Biogas Crops – Part II: Balance of Greenhouse Gas Emissions and Energy from Using Field Crops for Anaerobic Digestion

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ABSTRACT

Several field crops, cultivated under north-eastern German conditions, are analysed for their ecological benefit if used for anaerobic digestion. The analyses is based on the assessment of cumulated energy demand necessary for the cultivation at different fertilisation levels, transport and storage of these crops as well as on the assessment of greenhouse gas emissions deriving from these processes. Although the values obtained are quite similar to each other this picture completely changes if considering the methane formation potential and hence the electricity available from these renewable energy sources. Cereals like rye, triticale, barley and maize as well as alfalfa show relatively low values of GHG emissions, and cumulated energy demand whereas hemp and Jerusalem artichoke have a considerable worse balance. In the case of high fertiliser input during cultivation the value of GHG emissions for Jerusalem artichoke even approaches the value for electricity produced within the German power-mix. Open-top tanks for digested energy crops may be a serious source of additional methane emissions.

Keywords: cumulated energy demand, greenhouse gas emission, life cycle assessment, methane emission, crop cultivation

1. INTRODUCTION

Biofuels are suitable to substitute fossil fuels as energy sources. Therefore a substantial contribution can be achieved in the effort to mitigate the additional greenhouse effect. In 2020 renewable resources shall cover 20% of the primary energy demand within the European Union. In the second half of the century this contribution has to reach 50% in order to prevent an unpredictable extent of climate change (IPCC, 2001). Among renewable resources anaerobic digestion and utilisation of the biogas produced will play a considerable role as biogas is an universal energy resource comparable with natural gas.

Using manures from animal husbandry for anaerobic digestion has a very positive ecological effect. The life cycle assessment delivers an avoidance of greenhouse gas (GHG) emissions of approx. 600 g $CO_2eq \cdot kWh^{-1}$ of electricity and heat generated from biogas based on manure (Jungmeier *et al.*, 1999). The increasing use of field crops for anaerobic digestion may lead to a different assessment: at first the cultivation of these crops is responsible for a considerable amount of greenhouse gas emissions, at second the digested slurry from biogas crops is a completely new source of greenhouse gas emissions. In addition, it is also important to analyse whether the anaerobic digestion from biogas crops provides more energy than is used for the production, transport and storage of these crops.

Former studies on the environmental impact put more emphasis on conversion routes of bioenergy or the use of different feedstock such municipal organic waste (Berglund and Borjesson, 2006; Borjesson and Berglund, 2006). Studies that also assess the impact of crop cultivation often refer to unit size of field area rather than the energy output of the system (Hanegraaf *et al.*, 1998) which makes a comparison of results difficult. Therefore, this paper focuses on the environmental impact in form of GHG emissions and energy balance of the processes necessary for the supply of feedstock to the biogas plant.

2. MATERIALS AND METHODS

In order to assess the cumulated energy demand as well as the greenhouse gases balance of biogas crops the entire procedure of cultivation has to be considered together with the greenhouse gases balance due to the production of and the operation with the particular means for cultivation. GEMIS (Ökoinstitut and GH Kassel, 2002) and SimCrop (Ackermann and Plöchl, 2000; Plöchl *et al.*, 1998) are basic models for the life cycle assessment of products and processes. Whereas GEMIS provides basic data of various kind of energy generation and production of goods SimCrop puts emphasis on the production in agriculture and delivers data of many agricultural processes. Operations and inputs necessary for providing biogas crops for anaerobic digestion are summarised in Table 1 and Table 2. The cultivation of biogas crops has to take into account seedbed preparation, sowing, fertiliser applications, harvesting, transport and storage.

The biogas crops considered here are: winter rye (*Secale cereale*), winter barley (*Hordeum vulgare*), triticale (*Triticum x Secale*), maize (*Zea mays*), hemp (*Cannabis sativa*), Jerusalem artichoke (*Helianthus tuberosus*), and alfalfa (*Medicago sativa*).

