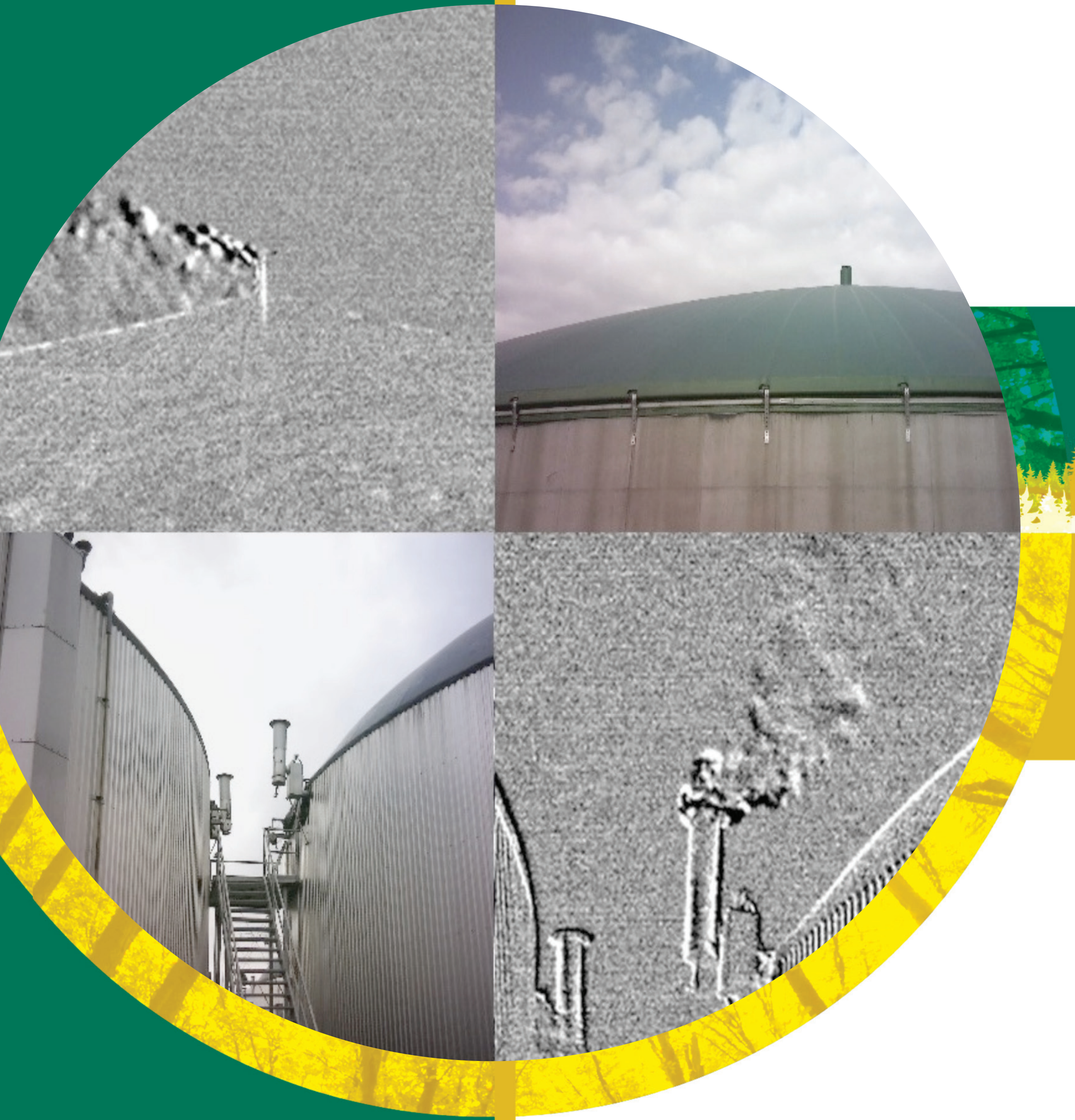
METHANE EMISSIONS FROM BIOGAS PLANTS

Methods for measurement, results and effect on greenhouse gas balance of electricity produced



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Methods for measurement, results and effect on greenhouse gas balance of electricity produced

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1. Executive summary

Methane is a potent greenhouse gas with a global warming potential much higher than carbon dioxide. Fugitive methane emissions from a renewable energy production system are not conducive to the ambition of reducing Greenhouse Gas (GHG) emissions. The biogas industry is growing and innovative technologies are associated with the rising numbers of facilities in operation. With new technologies it is essential to ensure minimum fugitive emissions; this leads to new challenges regarding emission monitoring, quantification and reduction. Within the biogas sector methane emission quantification is becoming a significant topic for the scientific community but is still under development for the industry sector. The methods used and the interpretation and evaluation of the results obtained is not as yet standardised. This report addresses methods used for evaluation, presents selected results of measurements, proposes mitigation measures and puts methane emissions in a context of a standard greenhouse gas balance in order to evaluate the impact of these emissions on the sustainability of the biogas system.

Methods

Currently several methods are in use and a variety of data sets have been provided from different international teams. The methods used can be distinguished into two major approaches. The single source method aims at an identification, quantification and summation of every emission source. The overall plant measurement aims at the quantification of the plant emissions in total and is effected by remote sensing. The approaches have different advantages and limitations and are therefore applicable for different purposes.

An additional complexity is that the methods applied by industry and by the scientific community can vary in general approach, execution, data analysis and interpretation; this can lead to non-comparable results. An important task for the future is therefore method harmonization including for documentation and reporting of the results. Factors influencing the results involve: the limitations of the methods used; the duration of measurement (in order to cover time variability of specific emission sources); the completeness of plant components measured and potential sources included but not belonging to the biogas facility (such as barns); and the operational mode of the plant. For a representative emission factor, which covers the average emissions during operation, all aspects need to be sufficiently well considered for a sound result.

Results of measurements

The parameters with the largest influence on the quantity of methane emissions can be distinguished by structural (the technologies deployed) and operational (plant management) means. The most important sources included: open storage of the digestate; the combined heat and power (CHP) engine; leaks; and the pressure release valve (PRV). Large quantities of uncontrolled methane emissions have been reported caused by single large leaks or long lasting pressure relief events.

It is very difficult to give general, average numbers for emissions from components or complete biogas plants. Firstly, the results given in literature have large differences due to the variations within the methodologies applied. Even emissions from the CHP engine show a substantial variability, although the methods for quantification are well defined and engine construction and operation should lead to similar emissions. Secondly, the plants are highly individualized and any generalisation needs to include a classification considering the plant design and plant operation in order to obtain a general emission factor for the sector. Thirdly, methane emissions need to be seen in context with other factors influencing GHG emissions and sustainability of the bioenergy installation. Looking at the methane emission in isolation will not allow assessment of the full impact of the system on the GHG emissions or sustainability in relation to renewable energy production or waste treatment.

The results available show a large variability regarding the amount of emissions from biogas plants. There are not sufficient data for a general assessment of the sector, but trends indicate which components should be monitored and which measures are useful to minimize the amount of released methane.

Reduction measures

The application of specific monitoring and maintenance and/or the application of specific technologies can reduce emissions. A crucial part of any operation should be a monitoring plan and in particular frequent monitoring of any potential emission sources on site. Some of the potentially larger sources (CHP, PRV and large leaks) are dependent on operation and time and therefore need to be routinely monitored. In case of high emissions, they can be substantially reduced by operational measures.

Reduction measures can include the following:

- **Emissions from digestate storage** should be minimized since they are one of the major sources. Either the digestate tank should be covered (gas tight with gas utilisation) or the degradation of the substrate should minimize the possibility of emissions. As soon as the digestate leaves the process its emission potential needs to be minimized. In case the digestate is used to condition substrate for better handling or to support hydrolysis in a pre-treatment step, this should happen within encapsulated units and any gas produced during this step should be treated. Any aerobic post-treatment should include a sufficient oxygen supply in order to avoid methanogenic activity. The monitoring of oxygen supply (or methanogenic activity) within the process is recommended.

- The **exhaust of the CHP** can contain high methane concentrations due to incomplete combustion. Frequent control and documentation of motor settings and frequent maintenance and control of methane concentrations can help to minimize these emissions. Further reduction can be achieved by means of post combustion of the exhaust gas, but this is an expensive solution. There are no catalysts for methane emission reduction available at the market for lean-burn engines. However, Selective Catalytic Reduction (SCR) is also discussed as an option for optimising the emissions from CHP since it allows the unit to operate with lower lambda (air fuel ratio) leading to lower methane emissions.

- In the case of **biogas upgrading technology,** depending on the applied type of technology, the concentration of methane in the off gas varies due to varying separation efficiency. In case of significant emissions caused by the off-gas, a post treatment is recommended. Frequent function control and monitoring of the performance of such devices is necessary.

