Methane emissions in biogas plants - Measurement, calculation and evaluation

Bernd Linke
Jan Liebetrau
Mathieu Dumont
Tobias Persson

Task 38?/JRC (IET)?
IEA Bioenergy

IEA BIOENERGY Task 37 – Energy from Biogas

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of the collaboration between IEA Bioenergy Task 37: Energy from Biogas and IEA Bioenergy Task 36: Integrating energy recovery into solid waste management systems.

The following countries are members of Task 37, in the 2012-2015 Work Programme:

Austria
Bernhard DROSG bernhard.drosg@boku.ac.at
Günter BOCHMANN guenther.bochmann@boku.ac.at

Brazil
Cicero JAYME BLEY cbley@itaipu.gov.br
José Geraldo de MELO FURTADO furtada@cepel.br
Jeferson Toyama jtoyama@itaipu.gov.br

Denmark
Teodorita AL SEADI teodorita.alseadi@biosantech.com

European Commission (Task Leader)
David BAXTER david.baxter@ec.europa.eu
Jukka RINTALA jukka.rintala@tut.fi

Finland
Outi PAKARINEN outi.Pakarinen@jklinnovation.fi

France
Olivier THÉOBALD olivier.theobald@ademe.fr
Guillaume BASTIDE guillaume.bastide@ademe.fr
Bernd LINKE blinke@atb-potsdam.de

Germany
Jerry MURPHY jerry.murphy@ucc.ie

Ireland
Mathieu DUMONT mathieu.dumont@agentschapnl.nl

Netherlands
Roald SORHEIM roald.sorheim@bioforsk.no

Norway
Tobias PERSSON tobias.persson@sgc.se

Sweden
Nathalie BACHMANN enbachmann@gmail.com

Switzerland
Ho KANG hokang@cnu.ac.kr

South Korea
Clare LUKEHURST clare.lukehurst@green-ways.eclipse.co.uk

UK
Charles BANKS cjb@soton.ac.uk

Written by

Edited by

Date of publication
Table of contents

1. Introduction
   1.1. Background of the report

2. Biogas feedstock technologies
   2.1 Sewage sludge
   2.2 Industrial wastewater
   2.3 Landfills
   2.4 Municipal- and food wastes
   2.5 Manure, crops and industrial waste

3. Methods for measuring and calculating of methane emissions
   3.1. Portable GasCam
   3.2. Closed chambers
   3.3. Other…. 
   3.4. Model based calculation of emissions from storage tanks

4. Inventory of methane emissions
   4.1. Storage of substrate and digester feeding
       Liquid substrates, Solid and stickable substrates
   4.2. Digester and processing
       Continuously fed operation, Batch-fed operation
   4.3. Digestate upgrading
       Solid-liquid separation, Liquor processing, Drying
   4.4. Digestate storage
       Open lagoons, Covered not gas tight tanks, Solid pile
   4.5. Digestate application
       liquid digestate, solid digestate
   4.6. Biogas utilisation
       Combined Heat an Power generation (CHP), Biogas cleaning and upgrading
       (Pressure Swing Adsorption, Water scrubbing, Chemical scrubbing, Membrane separation), Vehicle filling station

5. Evaluation of methane emissions
   Reference systems boundaries and functional units,
6. Current laws and regulations

7. References

1 Introduction

1.1 Background of the report

Climate change is one of the great challenges of the 21st century. Its most severe impacts may still be avoided if efforts are made to transform current energy systems. Renewable energy sources have a large potential to displace emissions of greenhouse gases from the combustion of fossil fuels and thereby to mitigate climate change. Most bioenergy systems can contribute to climate change mitigation if they replace traditional fossil fuel use and if the bioenergy production emissions are kept low (IPCC. 2012). According to IEA estimates, this sustainable potential of biomass in 2050 ranges between 200 and 500 EJ/yr. A significant share of the resources will have to come from energy crop production on surplus agricultural land to unlock this potential (Van Foreest, 2012).

Within the bioenergy sector the increased use of biogas opens up new fields of applications where biomass has not played a major role so far (Anonymus, 2009). Biogas production has been steady growth in recent years and make its contribution to renewable energy generation and reducing negative impacts on the environment, both in the form of GHG emissions and the pollution of soil and water courses (Wellinger et al. 2013). The European Biogas Association estimates that by 2030 per year the overall potential for biogas is at least 50 billion m$^3$. Thus, by 2030 and with the right policies in place, the industry could deliver 2-4% of the EU’s electricity needs and take a 15-30% share of the methane market.

