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A Database Approach for Simulating the Produced Greenhouse Gas Emissions from Biogas Plants

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Biogas plants are widespread in Germany and, particularly, in the Federal State of Bavaria, where the development of renewable energy sources has been very dynamic. While biogas can substitute fossil energy carriers for producing electricity and heat, greenhouse gas (GHG) emissions are also occurring along the biogas process chain. The accounting of the GHGs produced from biogas plants is an essential step for evaluating and improving this type of energy supply. We developed an effective approach for simulating diverse biogas chains in agriculture for predicting the resulting GHG emissions in relation to energy output. This approach is executed in three stages: (1) creating a database and filling it with collected and calculated data; (2) constructing the biogas plant sample using data from the database and user's input; and (3) running the database model for calculating and displaying the biogas plant's GHG inventory. The database comprises information on the location and management of the farm, the sourcing and composition of the input materials / substrates, and the combined heat and power unit (CHPU) for biogas valorization. The database is connected with a web-based application model, which presents the results in graphs, numbers and percentages.

1. Introduction

Of the world's overall energy supply, 82 % are covered by fossil fuels (IEA, 2016) releasing CO_2 emissions to the atmosphere that drive the anthropogenic greenhouse effect. Thus the use of renewable resources can combine a wide range of technological, economic, ecological and social advantages (Scheer, 2010). In Germany, the share of biogas amounts to 16.8 % of electricity from renewable sources (BMWi, 2016).
Though agricultural biogas production has the potential to reduce GHGs from the energy sector and the agriculture sector, the amount of emission savings depends as well on the reference energy system as on operational circumstances. Calculating the cumulative energy demand of and the GHG emissions from biogas plants in dependence of different environmental and technical factors has become a frequent topic of research, as results are showing a wide variability and are not transferable. Our goal was to enable farmers to easily simulate GHG emissions and energy consumption of their own biogas process to draw attention to a climate friendly and an efficient energy production. To achieve this, the idea was to create a tool which collects, calculates and displays specific farm information but also provides necessary parameters and default values. The processes of biogas plant construction, utilization and management contain a lot of data that should be united within a framework to profit from it, considering the latest developments of biogas production and GHG accounting.
A database is the method of choice to collect large amounts of data in an organized structure and retrieve it again for evaluation and modification. Relational Database Management Systems (RDBMS) have been largely used as they are able to provide efficient data storage and retrieval (Oliveira et al., 2016). In RDBMS a programming language is used that appends data or retrieves the required data from a database for direct display or employment of mathematical or conditional models and subsequent display of the results using a Windows or web application. Utilizing a web application with a graphical user interface transforms the data into a form that can be easily understood by farmers and consultants, and presents the different processes and requested data in one place: the webpage itself (Takahashi and Tanaka, 2016).

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Here we present a database approach for assembling a biogas system model and calculating the expected GHG emissions from it, taking into consideration the environmental and technical factors. The approach consists of a database attached to a web-based model, which uses the data from the database and from the user's input via an interactive web form for calculating the emitted GHGs of the biogas system.

2. Materials and methods

In order to estimate the GHG emissions that are produced from a specific biogas system, a database was created using the engine MySQL™ 5.6 and connected with a web-based application developed in PHP. Data and research have been sighted in advance for the construction of a practical modelling approach and structured as shown in the following.

2.1 Database

The database is divided into the following sections:

Input materials / substrates: This section describes in detail the used input materials for biogas production. The substrates are divided into two main categories of "energy crops" and "animal manure", where energy crops are classified to "crop silage", "forage green waste", "grains", "grassland", and "hay/cobs" and animal manure is distinguished into "liquid" and "solid". An example for this categorization of substrates is given in Table 1. The detailed data on crop production, e.g., the standard yield for each crop (LfStaD, 2014; Dilger and Faulhaber, 2006) in dependence of crop type (main/intermediate crop (LfL, 2013)) and yield level (favourable/less favourable/very favourable) is stored in a separate table. The values of mass fractions of dry matter, organic dry matter, nitrogen, phosphorus and potassium are differentiated with respect to growth stage and harvesting technique. Herbicides, insecticides, fungicides and growth regulators are summarized with the average quantities of active ingredients (Schraml and Effenberger, 2013; Roßberg et al., 2002). Standard emission factors (EF) for seed production in conventional and organic farming were taken from Ecoinvent (2013).

