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Hands-on model for assessing the greenhouse gas emissions and the fossil energy consumption of agricultural biogas plants

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In this article, we present an application for estimating and analyzing the greenhouse gas (GHG) emissions and cumulated energy demand of biogas production chains in agriculture, which was developed mainly for practitioners. The primary goal of this application is to illustrate: What are the important sources of GHGs along the biogas chain, and how can they be mitigated? In addition, figures for the individual specific CO_2-equivalent(CO_2e) emissions of electricity and heat supply from biogas are computed. In a reproducible manner, the application calculates the essential GHG sources within biogas systems, allowing for their comparison. In the underlying model, the process chain is separated into the sub-systems of energy crop production and biogas utilization. Using real-world data from ten biogas farms in Bavaria, we discuss the abilities and limitations of our application.

Keywords
Biogas, energy balance, greenhouse gas, mitigation, modeling

Abandoning the use of fossil energy carriers as soon as possible is indispensable for a drastic reduction in GHG emissions (IPCC 2013). About 80% of Germany's primary energy demand is currently still covered by fossil sources, including uranium (AGEB 2018). Consequently, the energy sector's share in the German greenhouse gas (GHG) inventory was about 85% for the year 2017 (UBA 2019). In order to promote a climate- and environment-friendly development of energy supply, the German Federal Government had enacted the Law on Renewable Energy ("Erneuerbare-Energien-Gesetz" – EEG), already in 2000. The EEG proved very effective so that from 2012 on, the legislator turned the focus from the further expansion of renewable energies (RE) to the reduction of the cost burden for private households. However, for energy production from biogas with its comparably high provision cost, competing in the electricity market is a hard road.

While bioenergy carriers have technological properties similar to fossil fuels, they are in principle "climate-neutral" with respect the carbon dioxide (CO_2) from the combustion of the biomass, as this is part of the short-term carbon cycle. In comparison to conventional storage procedures, GHG emissions are reduced significantly through the treatment of animal manure in biogas plants. The digested residues can be used as a fertilizer, directly or after additional treatment.

Public acceptance of biogas from energy crops, together with so-called first-generation liquid biofuels derived from food and feed crops, has dwindled in recent years. This increasingly critical view refers to a regionally concentrated, intensive production of energy crops, particularly maize, nuisance from the resulting agricultural transport activities, and ethical arguments such as competition with land for food production. Within the agricultural sector, biogas production has caused economical

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distortion of the market for rental land and increased nutrient surpluses in regions where numerous biogas plants using energy crops have been added to already large animal stocks (Reinhold 2013). It has to be made clear that biogas derived from crops that were primarily produced for energy production, exhibits significant GHG emissions and other environmental impacts such as acidification and eutrophication of ecosystems, originating both from cropland management and technical installations. Thus, there is a great demand for research on the environmental impacts of so far widely unconsidered integrated biogas concepts, e.g., based on the utilization of catch crops.

During the last ten years or so, numerous studies on the impacts of biogas systems on the environment, particularly climate change were published in the scientific literature (see Hijazi et al. 2016, for a review). Starting from model calculations (e.g., Scholwin et al. 2006, Vogt et al. 2008, Vetter & Arnold 2010), the trend turned towards the analysis of real-world biogas plants, based more or less on primary data (e.g., Lansche & Müller 2011, Schmehl et al. 2012, Bachmaier et al. 2013). Due to methodological differences in terms of scoping, data sources, functional units and reference systems, together with sometimes incomplete documentation, the results from different published studies cannot be compared on a numerical basis. At best, a qualitative comparison can be made.

If one aims at analyzing the GHG balance of energy production from biogas, he or she can basically choose between the following two options: Applying a special software tool for material flow analysis, such as GaBi ts (thinkstep AG, Leinfelden, Germany) or Umberto® (ifu, Hamburg, Germany), or using a common spreadsheet application. Special software offers a multitude of tools for depicting and evaluating material flow networks and, typically, an integrated inventory database of diverse processes; however, its handling requires considerable training time. When applying standard software, the user can concentrate on those processes which are essential for his research questions. On the other hand, the effort for programming, researching inventory data, and visualizing the results is greater than with dedicated software

Bachmaier (2012) was the first to model GHG emissions and cumulated energy demand (CEA) of combined heat and power (CHP) production from biogas for a larger set of real-world installations in agriculture. He used a dedicated software tool, amended with a VBA-script for automated data exchange, to develop a material flow model for agricultural biogas chains. The model was applied to 16 plants of which five were analyzed for two successive years, resulting in 21 different variants. The results of this case study illustrate a large variability in the GHG- and energy-balance of biogas plants in operation. For the 21 variants, the absolute difference in specific CO_2e emissions of electricity production between the plants with the smallest and the largest footprints was 607 g kWh^{-1}. Since he had to base his analyses on secondary data to a considerable degree, the author also performed Monte-Carlo-simulations for some of the important input parameters. In this way he found the following factors to dominate the uncertainty and variability in the specific CO_2e emissions of electricity production in agricultural biogas plants: Site-specific emission factors for nitrous oxide; supply of electricity to the plant from the grid; and the utilization ratio of co-generated heat.

Our work started from the question of how to acquaint practitioners in agriculture with the issue of GHG emissions from biogas systems. Soon, we identified the need for a tool that was simple and ready-to-use and, at the same time, provided a robust and specific assessment of the GHG balance of individual biogas systems. Supposedly due to both the difficulty of the task and, until recently, the limited demand from practitioners, such tools are hardly available. So far, specifying the specific GHG emissions of energy from biogas is statutory only for the case of utilizing biomethane as vehicle fuel, on the basis of the EU Renewable Energy Directive, as implemented with the German Directive on the Sustainability of Biofuels ("Biokraftstoff-Nachhaltigkeitsverordnung" – Biokraft-NachV). For this purpose, the tool 'BioGrace' is publicly available (Neeft et al. 2015). With this Microsoft®Excel application, the user can calculate the GHG balance of utilizing biogas from animal manure, organic municipal solid waste, and maize, as vehicle fuel or for CHP-production. However, the tool offers limited options to account for farm- and site-specific conditions.