Biogas has definite advantages, even if compared to other renewable energy alternatives. It can be produced when needed and can easily be stored. It can be distributed through the existing natural gas infrastructure and used in the same applications like the natural gas. Biogas is produced by anaerobic digestion of organic feedstock, the most common being; animal waste and crop residues, dedicated energy crops, domestic food waste, and Municipal Solid Waste (MSW). Biogas production is recognised as an integrated processes including feedstock supply and pretreatment; gas treatment and utilization, and recovery, pretreatment and use of digestate (Fig. 1).

Although biogas production and use are regarded as a very sustainable practice that can guarantee GHG savings (Masse et al. 2011) special attantion should be give to methane emissions within the biogas production and utilisation chain. However, the mitigation of climate change is strongly dependent on many factors, such as the choice of feedstock and operational practices. Energy and materials are consumed for cultivation and transport of feedstocks and emissions arise from the biogas plant operation, biogas utilisation and demand for transportation and disposal of the process residues (Poeschel et al. 2012). All these factors have to be considered in the quest for environmental friendly and sustainable energy
production from biogas and should be properly evaluated when formulating policies regulating the sector or providing subsidies (Boulamanti et al., 2013).

Fig. 1: Stages of biogas production systems (Poeschl et al. 2010, modified)

2. Biogas feedstock technologies

2.1. Sewage sludge

Typical sewage sludge comprises of primary sludge separated from wastewater during pre-settling and biological excess sludge from the activated sludge system has a concentration of Total dry solids (TS) and Volatile solids of 5% and 65 % TS, respectively (Fytili and Zabaniotou (2008). Anaerobic digestion is used to stabilize the sewage sludge and convert part of the volatile solids into biogas. The biogas can be applied as an energy resource either at the wastewater treatment plant itself or elsewhere. Currently, anaerobic digestion of sewage sludge is mainly applied at large and medium-sized wastewater treatment plants (Fig. 2). However, also a growing interest is observed in the application of anaerobic treatment in small-sized plants (Rulkens, 2008). According a study of the German Umweltbundesamt (UBA, 2008) the daily digester gas production per population equivalent (EGW) amounts to
19.6 L based on 96 million people in 1,150 treatment plants with anaerobic digestion. According data from Gujer (2007) with a value of 60 g VS EGW⁻¹ d⁻¹ the specific gas and methane yield (65% CH₄) results to 0.32 L gVS⁻¹ and 0.21 L gVS⁻¹, respectively. After anaerobic digestion sludge is treated as follows: a) secondary thickening (gravity, flotation, drainage, belt, centrifuges); b) conditioning (elutriation, chemical, thermal); c) dewatering (plate press, belt press, centrifuge, drying bed); d) final treatment (composting, drying, line addition, incineration, wet oxidation, pyrolysis, disinfection); e) storage (liquid sludge, dry sludge, compost, ash); f) transportation (road, pipeline, sea); g) final destination (landfill, agriculture/horticulture, forest, reclaimed land, land building (Fytili and Zabaniotou (2008).

Figure 2: Digester (10,500 m³ each) of the waste-water treatment plant Dresden-Kaditz (Germany)