- The biogas containing components should be frequently monitored to identify **leakages**. This includes surveys with leakage detection systems such as methane cameras and handheld lasers. Such a survey should be carried out every 1 to 3 years, depending on the status (age and number of leaks found) of the plant. Monitoring for elevated methane concentrations within the off-gas streams from air inflated double membrane roofs should be included in routine measures.

- **Plant management** should aim at avoidance of PRV releases (and flaring events) in order to minimize emissions and losses in general. This includes the automatic operation of the flare linked to the filling level of the gas storage. A stationary flare is required, which is operational in parallel to the CHP and kicks in before the PRV opens. The filling level of the gas storage should be well below 80 % during normal operation (in order to compensate weather and operation induced changes); a value of around 50 % is recommended. The level indicators need to be capable of delivering precise measurements in any range of filling level. Connected membrane gas storage systems need to be adjusted to each other in order to allow controlled filling levels and pressure conditions in all vessels under all process conditions. Accordingly gas transfer between several gas storage systems needs to be controllable in order to avoid unbalanced filling levels as well as pressure ratios, which might lead to PRV release in one vessel although other vessels have idle or spare capacity. In case flare operation is not set to avoid PRV events, a monitoring system for PRV operation is recommended to record the number and duration of release events. The gas management system can also include the adjustment of feeding during shutdown of the gas utilisation or periods of reduced load of the CHP. Adequate dimensions of pipes, blowers in the gas pipes and controllable air pressure in the air inflated roofs are measures to achieve well balanced filling levels in all gas storages.

GHG balance

When putting the methane emissions into a context of a GHG balance of the bioenergy system, it becomes apparent that beside the fugitive methane emissions other important factors (in decreasing order) include: the substrate used; the heat utilization; and the parasitic energy demand. In case of a clear GHG reduction target the plant design needs to be chosen carefully, since some components (such as CHP unit, open digestate storage) cause inevitably certain emissions once in operation.

By using the data and methodology adopted by the European Commission, and assuming 30 % of the Fossil Fuel Comparator (FFC) for electricity as a targeted limit for the operation, it was shown that energy crop based plants will experience difficulties in reaching this reduction target without specific measures (such as heat utilization or exhaust treatment at the CHP) since the energy crops come with a GHG burden associated with the production of the crop. Manure based plants come with a large credit due to avoided emissions from raw manure storage. Consequently, manure digestion reduces emissions significantly and this effect is also to be seen in co-digestion systems.

Outlook

The major task for the future is an improvement of precision, reproducibility and representativeness of the methods used for emission quantification. A method harmonization or at least a defined protocol will be necessary to compare results from different measurements. An important aspect of the documentation is the definition of the status of the plant and how highly time variant emissions (such as PRV release events) are included in a long-term reference time period. Only comparable results in combination with a sufficient number of plants analysed will lead to a better understanding of the emissions from the whole sector and a reliable data base for emission inventory. A general task for the future is to raise awareness within plant operators and plant manufactures of this issue. Only if the industry is sensitive to the subject, can emissions be further reduced.

2. Introduction

2.1 Background of the report

Climate change is one of the great challenges of the 21st century. The most severe impacts may still be avoidable if substantial efforts are made to transform current energy systems. Renewable energy sources have the potential to reduce emissions of GHG when compared to the combustion of fossil fuels and thereby to mitigate climate change. Bioenergy systems can contribute to climate change mitigation if they replace traditional fossil fuel use (IPCC, 2012).

Within the bioenergy sector the increased use of biogas opens up new opportunities in areas where biomass has not played a major role so far (Anonymous, 2009). Biogas production has been growing steadily in recent years and has made 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 overall annual potential for biogas will be at least 50 billion m^3. Thus, by 2030 with the right policies in place, the industry could deliver 2–4 % of the EU's electricity needs and provide a 15–30 % share of today's methane (natural gas) market. The concurrent contribution to the heat demand as a by-product of the electricity provisions by means of combined heat and power units has not been recognized adequately yet.

Biogas can be produced by anaerobic digestion of almost every wet organic feedstock (with the exception of lignin). The most common substrates used for biogas production are: animal waste and crop residues; energy crops; domestic food and garden waste; industrial wastewater; municipal sewage sludge; and the organic fraction of Municipal Solid Waste (MSW). Biogas production and utilisation is recognised as an integrated process including for feedstock supply and pre-treatment, gas production, treatment and utilisation as well as recovery, pre-treatment and use of digestate. Figure 1 highlights possible process components and processing pathways for anaerobic digestion.

Although biogas production and use are regarded as a very sustainable practice that can guarantee GHG savings (Masse et al. 2011) special attention should be given to methane emissions within the biogas production and utilisation chain. If released uncontrolled into the atmosphere methane represents a very potent GHG, a safety hazard and last but not least the emission also represents an economic loss. It should also be mentioned that the public acceptance of biogas facilities is strongly dependent on the proof of low emissions. Besides methane there are other gases such as ammonia and nitrous oxide (a significant GHG), which might be emitted from biogas systems. However, this publication focuses on the methane emissions from the biogas production process, since the methodology of measurement is different and the effect of methane on the GHG balances is more pronounced (Agostini et al. 2015). The work in this report will concentrate on production of electricity from biogas rather than gas grid injection.

When referring to emissions, a sufficiently precise determination of the quantity of emitted gases is a crucial point since any practical assessment at a biogas plant as well as evaluations for authorities, stakeholders from the energy sector, for certification systems and the national GHG inventories requires an authoritative number on the amount of gases emitted. For whatever reason the investigation of a plant is carried out – any emission reduction and respective operational optimization of biogas facilities depend on the previous identification and quantification of emission sources.

During recent years the topic has gained more and more attention and there are several publications describing methodology and results of emission measurements. Using these results numerous GHG balances and life cycle assessments have been carried out. The results of such assessments depend on additional factors such as for instance: the origin and production of feedstock; the operation of the system and resources used; credits for by-products and the disposal of wastes from the process. 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).

The report aims at giving an overview of the state of the art of methane emission measurements at biogas plants, results obtained, mitigation measures and a perspective on the impact of these emissions on GHG balances and sustainability of biogas production in producing electricity.

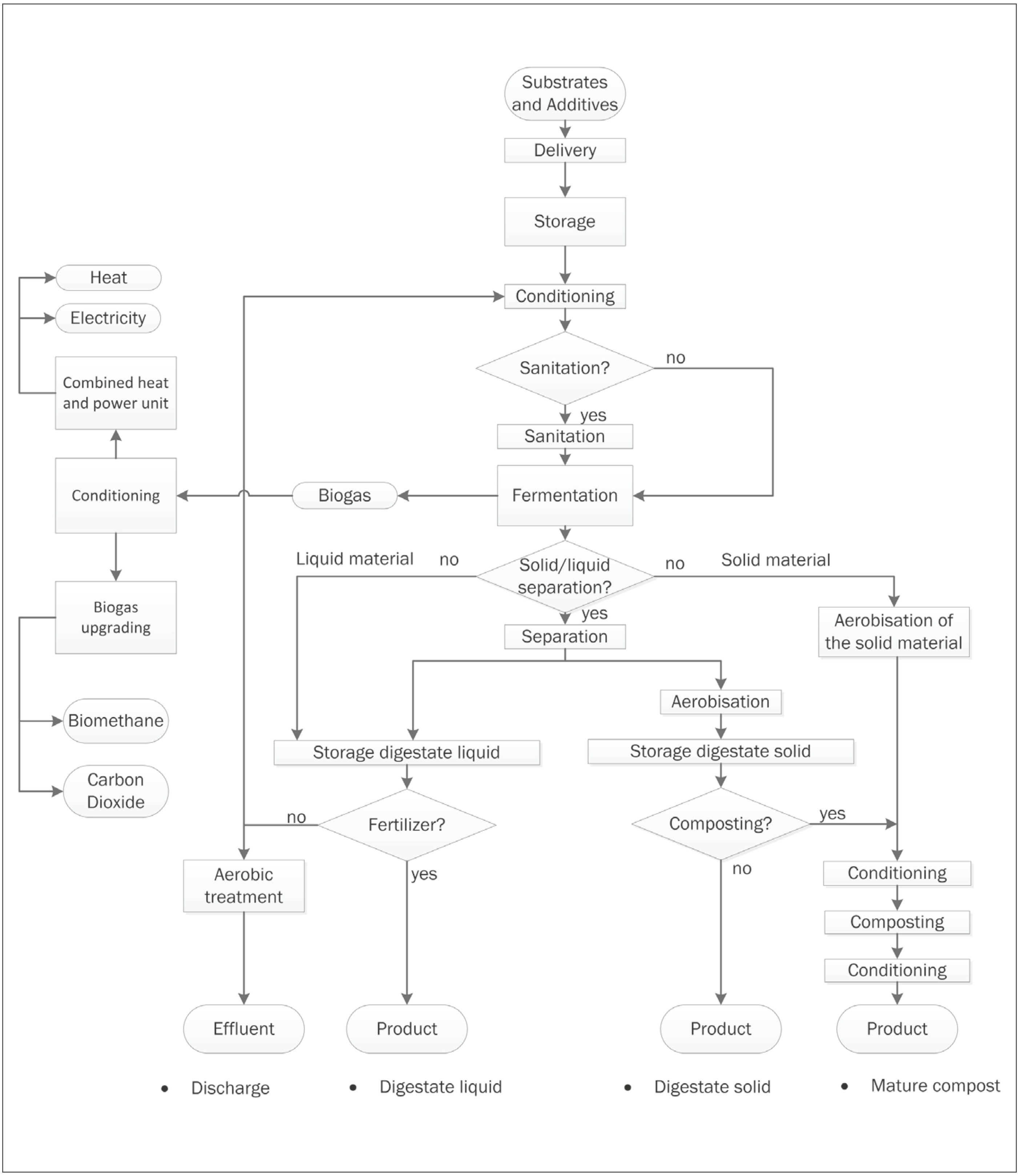

Figure 1: Possible process components and processing pathways for anaerobic digestion

3. Challenges for emission measurements

Biogas plants aim to produce renewable energy with methane as the energy vector. Consequently, an unwanted and/or inevitable emission from the process is methane, which is a powerful greenhouse gas. An efficient and sustainable biogas system must ensure these emissions are minimised. The first step to a successful emission mitigation strategy is the identification and quantification of emission sources.