At the Institute of Agricultural Engineering and Animal Husbandry within the Bavarian State Research Center for Agriculture (LfL), work on the assessment of GHG emissions from agricultural biogas systems commenced in 2004. Whenever available, the respective studies were based on primary data (Effenberger et al. 2006, Bachmaier et al. 2008, Bachmaier et al. 2010, Ebertseder et al. 2012). Against this background and the requirements identified in research and knowledge transfer as outlined above, the authors aimed at developing a software application for modeling and evaluating the GHG and energy balance of biogas plants in agriculture, with a geographic focus on Bavaria. This application should be useful both for educational and analytical purposes, in order to minimize GHG emissions and resource consumption of biogas plants in operation. This paper describes the methodology and engineering of the software application, and illustrates its functions using modeling results for a number of farms from the LfL's Biogas-Monitoring program.

Materials and methods

Initially, we developed a calculation model of agricultural biogas plants in Microsoft®Excel. In a second step, a simplified version of this model was programmed in PHP as a web application (Maze et al. 2017). So far, this version is restricted to the calculation of GHG emissions. While the Microsoft®Excel application is intended for researchers, the web application was designed for ease-of-use for virtually any operator of a biogas plant. The 'GHG Calculator' is available for free at www.thg-rechner.de, both in German and English languages. Users are encouraged to enter as much farm-specific data as possible into the calculation model. If certain information from the farm is lacking, this is filled up with default values so that the 'GHG Calculator' will still produce a result.

In principle, the calculation procedures for the impact assessment of global warming and cumulated energy demand are consistent with the methodology of life cycle analysis according to Nagus (2006). Figure 1 illustrates the boundaries and major parameters of the modeled biogas system which is divided into the two sub-systems of (1) the supply of input materials for anaerobic digestion and (2) the production and utilization of biogas as an energy carrier. The calculations are based on the period of one fiscal year. The inventory includes the three main GHGs from agriculture: Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). For evaluation, the GHG potentials over a time horizon of 100 years according to Forster et al. (2007) are used, i.e., 1 for CO_2, 25 for CH_4, and 298 for N_2O. The life cycle inventory of the biogas system is calculated and evaluated for the environmental impacts of global warming and cumulated energy demand for manufacturing (CED-M). The CED is a measure of describing the demand for final energy at the point of utilization, not the supply of primary energy (VDI 2012). For evaluation with the Microsoft®Excel application, the user can select from different allocation methods – usable energy, exergy, efficiency (eta) – or system extension (natural gas heating, fossil heating fuel mix, German electric grid mix, fossil electric grid mix).

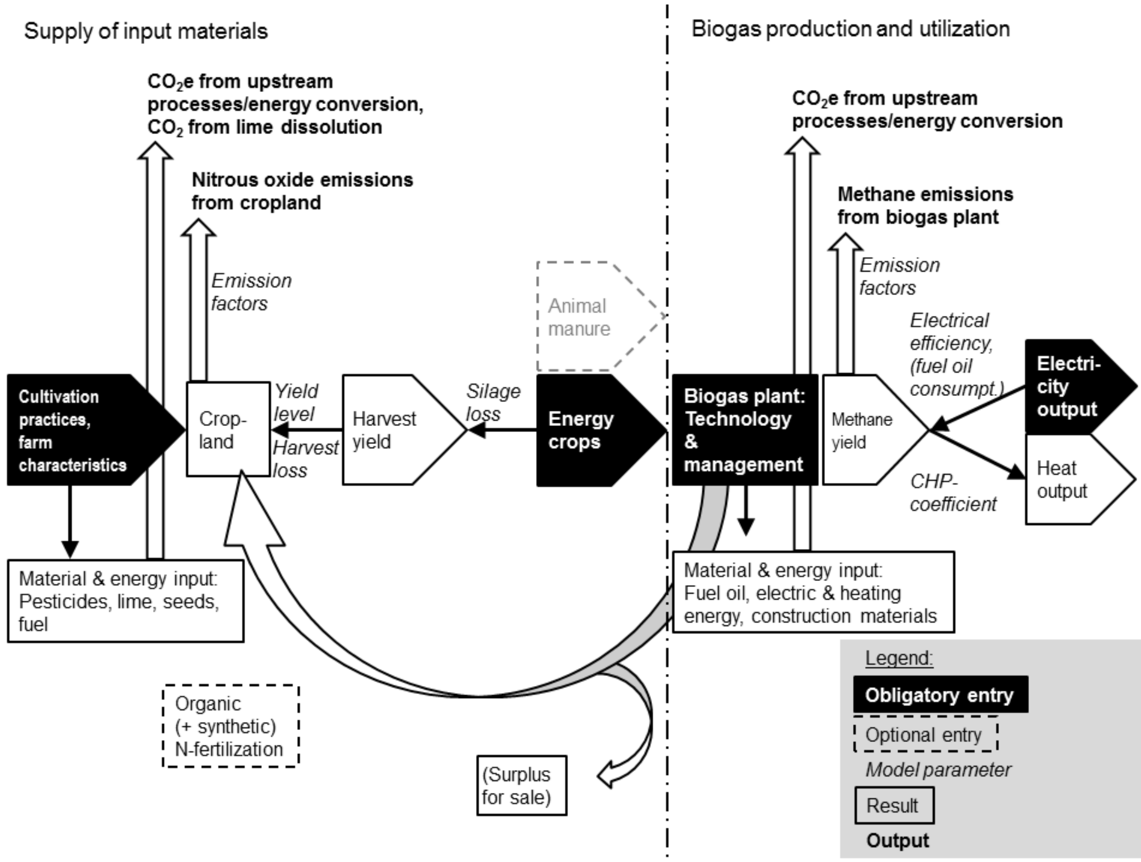

Figure 1: Sketch of the modeled biogas system, reaching from the cultivation of energy crops to the production and utilization of biogas as energy carrier.