2.2 Industrial wastewater

Anaerobic digestion is the most suitable option for the treatment of high strength organic waste-water effluents from: Agro-food industry (Sugar, potato, starch, yeast, pectin, citric acid, cannery, confectionary, fruit, vegetables, dairy, bakery), Beverage (Beer, malting, soft drinks, wine, fruit juices, coffee), Alcohol distillery (Can juice, cane molasses, beet molasses, grape wine, grain fruit), Pulp and paper industry (Recycle paper, mechanical pulp, sulphite pulp, straw bagasse) (Figure 3) and other (Chemical, pharmaceutical, sludge liquor, landfill leachate, acid mine water, municipal sewage). One of the major successes in the development of anaerobic wastewater treatment was the introduction of high-rate reactors in which biomass retention and liquid retention are uncoupled. High biomass concentrations enable the application of high COD loading rates, while maintaining long solid retention times (SRT) at relatively short hydraulic retention times (HRT). Different high-rate systems were developed over the last three decades including the anaerobic contact process (ACP),
anaerobic filters (AF), the upflow anaerobic sludge blanket (UASB), fluidized bed (FB) and expanded granular sludge bed (EGSB) and the baffled reactors. Analysing the reasons why the selection for anaerobic wastewater treatment was made, the following striking advantages over conventional aerobic treatment systems can be given: a) reduction of excess sludge production up to 90%, b) no use of fossil fuels for treatment c) high applicable COD loading rates reaching 20-35 kg COD per m³ of reactor per day, d) production of about 13.5 MJ CH₄-energy per kg COD removed, giving 1.5 kWh electricity (assuming 40% conversion efficiency), e) anaerobic sludge can be stored unfed and reactors can be operated during agricultural campaigns only e.g. 4 months per year in the sugar industry, f) rapid start up < 1 week, using granular anaerobic sludge as seed material (van Lier et al., 2007). But, application of UASB reactors for treating domestic wastewater have shown considerably high losses of dissolved methane in the anaerobic effluents and implying the need of research on technologies aimed at recovering such energetic greenhouse gas (Souza et al. 2011).

Figure 3: BIOPAQ Wastewater treatment plant in paper industry (Roermond, NL), sludge granules

2.3 Landfills

Significant interannual variations in the growth rate of atmospheric CH₄ justify the development of an improved methodology for landfill emissions, the largest anthropogenic source in many developed countries (Bogner, 2003). Landfill gas (LFG) is a naturally occurring by-product of the decomposition of organic waste in sanitary landfills, and is produced during the microbially mediated degradation of the organic portion of waste. An example of the conversion of a biomass into usable energy can be seen in sanitary landfills that produce an amount of biogas of about 0.350 Nm³/kg of solid urban waste. Landfill gas is generated under both aerobic and anaerobic conditions. Aerobic conditions occur immediately after waste disposal due to entrapped atmospheric air. The initial aerobic phase is short-lived and produces a gas mostly composed of carbon dioxide. Since oxygen is rapidly depleted, a long-term degradation continues under anaerobic conditions, thus producing a gas with a
significant energy value that is typically 55% methane and 45% carbon dioxide with traces of a number of volatile organic compounds (VOC). Whenever economically feasible, gas collection systems are recommended for landfill gas emissions control, and liner designs have been configured to prevent lateral biogas migration. However, collection systems are not 100% efficient, however, and emissions may also escape preferentially from and around walls and along the routes of installed landfill equipment. Historical practice suggests that collection systems may operate less than half the time that landfill gas (LFG) is produced, because they are only economically feasible when methane concentrations are high. Once methane concentrations fall below 35–40% and total gas production rates are 30–50 m3 h⁻¹, treatment in combined heat and power plants (CHP plants) becomes technically and economically infeasible (Huber-Humer et al. 2008). Most of the CH₄ and CO₂ is generated within 20 years of landfill completion, whereas emissions may continue for 50 years or more (Zamoranoa et al., 2007).

Figure 3: Landfill gas utilisation, Haase Energietechnik AG, Germany

2.4 Municipal- and food wastes

Due to the large environmental impact of landfills separate collection of fractions of MSW has increased significantly. Since Mata Alvaresz (2000) has published the review paper regarding anaerobic digestion of organic solid wastes many examples exist on the use of anaerobic digestion (AD) to treat the mechanically separated biodegradable fraction of municipal waste (Al Seadi et al., 2013). When AD is used to process source segregated waste it not only produces biogas, but also presents an opportunity to recover additional value from the waste material, in the form of a quality assured nutrient-rich fertiliser product that can be applied to agricultural land used in food production (Banks et al., 2011, Lukehurst et al., 2010). Lissens et al. (2001) have been compared the most common types of anaerobic digesters for solid wastes. Batch systems have the most simple designs and are the least expensive solid waste digesters. They have high potential for application in developing
countries. Two-stage systems are the most complex and most expensive systems. Their greatest advantage lies in the equalisation of the organic loading rate in the first stage, allowing a more constant feeding rate of the methanogenic second stage. However, the large majority of industrial applications use one-stage systems and these are evenly split between 'dry' (Fig. 4) systems (wastes are digested as received) and 'wet' systems (wastes are slurried to about 12% total solids). As a whole, 'dry' designs have proven reliable due to their higher biomass concentration, controlled feeding and spatial niches. Moreover, from a technical viewpoint the 'dry' systems are more robust and flexible than 'wet' systems.

