycle assessment (LCA) of biogas (i.e. bio-methane that has been upgraded and injected into the natural gas grid), taking into account the processes of fermentation, upgrading and injection to the grid for two different types of biogas plants thus examining the current state of the art as well as new, large-scale plants, operated by industrial players. Not only technical and engineering aspects are taken into account here, but also the choice of feedstock which plays an important role as to the overall ecological evaluation of bio-methane.

The substrates evaluated in this paper – aside from maize – are rye, sorghum, whole-crop-silage from triticale and barley, and the innovative options of agricultural grass (*Landsberger Gemenge*, a mixture of *hairy vetch (vicia villosa), crimson clover (trifolium incarnátum) and Italian ryegrass (lolium multiflorum)*) as well as a combination of maize and sunflower.

Key words: Bio-methane; Life cycle assessment; Cop-rotation systems

1. INTRODUCTION

Biogas is produced through fermentation of wet biomass. Unlike most European countries, most plants in Germany use energy crops from dedicated farming as a feedstock, rather than residues or sewage gas.

Since late 2006 several projects for injection of upgraded biogas into the natural gas grid have been set up. The aim is to use the existing infrastructure to distribute the bio-methane to a larger number of end users. Bio-methane-defined as raw biogas after upgrading - as a perfect substitute for natural gas can thus be used in

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combined heat and power (CHP) applications as well as for provision of domestic heat or as an alternative vehicle propellant.

Considering the process of upgrading, injection and distribution to different end users, the biogas industry has moved forward from the local, small-scale "on-site" energy supply model to new markets and possibilities. However there is still debate as to what role bio-methane can play as a regional, agricultural energy carrier, and as to its climate impact.

The author provides an integrated life cycle assessment (LCA) of biogas (respectively bio-methane after upgrading and injection into the natural gas grid), taking into account two different types of biogas plants: (1) the current state-of-the-art as an industrialized, but average efficient biogas plant in the year 2008 (labelled as "state of the art") and (2) a new, large-scale plant with optimized technology, representing already the next generation of biogas plants by widely exploiting the optimization potential of the near future (labelled as "optimized technology"). The focus is thus on large biogas plants (≥ 1 000 Nm3/h); the given results do not, therefore, hold in any case for small-scale, agricultural biogas plants. The two different types of plants and the specific technical features are outlined in the following section 2.

Already, several studies regarding the overall GHG emissions and LCA of biogas or bio-methane based on energy crops exist (e.g. [1], [2], [3], [4]) have been published. As has been shown [5], comparison of the results is rather difficult as the LCA depends strongly on the feedstock used, the technology applied and the assumptions taken for the agricultural and technical aspects. As well, the functional unit as well as the system boundaries vary. Thus, the relevant assumptions for the presented analysis are laid out in this paper.

The analysis is not only based on system engineering, but also on different feedstock provided in crop rotation systems for different locations in Germany. The focus of this paper is, however, to analyze the effects from different assumptions regarding nitrous oxide emissions to the climate protection potential of bio-methane, produced in different configurations of plants. The results of the sensitivity analysis regarding the assumptions on nitrous oxide emissions and the effects to the LCA are presented in section 5.

2. TECHNOLOGICAL PROCESS CHAIN OF BIO-METHANE

The technological process chain of bio-methane is pictured in the following scheme. Simplified, the process chain can be divided into four steps: (1) provision of substrates, (2) fermentation to biogas through anaerobic digestion, (3) upgrading of the raw gas to the same quality as natural gas, (4) handling of digestates. The provision of the energy needed for the operation of the reactor and the upgrading unit can be seen as a fifth step. In all process steps greenhouse gas (GHG) emissions can evolve: directly through leakage of methane, or indirectly through the use of fossil energy or agricultural processes.