For the sub-system of biogas production and utilization, the calculation starts from the electricity yield (Figure 1). The reason for this procedure is that electricity yield is always known and measured much more precisely than methane yield. Also, the calculation error resulting from inaccuracies regarding the utilization ratio of the CHP-unit (CHPU) and, if applicable, consumption of fuel oil, is deemed much smaller than that of calculating methane yield based on the amount of input materials. In the model, the electrical utilization ratio of the CHPU is either categorized based on the nominal electrical output according to Aschmann & Effenberger (2012) or calculated from a regression function (Table 1); the thermal utilization ratio is calculated from the CHP coefficient or taken from Table 1.

Table 1: Estimation of electrical and thermal utilization ratios of the CHPU in dependence of nominal electrical output.

	Nominal electrical output P_{el} in kW			
	≤ 75	**76…475**	**476…800**	**801…2000**
Electrical utilization ratio η_{el}, %	32.0	35.0	38.5	40.0
	or: η_{el} = 2,7029 × ln(P_{el}) + 21.074			
Thermal utilization ratio η_{th}, %	50.0	44.0	42.0	43.0

Optionally, transformation losses during feed-in of the electricity into the public grid can be included in the calculation (by default: 1.5%). These were excluded from the calculations presented in this paper (cf. Table 3).

Cumulated methane emissions from the plant are modeled using emission factors with respect to calculated gross methane yield as given in Table 2. The inventory for the manufacturing of building materials for the biogas plant is calculated on the basis of electricity yield, using values of 2.87 g kWh^{-1} for CO_2e emissions and 0.01 for CED, taken from Dreher et al. (2012). CED for the construction of the plant as well as for the supply of materials during operation such as additives, activated carbon, engine oil, etc. was neglected.

Table 2: Modeling of methane emissions from the biogas plant and the CHPU; emission factors are in percent of gross methane yield.

Specification of methane sources within the biogas plant and the CHPU	Methane emission factor
Leakage through diffusion	0.2 %
Methane emissions from CHPU with exhaust gas („methane slippage“)	1.5 %
Additional sources:	
If an automatic gas flare is not present:	0.5 %
If plant is not checked for leakages on a regular basis:	0.3 %
If the biogas produced from the storage tank for digested residues is not captured (residual methane potential not known/tested):	1.5 % / according to result

For the sub-system of the supply of input materials for anaerobic digestion, the calculation starts from the input mass of energy crops (Figure 1). Animal manure is included as input, yet with “zero environmental footprint”. It has to be stated that this calculation procedure favors the biogas system in comparison with animal husbandry. In the model, it is assumed that the residues from the digestion of energy crops are brought back to the cropland, whereas the digested animal manure is redirected to animal husbandry, based on the amount of nitrogen input. In the current version of the model, the use of other residual and waste materials is not incorporated.

From the input mass, the land area required for the cultivation of energy crops is calculated assuming mean standard yields for Bavaria over five years and including losses during storage. To improve the accuracy of the calculated results, the user is prompted to submit specific data on harvest yield level, cultivation period, number of cuttings, maturity stage and dry matter content at harvest, and silage quality. Based on the calculated area of cropland, the model evaluates the application of synthetic and organic nitrogen (N) fertilizers, which induces emissions of N_2O from the soil. For Bavaria, aggregated N_2O emission factors can be selected on a county basis. The model also incorporates the CO_2 emissions from the decomposition of lime in the soil as well as from the consumption of diesel fuel for field work. Furthermore, so-called indirect N_2O emissions from nitrate leakage and ammonia deposition are calculated (Dong et al. 2006). Emissions of ammonia (NH_3) during landspreading are modeled in dependence of the technique used for application of the digested residue. As this information was not available for all of the farms in this assessment, we used a mean NH_3 emission factor that was derived from statistics on application techniques used in Germany (Table 3). Similarly, NH_3 release from the application of mineral fertilizer is calculated using a mean emission factor that is derived from the sales of different nitrogen fertilizers in Bavaria. The consumption of diesel fuel for field work and transport is estimated as a function of tillage, farm-to-field distance, and field size, according to the 'Fieldwork Calculator' by the "Kuratorium für Technik und Bauwesen in der Landwirtschaft – KTBL" (KTBL 2014).

Based on the mass and composition of the input materials, the amount of digested residue is modeled and distributed to the individual crops according to their nitrogen uptake. For conventional farms, the additional application of N with synthetic fertilizer can be specified. By default, the amount of additional N that is required to balance overall N removal is calculated. Since it is outside the system boundary, the supply of N contained in animal manure is excluded from the nitrogen balance (Bacenetti et al. 2013). Finally, the model also includes emissions from the provision of seeds, pesticides, diesel fuel, mineral fertilizer, and lime. For further details on the calculation procedures of the sub-system of energy crop supply, the reader is referred to Effenberger et al. (2014).

For the assessment presented in this paper, we used the Microsoft®Excel application of the 'GHG Calculator' which allows a quick calculation of the CO_2e balance for a set of biogas farms by means of a macro. This set comprised ten farms which are located in Bavaria and had been evaluated within the LfL's Biogas-Monitoring program (Kissel et al. 2015, Streicher et al. 2016). These are all "conventional" farms which are characterized in Table 4. Common assumptions for all of the plants are compiled in Table 3. As a rather distinct feature for Bavaria, the farms with ID 8 and 12 are practicing no tillage.