The calculations of this assessment are based on the investigation of the methane production potential of several cereals and other crops (Heiermann *et al.*, 2009). The results of these lab-scale experiments are summarised in Table 3. In order to account for practical conditions rather than laboratory situation these values are decreased by 20% for further calculations.

For the cereals winter rye, winter barley, and triticale as well as for maize, and alfalfa yields and fertiliser requirements are based on the cultivation practices as described for areas of agricultural quality III in the State of Brandenburg in the northeast of Germany (Braun *et al.*, 2001). In the cases of hemp and Jerusalem artichoke results obtained from experimental fields of the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB) were used, based on three fertilisation regimes (Scholz *et al.*, 1999):

1. 150 kg N-fertiliser in three applications with a mineral basic fertilisation
2. 75 kg N-fertiliser in two applications with a basic fertilisation of either wood ash or straw ash
3. 0 kg N-fertilisation and no basic fertilisation

Table 1. Yields and fertiliser inputs of selected biogas crops. Data derived from Braun *et al.* (2001) and refer to areas of medium agricultural quality in northeast Germany. Data indicated with * are derived from ATB experimental field site. High input (index h.i.) and low input (index l.i.) are assumed to ±50% fertiliser input and resulting 10% increase and 20% decrease in yield, respectively, compared to standard values. (FM = fresh matter, ODM = organic dry matter)

Biogas crop	FM yield [t ha^{-1}]	ODM yield [t ha^{-1}]	N-fertiliser [kg N ha^{-1}]	P-fertiliser [kg P_2O_5 ha^{-1}]	K-fertiliser [kg K_2O ha^{-1}]
Rye	27.0	8.6	92	48	83
Rye$_{h.i.}$	29.7	9.4	138	72	125
Rye$_{l.i.}$	21.6	6.9	46	24	42
Barley	30.1	9.0	106	52	111
Barley$_{h.i.}$	33.1	9.8	159	78	167
Barley$_{l.i.}$	24.1	7.2	63	26	106
Triticale	22.0	7.4	95	45	88
Triticale$_{h.i}$	24.2	8.2	143	78	132
Triticale$_{l.i}$	17.6	5.9	48	23	44
Maize	27.4	9.0	114	56	147
Maize$_{h.i.}$	30.1	9.9	171	84	221
Maize$_{l.i.}$	21.9	7.2	57	28	74
Hemp*	33.5	10.0	75	7	11
Hemp$_{h.i.}$*	35.6	10.7	150	57	99
Hemp$_{l.i.}$*	29.2	8.8	0	0	0
Jer.artichoke*	13.7	4.1	75	7	11
Jer.artichoke$_{h.i.}$*	14.0	4.2	150	57	99
Jer.artichoke$_{l.i.}$*	12.6	3.8	0	0	0
Alfalfa	47.1	7.6	15	72	293

Table 2. Type and frequency of operations for cultivating selected biogas crops. Number of fertilisation operations is increased by one for high input variants and decreased by one for low input variants due to number of fertilisation turns.

Biogas crop	Ploughing and seedbed preparation	Sowing	Fertilisation and other operations	Harvest	Trans-port	Storage	Sum
Rye	3	1	2.5	1	1	2	10.5
Barley	3	1	2.5	1	1	2	10.5
Triticale	3	1	2.5	1	1	2	10.5
Maize	3	1	2	1	1	2	10.0
Hemp	3	1	2	1	1	2	10.0
Jerusalem artichoke	3	1	2	1	1	2	10.0
Alfalfa	0.67	0.33	1.33	3	1	2	8.3

In order to run the further calculations with three different yields and inputs for all of the crops (i.e. winter rye, winter barley, triticale, maize) we assumed that N-fertiliser and hence phosphorous and potassium are applied in 50% above the optimum and in 50% below optimum. From average yield to fertiliser relationships we assumed further that the excess application of fertiliser resulted in a 10% increase in yield whereas the reduced fertiliser input decreased yield by 20%. These data are all available from the data collection for the same areas of agricultural quality (Braun *et al.*, 2001). As alfalfa is in symbiosis to nitrogen-fixing bacteria it does not depend on N-fertilisation. A minor start-up fertilisation of 15 kg $N \cdot ha^{-1}$ only is considered prior to emergence. In Table 1 yields (fresh matter – FM and organic dry matter – ODM) and fertiliser inputs are summarised for all biogas crops regarded in this investigation. In addition to the yield to fertiliser relationship it is assumed, although less realistic, that the reduction of crop protection measures to zero does not affect yields.