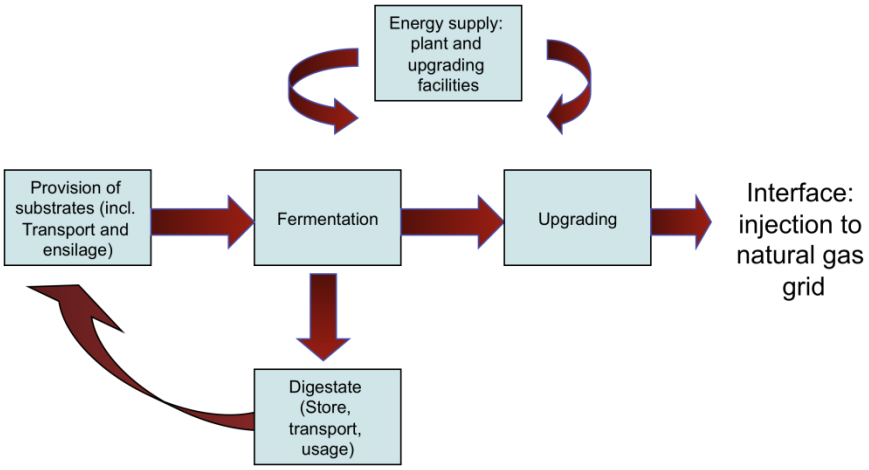


Fig. 1: Scheme of Technological Process Chain of Bio-methane

The four process steps will be briefly described in the next paragraphs. The input data to the LCA for both plant configuration types as resulting from the description is listed in table 1.

2.1 Provision of Substrates

This step includes the cultivation and harvest of the energy crops as well as the ensilage. Illustrative, maize will be taken as a reference crop, while the full LCA has been made for five different crop rotation systems. Most relevant are the data on N-P-K-fertilizers, lime, pesticide and diesel used in machinery. This data has been provided by [6] and represents the actual situation on five different locations in Germany.

Furthermore, emissions of nitrous oxide from microbial processes in the soil have been taken into account to the amount of 1 % of the deployed nitrogen fertilizer[7]. This assumption and the given effect will be examined closer in section 5 of this paper.

During ensilage of substrates material losses between 5 and 15 % occur, according to [8]. Those numbers have been chosen as maximum and minimum value for the two plant configuration types.

2.2 Fermentation

In the reactor itself there can be leakage of methane due to not properly sealed elements, diffusion from gas-bearing parts or process disturbances. The exact amount of leakage is not exactly scientifically assessed yet, so there is the need for further examination and the quality of data is less than for the other figures. In accordance with previous studies (as in [9] and [2]) a number of 1 % of the methane production has been applied. As long as accurate measurements have not been done it is assumed that emissions will be halved for the optimum case presented in the optimized technology.

Another important parameter is the yield of crude biogas that can be achieved during the digestion. It depends a lot on the constitution and quality of substrate, but also on the construction of the reactor itself. So far, for maize as reference crop, for the calculation a value of 200 m3 per ton of fresh mass (tFM) has been used [10], but operating experience from plant operators show, that even to-day 10 – 20 % more can be achieved.

2.3 Handling of Digestates

As mentioned before the LCA is done for large-scale professional operated plants, so it is assumed that the storage of digestate is fully covered and no methane leakage will occur at this point. Nevertheless, in the sensitivity analysis the effects of a not completely covered storage will be explored to give a perspective of the importance of this section.

The digestate will be returned to the cultivation of the crops and deployed as fertilizer. The nutrients are not decomposed during the digestion and phosphate and potassium can be fully regained. Between 50–70 % of nitrogen in the digestate are plant available and can substitute mineral nitro-gen fertilizer[11].

Tab. 1: Input Data for the LCA for the Plant Configuration Types: State of the Art and Optimized Technology

			State of the art	optimized Technology
provision of substrates*	diesel	l/ha	82,9	82,9
	N-fertilizer	kg/ha	141,75	141,75
	material loss ensilage	% mass	**15**	**5**
	N2O emissions (soil)	%**	1	1
fermentation	CH4 leakage reactor	Vol %	**1**	**0,5**
	yield of raw gas	m3 / t FM	**200**	**220**
handling of digestate	CH4 leakage store	%	0	0
	subsitution of von N-fertilizer (mineral)	%	70	70
	subsitution of von P,K-fertilizer (mineral)	%	100	100
up-grading	CH4 slip	%	2	2
	remaining CH4	%	0,01	0,01
energy supply	electricity (reactor)	kWh el/ t FM	36	36
	heat (reactor)	kWh th/ t FM	83	83
	electricity (PSA)	kWh el/m3 BG	0,3	0,3
	heat (PSA)	kWh th/m3 BG	0	0

***exemplay for maize, without accounting of digestate**
****** calculated in % of nitrogen fertilizer deployed**

2.4 Upgrading

The Pressure Swing Adsorption (PSA) is chosen as an example for upgrading technologies to be depicted for this article. Highly relevant is the slip rate of methane, which is about 2% with most PSA procedures[12]. As there is a regulation of methane slip since the beginning of 2009 in Germany[13], currently it is the common method to put a burner after the PSA to convert the methane catalytically or thermal to carbon dioxide. Again, for both plant configuration types a methane slip following the after treatment of 0.01% is assumed.

