A weak point analysis tool to reduce greenhouse gas emissions and energy consumption of agricultural biogas plants

Bianca Zerhusen and Mathias Effenberger, Bavarian State Research Centre for Agriculture, Institute for Agricultural Engineering and Animal Husbandry, Voettinger Strasse 36, D-85354 Freising

Abstract

As a direct substitute for fossil energy carriers, biogas can help protect the climate and save finite resources. The environmental impacts of biogas systems are dependent on technical concepts and conditions of use. Along the entire process chain, greenhouse gases (GHGs) are emitted and energy is consumed, which determines process efficiency and energetic pay-off time of biogas production. Besides economic and technological factors, such as input materials, digester technology and biogas utilization pathways, there are also various management options to improve the environmental performance of biogas systems.

To draw the attention of plant operators on management options for reducing GHG emissions and cumulated energy consumption (CEC) of biogas plants, a web-based footprint tool was developed. The goal of this application is to assess and display the specific status of a biogas plant with respect to GHG emissions and CEC, and to present effective optimization measures.

To assess the most important material flows of a biogas plant, the footprint tool collects as much specific information as possible from the user by means of an inquiry. If case-specific data is not available, default values are provided. The biogas footprint tool uses simplified material and energy flow models for the agricultural processes and for the processes of biogas production and utilization, in order to determine the main GHG sources and energy consumers of the respective biogas system. Rather than focusing on absolute values of specific GHG emissions and CEC, which are subject to considerable inaccuracies, the tool displays the proportions of different emission sources and energy consumers. Thereby, the owner or operator receives fundamental knowledge about the weak points in the emission and energy balance of his biogas plant. Additionally, the main GHG sources and energy consumers are classified as to whether they are primarily dependent on investment or management decisions.

Moreover, the tool calculates the optimal scenario for the specific biogas plant in comparison to its actual status. In this way, effective measures for improving the environmental performance of the biogas plant are presented. These encompass, e.g., reducing loss of organic matter during silage preparation, avoiding methane losses through regular maintenance and biological improvement and a higher utilization rate of existing heat capacities. Losses of methane during fermentation and storage of digestate can be assessed with the tool in two ways: Avoiding methane loss from the biogas system leaves the plant operator with a greater amount of fuel which he can either utilize for increasing combined heat and power (CHP) generation or for maintaining the same energy output with reduced amounts of feedstock. The model could also be used to investigate the influence of different allocation approaches.
to specify the analyzed environmental impacts of combined heat-and-power generation from biogas, in contrast to the use of credits with respect to a particular reference system.

Our proposed software application provides an easy-to-use tool for biogas plant operators to perform a weak-point analysis and to identify effective improvement measures regarding the GHG emissions and the CEC of their biogas system.

**Keywords:** Bioenergy, Life-Cycle-Assessment, combined-heat-and-power, web application

1 Introduction

1.1 State of the Art

In Germany agricultural biogas technology has experienced a strong growth in plant numbers and installed power since the year 2000. This development was initiated by governmental encouragement and a long-term financial support ensured by the Renewable Energies Act and following amendments (Witt et al., 2012). The promotion was tied up with the political strategy to reduce national GHG emissions from energy production and add value to the domestic economy. According to UBA (2013) national GHG Emissions are dominated by the Energy sector (83% of overall emissions) and biomass is one of the outlined measures to meet the ambitious reduction goals of 40% by 2020 and 80-95% by 2050 compared to 1990 (BMU, 2014). Besides creating an additional source of income for agriculture, an objective was to reduce the dependency on fossil energy carriers which are mainly imported at shares of 79% for hard coal, 86% for natural gas and 97% for mineral oil, based on primary energy consumption (Andruleit et al., 2012). These intentions and the resulting development illustrate the implied social and governmental responsibility of agricultural biogas systems for a climate friendly energy production and a low consumption of fossil energy carriers. Furthermore in agricultural production climate is a determining factor for yields, plant protection and product quality. Therefore agriculture has an Interest and self-responsibility to ensure a sustainable agricultural production.

Due to manifold technical concepts and operating conditions, the results of life cycle assessments of existing plants are highly variable (Bachmaier, 2012), and thus cannot be used on a general basis. On the other hand modelling approaches mainly considering average conditions of production cannot describe an individual case. Research has discovered important coherencies in impact assessment and pointed out different measures to reduce environmental impacts. However, as quantifying mitigation potentials is subject to the used methodological approach, it is not possible to compare mitigation impacts on a quantitative basis, but only with respect to the effective direction. Among outlined measures to improve the environmental performance of biogas systems, some are rather economically and technologically determined, such as input materials, digester technology and biogas utilization pathways, while others are concerning management.