Table 3. Lab-scale methane yields and 20% reduced yields to simulate practice conditions of selected biogas crops[1] at optimum harvest stage as obtained from Heiermann *et al*. (2009)

Biogas crop	lab-scale methane yield[1] [$m^3\ CH_4 \cdot kg_{ODM}^{-1}$]	in-practice methane yields [$m^3\ CH_4 \cdot kg_{ODM}^{-1}$]
Winter rye wcs[2]	0.448	0.358
Winter barley wcs	0.473	0.378
Triticale wcs	0.485	0.388
Maize silage	0.507	0.406
Hemp silage	0.259	0.207
Jerusalem artichoke silage	0.252	0.202
Alfalfa silage	0.353	0.282

[1] mean values of different varieties
[2] wcs = whole crop silage, i.e. silage produced from cut shoots including stems, leaves and grains

In average 10 to 11 operations per year are necessary for the cultivation of the biogas crops considered here. It is assumed that high fertilisation needs one additional operation, whereas low fertilisation also decreases the number of operations by one and that zero N-fertilisation decreases that number by two. In Table 2 all necessary operations for the cultivations are described together with their applications per year. For the transport we considered an average distance from field to storage of 10 km and that the crops are generally ensiled for storage. Silos are made of concrete and silage is covered with plastic foil.

After anaerobic digestion the digested material is usually stored in open-top storage tanks, similar to the tanks used for the storage of undigested animal manure. Owing to legislative conditions storage can last for up to 180 days. The digestate enters the storage tank with a temperature of approx. 40 °C. For further calculations it can be assumed that the digestate has an average temperature of 20 °C and an average storage time of 90 days.

Cumulated energy demand is expressed as GJ per hectare. GHG emissions are accumulated to CO_2-equivalents using the greenhouse warming potentials of the (IPCC, 2001), i.e. methane has 23-fold potential of carbon dioxide and nitrous oxide is 296-fold as effective.

The methane emission that can occur from these storage conditions has to be related to the energy that can be generated from the methane produced in the digesters. These emissions, expressed as CO_2 equivalents per kWh produced (GHG), are independent on the methane potential of the particular feedstock and can be described with the following equation:

$$GHG = \frac{\frac{\Pi_{CH_4}}{\Phi_{CH_4}} \rho_{CH_4} GHP}{\eta_{el}} \qquad (1)$$

Π_{CH4} methane emission from storage in % of methane formation potential of the feedstock

Φ_{CH4} methane formation in the digester in % of methane formation potential of the feedstock

ρ_{CH4} density of methane (722 $g \cdot m^{-3}$)

GHP greenhouse potential of methane (23 fold of CO_2)

η_{el} electrical conversion efficiency of the entire chain (3.51 $kWh \cdot m^{-3}$) assuming an electrical efficiency of the CHP of 0.39 and losses as well as internal consumption of 10% of the electricity produced

3. RESULTS

3.1 Cumulated Energy Demand and GHG Emissions from Energy Crop Cultivation on a Hectare Basis

Both cumulated energy demand (Figure 1) and GHG emissions (Figure 2) show a clear dependence on fertilisation level within each crop species. The cumulated energy demand has the same distribution pattern across species and fertilisation levels as it is for the GHG emissions. The highest values are obtained for maize silage with a fertilisation level of 171 kg $N \cdot ha^{-1}$ and amount to more than 12 $GJ \cdot ha^{-1}$ and 1600 kg $_{CO2eq} \cdot ha^{-1}$, respectively. Similar values are reached by barley and hemp. Triticale and rye range roughly ten percent below the high value. Jerusalem artichoke has even 20% lower values. Alfalfa shows the lowest values but one has to consider that the fertilisation level of these is much lower than for the other species. The relatively high values of alfalfa correspond to the rather high input of potassium fertiliser. The values obtained from variants with no nitrogen fertilising still have input of the other fertilisers. Nevertheless, it can be seen that fertilising is responsible for more than 80% of the cumulated energy demand and also for more than 80% of the GHG emissions.