Table 3: Common assumptions for the comparative assessment of the GHG balance for ten agricultural biogas plants from the LfL's monitoring program.

Parameter	**Specification**
Number of cuts per year for clover/-grass and grassland	4
Cultivation period, years	
Permanent grassland	20
Clover/-grass	3
Other	1
Distance from field to farm, km	2
Field area, ha	2
Share of purchased input materials (m/m), %	10
Transport distance for purchased input materials, km	6
Emission factor for ammonia during the application of digested residues to cropland / grassland, kg NH_3-N kg TAN^{-1}	0.13 / 0.28
Silage losses (m/m), %	8
Floating layer present in storage tank for digested residues?	yes
Biogas plant inspected on a regular basis?	no
Fuel oil for CHPU (if applicable)	Rapeseed oil
Transformation losses, %	0

Results and discussion

Firstly, we present and discuss the results from the assessment of the ten biogas farms characterized in Table 4, which was prepared with the Microsoft®Excel application of our 'GHG Calculator'. Secondly, we use the example of a single farm to illustrate the functions of the web application. When developing the web 'GHG Calculator', we presumed that, for the owner of a biogas farm, it is of prior importance to gain a basic understanding of what the major sources of GHG emissions along the biogas chain are and how they can be mitigated. In second place comes the robust calculation of an individual value for the specific CO_2e emissions of energy from biogas.

Table 4: Characteristics of the ten biogas farms for the comparative assessment of CO_2e emissions.

ID	3	4	5	8	10	12	9	11	6	7
Category	**Grassland**			**Energy crops**			**Animal manure bonus**		**Animal manure**	
Supply of input materials										
Share of different types of input materials (m/m), %										
Energy crops (EC)	60	58	65	72	98	96	64	66	19	23
Thereof grass, %	65	84	68	18	18	-	27	25	14	-
Animal manure	40	42	35	8	2	4	36	34	81	77
Bio waste/residues	-	-	-	20	-	-	-	-	-	-
N_2O-emission factor, %										
Cropland	1.8	2.2	0.7	1.6	3.0	2.0	1.0	1.0	1.0	1.3
Grassland	0.9	0.7	0.5	0.7	1.0	0.9	0.7	0.7	0.7	0.8
Biogas production and utilization										
CHPU: Nominal electrical output, kW	147	100	625	536	750	800	190	920	103	75
Storage of digested residue	C	O	C	O	C	C	O	C	C	O
Supply of electricity to biogas plant	G	G	G	G	O	83% G, 17% PV	G	G	G	G
Share of parasitic electricity demand, %	7.2	17.3	11.6	9.8	7.7	6.5	9.6	6.2	8.0	7.6
Share of parasitic heat demand, %	21	43	21	20	15	5	13	16	26	34
Automatic gas flare present?	no	no	yes	yes	yes	yes	no	yes	no	no
Utilization ratio of heat output, %	22	100	38	33	87	61	100	65	85	36

CHPU: Combined heat-and-power unit; C: Closed with biogas capture; O: Open w/out biogas capture; G: Public grid; O: Own production; PV: Own photovoltaic plant.

Characteristics of the ten biogas farms in terms of input materials, energy flows, and energy utilization ratios are given in Table 4. "Share of parasitic electricity demand" of the biogas plant comprises the electricity consumed for operating agitators, pumps, coolers, the gas blower, etc., as a fraction of gross electricity output of the CHPU. "Utilization ratio of heat output" comprises the fraction of thermal energy that is supplied to external consumers such as a district heating network or a stable, in relation to the amount of heat available after covering the demand for heating the digesters. For the following comparative assessment, the ten biogas plants were categorized according to their input materials (see Table 4): "Grassland" – IDs 3, 4, 5; "Energy crops" – IDs 8, 10, 12; "Animal manure bonus" (i.e., energy crops + animal manure) – IDs 9 & 11; and "Animal manure" – IDs 6 & 7 ("Animal manure plants" as specified in the EEG 2012/2014 that use a minimum of 80% (m/m) of animal manure in the input were not included in the assessment). Plant 11 which is discussed in further detail below belongs to the category “Animal manure bonus”.

Apparently, the distribution of CO_2e emissions from a biogas system is strongly influenced by the presence or absence of the following sources: supply of fuel oil to the CHPU, open storage of digested residues, supply of electricity from the public grid, and use of synthetic fertilizer. At first sight, we can therefore identify hot spots of CO_2e for some of the plants: IDs 7, 8, and 9 feature open storage tanks for the digested residues; ID 4 consumes an excessive share of electricity from the grid, at the same time it does not use any synthetic fertilizer; ID 11 has the highest share of “fixed” emissions, in particular from the CHPU, but offers further mitigation potential by reducing the amount of synthetic fertilizer (Table 4, Figure 2).