3.1 Type of sources

Emission sources have certain characteristics, which determine the possible methodology for identification and quantification of the source. In the following, categories are applied, which focus mainly on the method for the analysis of the emissions source.

Location – Identified (known) and unidentified sources

Identified (known) sources, such as the CHP exhaust or open digestate storage can be investigated directly, since the location of the source is known. Unknown sources can be either large sources such as leakages or a sum of small sources (diffuse sources). In case of a detailed source analysis the large sources have to be identified and then analysed individually. Diffuse sources are as per definition too small and/or too many to investigate individually with reasonable effort. Diffuse emission sources can only be analysed with an appropriate method, which comprehends the overall emissions of a plant.

Size and type– point and area source

A second distinction can be made between point and area sources. Point sources such as the CHP exhaust or pressure relief valves (PRV) will require different measurement techniques as compared to a large area source such as an open digestate storage tank, a biofilter surface or a substrate heap.

Time – constant and temporary/time dependent sources

Last but not least a consideration of the time dependency of the sources is important. There are almost constant sources such as the CHP exhaust, which can be measured at any point of time and the emission rate can be easily transferred to long-term plant operation. On the other hand, temporary sources with highly unpredictable characteristics such as the release event of an overpressure valve or emissions from digestate storage need to be identified and quantified by different strategies. In particular, extrapolation and transfer of such sources to long-term operation of the plant or the calculation of emission factors need to be carried out carefully.

3.2 General aspects for emission measurements

In general, there are two different approaches when it comes to emission measurements. The first approach is the attempt to identify and quantify every single source on site. The results of the single source quantification are added up and the sum represents the overall emission rate of the plant.

The second approach considers the overall plant as one single emission source and the overall emissions of the plant are determined. This is usually achieved by means of a combination of concentration measurements (remote sensing or gas sampling) at a defined distance from the plant and the use of models (e.g. micrometeorological models) to calculate the emission source. Table 1 displays the strengths and constraints of the two measurement concepts.

Table 1: Comparison of emission quantification methods

	Single source measurement	Overall plant measurement
Strengths	Identification and quantification of single sources Emission rates of single sources are analysable and direct mitigation strategies can be deduced Low detection limit (single source and total emission rate) Independent of weather conditions Effort adjustable to the requirements	Long-time measurements with high resolution possible No influence on plant operation Time effort quite independent from plant size All emissions sources are recorded Time variant emissions are detectable during long term measurements
Constraints	Time variant emission sources are difficult to identify Unknown and diffuse sources are not included High effort on large plants with many digesters Influence of measurement on emissions (e.g. chamber methods)	No identification of single sources possible Highly dependent on wind conditions and topology around the plant Influence of the uncertainties of dispersion models and/or atmospheric mixing Difficulties with separation of other sources nearby (e.g. barns)

It can be concluded that the two methods complement each other. The single source method is the better choice for leakage identification and mitigation strategies, whereas the remote sensing method delivers the overall emissions and allows the monitoring of temporal emissions caused by specific operating modes of the plant. Depending on the purpose of the plant investigation, the proper method can be selected. Alternatively both methods can be used and serve as a check on the other.

3.2.1 Point sources

Point sources have a space limited emission zone and can therefore be analysed completely. Examples are the exhaust of combined heat and power units, small and accessible leakages, the exhaust pipes of overpressure valves, the outlet of two layer inflated domes, and the exhaust pipes of contaminated air from encapsulated plant components (Figure 2). The characteristic of these sources is a defined area, which can be covered completely by the measurement. Usually the quantification of the source can be accomplished by means of flow measurements in pipes and simultaneously conducted concentration measurements in the gas stream. In the case of leakages, the construction of a chamber around the source might be necessary for the establishment of a defined and easy to measure flow rate. The emission rate is calculated based on flow rate and concentration.

3.2.2 Area sources

Area sources have a defined size, which are too large to cover completely with one measurement. Examples are open digestate (Figure 3) and substrate storage tanks or heaps, large biofilters and open windrows of post composting processes (if not encapsulated and connected to an air collection system). When applying the single sources method a defined part of the area is analysed and the results are extrapolated to the overall area. Commonly open or closed chamber systems are used to cover a defined area of the source for emission determination. Within large tanks the chamber needs to be installed in several locations in order to get an average value for the tank. Unfortunately, the emission rate from the area cannot be assumed to be evenly distributed or constant over time. Digestate storage tanks are usually not mixed, the temperature is dependent on ambient air temperatures and the filling level is variable according to manure spreading periods (when some of the digestate is removed from storage and applied to land). Compost windrows on the other hand have variable emissions depending on structure of the material, the turnover frequency and the activity of the material.

These characteristics make it quite difficult to get a reproducible result, which represents a longer period of operation. Therefore the measurements, without any other additional operational data, result in an emission quantity, which can only represent the very time of the measurement.

Figure 2: a) Point source pressure relief valve (PRV) (DBFZ)

b) vane anemometer for flow measurement in point sources (DBFZ)

Figure 3: a) Digestate storage in an open lagoon

b) Measurement setup at an open biofilter [DBFZ]

3.2.3 Diffuse and unknown sources

According to the UN-ECE PRTR Protocol (UNECE, 2009) diffuse sources means: "the many smaller or scattered sources from which pollutants may be released to land, air or water, whose combined impact on those media may be significant and for which it is impractical to collect reports from each individual source".

Even if this has been defined for a much larger frame, the statement is also applicable for biogas plants. According to this definition diffuse sources would include small leakages, emissions from spoiled surfaces and unidentified emission sources. These kinds of sources can only be identified by the overall plant measurement based on remote sensing. The single source measurement cannot quantify diffuse emissions, since they are per definition too small or too many to collect data from.

The term diffuse is also used for either not confined or collected and unknown sources, which are not easy to measure. Such a definition would include every source except the ones, which can be measured within a pipe. Within the term diffuse there are further specifications possible which describe the type and time of occurrence (VDI, 2005b). In this publication the term diffuse source is used as per the first definition.

3.2.4 Time variant emissions

Some emissions are dependent on specific operational conditions. Examples are the release of overpressure valves or emissions from the digestate tank. The occurrence of an emission event might even be highly unpredictable and dependent on infrequent operation modes of the plant as for example in the case of the release of an overpressure valve. Such emissions can only be analysed by means of long term measurements of either the specific potential emission source (provided the source is known) or the overall plant (includes all sources).

4. Devices for emission measurements

4.1 Portable imaging infrared camera

Portable imaging infrared (IR) cameras (Figure 4) have been developed based on passive remote gas detection by infrared spectro-radiometry. Based on the spectral analysis of radiation in the infrared spectral range, which is absorbed and/or emitted by the molecules of a gas cloud, an IR camera enables the visualization of gas clouds. The limit of detection of an IR camera (as given by the manufacturer) amounts to about 50 ppm*m (Esders GasCam SG). It depends on the background and the temperature difference between the gas and the background. By means of the passive infrared method, it is possible to visualise gas plumes in front of an unreferenced background such as the sky. Box 1 details features of an FLIR infrared camera system. There are other producers of such systems including Esders.

Gas clouds moving in free space can be visualized in real time and emission sources along the entire biogas process chain can be located. Typically, leaks at a distance of 0 up to at least 30 to 40 meters (dependent on the size of the leak and the conditions) can be detected. The detection limit (FLIR product) is given by the company as 8 l h^{-1} (for GasFindIR, which is the previous model of GF 320; Benson et al. 2006), users of such equipment give 12 l h^{-1} (8 m distance, no information about wind conditions) as a threshold (Clemens et al., 2014). The big advantage here is that large plant sections can be evaluated in a short time. In addition, inaccessible components of the plant such as elevated gas pipes or rubber domes can be checked with an IR camera.