Table 1: Example of the categorization of the input materials in the database

Category 1	Category 2	Category 3	Category 4	Category 5
Energy crops	Crop silage	Corn silage	Maize silage	maize silage (corncob formation)
				maize silage (ripening)
			Maize-CCM	CCM grain stem (3.5 % crude fibre content)
				CCM grain stem (5.3 % crude fibre content)

Biogas utilization: The tables in this section describe the combined heat-and power unit, including the engine type (spark-ignition or dual-fuel) and, if applicable, the ignition fuel (rapeseed oil or biodiesel). Furthermore, the biogas plant electricity supply, which could be from its own electricity production, grid mix, hydro power, wind power or photovoltaic. The utilization of the heat output is specified with respect to parasitic heat demand of the biogas plant, heat sales, and electricity production from off-heat where applicable.

Farm: Including farm location on the basis of Bavarian counties, farming system (conventional/organic) and tillage/no-tillage (for conventional farms), the average farm-field distance and field size, the dry matter loss of silage depending on silo cover, and the techniques for application of the digested residues to cropland/grassland are contained and described in this section.

Transport: This part summarizes all parameters for calculations of the fuel consumption (l/ha), according to KTBL (2014) fieldwork calculator, for each crop including the cultivation, fertilization, plant protection and harvesting processes, taking into consideration the farm-field distance, field size, and farming system.

Languages: The model content is stored in the database with the languages German and English.

2.2 The web application

The web application guides the user through six forms constructed for an organized data entry: (1) Information on the biogas plant construction and operation; (2) farm information; (3 - 5) details on the input materials and the use of the digested residues; and (6) data on the utilization of the biogas. The user´s entries are used for calculating the GHG emissions and the cumulative energy demand of the individual biogas system. The web forms are interactive depending on the user's entries. The input data for the constructed biogas plant model can be downloaded as xml-file, and uploaded to display the results or modify the input data.

2.3 GHG accounting

The used GHG emission sources and values in the web-model are described in Zerhusen & Effenberger (2014), where the model is divided into two sub-models: substrate supply and biogas utilization.

In the substrate supply sub-model, GHG emissions from the cultivation, harvest, transport, and silo storage of energy crops are calculated. Nitrogen fluxes are calculated as follows:

- The complete amount of N in slurry and manure is delivered to energy crop/forage production in the form of digested residue as organic fertilizer.
- The user can enter the additional amount of mineral fertilizer – or “0” if no mineral fertilizer was applied. If no entry is made, the amount of mineral fertilizer is calculated from the difference of nitrogen removal and nitrogen from organic fertilization.
- Nitrous oxide emissions due to nitrogen fertilization are calculated using county specific EFs for cropland and grassland (Dechow and Freibauer, 2011).

The biogas production and utilization sub-model summarizes the GHG emissions from the construction and operation of the biogas plant and the CHPU. Emissions during the biogas process can be varied by the user, by information on the automatic gas flare installation and inspections on leakages on a regular basis, gas-tight covers with connection to the gas system (CH_4) or floating layers (NH_3) on the digested residues storage. Electrical and thermal efficiencies and electricity supply sources are modelled due to user input.

3. Results and discussion

3.1 Discussion of modelling results

In order to exhibit the models usefulness, Table 3 shows the results for two examples of real biogas plants.

Table 3: Characteristics of the two biogas plants that were analysed with the model

Plant ID	Biogas plant “A”	Biogas plant “B”
Number of engines in CHPU	3	1
Engine type	Spark ignition engine	Dual fuel engine
Automatic flare?	No	Yes
Origin of purchased electricity	Own CHPU (biogas)	Grid electricity
The storage tank for digested residue	Sealed	Not sealed
Electricity output per year, kWh	4,941,446	1,778,133
Heat sales per year, kWh	3,427,343	1,227,071
Number and selection of input materials (in descending order w/respect to mass share)	6: Beef cattle manure, maize silage, barley silage, ryegrass silage, winter wheat grain, maize silage-CCM	4: Maize silage, meadow grass green, ryegrass silage, winter wheat grain
Farming system	Conventional	Organic
Mineral N fertilizers per year, kg/ha	Default	0
Nitrous oxide emissions: EF_{grass}/EF_{crop}	0.99/2.98	0.87/1.97

The displayed emissions in the web model are divided into the substrate provision (Figure 1) and the biogas production and utilization (Figure 2) emissions, and each sector shows rather avoidable (management dependent) and unavoidable (investment dependent) emissions. The web model presents total GHG emission shares as well as the presented detailed GHG distribution graphs (Figure 1 & Figure 2).

The biggest share of total emissions at biogas plant “A” was presented by the avoidable substrate provision section with 77 %, from which 47.3 % originated from the utilization of mineral fertilizers (15.8, 29.1 and 2.4 % production, direct and indirect emissions, respectively). The second biggest share of total emissions was recorded for the unavoidable biogas production and utilization with 16%, while the unavoidable substrate provision and the avoidable biogas production and utilization showed small GHG emission shares with 4 % and 3 %, respectively. Nevertheless, the avoidable biogas production and utilization GHGs at biogas plant “B” gave the highest percent with 48 %, followed by the avoidable GHGs from substrate provision and the unavoidable biogas production and utilization GHGs with 27 % and 20 %, respectively, whereby the lowest share was 7 % for GHGs from the unavoidable substrate provision part.