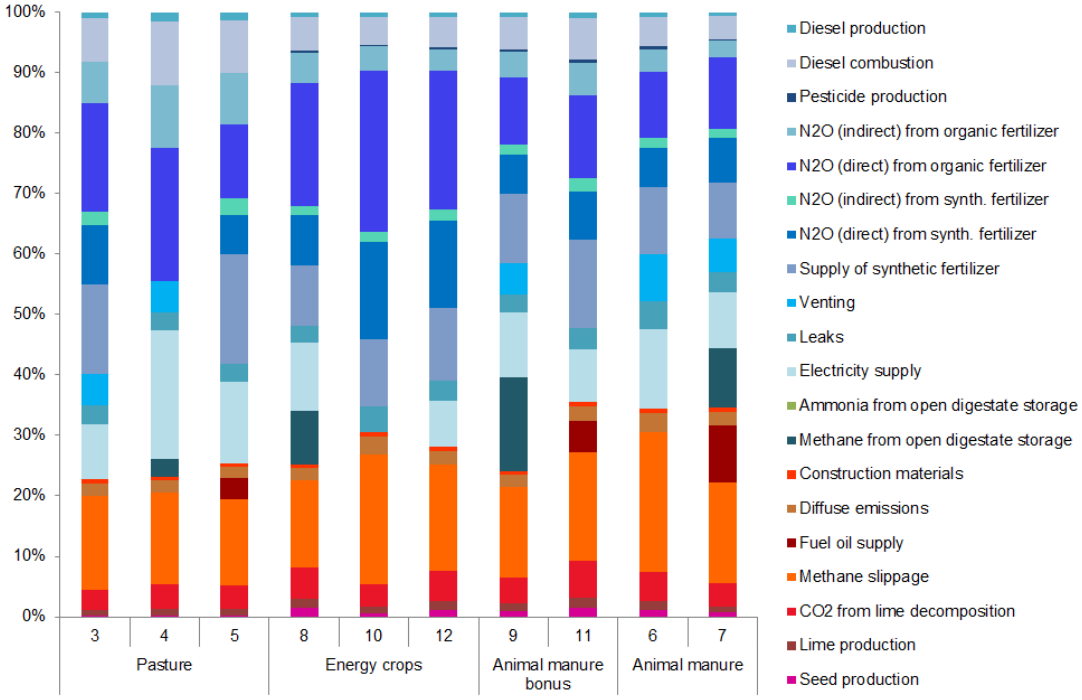

Figure 2: Distribution of specific CO_2e emissions from individual sources for the ten biogas plants, categorized with respect to input materials.

In the web application, CO_2e emissions are by default allocated to electricity and heat outputs based on exergy. Exergy describes the fraction of energy that can be converted into mechanical work. For reasons of simplification, this “exergy factor” was assumed as 0.35 for thermal energy flows and 1 for electricity. For the ten biogas plants, the resulting values for the specific CO_2e emissions range from 248 to 369 g per kWh of electricity fed into the grid, and from 134 to 713 g per kWh of heat supplied to external users. Since this is discussed as an important technical option for mitigating CO_2e emissions from animal husbandry, the ‘GHG Calculator’ does also model the CH_4 and N_2O emissions that are avoided by utilizing animal manure in biogas plants, in comparison to storing it in conventional open systems. In our assessment, these avoided CO_2e emissions range from 2 to 384 g per kWh of electricity output. For the two “animal manure” plants with IDs 6 & 7, these avoided flows of GHGs are larger than the overall CO_2e emissions from the biogas chains (Table 5).

Table 5: Distribution of CO2e emissions to electricity and heat for the ten biogas plants, applying exergy allocation and credits for avoided emissions during conventional storage of animal manure.

Category	ID	Share of emissions allocated to electricity	Share of emissions allocated to heat	Specif. CO_2e of electricity (gross)	Avoided CO_2e animal manure storage allocated to el.	Specif. CO_2e of electricity (net)	Specif. CO_2e of heat
		%	%	g kWh^{-1}	g kWh^{-1}	g kWh^{-1}	g kWh^{-1}
Grassland	3	71	29	319	-73	247	713
	4	71	29	329	-106	223	205
	5	71	29	344	-77	267	446
Energy crops	8	71	29	348	-11	337	523
	10	72	28	272	-2	270	134
	12	72	28	300	-7	293	205
Animal manure bonus	9	72	28	369	-59	310	157
	11	74	26	299	-58	241	214
Animal manure	6	71	29	248	-280	-33	155
	7	74	26	341	-384	-43	564

If emissions are completely allocated to electricity output, the resulting specific CO_2e emissions range from 347 to 510 g kWh^{-1}. Applying system expansion with substitution of heat from natural gas and including avoided GHG emissions from conventional animal manure storage, specific CO_2e emissions of electricity output in the ten biogas plants are calculated in the range from -116 to 402 g kWh^{-1}, with a median value of 201 g kWh^{-1} (Table 6). With a respective value of 206 g kWh 1, plant “11” of category “animal manure bonus” is in the upper-medium range (Figure 3).

Table 6: Comparison of calculated specific CO_2e emissions of electricity output, g kWh^{-1} for the ten biogas plants using allocation by exergy or system expansion with substitution of heat from natural gas.

	Specif. CO_2e (Exergy, gross)	Specif. CO_2e (gross)	Avoided CO_2e from animal manure storage	Substitution of heat from natural gas	Specif. CO_2e (Exergy, net)	Specif. CO_2e (System expansion)
Minimum	248	347	2	52	-43	-116
Maximum	369	510	384	255	337	402
Median	324	456	66	148	257	201