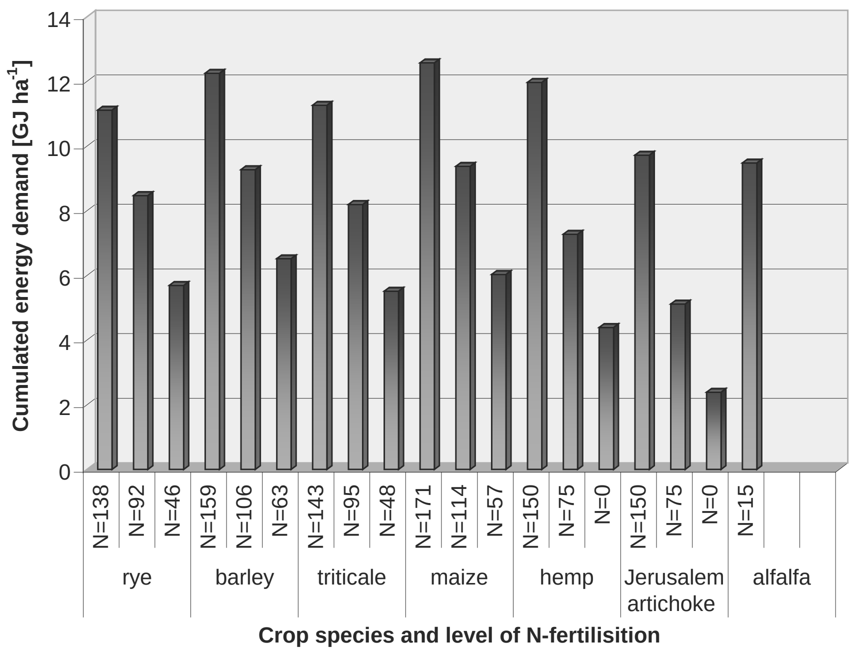

Figure 1: Cumulated energy demand per hectare for several crop species. With exception of alfalfa for each species three fertilisation levels are considered: optimal input, 50% excess and 50% reduction. These levels are characterised by the N-input in $kg{\cdot}ha^{-1}$.