When applying these technologies the following aspects should be considered. The IR camera is not very suitable for indoor measurements. The actual occurring methane concentrations need to be confirmed by other devices since, weather conditions, temperature of the released gas, and measurement set up, have an influence on the visibility of the emissions. The camera is easy to handle and the emission source is visible, which makes leakage detection easy. The size of the leakage can be roughly estimated from the visible emission rate.

Box 1: Features of one possible IR camera system:

Device:	Imaging IR camera
Producer:	FLIR
Type:	GF 320
Measurement principle:	Passive infrared
Measurable gases:	Methane, Ethane, Propane, Butane, Ethylene and others
Temperature range:	- 40 – 350 °C
Temperature uncertainty:	±1 °C for temperature range 0 – 100 °C and ±2 % of the reading for the range > 100 °C
Leakage range (declaration for the previous model GasFindIR):	Depending on temperature difference/ distance to source; detection limit for methane (laboratory): about 8 l h^{-1} (release of pure methane, 3 m distance and 8 km h^{-1} wind (Benson et al., 2006)
Explosion protection:	Not protected

Figure 4: a) IR camera during use on the DBFZ exploratory biogas plant (handheld device from FLIR) b) Camera setup GasCam (Esders GmbH, Haselünne)

4.2 Portable methane laser

The portable methane laser is, like the IR camera, a remote sensing measurement technology. In contrast to the camera, the laser is based on an active IR measurement principle. From the device an IR laser beam with a certain wavelength (e.g. 1,653 nm) is emitted and reflected back from a surface to the detector in the device. The intensity of the reflected laser light decreases exponentially with raised distance from laser source to reflection surface. Due to the installed laser diode and the selected wave length the device is sensitive to methane. From the measured absorption the device calculates path integrated methane concentration stated in ppm*m. The measured value has to be divided by the distance to the reflection surface to get path-averaged concentration in ppm. This principle is schematically shown in Figure 5. Box 2 gives features of one possible methane laser. Brands include Growcon or Sewerin lasers.

The laser is able to determine the methane concentration at the direct leakage spot. However, only path average results are available. The laser is explosion proof, applicable for indoor leakage detection, and allows inaccessible components to be analysed. It gives an actual methane concentration value; this is not the case for the IR camera. It has a low detection limit. The leakage is not visible, which might make the identification of the actual leakage point difficult.

4.3 Remote sensing systems

Remote sensing systems operate over distances and are either able to detect path averaged concentrations over the measuring path or can even give a spatial resolution of gas plumes.

An often used technique to measure gas concentrations on an open path is a tunable diode laser absorption spectrometry (TDLAS) (Figure 6). The device emits laser light in near IR, which is reflected by a retroreflector positioned at a certain distance. Subsequently, the device detects the reflected light again. The wavelength emitted by the laser diode is tuned over a certain absorption line of a specific gas, in this case methane. Depending on the wavelength, the light is absorbed by the methane molecules within the measurement path. From the detected light intensity per wavelength, the number of molecules, and the path averaged gas concentration can be determined.

Tuning over one specific absorption line has the advantage of single gas detection and the risk of interferences with other present gases is reduced. The response time is low.

Box 2: Features of one possible portable methane laser

Device:	Portable methane laser
Producer:	GROWCON
Type:	LaserMethane® *mini* Gen2
Measurement principle:	TDLAS (Tunable Diode Laser Absorption Spectroscopy)
Measurement range:	1 – 50.000 ppm m (depending on distance/reflection surface)
Measurement uncertainty:	± 10 % (1000 ppm m and 2 m distance)
Calibration:	Self-calibrating by integrated gas measuring cell
Explosion proof:	II 2G Ex ib IIA T1

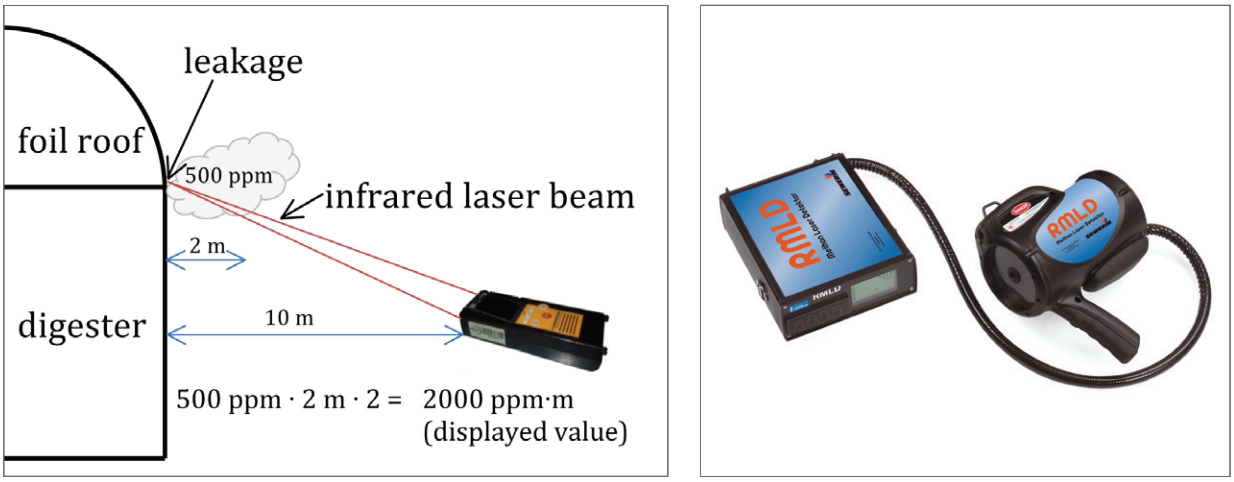

Figure 5: Use of a portable methane laser to detect leakages (left: Holmgren et al., 2015; right: Hermann Sewerin GmbH, Gütersloh)

Figure 6 Open path tuneable diode laser systems in use at a biogas plant (DBFZ)

Box 3: Features of one methane laser

Device:	Portable methane laser (application is stationary)
Producer:	Boreal
Type:	GasFinder 2.0
Measurement principle:	TDLAS (Tunable Diode Laser Absorption Spectrometry)
Measurement range:	1 to 500m, LDL 1ppmm for methane
Measurement uncertainty:	1 ppmm
Last calibration:	Self-calibrating by integrated gas measuring cell
Explosive protection:	No

The device delivers a path-integrated concentration (ppm*m). The possible path lengths depend on the setup and the size of the source area and range usually up to 500 m. The restriction for the system is that one laser can measure only one target gas, and in case of dust, steam or fog the laser beam is diminished too much and the analysis will not be possible.

Besides this system there are other options for remote sensing devices as for instance the open path Fourier Transform Infrared Spectroscopy (FTIR). This system is more sophisticated and requires more effort for proper handling and data evaluation. On the other hand, a variety of gases can be measured at one time. Both systems require a (microscale) meteorological model to calculate emission rates from a source. Additional options are Light Detection and Ranging (LIDAR) and differential absorption LIDAR (DIAL), which allow also a spatial resolution of the measured gases, but require even more effort for an onsite plant evaluation (Merril et al., 2011).

Another approach of remote sensing is measurement of gas concentrations on transects in the down-wind plume of the source using cavity-ring down spectroscopy (Mønster et al., 2014). The options to use these measurements for emission rate calculation will be discussed in chapter 5.2.

Box 3 lists features of one potential device for methane measurements. Other producers of TDLAS systems include: PKL Technologies; Neo Monitors; Unisearch Canada.

4.4 Portable gas analyser

Portable gas analysis devices used for emission analysis have usually been produced for applications other than emissions from biogas applications. In comparison to the open path technologies, these systems take a sample from ambient air and analyse these inside the device. Such devices can be used to identify elevated concentrations in the ambient air or within defined flow rates, gas concentrations for the calculation of the emission rate. Depending on the sensor or the measurement principle within the device the measurement range and measurement uncertainty are quite different.

Portable biogas analysers (Figure 7, Box 4) are usually used for the evaluation of gas composition of biogas, equipped with infrared sensors for methane and carbon dioxide and optionally additional gases such as oxygen and nitrous oxide. Since the main purpose of these devices is the analysis of biogas they have limited value for the emission measurements – the measurement precision in the low concentration range (ppm) is insufficient. Such analyzers help to identify leakages and to verify the release of biogas; they can help to identify dangerous concentrations in the range of the explosion limit. They are quite commonly in use within the sector. Table 2 outlines the measurement range and the accuracy available in one optional device. Portable Flame Ionization Detectors (FID) can provide a much more precise analysis of gases with low content of organic carbon. The FID gives a good result on combustible hydrocarbons. Since methane is usually the main component of hydrocarbons emitted from a biogas plant, other hydrocarbons can be neglected and the method is precise enough for the purpose. There are devices available, which have been developed for landfill monitoring. They can be easily carried. However the measurement principle is not explosive proof. For continuous measurements of low concentrations of methane a portable FID from Bernath (Atomic 3006) is an example (Box 5).