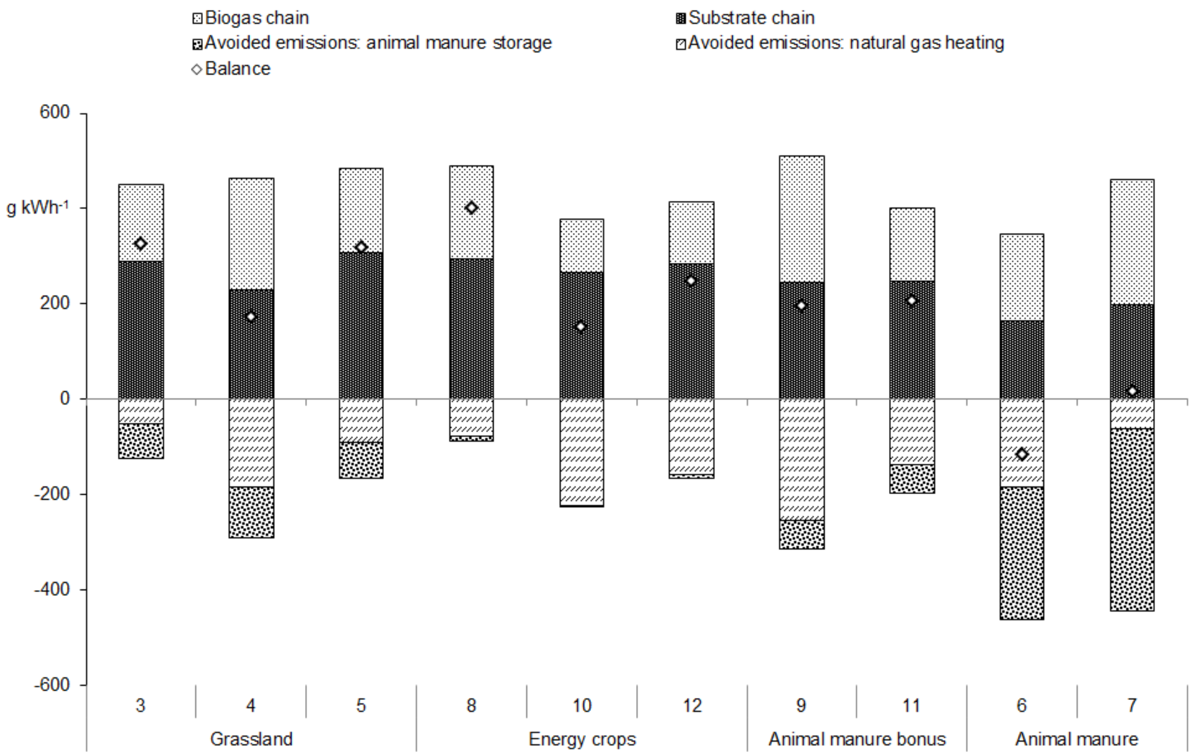

Figure 3: Comparison of the aggregated CO_2e balance for the provision of electricity, g kWh^{-1} for the ten biogas farms, categorized with respect to input materials; calculations were performed using system expansion including avoided emissions from conventional animal manure storage and through substitution of heat from natural gas.

In the following, we illustrate how the different CO_2e sources along the biogas process chain are itemized by the 'GHG Calculator' web application, using the example of the biogas farm with ID 11. For this purpose, the application produces a pie chart, in which so-called "unchangeable" emissions are colored in red shades, while so-called "avoidable" emissions are colored in blue shades (Figure 4). In this context, "avoidable" designates those emission flows which could be mitigated by changes in agricultural practices (e.g., type and amount of synthetic fertilizer applied) or through technical measures (e.g., covering the storage tank for digested residues for capturing the released biogas).

With a share of about one third of liquid pig manure and two thirds of energy crops (Table 4), the input mix of biogas plant "11" is adjusted to meet the requirements for earning the so-called "animal manure bonus" according to the EEG. This plant is well-equipped from the perspective of technical mitigation of CO_2e emissions: Biogas released during storage of digested residues is captured and the plant features an automatic gas flare (thus, these emission sources do not show up in Figure 4). As a consequence, with a share of 18% of total CO_2e the methane slippage from the engine becomes the largest emission source; second come emissions from the supply of synthetic fertilizer with a share of 14.5%, and third nitrous oxide emissions from digested residue fertilizing with 13.8%. The cumulated share of the production and application of synthetic and organic nitrogen fertilizer to produce energy crops adds up to 44% of the total CO_2e emissions from this biogas farm.

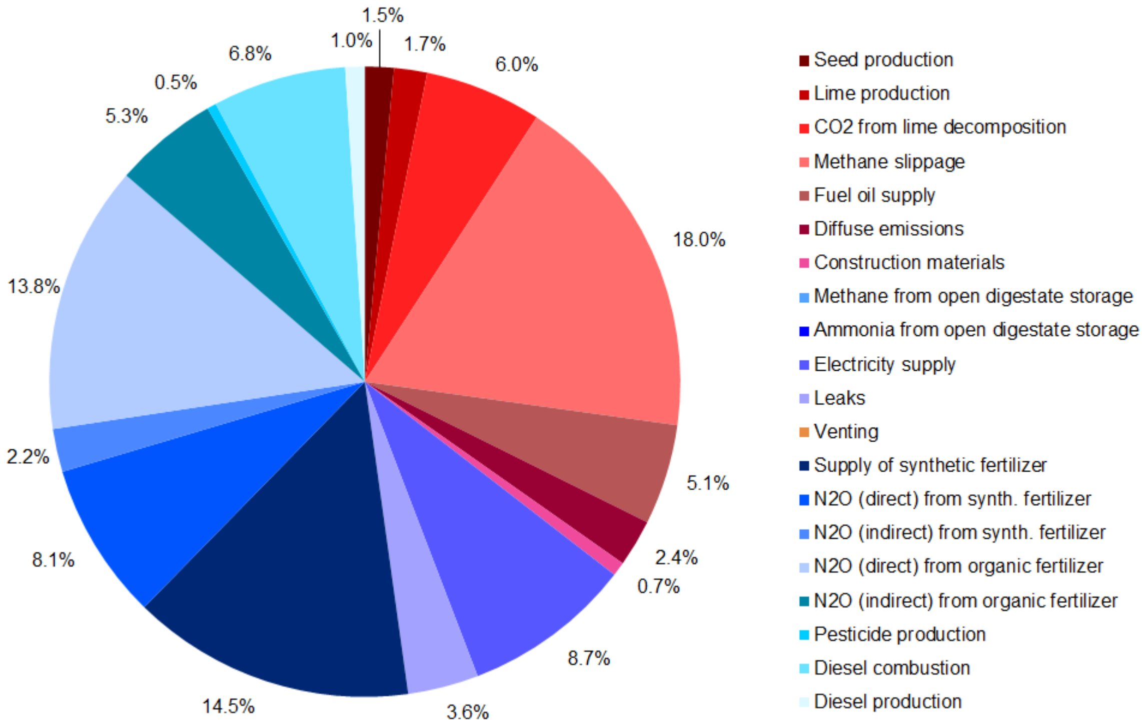

Figure 4: Pie chart from the ‚GHG Calculator' web application, illustrating the division of CO_2e emissions for the biogas process chain of plant „11".