2.5 Energy Supply

For the operation of the biogas plant and the upgrading facilities energy is needed in form of heat for the reactor and electricity for the stirring unit and pumps. The PSA needs electrical and thermal energy, as well. The data is taken from [12] and from the plan operator.

3. GREENHOUSE GAS EMISSION FACTORS OF BIO-METHANE

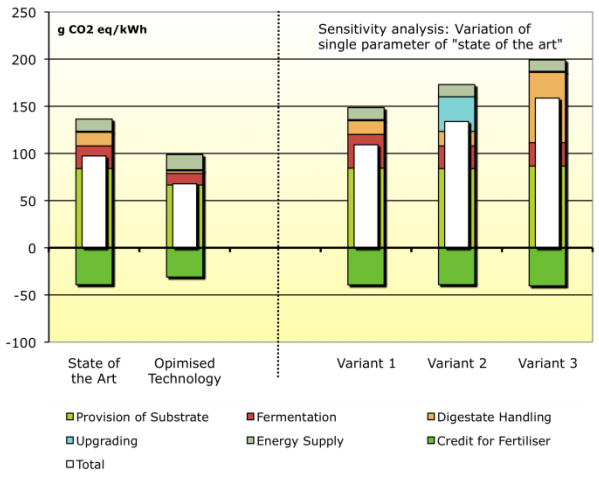
Two different types of biogas plants have been in the focus of the study: the current state of the art as well as a new, large-scale plant, operated by industrial players (optimized technology). The input parameter for both vary regarding the material loss in ensilage, the yield of raw gas achieved and the methane leakage from the reactor, as can be taken from Table 1. In the following chapter, first the emission factors of this two plant configurations will be shown, before evaluating single aspects in a sensitivity analysis.

3.1 Comparison of Plan Configurations

Figure 2 shows the results of the LCA for the GHG emission factors of both plants and the sensitivity analysis. Both plants are operated in a professional way, nevertheless the difference between both types is clearly visible (columns on the left hand side). Compared to the state of the art plant, GHG emissions can be decreased by about 30%, from 97 g CO_2eq/kWh to 67 g CO_2eq/kWh, if the currently available most optimized technology is applied.

The difference between the two configurations is mostly due to a combination of lower los during ensilage and a better yield of raw gas for the optimized technology. Furthermore, a minor leakage of methane from the reactor and a better handling of nitrogen during digestate deployment are visible.

When the technical aspects are optimized as far as possible with today's technology, it is obvious, that the provision of substrates is the main factor for GHG emissions. For the optimized technology plant, its share is about 52 % of the overall balance, having taken the credit for digestate already into account. Research as to the further reduction of GHG from the process chain of bio-methane should therefore focus not only on technology, but on feedstock supply, as well.



Variant 1: increased methane leakage in reactor (1,5% instead of 1%); Variant 2: increased methane slip in PSA (no after treatment, slip of 2% instead of 0,01%); Variant 3: digestate store not completely covered – moderate emissions of 2,5% of gas stored

Fig. 2: GHG Factors of the Process Chain Bio-methane: Relation of Two Plant Figurations Considered and Sensitivity Analysis

3.2 Sensitivity Analysis: Technical Aspects

Direct emissions of methane have the highest single influence to the overall GHG balance, as methane has a higher global warming potential (GWP) as carbon dioxide. Therefore, the process steps where leakage of methane occurs, need to be looked at especially carefully when optimising the production of bio-methane. The following sensitivity analysis is done for three of those steps for the plant according to the current state of the art:

Variant 1: leakage of methane from the reactor itself is raised from 1 % to 1,5 % due to the mentioned insecurity regarding the quality of data;

Variant 2: no after treatment of methane leakage from the upgrading unit, the methane slip is still considered to be 2 % instead of 0,01 %;

Variant 3: it is assumed, that the digestate store is not completely covered. Here, rather moderate emissions of only 2,5 % are depicted, while practical experiences show [14], that up to 15 % and more can be occur. Some of the older and smaller agricultural biogas plants even have open digestate stores. Such plants are, however, not in the focus of this article. The number of 2,5 % has been chosen to give an impression of the high relevance of methane leakage from the digestate store.

This sensitivity analysis is done in full knowledge, that it is mandatory to cover the digestate store and put an after treatment to the upgrading unit, in order to get the full subsidy for bio-methane production and use (innovation bonus in the renewable-energy-law EEG). Admittedly, there is a maximum in plant size of 700 Nm^3/h for this innovation bonus anyway[15], so it cannot be in any case assumed, that the guidelines and specifications will be met from all biogas plants. Therefore, it does make sense to clarify the impacts of non-compliance with the regulation to climate change.