The measurement uncertainties of the BM 2000 are shown in Table 2.

A portable FTIR has much more options regarding the analysis of components within the gas mixture. FTIR are for instance used for the determination of formaldehyde within the exhaust gases of CHP units. For the determination of only methane in a gas mixture, the effort of purchasing and operating such a system might not be justified for the purpose.

4.5 Analysis of gas samples

The quantification of emission rates is usually based on flow and concentration measurements. In case the concentration cannot be analysed onsite by means of portable gas analysis devices, a sample has to be taken and brought into a laboratory for further analysis. Samples can be taken using evacuated glass vials (e.g. 22 ml volume), which are easy to handle for further analysis (EN ISO 25139:2011-08, 2011, VDI, 2005a). Other options are the sampling with gas-bags. Gas bags are usually not available in large numbers and difficult to handle with increasing numbers therefore only applicable if a limited amount of different samples are taken. In the laboratory the options regarding the analysis method are much better than in the field, however the main disadvantages are the time lag until the results are available, the limited number of samples, which can be taken and the relatively high costs. On the contrary, online methods deliver an immediate and continuous signal. Char-

Figure 7: Available biogas monitors (DBFZ)

Box 4: Features of the biogas monitor

Device:	Portable biogas monitor
Producer:	Geotechnical Instruments Ltd
Type:	BM/GA 2000
Volume flow of integrated pump:	0.3 l min^{-1}
Integrated air pressure sensor:	900 … 1 100 mbar (± 5 mbar)
Calibration	with test gas
Explosion protection:	Ex II 2G EEx ibd IIA T1 Gb

Table 2: Measurement range and uncertainties of the BM 2000

		CH_4 in vol. %	CO_2 in vol. %	O_2 in vol. %
Measurement range		0 – 100 (IR)	0 – 100 (IR)	0 – 25 (Electrochemical)
Uncertainty	0 – 5 vol. %	± 0.5	± 0.5	± 1.0
	5 – 15 vol. %	± 1.0	± 1.0	± 1.0
	> 15 vol. %	± 3.0	± 3.0	± 1.0

Box 5: Capabilities of portable FID

Features of the FID:

Measured components:	Hydrocarbons, chlorinated hydrocarbons
Temperature of analytical chamber:	200 (60–240) °C
Warm-up time:	approx. 15 minutes
Measuring Ranges:	smallest range 1ppm relative to C_3H_8; largest range 10% by volume
Linearity:	up to 100,000ppm, between a decade range, ±1%, over the complete measuring range ±5%
Detection Limit:	<1.5% of final value of measuring range, smallest value 15ppb C_3H_8
Detection signal rise time (T90):	<0.9 seconds
Consistency of results:	30–200 (repeated measurement will obtain the same value)
Sample Gas Flow:	approx. 1.2 l/min

Table 3: Analytical measurement methods

Gas	Sampling	Measurement method	Measurement device	Standard
Methane (CH_4)	Evacuated vials (less than 10 mbar absolute pressure)	Gas chromatograph with an auto sampler and flame ionization detector (FID) for CH_4 and electron capture detector (ECD) for N_2O	Agilent 7890A GC System	EN ISO 25139:2011-08 (2011)
Nitrous oxide (N_2O)				VDI (2005a)

acteristics of analytical measurements in Gas Chromatographs are outlined in Table 3 and Table 4.

Table 4: Uncertainty of a stationary laboratory GC (DBFZ data)

		CH_4 in Vol. %
Measurement range		1.96 – 39,540 ppm
Uncertainty	1.96 – 100.09 ppm	± 8 %
	100.09 – 2,001 ppm	± 7 %
	1,977 – 39,540 ppm	± 3 %

4.6 Measurement of flow rates

The flow rates can be determined by means of vane anemometer or pitot tube with a microanemometer. Based on the cross section area of the investigated pipes and the measured flow rates the volume flows will be calculated as per Table 5.

Table 5: Devices for flow rate measurements

Device	Measurement range	Accuracy
Vane anemometer, e.g. Testo 416	0.6 – 40 m s^{-1}	0.2 m s^{-1} and ±1.5 % from measurement value
Pitot tube and sensor for pressure difference, e.g. Ahlborn FDA602	±1,250 Pa 1 – 40 m s^{-1} ±6,800 Pa 2 – 90 m s^{-1}	±0.5 % from upper range value

5. Methods for measuring and calculation of methane emission rates

5.1 Single source method

The method requires the identification and quantification of every single emission source on site. Accordingly, the procedure can be described as follows:

1. Identification of emission sources;
2. Setup for emission sources with respective methods for:
   - Digestate storage;
   - Leakages;
   - Upgrading units;
   - Pressure relief valves;
   - Exhaust pipes (e.g. CHP units or gas collection systems);
   - Open (in case no centralized air collection system available) post composting windrows.
3. Determination of flow rate;
4. Determination of concentration of target gas;
5. Calculation of emission rates;
6. Summation of all sources.

In the following, several measurement setups at different emission sources are briefly introduced. The on-site approach and the corresponding methods can be significantly different. In Holmgren et. al. (2015) results of measurements carried out by several teams from different countries, who investigated one biogas plant during one week are summarized. It became apparent, that the definition of emission sources can be different, as well as the approach to measure them. Additionally, the emissions from the investigated plant were shown to be time variant and the different teams have not identified all sources. However, even if the single measurements diverged among them, the overall results were in the same range. Normally, the possibility to have several teams on site will not occur under normal conditions and therefore the plant evaluation has to be carried out with care. In any case it will never be certain that all emission sources are recorded.

5.1.1 Identification of emission sources – leakage detection

Leakage detection on biogas sites has been a topic of increasing interest since development of imaging infrared cameras, which allow the visualisation of emissions,

and makes the process much easier. However, the equipment alone does not ensure a sufficient plant evaluation and so far no specific standard procedure for leakage detection for biogas plants has been defined. There are some approaches from industrial entrepreneurs to define basic requirements for leakage detection of biogas facilities (Clemens et al., 2014). In any case, it should be mentioned that the identification of a leak does not provide information on the emission rate coming from the leakage nor does a concentration measurement in the proximity of a leak provide an accurate assessment of the concentration of the methane in the leak.
In Clemens et al. (2014) basic equipment for any plant inspection is recommended as follows:

- IR camera;
- Methane sensitive gas analyser;
- Devices for documentation of weather conditions (ambient pressure, temperature, wind speed);
- Devices for the evaluation of flow rates.

The documentation of the results according to (Clemens et al., 2014) should include:

- Weather conditions as ambient pressure, temperature, wind speed, cloudiness, precipitation;
- Description of the plant with site plan/drawings or photos;
- Operational state of the plant (gas storage filling level, gas pressure, CHP performance);
- Site plan of the discovered leaks (leakages need to be documented based on pictures and film);
- Qualitative evaluation of leakage based on a matrix containing factors such as estimated flow, location (closed room or open), accessibility, potential of expansion of the leak, distance to ignition source.

During the plant evaluation it should be made clear that all plant components are covered sufficiently during the survey. The logging of the camera positions during the plant survey might help to verify that all parts of the plants have been evaluated.

5.1.2 Open/dynamic chambers

Open 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 to 0.7 m². The open chamber method has been also applied for the investigation of leakages and covered digestate tanks.

The open chamber has an input and output pipe and a connected blower to produce a constant airflow through the chamber (Figure 8 and Figure 9). The gas from the emission source (leakage) and the fresh air are mixed in the space within the chamber and the concentration of the target gas is analysed by sampling the gas in the input and output stream of the chamber. The quantity of the emission source is calculated from the concentration difference and the flow rate of the blower by using Equation 1 from (Liebetrau et. al. 2013b).