Although our sample is by far too small to derive general conclusions with respect to different types of biogas farms, we will discuss a few observations from the assessment of the CO_2e balance for the ten plants. In Figure 3 it is quite obvious that the share of animal manure in total input mass has a very strong impact on CO_2e emissions if avoided GHG emissions from conventional manure storage are allocated to electricity from biogas. However, those farms which have adjusted their input mix to the requirement for the EEG "animal manure bonus", i.e. a minimum share of 30% of animal manure, they can offset only about a quarter to half of the CO_2e emissions that are released during the production of energy crops. Biogas farm "8" is the only one in our assessment which uses bio-waste/residues, with a share in the input mix of 20% (m/m). Nevertheless, the gross CO_2e emissions for this farm are comparably high due to the large share of energy crops and the open storage of the digested residues. Since only a small amount of avoided emissions can be credited from the share of 8% of liquid animal manure in the input mix, farm "8" comes out with the highest net specific CO_2e emissions.

The biogas farms with IDs 4, 6, 9, and 10 reach utilization ratios of available heat of 85% or more, and only for such a high degree of heat utilization, the GHG emissions from the biogas system can be nearly offset by the substitution of natural gas (Figure 3). When extending the system in this way, we used a credit of 284 g kWh^{-1} for the specific CO_2e emission of heating energy from natural gas (IINAS 2017). The maximum value for the CO_2e footprint of electricity provision from biogas in our analysis is on a par with the current German grid mix. This means that the electricity fed into the grid from a biogas plant that is utilizing mainly dedicated energy crops and wasting most of the CHPU heat output, does not achieve any GHG mitigation. The median value of specific CO_2e emissions of electricity from our sample of ten biogas plants is 66% lower than the German grid mix. For the best case in this assessment, the net specific CO_2e emissions with the approach of system expansion become negative, at a level of 120% below the German grid mix, reflecting specific mitigation of 700 g CO_2e per kWh of electricity output.

As an additional feature, the 'GHG Calculator' offers the option of evaluating on-farm measures for the mitigation of GHG emissions. Here, we assessed the changes in the GHG-balances for the ten biogas plants if the following measures were applied (provided that these had not been realized beforehand):

a. Periodic checking of the biogas plant for gas leaks + installation of an automatic gas flare + capturing the biogas released during digested residue storage
   → Methane loss is reduced, resulting in an increase of the usable methane yield
   → Demand for input materials/cropland is reduced while usable methane yield is kept constant (Scenario 1) OR
   Electricity output from the same amount of input materials is increased (Scenario 2);
b. Covering the parasitic electricity demand of the biogas plant from the CHPU output, thus feeding only the surplus electricity into the grid
   → GHG footprint for electricity consumed from the grid is cancelled and, at the same time, less electricity from biogas is fed into the grid;
c. Using all of the available heat output from the CHPU for substituting heating energy from natural gas
   → CO_2e footprints and division between electricity and heat will change.

Table 7: Changes in the amount of energy delivered from the ten biogas plants as a result of applying selected measures for GHG mitigation: comparison of scenario 1 (keeping electricity output constant while saving input materials) and scenario 2 (keeping the amount of input materials constant while increasing electricity output); negative values: reduction; positive values: increase.

Category	ID	Scenario 1				Scenario 2					
		Electricity feed into grid		Heat sales		Electricity output		Electricity feed into grid		Heat sales	
		kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Grassland	3	-67,672	-7	601,666	348	2,848	0.3	-64,947	-7	604,013	350
	4	-83,556	-17	0	0	2,910	0.6	-80,948	-17	1,889	1
	5	-519,935	-12	2,292,461	161	13,514	0.3	-507,361	-11	2,303,657	162
Energy crops	8	-411,104	-10	2,355,007	206	51,699	1.2	-362,429	-9	2,397,912	210
	10	0	0	725,798	15	19,678	0.3	-483,665	-7	742,287	16
	12	-389,292	-6	2,161,576	64	18,182	0.3	-371,815	-6	2,178,244	65
Annimal manure bonus	9	-144,650	-10	0	0	28,056	1.9	-118,207	-8	25,206	2
	11	-332,335	-6	1,378,442	53	16,211	0.3	-316,725	-6	1,390,464	53
Animal manure	6	-71,587	-8	98,866	17	2,708	0.3	-69,009	-8	100,910	18
	7	-47,066	-8	234,365	176	7,338	1.2	-40,061	-6	238,707	179

Table 8: Changes in (specific) CO_2e emissions for the ten biogas plants as a result of applying selected measures for GHG mitigation: comparison of scenario 1 (keeping electricity output constant while saving input materials) and scenario 2 (keeping the amount of input materials constant while increasing electricity output).