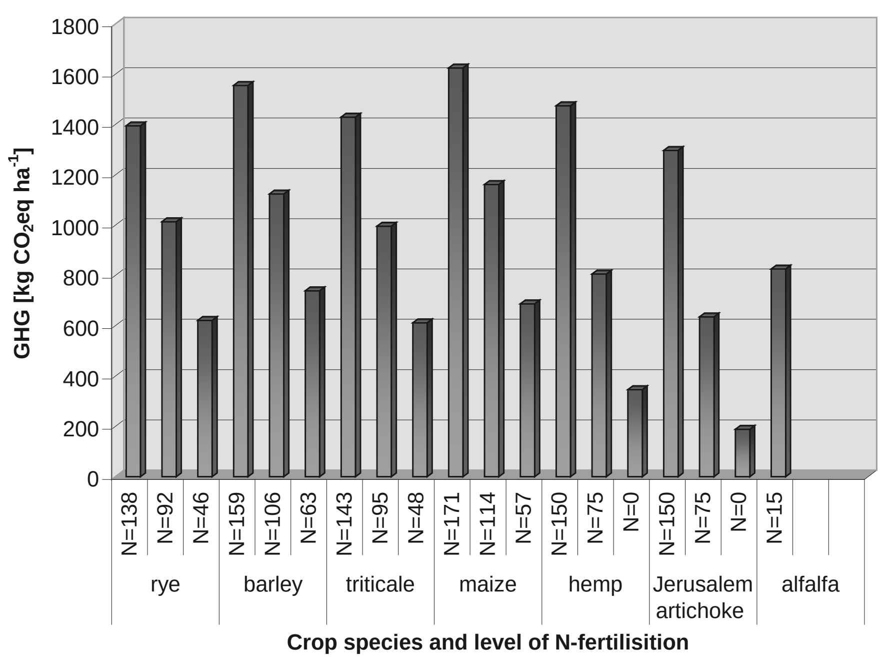

Figure 2: GHG emissions per hectare for several crop species. With exception of alfalfa for each species three fertilisation levels are considered: optimal input, 50% excess and 50% reduction. These levels are characterised by the N-input in $kg{\cdot}ha^{-1}$.

3.2 Cumulated Energy Demand and GHG Emissions from Energy Crop Cultivation Related to Electricity Produced

Cumulated energy demand (Figure 3) as well as the GHG emissions (Figure 4) are still dependent on fertilisation level within a species if they are referred to electricity produced from the methane rather than to unit area. But if the values are compared from species to species the picture is completely different. It can be seen the strong influence of the methane formation potential. Hemp and Jerusalem artichoke with methane yields of approx. 200 $m^3 \cdot t_{ODM}^{-1}$ show 4-fold higher values of both cumulated energy demand and GHG emissions than the other crop species. Within one species it also can be seen that the increase of crop yield per unit area has a reducing effect on the difference between values for high input and low input variants. Nevertheless, the higher yields cannot counterbalance the effects from the higher inputs. The difference between species is less than the difference between fertilisation levels within one species.

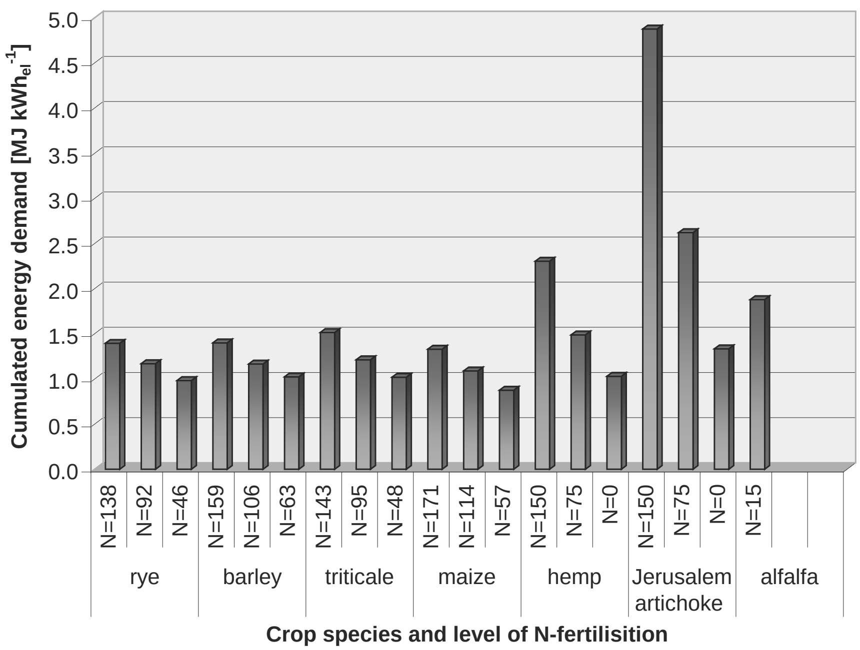

Figure 3: Cumulated energy demand per kilowatt-hour electricity available from anaerobic digestion for several crop species. With exception of alfalfa for each species three fertilisation levels are considered: optimal input, 50% excess and 50% reduction. These levels are characterised by the N-input in $kg \cdot ha^{-1}$.

The values for optimal input range between 1.09 and 1.21 $MJ \cdot kWh_{el}^{-1}$ for rye, barley, triticale, and maize, i.e. that approx. three-fold energy is available than is used. GHG emissions of these species at optimal input range from 135 to 147 $g_{CO2eq} \cdot kWh_{el}^{-1}$.