![Figure 4: OFMS treatment plants, DRANCO (left) and COMPOGAS (right)](image)

### 2.5 Manure, crops and industrial waste (Co-digestion)

The vast majority of biogas plants digest simultaneous a homogenous mixture of two or more substrates and this is called co-digestion and offers several ecological, technological and economical advantages e.g. improved nutrient balance, optimisation of rheological qualities, gate fees and biogas recovery (Braun and Wellinger, 2003). Historically, anaerobic digestion has mainly been associated with the treatment of animal manure and sewage sludge from aerobic wastewater treatment. Nowadays, most of the agricultural biogas plants digest manure
from pigs, cows, and chicken with the addition cosubstrates to increase the content of organic material for achieving a higher gas yield. Typical cosubstrates are harvest residues, organic wastes from agriculture-related industries, and food waste, collected municipal biowaste from households and energy crops (Weiland, 2010). A major driver for co-digestion were large scale centralized biogas plants in Denmark codigesting mainly manure, together with other organic waste such as industrial organic waste, source sorted household waste, and sewage sludge (Angelidaki and Ellegard, 2003). This concept have been tested and well applied for different industrial organic wastes (Kaparaju and Rintala, 2005; Al Seadi et al. 2013; Allen et al. 2013). The biogas production cycle represents an integrated system of renewable energy production, resources utilization, organic wastes treatment and nutrient recycling and redistribution, generating intertwined agricultural and environmental benefits, as follows a) Renewable energy production, b) Cheap and environmentally healthy organic waste recycling, c) Less greenhouse gas emission, d) Pathogen reduction through sanitation e) Improved fertilization efficiency, f) Less nuisance from odors and flies and g) Economical advantages for the farmers (Holm-Nielsen et al. 2009).

![Co-digestion plants, Denmark (left) and Germany (right)](image)

3. **Methods for measuring and calculating of methane emissions**

3.1. **Portable GasCam**

*Function*

The GasCam is an innovative development in the field of passive remote gas detection by infrared spectro-radiometry. Based on the spectral analysis of radiation in the infrared spectral range which is absorbed by the molecules of a gas cloud, and/or emitted, the GasCam enables the visualization of gas clouds. The limit of detection of the GasCam amounts to about 80 ppm\(^*\)m. It depends on the background and the temperature difference between the gas and the background. By passive infrared method, it is possible to visualise gas spreads in front of a unreferenced background such as the sky.

*Application in biogas plants*
Gas clouds moving in free space can be visualized in real time and locate emission sources along the entire biogas process chain accurately and efficiently. Typically leaks at a distance of 0 to at least 100 meters and longer can be detected. With the GasCam even small leaks can eg 5 l/h are detectable. The big advantage here is that large plant sections can be tested in a short time. Exit points of the gas can be visually recognized quickly with the GasCam. However, with a conventional gas detector exact localization can take a long time because even in light winds only occasionally gas is detected. Also difficult to access areas of the plant (example: gas pipe in 8m height) can be checked with the GasCam since this is a passive detection system which also can be measured against the sky.

![GasCam application in biogas plants (Esders GmbH, Germany) and Methane laser](image)

3.2. Closed chambers

Closed floating chamber methods have been used extensively to quantify GHG fluxes from liquid manure storage facilities. Experimental approaches using floating chambers typically have relied on four to six chambers with area ranging between 0.1 and 0.7 m². Although the method is relatively easy to deploy under field conditions, disadvantages associated with chamber use include perturbations of the natural conditions and inhibiting effects of concentration build-up in closed chambers (Park et al. 2010). The chamber has an input and output pipe and a connected blower to produce a constant air flow through the chamber. The gas from the emission source (leakage) and the fresh air are mixed in the space of the chamber and the concentration of the target gas is analysed by sampling the gas in the in- and output stream of the chamber. Methane is detected by gas chromatography with a flame ionization detector (FID). The flow rate is measured by a vane anemometer or a Pitot tube. Then the quantity of the emission source is calculated from the concentration difference and the flow rate of the blower by using the following equation (Liebetrau et al. 2013),

$$\text{Quantity} = (C_{\text{out}} - C_{\text{in}}) \times \text{Flow Rate}$$
\[ F = Q \cdot \rho (c_{out} - c_{in}) \quad (1) \]

with \( F \), emission flow rate (mg h\(^{-1}\)), \( Q \), air flow rate (m\(^3\) h\(^{-1}\)) \( \rho \), density of the target gas (kg m\(^{-3}\)), \( c_{out} \), exhaust gas concentration (mg kg\(^{-1}\)), and \( c_{in} \), background of the gas concentration (mg kg\(^{-1}\)). The emission rate can be calculated from the slope of the gas concentration, the chamber volume and the encapsulated surface area (0.25 m\(^2\)) according Equation (2).