		Scenario 1				Scenario 2		
Anlagen-typ	ID	Specif. emissions to electricity	Specif. emissions to heat	Total yearly emissions	Reduction in cropland	Specif. emissions to electrici-ty	Specif. emissions to heat	Total yearly emissions
		%	%	%	ha	%	%	%
Grassland	3	-13	-82	-19	2.2	-11	-82	-17
	4	-20	-34	-34	1.8	-19	-33	-32
	5	-6	-68	-17	3.9	-6	-68	-16
Energy crops	8	-16	-75	-24	7.6	-16	-75	-23
	10	-5	-18	-5	2.9	-5	-17	-4
	12	-5	-46	-11	1.3	-5	-46	-11
Animal manure bonus	9	-30	-37	-37	6.4	-28	-35	-34
	11	-7	-43	-13	2.7	-7	-43	-12
Animal manure	6	-20	-37	-26	0.7	-19	-37	-25
	7	-23	-74	-29	0.8	-23	-74	-28

If the parasitic electricity demand is covered by the CHPU, the amount of electrical energy fed into the grid is reduced, accordingly. Depending on the initial situation, the heat sales from the biogas plants could be increased to a varying degree (Table 4, Table 7). For scenario 2, preventing the loss of methane through leakage translates into an increase in electricity output by 0.3 to 1.9%. At the same time, this is by far offset by parasitic electricity consumption, so that electricity feeding to the grid is 6 to 17% lower in comparison to the initial situation. For farm "10" which practiced surplus feed-in beforehand, the scenarios also result in an overall reduction of electricity output. This is a result of the longer runtime of the CHPU, which consumed about 60% of the overall parasitic electricity demand of the biogas plant. The heat sales are generally higher for scenario 2 in comparison to scenario 1, as heat and power outputs are coupled.

In both scenarios, the greatest reduction in overall GHG emissions is calculated for farms "9", "4", "7", "6", and "8", in the order of declining relative reduction. This is above all the result of preventing the leaking of methane from the biogas plants. By reducing methane leakage, the demand for cropland on those farms that use mainly energy crops for biogas production could be reduced by 0.8 to 7.6 ha (Scenario 1: constant electricity output). At the same time, this would mean a decrease of CO_2e emissions from the supply of energy crops. Keeping cropland area constant in scenario 2 reduces total GHG mitigation on the farms by 1 to 3% (absolute values), in comparison to scenario 1. The specific CO_2e emissions of electricity supply from the ten biogas plants are reduced by 5 to 30 % for scenario 1 and by 5 to 28% for scenario 2 (Table 8). Not surprisingly, the largest potential for mitigating the specific CO_2e emissions from heat supply is achieved for those biogas plants which initially sold relatively little heating energy (IDs 3, 5, 7, 8, 11).

Finally, there remains the question of how feasible the proposed measures for mitigating CO_2e emissions from biogas plants really are. Calculating the actual effects on the farms' economics would be a complex task and is beyond the scope of this paper. Typically, the farmer's decision on the implementation of such measures will at first be determined by their monetary costs, which are quite variable. Periodical checking of the plant for leaks means some extra effort plus limited expenses for the equipment required. While the costs of an automatic gas flare are considerable, they should not impose a financial hurdle – except for the case of a small farm-based biogas plant for the sole digestion of animal manure. In contrast, before an existing open storage tank is retrofitted to collect the residual biogas, the owner of the plant would normally carry out a cost-benefit analysis. According to Vogt et al. (2008), the retrofitting would have to produce an additional gas yield of 2 to 6% for biogas plants using mainly energy crops and 6 to 17% for plants that use mainly animal manure, in order to be profitable. The problem is that it is impossible to determine the exact additional gas yield that can be expected, in advance, but its likely maximum can be estimated from a test for residual biogas yield at psychrophilic conditions (20 °C; Ebertseder & Lichti 2015). However, the respective values found in field-studies for digested residues from energy-crop-biogas plants were mostly below 2% (Lehner et al. 2009, Lehner et al. 2010, Oechsner et al. 2015). Finally, the profitability of selling heat from the biogas plant will mainly be determined by the size of available heat sinks in the vicinity.

If a biogas plant switches from complete feed-in of the electricity output to surplus feed-in, this does not affect the overall CO_2e emissions of the electricity supply system. However, if it fits with site conditions, an alternative approach could be to operate biogas plants with co-generation in such a way that both heat and electricity outputs are utilized locally to the maximum possible extent. The public grid would then only be used to cover any residual load or feed-in surplus electric energy. The Bavarian State Research Center for Agriculture has tested this approach on one of its experimental farms: With the combination of a biogas plant with two CHPUs and variable feeding with sugar beets, and a photovoltaic plant, it was possible to cover the local electricity demand to a degree of 71% on an annual basis, and 86% on a weekly basis (Lichti et al. 2018). The operation of the biogas-driven CHPUs was such that the unit with the smaller output (nominal electric power, Pel = 75 kW) was switched on or off based on 4-hour-intervals, while the unit with the larger output (nominal electric power, P_{el} = 203 kW) was modulated in steps from a minimum load of 122 kW up to full load. With this mode of operation, the produced surplus was less than one percent of the total electricity generation from biogas. The calculated amount of avoided CO_2e emissions, in comparison to supplying the annual electricity consumption of the experimental farm from the grid, was about 451 tons (Lichti & Tappen 2019).

Conclusions

With our 'GHG Calculator' web application, the CO_2e balance of energy supply from biogas can be determined based on individual farm data. The application is thought as a tool for educating biogas plant operators about the main levers for mitigating GHG emissions along the process chain of energy provision from biogas. The following specific features of the 'GHG Calculator' should be highlighted:

- All major sources of CO_2e along the process chain are quantified.
- Default values were programmed so that the application always calculates a result, even if farm-specific data is not or only partially available; the more individual information is entered, e. g., level of harvest yield or chemical analyses of input materials, the more accurate the result.
- The transparent calculation method allows for principal comparability of the results for different farms. In addition, the application can be used to project how the initial GHG balance would change if certain mitigation measures were applied.

If biogas production is a well-integrated part of agricultural operations, it does not only provide renewable energy, but also a number of positive side-effects such as increasing the yield level in organic farming or expanding crop rotation. These effects are interacting with CO_2e emissions and should therefore be implemented during further development of the 'GHG Calculator'.

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