As shown in Figure 1, the unavoidable substrate provision sector emissions for “A” and “B” showed the same behaviour with similar distribution: the supply of seeds, supply of lime and CO_2 release from lime had the shares 12.2, 19.2 and 68.1 % for farm “A” and 10.1, 19.8 and 70.1 %, respectively, for farm “B”. This similarity was caused by; 1) the similar seed supply amounts, where emission values from Ecoinvent (2013) only differ little, if the used seeds are conventional or organic. 2) the common three of the four used energy crops at the two biogas plants; 3) the lime emissions calculations, which are only varied for arable land with an average value of 13.5 dt CaO ha^{-1} (Wendland et al., 2012) and 6 dt CaO ha^{-1} for grassland (UBA, 2013).

For the organic farm "B", the avoidable substrate provision sector showed no emissions from mineral fertilization and pesticide production. However, the highest share in this sector for the two plants was reflected by the direct nitrous oxide emissions from the digestate fertilization with values of 42.9 and 69.2 % for the plants "A" and "B", respectively, whereas the indirect nitrous oxide emissions from the digestate fertilization were 5.1 % at biogas plant "A" and 14.4 % at biogas plants "B". The diesel combustion and production had similar proportions referring to total emissions for the two plants (diesel combustion had shares of 3 and 3.9 %, diesel production of 0.4 and 0.6 % for "A" and "B", respectively), while emissions from fertilization where higher for biogas plant "A". A similar amount of diesel input can be explained by the same average field size and field-farm distance at the two suggested plants. In addition, three common energy crops have been used at the two biogas plants, whereas the diesel demand is a crop dependent value.

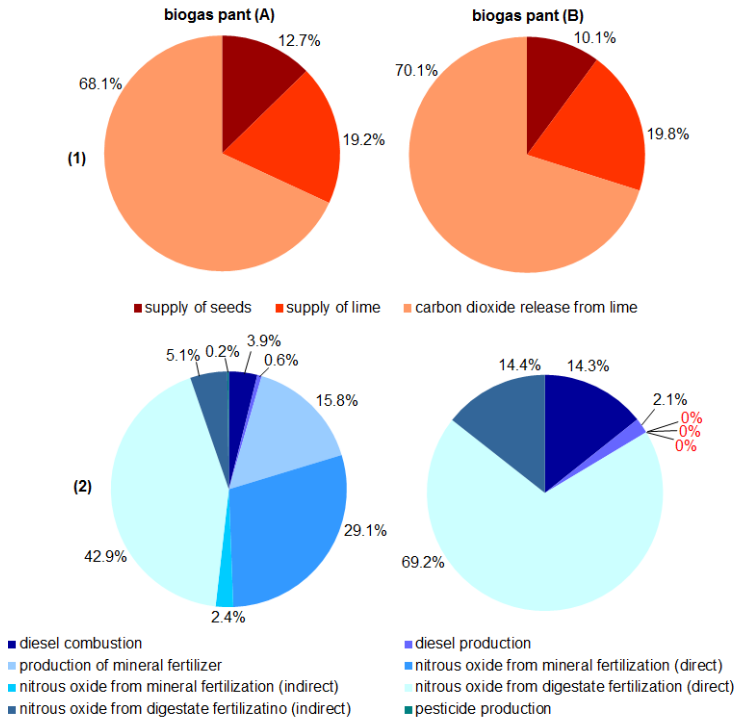

Figure 1: Distribution of the unavoidable GHG emissions in red grades (1) and avoidable GHG emissions in blue grades (2) from substrate supply for the first [A] and the second [B] biogas plant.

The biogas production and utilization sectors are illustrated at Figure 2. The unavoidable biogas production and utilization sector contained no fuel-oil supply emissions for biogas plant "A", where the used three motors at that plant were "Spark ignition engines", while the fuel-oil supply emissions represented a share of 43.4 % at plant "B" with using the "Duel fuel engine". The highest emission share at the biogas production and utilization sector occurred at the CHPU with the methane slip in the exhaust gas from an incomplete combustion in the engine. Expressed in numbers, the shares made up 85.6 and 48.1 % of unavoidable biogas production and utilization emissions for the plants "A" and "B", respectively. The unavoidable diffuse emissions are assumed to be 0.2 % of the produced methane (Liebetrau et al., 2011) and therefore caused 11.5 % of unavoidable GHGs for plant "A" and 6.6 % for plant "B". The emission intensity of the supply of building materials represented 3 and 1.9 % of unavoidable emissions for plant "A" and "B" respectively, where it is estimated with 2.87 g CO_2eq kWh_{el}^{-1} (Bachmaier, 2012).
Because the electricity supply at biogas plant "A" originated from the own biogas plant, this plant showed no electricity supply emissions, whilst emissions from the grid electricity source caused 18.9 % of avoidable GHGs at biogas plant "B". Furthermore, the storage tank for digested residues was sealed at Plant "A", so no methane or ammonia emissions from open digestate storage appeared. By contrast, at Plant "B" the storage tank was not sealed and methane emissions from open digestate storage were 70.4 % of avoidable GHGs, which was at the same time the highest share of total emissions at that plant. Therefore, the biogas production and utilization sector of avoidable GHGs at plant "A" contained 100 % emissions from leakages and faulty installation, while leakages and faulty installation caused only 4 % of this sectors emissions at plant "B".