Equation 1

$$E = \frac{\dot{V} \cdot \rho \, (C_{out} - C_{in})}{A}$$

E	Surface specific emission mass flow in mg CH_4 h^{-1}
$\dot{V}$	Air flow in m^3Air h^{-1} STP, dry
ρ	Gas density of methane in mg ml^{-1}
C_{out} and C_{in}	Exhaust and background methane concentration in ppmv (mlCH_4 m^{-3}Air)
A	Encapsulated surface area of the chamber in m²

The equipment and the method need to take into account, that by applying an open chamber there is the possibility, depending on the emission source, of reaching the explosion limit. If the concentration reaches a specific value (e.g. 20 % of the lower explosion limit) the volume flow of the blower should be increased to lower

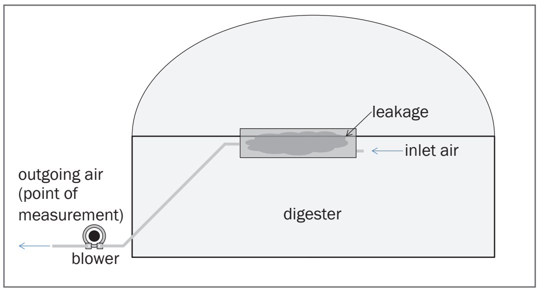

Figure 8: Methane emissions from leakage a) graphic account (DBFZ)

b) picture documentation (DBFZ)

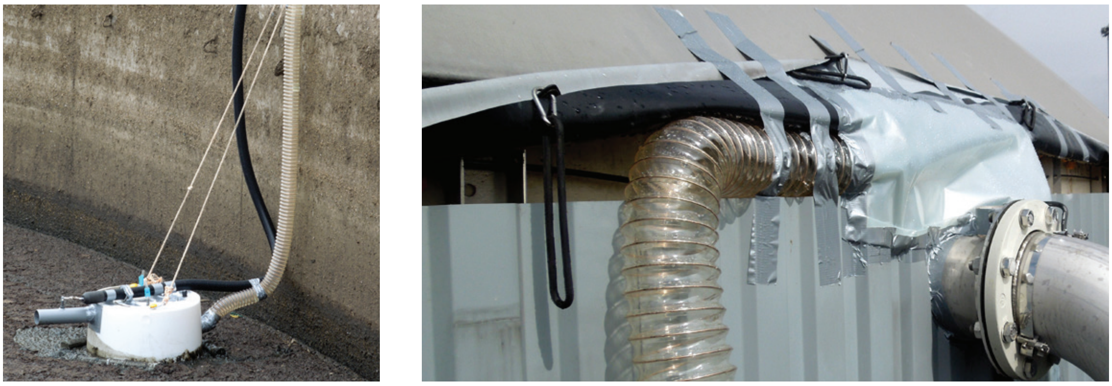

Figure 9: a) Methane emissions from digestate (DBFZ) b) digester (DBFZ)

the measured concentration.

In case the open chamber concept is applied at leakages, the identified leakage is encapsulated, thus creating a “chamber” around the leakage and producing a constant flow by means of a connected blower. The blower flow rate should be set as low as possible in order to avoid influence on the emission source.

Another component, which can be evaluated by means of the open chamber principle, is the two-layer dome (Figure 10). The outer layer of the flexible roof, which functions as a weather cover, is kept stable by means of a blower. The inner layer, which holds the gas, is flexible in order to guarantee a flexible filling level. In case of leakages or gas diffusion through the inner membrane, the emissions can easily picked up in the outgoing air from the air inflated outer layer.

A similar situation is given for the analysis of a covered, but not gas tight digestate tank (Figure 11). In such a case, a blower can be installed and the headspace of the digestate tank is replaced, until a constant concentration of the target gas is obtained within the outgoing air. Then the emission rate and the outgoing flow rate are in balance and the emission rate can be calculated. The chamber would be, in that case, the whole digestate tank.

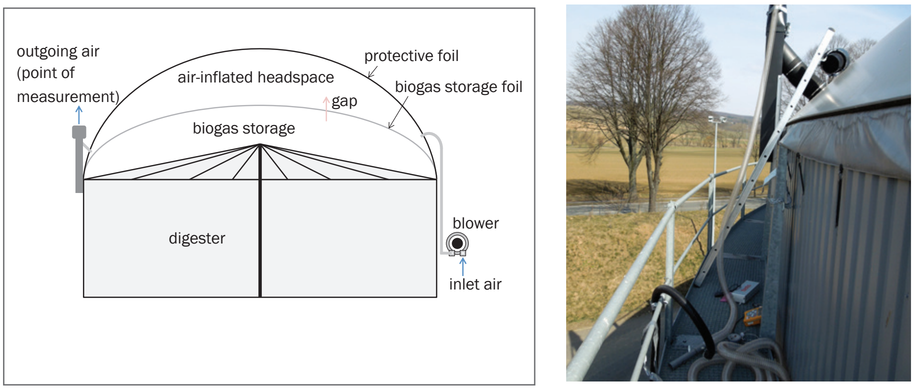

Figure 10:
a) Double layer inflated roof (DBFZ)
b) measurement setup at a digester (DBFZ)

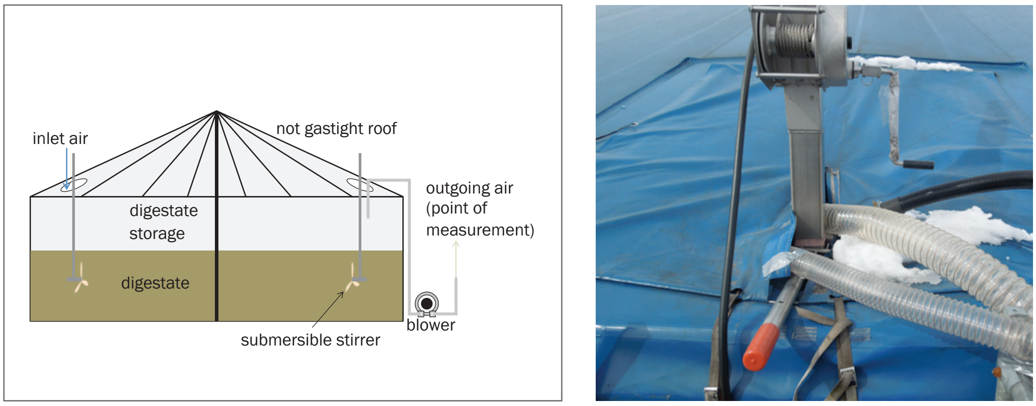

Figure 11:
a) Covered digestate storage
b) measurement setup at a storage tank

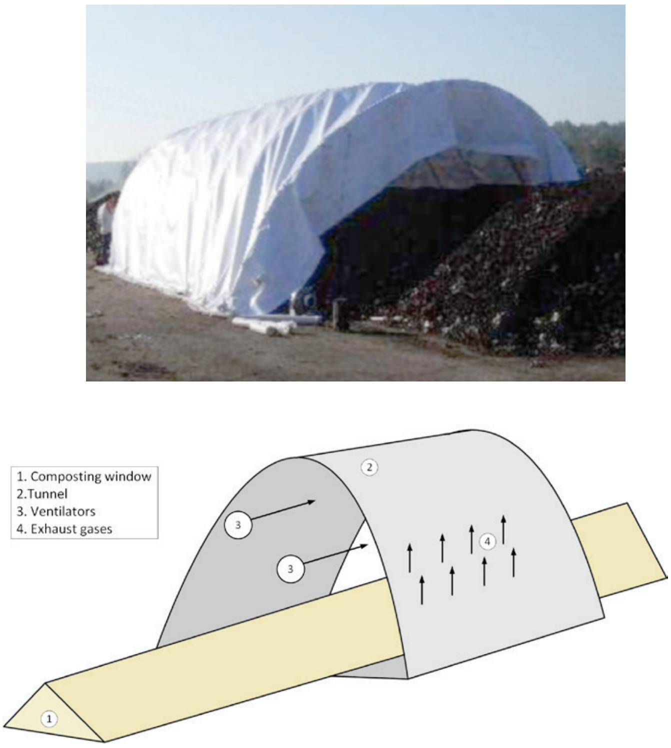

Figure 12: a) Wind tunnel for the evaluation of emissions from composting heaps treating digestate b) Wind tunnel (Phong, Nguyen, 2012)

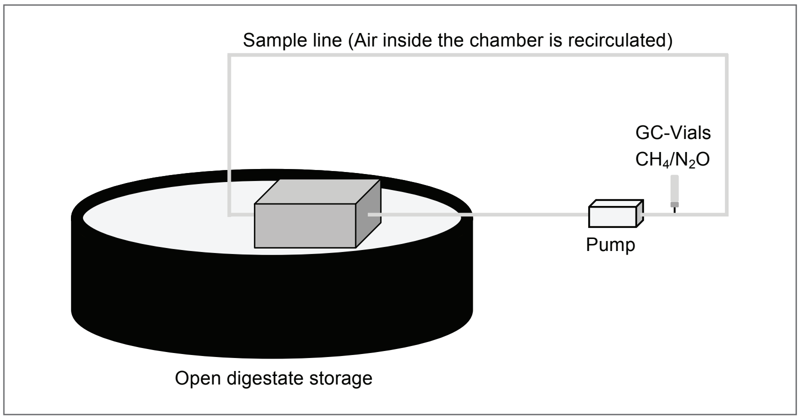

Figure 13: Measurement setup for a measurement based on a closed chamber system (DBFZ)

Large scale open chambers have been used to evaluate the emissions from composting heaps during post treatment of digestates (Figure 12).