\[ F = \frac{\partial c}{\partial t} \cdot \frac{V}{A} \quad (2) \]

with \( F \), specific emission flow rate (mg m\(^2\) h\(^{-1}\)), \( \partial c / \partial t \), slope of the gas concentration (mg m\(^{-3}\) h\(^{-1}\)), \( V \), chamber volume (m\(^3\)), \( A \), encapsulated surface area (m\(^2\)).

Figure 7: Methane emissions from digesate (left) and digester (right) (Germany)

Figure 8: Sketch of a closed container with a lid and outlet for gas sampling (Sweden)

3.3 Other… from...
EU project “Comparison and evaluation of measurement methods to determine methane emissions from biogas plants” (Sweden, Denmark, France Germany)

3.4 Model based calculation of emissions from storage tanks

Based on volatile solids (VS) of the input feed the maximal methane yield from the storage tank \( y_{\text{max CH}_4}^{S,VS_{\text{inp}}} \) (emissions) can defined as the difference between the maximal methane yield of the input feed \( y_{\text{max CH}_4}^{VS_{\text{inp}}} \) and the methane yield produced in the digester \( y_{\text{CH}_4}^{D,VS_{\text{inp}}} \) (3), (Fig. 9).

\[
y_{\text{max CH}_4}^{S,VS_{\text{inp}}} = y_{\text{max CH}_4}^{VS_{\text{inp}}} - y_{\text{CH}_4}^{D,VS_{\text{inp}}}
\]  

Figure 9: Schematic view of model calculation

Different feedstocks e.g. organic fraction of municipal solid waste (OFMSW), food waste, sludge, animal manure or biogas crops are characterised in different biomethane potential. This value determines both the methane yield of the digester and the methane emissions from the storage tank. While the methane yield of the digester depends mainly from the hydraulic retention time and the temperature in the digester the methane emissions from the storage tank are influenced from the temperature in the storage tank and the storage time. Below the calculation of the relevant parameter will be documented using the example of a certain cow slurry.

Detection of biomethane potential (BMP)

The biomethane potential (BMP) can determined according to the VDI guideline 4630 at standard conditions (1013 bar, 0°C) e.g. using a Bioprocess control device. Based on the cumulative methane yield in course of time and curve fitting by means of a HILL (1) or CHPMAN (2) function the maximum methane yields \( y_{\text{max CH}_4}^{VS_{\text{inp}}} \) was calculated to 282 L kg\(^{-1}\) (Fig. 10).
**Figure 10: Plot of BMP detection with HILL (1) curve fitting**

**Methane yield produced in the digester**

Methane yield produced in and CSTR digester \( y^D_{VS_{np}} \) can be calculated from a simple equation (4) as a function of hydraulic retention time \( HRT \) maximal methane yield of the input feed \( y^V_{max CH_4} \) and a first order reaction rate constant \( k^D \) (Linke, 2006).

\[
y^D_{VS_{np}} = \frac{y^V_{max CH_4} \cdot k^D \cdot t^h}{(c^b + t^h)} \quad (1)
\]

\[
y^D_{CH_4} = y^V_{max CH_4} \cdot (1 - e^{-\frac{t}{HRT}}) \quad (2)
\]

By solving (3) to \( k^D \cdot HRT \) we get

\[
k^D \cdot HRT = \frac{y^D_{VS_{np}}}{y^V_{max CH_4} - y^D_{CH_4}} \quad (5)
\]

and can make a linear plot of \( \frac{y^D_{VS_{np}}}{(y^V_{max CH_4} - y^D_{CH_4})} \) against \( k^D \cdot HRT \) (Fig. 11). Values for \( y^D_{CH_4} \) are obtained from long term experiments by daily fill and draw mode and stepwise decrease of \( HRT \) and considering the steady state in the CSTR (Fig. 11).
The slope of the line is equivalent of the reaction rate constant and results to \( k^D = 0.0976 \, d^{-1} \). Considering the maximum methane yields \( y_{\text{max CH}_4} \) of 282 L kg\(^{-1}\) the methane yield \( y_{\text{CH}_4} \) for \( HRT = 30 \, d \) is obtained to 211 L kg\(^{-1}\). According to this the maximal methane yield from the storage tank (emissions) results to

\[
y_{\text{max CH}_4} = 282 - 211 = 71 \, L \, Kg^{-1}.
\]