The three variants are shown in the right columns of Figure 2.

3.3 Sensitivity Analysis: Nitrous Oxide Emissions

Nitrous oxide emissions are not the most important factor in the overall GHG balances, but they still play a role. The current controversy discussed matter of nitrous oxide emissions from organic processes can be of highly importance to the overall GHG balance of bio-methane.

In the above described examinations and results, a value of 1 % of deployed nitrogen fertilizer was assumed to be emitted as nitrous oxide, following the current IPCC reports [16]. A lot of recent international research indicates, however, that this data might be much too low. [17] indicated, that this factor of 1 % should be multiplied by 3 or even 5 to take the indirect emissions of nitrous oxide into account, while on the other hand preliminary test with nitrification inhibitors show, that at least for some German locations the (direct) N_2O emissions could be halved to 0,5%[18, 19].

Therefore, in a sensitivity analysis, values from 0,5% to 5% were calculated. The calculation shows, that the overall GHG balance rises for the state of the art technology from 97 g CO_2eq/kWh if 1 % is applied to 115,8 g CO_2eq/kWh (2 %) and even 171 g CO_2eq/kWh for 5 % nitrous oxide emissions of nitrogen fertilizer deployed.

In this assumed "worst case", there is not much margin of error for the plant technology: if the current state of the art technology is deployed, for example even minor leakage of methane from the digestate store can diminish the GHG difference of bio-methane to natural gas to nearly zero, thus annihilating the climate protection potential of the renewable energy carrier.

4. PROVISION OF SUBSTRATES – GHG BALANCE OF REGIONAL ADJUSTED CROP ROTATION SYSTEMS

In cooperation with agricultural experts from TLL, Jena, for five different locations throughout Germany regionally adjusted crop rotation systems for the provision of biogas substrates were composed[6]. They all contain maize as the most advantageous energy crop due to the high yield of raw gas as well as the high agricultural yield per acreage, but they all contain different crops as well, as they are typical and well known in the specific regions.

The crop rotation systems are built in a way, that they are adjusted for the production of biogas substrates. Nevertheless, the supply of biogas plants shall not take a part bigger as 30–40 % of the overall crop rotation system, to guarantee the farmer flexibility and security of income for his farm. Also, the production of biogas substrates shall be integrated in the conventional agricultural business as unproblematic as possible. Regional characteristics and specifications therefore have been taken into account while composing the crop rotation systems.

The approach was not so much to not use maize, but to use not only maize, in order to contribute to a more diversified agriculture. So, at all locations, maize is deployed, followed by rye and sorghum at four respectively three locations. By choosing silage from the whole crop from triticale and barley as well as cultivated grass (*Landsberger Gemenge*) and a combination of maize and sunflower, at each of the locations a new option is tested, that is not state of the art today.

In a first step, the substrates that are combined on the same acreage in one year are depicted in Figure 3, where there are two columns for each location. In Dornburg, Güterfelde and Soest maize is the main crop and not combined with another crop in the same year. The system is complemented by rye and sorghum or whole-crop-silage from barley, respectively. At Gülzow maize is combined on one field with rye or whole-crop-silage from triticale, in Ascha maize is combined with rye and grass (*Landsberger Gemenge*). In the graph are only the emissions from the provision of the substrates depicted, without the conversion to bio-methane.

The results are standardised to kilowatt hour of methane. Therefore the yield of biomass from the field and the yield of raw gas per ton of biomass have a huge influence on the diagram. For example, the amount of nitrogen fertilizer per hectare is higher for the cultivation of maize than for rye or sorghum. But as the yield both of biomass as of raw gas is considerably higher for maize as for rye and sorghum, the bar indicating nitrogen fertilizer in Figure 3 is lower for maize and higher for the other crops, that are less advantageous regarding biogas production.