1.2 Scopes

To achieve an adoption of best practice in biogas production, climate protection and primary energy consumption are necessary assignments for agricultural consulting. Therefore mitigation options that have been detected by scientific research must be transferred to farm level to support farm managers with the essential knowledge and skills. By considering specific conditions on the analysed farm, the operator can recognize his/her individual initial situation and create a strategy to improve the operation. In this way, our tool aims for a compromise of self-evaluation and scientific assessment to analyse relevant variables and possible actions.
2 Materials and methods

2.1 Technical concept

Microsoft Excel was used to develop a draft calculation model which describes material and energy flows throughout the biogas process chain and estimates associated GHG emissions and CEC. For this purpose the footprint tool collects as much specific information as possible from the user by means of an inquiry. An easy to use inquiry interface was created, building the basis of calculations and modifications for further analyses. The model then was converted into a web application offering several advantages such as up-to-dateness of the tool, automatization of calculation procedures and easy access.

2.2 Methodological concept

Rather than focusing on absolute values, the methodological concept intends to provide fundamental knowledge about the weak points in the emission and energy balance. A Life cycle assessment approach taking into account specific conditions of particular biogas systems was realized. Data availability at farm level was checked to support the user with data proposals (default values) if no case-specific data is available. Building the calculation model, the long-term perspective of building a benchmark-tool with an existing, less detailed dataset was accounted for. For that reason, general assumptions where implemented (matching the default values) and in some cases divergent assessment approaches are needed.

Emission sources and energy consumers with their relative contribution were classified as to whether they are primarily dependent on investment or management decisions, primarily, noting that a clear separation is not always possible. Scenarios where defined to assess the effect of mitigation actions for the specific biogas system. The user can choose and combine provided options for different sections of the biogas system. For biogas production and utilization options in five different areas are considered (see example in results section, fig. 2). For substrate provision options in three different areas are analysed: 1. direct land use change, 2. silage preparation (loss of dry matter) and 3. manure management.

Besides, the potential of biological improvement for higher methane yields is assessed by comparison of theoretical methane yields derived from substrate digestibility and methane yields from back-calculating of electricity fed into the grid. Losses of methane can be assessed with the tool in two ways: Avoiding methane loss from the biogas system leaves the plant operator with a greater amount of fuel which he can either utilize a.) for increasing CHP production or b.) for saving input materials while maintaining the same energy output. By comparison of the scenario results and the initial status, the relative potential can be presented and conclusions can be drawn on which is the primary strategy to reduce emissions and energy consumption. Additionally suggestions are made on a qualitative basis.

The developed model could also be used to investigate the influence of different allocation approaches on environmental impacts of the CHP generation, in contrast to the use of credits with respect to a particular reference system.

2.3 Functional unit and system boundaries

Although a holistic model is striven for, the present model does not account for the end use of products as it ends at the farm gate. The functional units are the used amounts of heat (kWh\textsubscript{h}) and power (kWh\textsubscript{e}). For the inventory, biogas production is considered to be an independent system. The assessment was divided into two steps.

The first step treats production and provision of energy crops. The emission and energy load of manure is assumed to be an item in transit, coming to effect outside the system boundary when animal feedstuff is produced. Other substrates can be classified as by-products and waste. While waste is assumed to enter the process without any upstream energy consumption or emission, ecological impact allocation has to be used for by-products. This highlights
the benefit of evolving new utilization concepts for waste materials. Digestate from waste and by-products are assumed to leave the system to other production systems with unchanged GHG emissions and CEC (fertilizer value and humus reproduction may be different).

The second step considers biogas production and utilization. Electricity and heat are the main products of the biogas system. Therefore yearly emissions of the production chain are allocated to both products applying exergetic allocation according to EU KOM (2010) with a Carnot efficiency of 0.3546 for heat at 150 °C (423 Kelvin).

2.4 Data acquisition

The global warming potential for a 100-year time horizon is assumed to be 1 kg CO$_2$e * kg$^{-1}$ CO$_2$, 25 kg CO$_2$e * kg$^{-1}$ CH$_4$ and 298 kg CO$_2$e * kg$^{-1}$ N$_2$O according to IPCC (2007). Besides direct emissions of GHG indirect effects through nitrate leaching (0.3 kg N$_{leached}$ * kg N$_{applied}$$^{-1}$ and 0.0075 kg N$_2$O-N * kg N$_{leached}$$^{-1}$) and atmospheric deposition of nitrogen from ammonia emissions (0.01 kg N$_2$O-N * kg NH$_3$-N$^{-1}$) are considered according to IPCC (2006).

To estimate the theoretical methane yield (according to Keymer & Schilcher, 2003 and Baserga, 1998) and the amount of digestate (according to LfL, 2013a), values for DM, oDM, digestibility-quotients, composition of raw protein, raw fibre, raw fat, nitrogen-, phosphorous- and potassium-content were derived from LfL (2013c). In crop farming the model uses unique, Bavarian parameters. For crop yields, default values were taken from Bavarian State Office for Statistics and Data Processing for a five-year average, supplemented with data by Dilger & Faulhaber (2006). If no specific values for the region could be found, other literature was adduced. The ratio of prior harvest product to by-product was taken from LfL (2013b).

Assumptions where made for grass and trefoil-grass concerning cutting frequency, growing period and share of legumes. All provided information can be adjusted individually in a detailed subdivision. Fuel consumption of agricultural machinery was taken from KTBL (2013) for agricultural procedures as described in KTBL (2006) and can be scaled for ecologic, till and no till cultivation, field size and on farm / off farm transport distance. Machinery chosen was mainly small (67kW) and medium soil workability was assumed.