**Methane yield from the storage tank**

By combining (3) and (4) the maximal methane yield from the storage tank \( y_{\text{max CH}_4} \) (emissions) can be calculated from (6)

\[
y_{\text{max CH}_4} = y_{\text{max CH}_4} \left( 1 - \frac{HRT \cdot k^{\text{eff}}}{HRT \cdot k^{\text{eff}} + 1} \right)
\]

With increasing of \( HRT \) the methane yield in the digester increases. Consequently, the maximal methane yield from the storage tank \( y_{\text{max CH}_4} \) (emissions) decrease (Fig. 12).
By assuming a linear reaction rate the actually methane yield in the storage tank \( y_{CH_4}^{S,VS_{top}} \) is given by (7).

\[
y_{CH_4}(T,t) = y_{max CH_4}^{S,VS_{top}} \cdot (1 - \exp(-k^S(T) \cdot t))
\]

(7)

where \( k^S(T) \) is the first order linear reaction rate. By solving (7) to \( k^S(T) \cdot t \) we get

\[
k^S(T) \cdot t = -LN \left( \frac{y_{max CH_4}^{S,VS_{top}} - y_{CH_4}^{S,VS_{top}}}{y_{max CH_4}^{S,VS_{top}}} \right)
\]

(8)

In order to calculate the first order linear reaction rate \( k^S(T) \) the methane production of the digester effluent which is operated at the given \( HRT \) must be determined over about 60 days at two different temperatures. From the slope of the lines reaction rate constants can be calculated to \( k^S(22^\circ C) = 0.0086 \, d^{-1} \) and \( k^S(37^\circ C) = 0.0238 \, d^{-1} \) (Fig. 13).
Figure 13: Plot of the slope for $k^S(22°C$ and $37°C$)

To illustrate the effect of different temperatures on methane emissions in course of time a modified Arrhenius Equation (Randall et al., 1982) with a temperature term $f_T$ can be used and calculated on base of the reaction rate constants $k^S(T)$ at $22°C$ and $37°C$ from (9) and (10) with $T_2 \leq T_1$.

$$\frac{k^S(T_2)}{k^S(T_1)} = f_T^{T_2-T_1} \quad (9)$$

$$f_T = \left(\frac{k^S(T_2)}{k^S(T_1)}\right)^{\frac{1}{T_2-T_1}} = \left(\frac{0.0238}{0.0086}\right)^{\frac{1}{37-22}} = 1.0699 \quad (10)$$

Furthermore, Eq. 9 can be rewritten to compute $k^S(T)$ for an arbitrary temperature $T$ with $7°C < T < 37°C$ from (11).

$$k^S(T) = \frac{k^S(37)}{f_T^{37-T}} = \frac{0.0238}{1.06995^{37-T}} \quad (11)$$
Therefore all the conditions for the application of (7) are fulfilled to make a plot for the formation of methane in the storage tank in course of time (Fig. 14).

Figure 14: Methane yield from digestate in the storage tank in course of time at different Temperatures

**Conversion method for other units**

In the measurement of methane emissions from storage tanks methane emission values based mostly to mass of digestate. For conversion of methane yield based on VS in the input feed $y_{CH_4}^{VSS_{inp}}$ into methane yield based on fresh mass of digestate $y_{CH_4}^{mS}$, the following method can be applied. A portion of the substrate mass $m_{inp}$ which passes into the digester is formed into biogas from both the digester $m_{BG}^D$ and the storage tank $m_{BG}^S$. Considering the remaining mass of the substrate mass $m^S$ of digestate in the storage tank $m_{inp}$ we get Eq.1:

$$m_{inp} = m^S + m_{BG}^D + m_{BG}^S$$  \hspace{1cm} (12)

The biogas yield related to fresh mass in the storage tank is:

$$y_{BG}^{mS} = \frac{m_{BG}^S}{m^S}.$$  \hspace{1cm} (13)