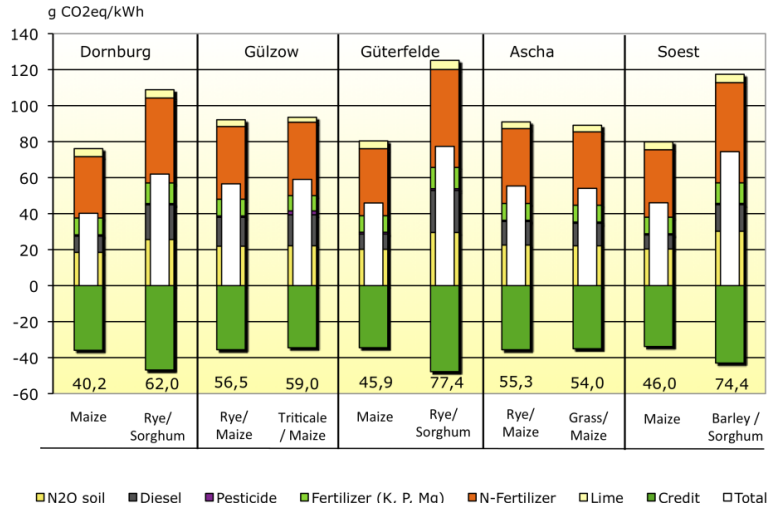


Fig. 3: Resulting GHG Balance from the Crop Rotation System at the Five Locations

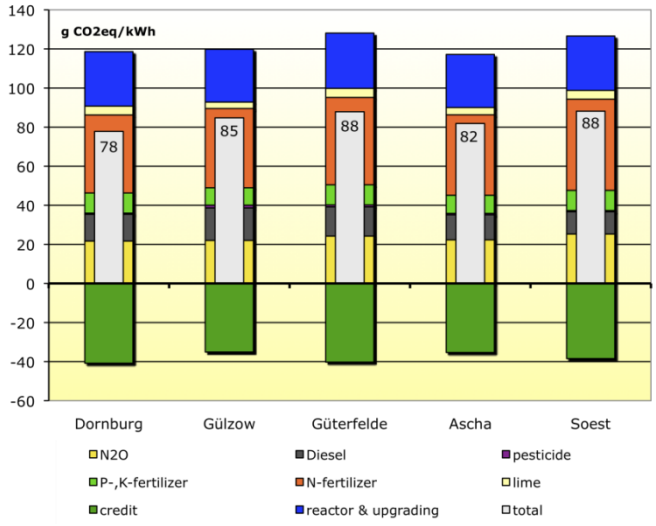


Fig. 4: Resulting GHG Balance at the Locations

In the next step, the respective substrates are combined for the each location. The crop rotation systems are perennial: after about five years, the rotation starts again. In order to supply the biogas plant with always the same

combination of substrates, the same system is applied at different farms, but shifted. This is according to established experiences in the large-scale biogas plants today.

At each location, the combination of substrates contains a minimum of maize. Therefore, in comparison of the resulting respective feedstock supply, the difference between the locations is not as considerable as shown before. This is visible from Figure 4.

As can be seen, the difference between the five locations vary only between 78g CO_2eq/kWh (Dornburg) and 88g CO_2eq/kWh (Güterfelde), if the credit for use of digestate instead of mineral fertilizer is taken into account. This is in line with the current state of the art, as both plant operator as crop cultivator benefit from it.

The main goal of the examination was to prove that there are other choices than just maize as substrate, that can still result in acceptable GHG balances which are not much higher than the ones achieved with maize only.

So even from an climate protection point of view, there is no need to plant maize in large-scale monocropping farms, which is strongly not recommended from an biodiversity, ecological and even agricultural point of view, as monocropping may allow pest and rodents to spread and is not in line with good agricultural praxis.

5. CONCLUSIONS

Two different types of biogas plant configurations have been closely examined and analyzed: a state of the art plant and one deploying the currently most optimized technology. The results of the LCA hold not in any case for small-scale plants that might not be equally professional operated.

Once the technology is optimized to the point of only marginal methane leakage from the reactor, a considerable yield of raw gas from the substrates, and, most importantly, a closed store for digestate, the cultivation of substrates contributes to the biggest amount to greenhouse gas emissions of the whole process chain.

Bio-methane can be produced from energy crops from dedicated farming without harming or negatively effecting the environment more than from conventional agricultural farming for food and feed production, if regionally adjusted crop rotation systems are deployed. The substrates evaluated in this paper – aside from maize – are rye, sorghum, whole-crop-silage from triticale and barley, and the innovative options of agricultural grass (*Landsberger Gemenge*) and a combination of maize and sunflower.

Regarding the resulting GHG emission factor of bio-methane, a slight increase can be noticed when applying regional adjusted crop rotation systems. On the other hand side, monocropping has its own disadvantages, as an increased risk of pest and rodents and an insecurity of income for the farm in years, when maize is not growing in an optimal way.

The farmer as well as the plant operator should therefore plan with a combination of at least three or four different substrates for the biogas plant. These can vary considerably for different locations, but a broad choice of crops is available, that allows for a satisfying GHG balance, as well.

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