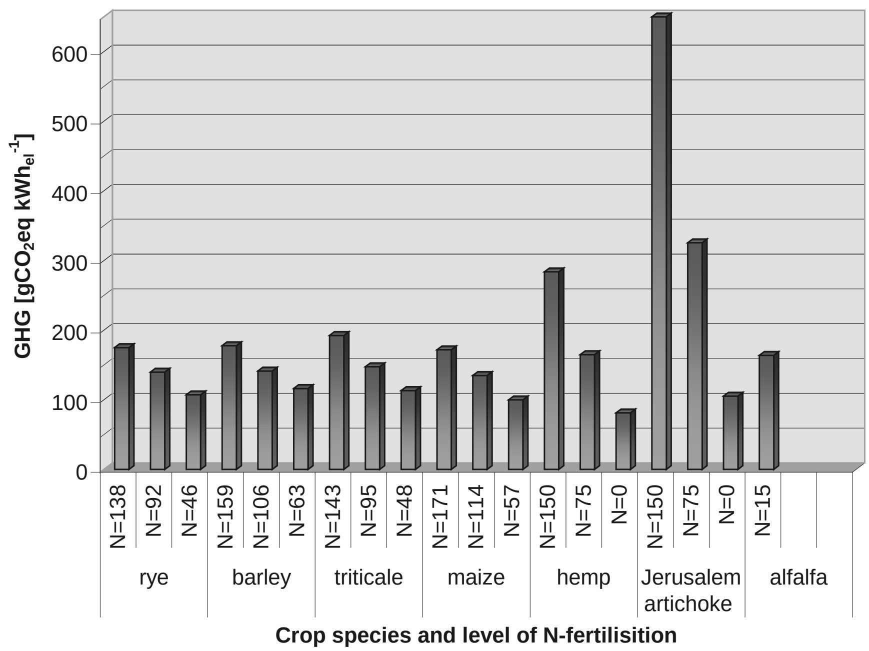

Figure 4: GHG emissions per kilowatt-hour electricity available from anaerobic digestion for several crop species. With exception of alfalfa for each species three fertilisation levels are considered: optimal input, 50% excess and 50% reduction. These levels are characterised by the N-input in kg·ha^{-1}.

3.3 GHG Emissions from Storage of Digested Field Crops Related to Electricity Produced

GHG emission per kWh electricity produced from storage is independent from the maximum methane formation potential of the crop. But it is strongly dependent from the degree of methane formed within the gas-tight system of digesters and the remaining potential in storage tank. It would also be strongly dependent on the electrical efficiency of the total conversion chain, but this parameter does not vary very much and is approx. 0.35 kWh·m^{-3} for current technology.

In Table 4 the GHG emissions as g $_{CO2eq}$·kWh$_{el}^{-1}$ are shown in dependence on degree of methane formed in the digester and the emissions from the remaining methane formation potential in the storage. Methane emissions from storage of 5 to 7% of the maximum methane formation potential imply already a remarkable risk to exceed the GHG emissions of electricity produced from natural gas, i.e. 400 g CO_2eq·kWh^{-1}.

Table 4: GHG emissions per electricity produced (g $_{CO2eq}$·kWh^{-1}) from storage of digestate independent on the particular biogas crops. Values below the thick lines exceed GHG emissions of electricity produced from natural gas.