Combining (Eq.12) and (Eq.13), the mass of digestate in the storage tank yields to:

$$m^S = \frac{m_{inp} - m_{BG}^D}{1 + y_{BG}^{mS}}.$$  \hspace{1cm} (14)
For calculation of \( m^S \) the value of \( y_{BG}^{m,S} \) is essential, which we get from Eq. 15 considering the biogas density \( \rho_{BG}^S \) and the methane content of the biogas \( \alpha_{CH_4}^S \) from the storage tank.

\[
y_{BG}^{m,S} = \frac{y_{CH_4}^{m,S} \cdot \rho_{BG}^S}{\alpha_{CH_4}^S \cdot 1000}
\]  

Knowing the value of \( m^S \), the methane yield from the storage tank related to the input VS concentration for a given storage temperature \( T \) results in Eq. 16. Alternatively, the methane yield based on the mass of digestate can be calculated from Eq. 17.

\[
y_{CH_4,T}^{VS_{inp},S} = \frac{y_{CH_4}^{m,S} \cdot m^S}{m_{inp} \cdot c_{VS}^{inp}}
\]  

\[
y_{CH_4}^{m,S} = \frac{y_{CH_4,T}^{VS_{inp},S} \cdot m_{inp} \cdot c_{VS}^{inp}}{m^S}
\]

4. Inventory of methane emissions

4.1. Storage of substrate and digester feeding

Liquid substrates, Solid and stickable substrate


4.2. **Digester and processing**

Continuously fed operation, Batch-fed operation

- Liebetrau, J., Weiland, P., Clemens, J., 2011. Emission analysis and quantification of fluxes in biogas plants in view of the ecological assessment of agricultural biogas production and inventory of the German agriculture. report 22023606 commissioned by the Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BML) / Fachagentur Nachwachsende Rohstoffe


- Büeler, E., Hermle, S., 2011. CH4 emissions from EPDM gas storage and their economic and environmental consequences. Report commissioned by Bundesamt für Energie BFE Switzerland


4.3. **Digestate upgrading**

Solid-liquid separation, Liquor processing, Drying

by the Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV) / Fachagentur Nachwachsende Rohstoffe


4.4. Digestate storage

Open lagoons, Covered not gas tight tanks, Solid pile

Liebetrau, J., Weiland, P., Clemens, J., 2011. Emission analysis and quantification of fluxes in biogas plants in in view of the ecological assessment of agricultural biogas production and inventory of the German agriculture. report 22023606 commissioned by the Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV) / Fachagentur Nachwachsende Rohstoffe


Büeler, E., Hermle, S., 2011. CH4 emissions from EPDM gas storage and their economic and environmental consequences. Report commissioned by Bundesamt für Energie BFE Switzerland


4.5. **Digestate application**

liquid digestate, solid digestate


4.6. Biogas utilisation

Combined Heat an Power generation (CHP), Biogas cleaning and upgrading (Pressure Swing Adsorption, Water scrubbing, Chemical scrubbing, Membrane separation), Vehicle filling station

Liebetrau, J., Weiland, P., Clemens, J., 2011. Emission analysis and quantification of fluxes in biogas plants in view of the ecological assessment of agricultural biogas production and inventory of the German agriculture. report 22023606 commissioned by the Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV) / Fachagentur Nachwachsende Rohstoffe


5. Evaluation of methane emissions

Reference systems boundaries and functional units,

References


UBA, 2008. Steigerung der Energieeffizienz auf kommunalen Kläranlagen
http://www.umweltbundesamt.de/search/content/Forschungsbericht%2520205%252026%2520307


Allen, E. Browne, J.D., Murphy, J.D. 2013. Evaluation of the biomethane yield from anaerobic co-digestion of nitrogenous substrates By: ENVIRONMENTAL TECHNOLOGY Volume: 34 Issue: 13-14 Special Issue: SI Pages: 2059-2068


Büeler, E., Hermle, S., 2011. CH4 emissions from EPDM gas storage and their economic and environmental consequences. Report commissioned by Bundesamt für Energie BFE. Switzerland


her Ergebnisunsicherheit mittels Monte-Carlo-Simulation. Dissertation, Universität für Bodenkultur Wien


Kaparaju, P., Rintala, J., 2011. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. Renewable Energy 36. 31-41