Emission factors for methane losses and ammonium emissions from biogas production and utilization were assumed according to scientific literature and expert knowledge. Methane emissions refer to the produced methane prior to any loss. The methane-slip at the CHP unit is defined as the fraction of methane in the exhaust gas flow due to incomplete combustion and was set to 1.5% (Aschmann & Effenberger, 2012; Vogt et al., 2008). Diffuse emissions of methane from biogas production can have diverse origins. There are area sources: Permeation or small fissures in foil roofs, open collection tanks for liquid manure or mixing in solid material. Moreover, there are point sources: leakiness of substrate insertion wells, open spillways, embedded sight glasses and maintenance manholes, rope openings, mounting of foil roofs, screw and pipe connectors, digestate withdrawals. Some of these can be avoided by regular maintenance for example checking the water level at the excess pressure safety or exchanging material on time to avoid material fatigue. Some deficiencies are more easily found and eliminated than others. Making up 1% altogether (Häring et al., 2011), diffuse emissions were divided into three categories:

<table>
<thead>
<tr>
<th>categories</th>
<th>EF [%]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. unavoidable emissions</td>
<td>0.2</td>
<td>(Liebetrau et al., 2011)</td>
</tr>
<tr>
<td>2. avoidable emissions (leakage)</td>
<td>0.3</td>
<td>own estimation</td>
</tr>
<tr>
<td>3. overpressure events</td>
<td>0.5</td>
<td>estimation (Bachmaier, 2012)</td>
</tr>
</tbody>
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According to Niebaum & Wirth (2008) category 1 and 2 add up to about 0.5% of produced methane. The splitting is somewhat arbitrary but is considered useful for the understanding of emission sources. Methane from digestate storage without gastight cover is accounted for.
using an EF of 1.5% according to the upper limit stated by VDI-guideline 3475-4 (60 days, 20°C) and discussed by Ebertseder & Preißler (2011).

Electric efficiency is detected as a function of installed power of the CHP unit:

\[ \eta_{el} = 2.7029 \ln(x) + 21.074 \quad (R^2 = 0.9751) \]

Thermal efficiency (\(\eta_{th}\)) is assessed by provided details on the power coefficient of the CHP unit. Electricity requirements are proposed to be 8% of produced electricity amounts. As heat requirements are mostly unknown 30% are set in place. This value is reduced if available heat capacities are insufficient due to user data on externally used heat amounts. Utilization of produced heat is supposed to be linked with a loss of 10%. For ignition oil an amount of 10% of gross energy supply to the CHP was assumed.

Ammonia emissions were derived from the German emission inventory methodology (Haenel et al., 2012). Emissions from open digestate storage without natural crust or gastight cover are calculated using an emission factor of 0.015 NH\(_3\)-N of total ammonia nitrogen. Ammonia emissions for spreading of digestate are assumed to equal those of pig manure at air temperatures of 15°C. Manure application technique comprises broadcast, trailing hose, trailing shoe, open slot and injection, distinguishing between grassland, field and incorporation practice: without incorporation and incorporation within less than four hours. Since the production of mineral fertilizers is associated with high amounts of fossil energy consumption and, consequently, brings along high GHG emissions, data of used amounts of mineral fertilizers is of a great importance for an accurate assessment. If no such data is provided by the user, values are estimated to compensate losses and achieve a balanced nitrogen cycle.

3 Results and Discussion

The following example is based on information assessed in the biogas monitoring project of the Bavarian State Research Centre (Ebertseder et al., 2012) and represents biogas plant no. 16_2010. Results displayed show the second model part of biogas production and utilization. For demonstration purposes, it was assumed that the digested residues are stored in an open tank and that a residual methane potential of 4% with respect to the methane yield of the input materials is released to the atmosphere. Resulting emission sources and energy consumers are presented to enable a weak point assessment (fig. 1).

![Figure 1: Distribution of energy consumers (left) and sources for greenhouse gas emissions (right). Blue grades: Investment depending, Reds: Management depending.](image-url)
To assist and encourage the operator of the biogas plant in the further planning process the application presents a selection of mitigation measures and their possible impacts. If methane losses are avoided and used for heat and power generation, the additional amount of methane and the resulting power and heat surplus is provided (fig. 2).

Figure 2: Results of the scenario analyses (additional methane is used for heat and power generation)

4 Conclusions and outlook

Our proposed software application provides an easy-to-use tool for biogas plant operators to perform a weak-point analysis and to identify effective improvement measures regarding the GHG emissions and the CEC of their biogas system.

Further work encompasses the assessment of biogas systems and the possibility to integrate benchmarks for horizontal comparison. Preparatory work has been done by implementing the idea in the methodological concept. Also, the integration of economic scores might trigger improvement in management and investments in technical equipment. To implement the tool into a whole farm approach, the environmental burden of manure input and fermentation-induced effects on fertilizer value and humus reproduction should be investigated.

5 References