Methane production in storage in % of methane formation potential	Methane production in digester in % of methane formation potential							
	60	**65**	**70**	**75**	**80**	**85**	**90**	**95**
1	78.9	72.8	67.6	63.1	59.1	55.7	52.6	49.8
2	157.7	145.6	135.2	126.2	118.3	111.3	105.1	99.6
3	236.6	218.4	202.8	189.2	177.4	167.0	157.7	149.4
4	315.4	291.1	270.3	252.3	236.6	222.6	210.3	199.2
5	394.3	363.9	337.9	315.4	295.7	278.3	262.8	249.0
6	473.1	436.7	405.5	378.5	354.8	334	315.4	
7	552.0	509.5	473.1	441.6	414.0	389.6	368.0	
8	630.8	582.3	540.7	504.6	473.1	445.3	420.5	
9	709.7	655.1	608.3	567.7	532.2	500.9	473.1	
10	788.5	727.9	675.9	630.8	591.4	556.6		
11	867.4	800.6	743.5	693.9	650.5	612.3		
12	946.2	873.4	811.0	757.0	709.7	667.9		
13	1025	946.2	878.6	820.0	768.8	723.6		
14	1104.0	1019.0	946.2	883.1	827.9	779.2		
15	1183.0	1092.0	1014.0	946.2	887.1	834.9		

4. CONCLUSIONS

Most of the crop species and fertilisation levels investigated supply more energy, in form of electricity, than energy is used for the production. The only exception is Jerusalem artichoke at high fertilisation level, which uses approx. 130% of the energy available as electricity after anaerobic digestion and cogeneration. But hemp at high fertilisation level and Jerusalem artichoke at optimal fertilisation level are still very close to the break-even value. Most of the energy used derives from mineral fertiliser production and accounts for up to 80% of the cumulated energy demand. A large quantity of this energy demand can be avoided if digested slurry is used as fertiliser instead, although the application of slurry uses more energy than the application of mineral fertiliser. Even if the energy demand of operations is doubled it is less than the half of energy demand by mineral fertiliser production.

Regarding GHG emissions from cultivation the values obtained are in general much lower than these of electricity generation from fossil fuels. The only exception here is again the high input variant of Jerusalem artichoke, which is almost equal to the value of GHG emissions due to electricity production in the German power-mix, which sums up to 627 $g_{CO2eq}·kWh_{el}^{-1}$ (Ökoinstitut and GH Kassel, 2002). All other values even do not exceed the value of electricity produced from natural gas accounting for 400 $g_{CO2eq}·kWh_{el}^{-1}$. Similar to the cumulated energy demand GHG emissions derive mainly from fertiliser production and thus could be reduced by application of digested slurry instead.

Although transportation has a contribution of approx. 5% to the GHG emissions this is only true under the assumed condition of 10 km distance between field and biogas plant. Increasing transportation distance to approx. 100 km would comprise for one third of the total emissions.

The positive contribution of biogas crops to the reduction of GHG emissions would be counteracted if methane emissions would escape from storage of digested material. These emissions can be prevented if the storages are covered gas-tight and/or retention time of feedstock containing biogas crops exceed 180 days (Linke and Mähnert, 2005). Nevertheless, digested material should be stored at temperatures clearly below 20 °C, in order to reduce the methane emission rate.

From the viewpoint of cumulated energy demand and GHG emissions silages of cereals and maize are recommendable biogas crops. Alfalfa is suitable as well for anaerobic digestion. Its methane formation potential is still strong enough to compete with the cumulated energy demand and the GHG emission during production. Although the cumulated energy demand and GHG emissions on a hectare basis for hemp and Jerusalem artichoke are low compared to these of cereals and maize they are not recommendable as feedstock for anaerobic digestion because of their very low methane formation potential. Although alfalfa is not as recommendable for anaerobic digestion as cereals there are other ecological aspects why alfalfa might be a considerable biogas crop: alfalfa fixes nitrogen from air and has very positive effects on soil quality for further cultivation. Further investigation of ecological value of biogas crops should not only focus on cumulated energy demand and GHG emission also on the effects of crop rotation and other aspects of cultivation.

As it could be demonstrated in other studies (Berglund and Borjesson, 2006; Borjesson and Berglund, 2006; Hanegraaf *et al.*, 1998) the influence of transportation of the feedstock over long distances and of unwanted methane emissions, e.g. from conversion processes or from digested slurry storage, will counterbalance the ecological benefit of energy from anaerobic digestion and hence have to be avoided as much as possible.

5. ACKNOWLEDGEMENT

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