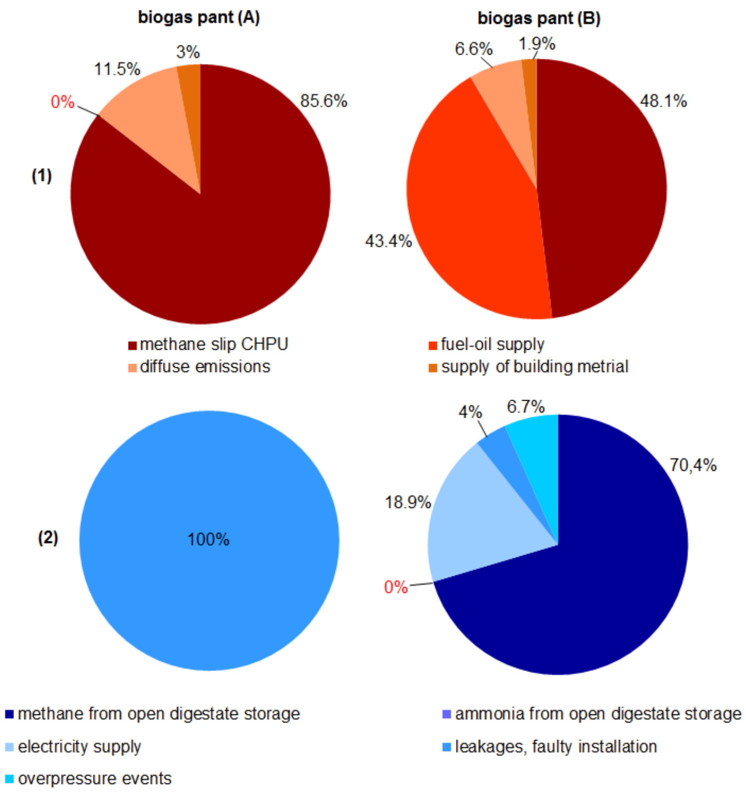

Figure 2: Distribution of the unavoidable GHG emissions in red grades (1) and avoidable GHG emissions in blue grades (2) from biogas production and utilization for the first [A] and the second [B] biogas plant.

3.2 Input and output data manipulation

After running the web-model, the user can save the input or output data and photos of all presented graphs. The input data was presented with all user selections in an organized readable one page, which could be saved or printed as pdf file. Furthermore, the input data could be downloaded in a readable xml-file. The user can upload this xml-file again to the web-model, which then creates the corresponding biogas plant example, calculates its GHG emissions and displays the results and the collected input data page without going through the whole form constructing steps again. The user can also modify his / her biogas plant example (changing the values, adding a new or deleting an existing substrate or motor) directly in the completed form with the collected input data.

4. Conclusions

The determination of the GHGs from biogas plants is essential for evaluating global warming impacts trough that source of energy and for eliminating GHGs by adjusting the biogas process and inputs. Therefore, a database approach has been developed consisting of 1) a database, 2) a web model with farm surveys to collect specific user data and 3) with algorithms and queries to calculate and display the total and categorized GHGs using the specific user information and data from the database. The web model interacts dynamically with the user, not only by constructing a biogas plant model but also by downloading and uploading the constructed model inputs. This database approach facilitates the evaluation of GHG emission balances for practical users. Furthermore, the users can evaluate mitigation options that relatively match their available resources. Mitigation options could be changing the electricity source, reducing mineral fertilizer amounts through improved digestate fertilization efficiency and a sealed digestate storage tank, adapted substrates and optimizing farm management through actions as well as through investments. The web model is available and can be accessed from “www.thg-rechner.de”. That database approach endeavours to establish biogas plant models that can easily be constructed and modified with sufficient dynamic interactions. However, the present study has some limitations that need further elaboration, where points such as humus, long term nutrient effects and optimizing the nutrient supply considering more than one element (nitrogen) are not yet included.

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