5.1.3 Closed/static chamber

The second chamber method is the so-called closed chamber (Figure 13) method. Different to the open chamber system the closed chamber is not purged by a constant flow of a carrier gas. The quantity of the emission source is estimated based on the assumption that the incoming gas results in a concentration increase within the chamber proportional to the emission rate. The method is only applicable for emission sources where the closed chamber is not hindering the flow of the gas of interest from the source. 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). In case of measuring on a liquid surface it needs to be considered that gases such as ammonia, which will establish equilibrium between gas phase and liquid phase concentration, cannot be evaluated with this method. The closed chamber method has been applied on biogas plants on open digestate tanks (Liebetrau et al., 2013a) or as a method to determine the permeability of membranes used for gas storage purposes (Clemens, 2014). It has also been applied to establish emission effects during application of digestates after distribution on agricultural land.

The surface area of the chamber and the number of repetitions of measurements should allow a representative analysis of the surface to be evaluated. In particular the surface of digestate storage tanks can have varying emissions rate distribution depending on factors like swimming layers or location of feed in from the digester (resulting temperature profile).

The emission rate can be calculated from the slope of the gas concentration (Figure 14), the chamber volume and the encapsulated surface area according to Equation 2.

Equation 2

$$E = \frac{\partial c}{\partial t} \cdot \frac{V}{A}$$

E	Surface specific emission mass flow in mg CH$_4$ h^{-1}
$\frac{\partial c}{\partial t}$	Slope of the gas concentration inside the chamber in mg m^{-3} h^{-1}
V	Chamber Volume in m^3
A	Encapsulated surface area of the chamber in m^2

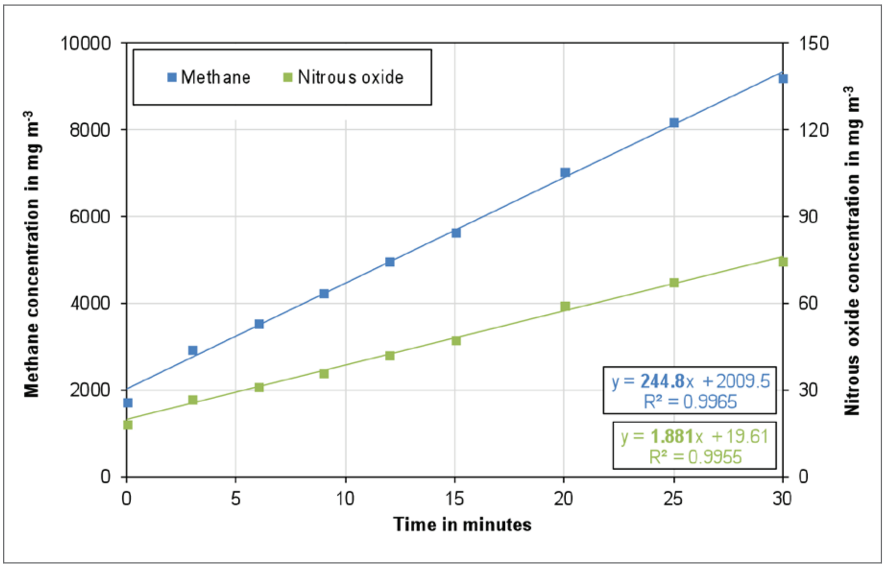

Figure 14: Example of a concentration increase within a closed chamber (Holmgren et al., 2015)

5.1.4 Pressure relief valves (PRV)

Quantification of emissions from PRVs represents a specific challenge. PRVs are safety devices. Therefore the installation of any additional equipment is strongly regulated. Besides the legal aspects of the installation of equipment on a safety device the functioning of the safety equipment shall not be impeded by the measurement or during installation in any way.

The evaluation of mass flows within the pressure relieve valves requires the installation of a flow velocity sensor. This reduces the sectional area and increases consequently the opening pressure of the PRV. PRVs (Figure 15 & 16) are designed to open at a certain overpressure and allow a flow rate in order to prevent damage to the roof. Before installing measurement equipment the consequences needs to be evaluated and if necessary the manufacturer of the PRV and the biogas plant need to be consulted.

The installation of a temperature sensor within the release pipe allows the detection of a release event, since the biogas temperature in the roof differs from the ambient temperature. During the release event, the sensor will detect a sharp temperature change. The temperature sensor allows only the reckoning of release events, but no flow quantification.

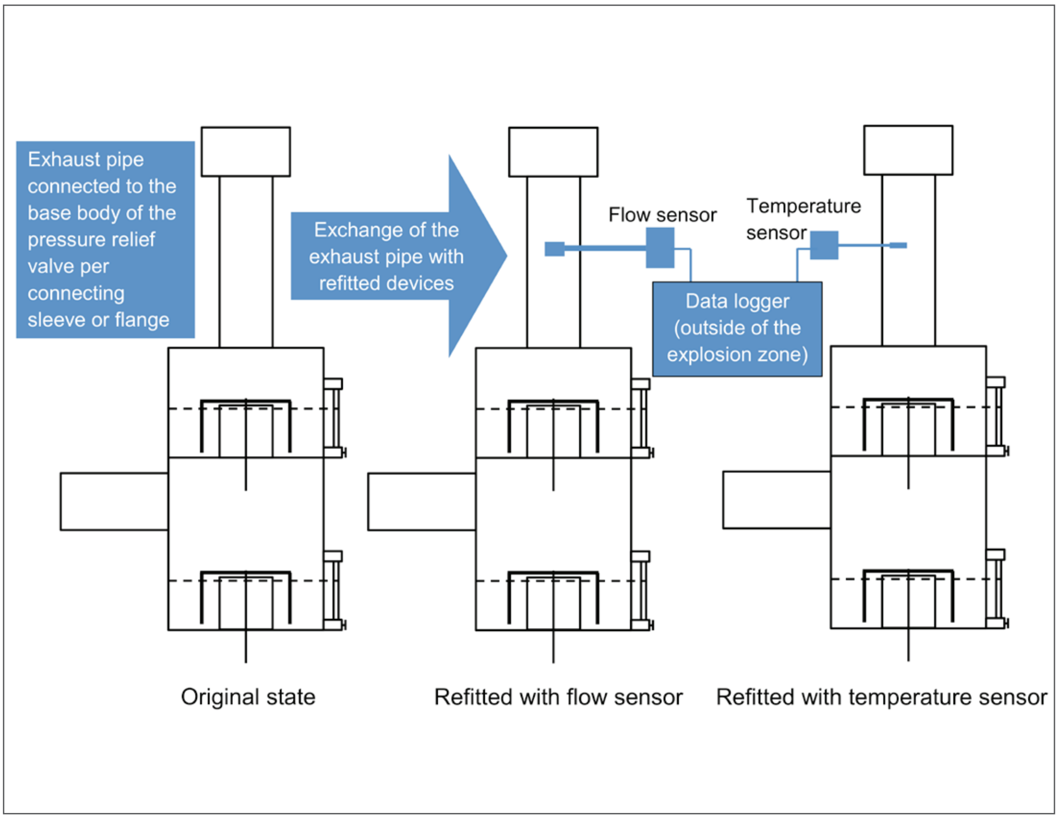

Figure 15: Schematic representation of the measurement setup for PRV monitoring (adopted from Heeren Hepolan GmbH, Schorba)

Figure 16: Measurement setup for PRV monitoring (DBFZ)

According to the construction of a pressure relief valve and the pressure situation within the gas collection and storage system the opening characteristics of the device are set. In case of changes at the device for measurement purposes the resulting pressure and flow characteristics needs to be evaluated and documented in a test certificate in order to avoid damage to the plant.

5.1.5 Summation of all single sources

In order to get an overall emission result of the plant, all sources need to be quantified and added up to an overall emission. However, there are limitations to this procedure. First of all it is very unlikely that all the emissions on site are found, since they might be too small to detect or be time variant. Secondly, the investigation of a large plant with many digesters requires laborious and time-consuming effort. In particular small leakages on digesters are difficult to find and laborious to quantify. The operational status and resulting emission situation of the plant might even change during the time period of the evaluation of the whole plant. In such cases it might be a strategy to identify the largest emission sources and quantify them in order to estimate the overall emissions based on these findings. In Liebetrau et al., (2013a) several emission sources at agricultural plants have been identified and quantified (Figure 17). Clearly the digestate tanks (if open or not gastight covered) and the gas utilisation dominated the methane emissions. However, sometimes, large leakages were found to have a significant impact on the overall emission. Recent investigations at pressure relief valves also indicate that, depending on the plant operation and technology used, the release of pressure relief valves can have a significant impact on the emissions (Reinelt et al., 2016).

Construction details of agricultural biogas plants appear to be different compared to waste treatment facilities. Here the emissions are often collected in an air collection system for further treatment. Usually components which require material handling such as delivering, pre-treatment and post treatment are located in a closed processing hall. In such a situation the analysis of emissions within the air collection system or at the exhaust of the post treatment system is possible.

The post treatment system for the collected air is in most cases a biofilter and/or an acid scrubber. Both have little to no impact on the methane emissions. In particular, the post treatment (in most cases composting) has been proven to be a potential source of significant methane emissions if not carried out properly. Figure 18 displays the amount of emissions measured on waste treatment facilities. In three cases the emissions from open

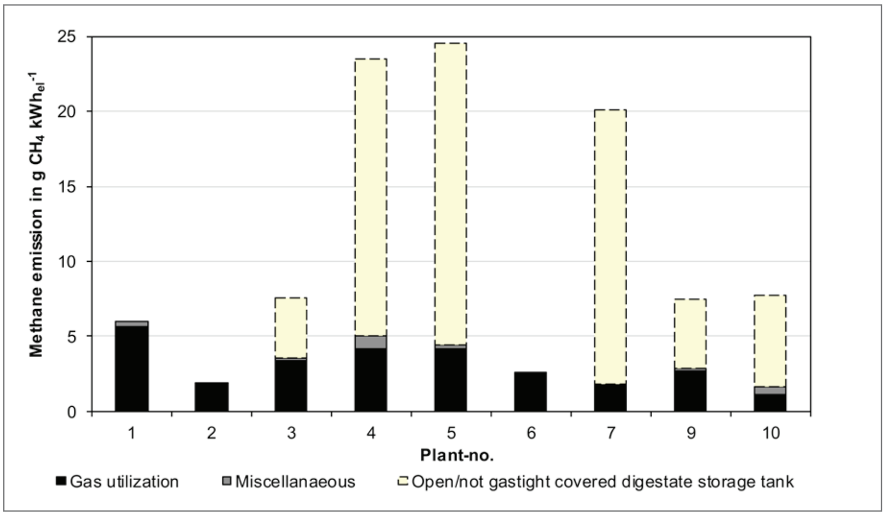

Figure 17: Main emission sources for methane (Liebetrau et al., 2013a)

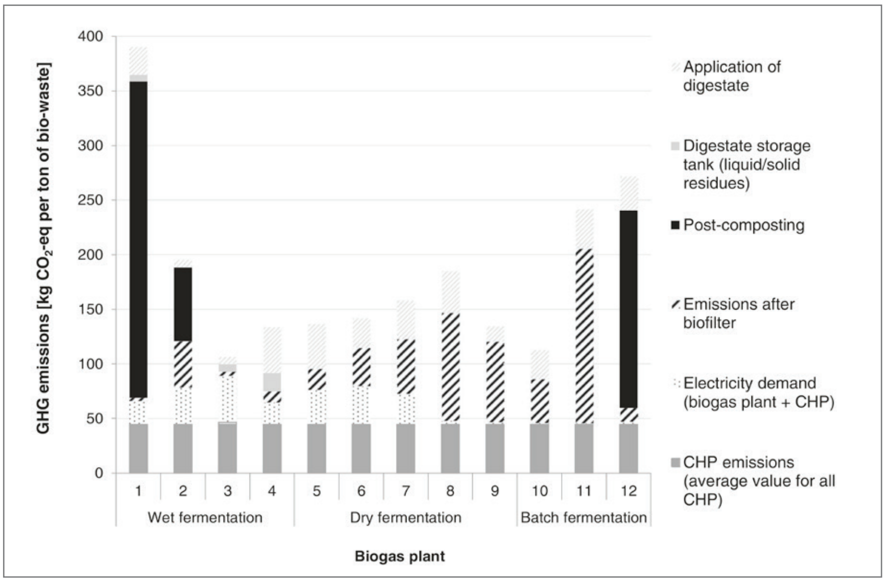

Figure 18: GHG emissions of biogas plants treating separately collected biowaste (Daniel-Gromke et al., 2015)

Figure 19: Measurements at a biogas plant (DBFZ)

windrow composting have been measured separately (since the composting was carried out in an open environment without an air collection system). The results indicate the substantial impact of the composting process on the overall emissions (Daniel-Gromke et al., 2015). The results of the measurement campaign, which also included ammonia and nitrous oxide measurements, identified methane as the dominating GHG source.

5.2 Total emission determination by means of remote sensing

The basic idea behind the described methods is that the emitted gas forms a plume, which is carried by the wind through the path of a properly arranged measurement system (Figure 19, Figure 20). Based on the time dependent behaviour of readings of the measurement equipment and a meteorological model or the use of a tracer gas, the emissions can be estimated.

The additional measurement of a background concentration is necessary to eliminate other upwind sources and the natural occurring concentration. Figure 20 represents the results of such a measurement and the principal of the measurement setup.

The method has some obvious limitations. The topography of the surroundings of the plant needs to be adequate for such a measurement. Buildings or trees might induce turbulences, which affect the quality of the modelling. The wind speed and the direction need to fit the requirements of the model and the topography. Last but not least, other sources, which are located nearby, might be difficult to differentiate from the emissions of the plant. In particular, in case of biogas installations on animal husbandry sites the emission from the barns might be blended in with the emissions from the biogas plant.

One option for the calculation of the emissions based on the open path measurements and the meteorological data is the use of the freeware such as WindTrax (Thunder Beach Scientific, www.thunderbeachscientific.com). Other commercial options include: LASAT (Ingenieurbüro Janicke, www.janicke.de) and MISKAM (Ingenieurbüro Lohmeyer, www.lohmeyer.de).

The analysis is based on the assumption of a level area ground source and a simulation of the stochastic movement of many air parcels. The assumed air parcels touch the ground at a certain point in their movement. In case this happens in the source region, the simulated air parcel picks up the characteristics of the emission source and transports this with the further movement of the air parcel. The simulation estimates the movement of the emissions recognized at the open path, backward in time to the emission source (Figure 21). WindTrax has numerous documented uses in peer reviewed scientific literature

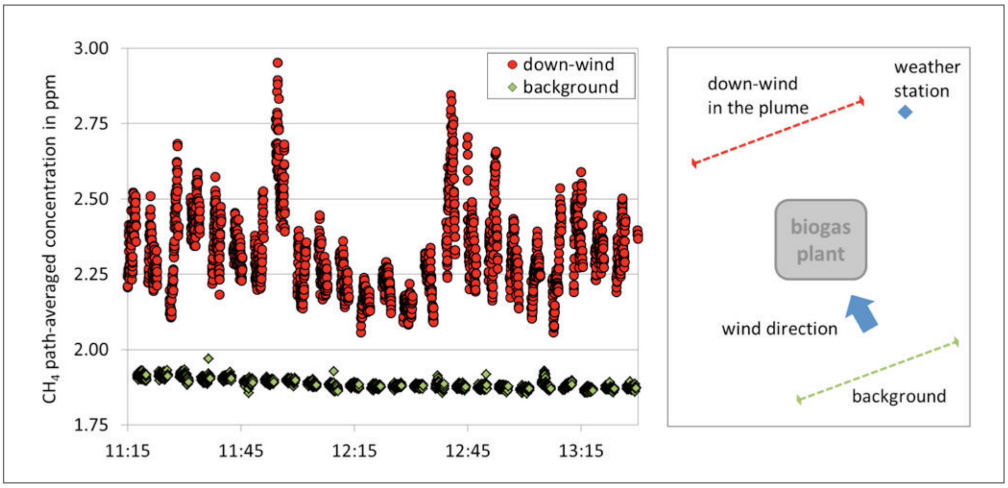

Figure 20:
a) Examples of upwind (background) and downwind concentration readings of an open path laser system (DBFZ);
b) schematic diagram of the measurement setup

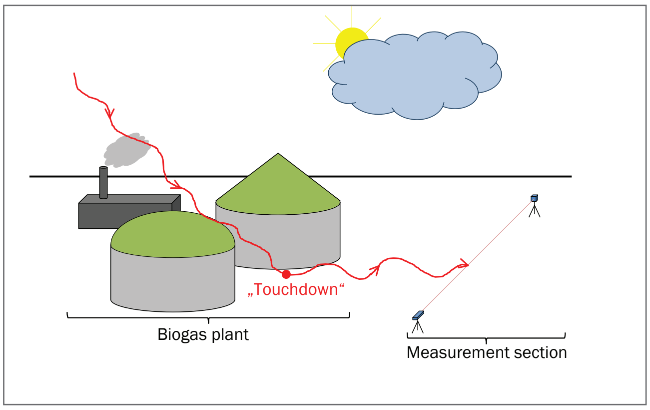

Figure 21: Schematic of the concept of WindTrax based simulation (DBFZ)

(Flesch et al., 2011; Harper et al., 2010; Laubach et al., 2013; Crenna et al., 2008; Gao et al., 2010; Groth et al., 2015; Hrad et al., 2015; Holmgren et al., 2015).

An inverse dispersion model based on a Backward Lagrangian Stochastic model is used within the software (Flesch et al., 2004). The model assumes the source to be an area source and does not consider buildings or other elevated constructions in particular. However, the effect of such elevated structures becomes less relevant with increasing distance from the structure (Gao et al., 2010).

The model also allows the inclusion of known point sources. This makes it possible to improve the accuracy of the calculation.

Windtrax requires the following input parameters:

- Meteorological conditions (mean values per ¼ h)
- Concentrations (background and downwind) (mean values such as per ¼h)
- Area source geometry.

The result of the simulation is an emission rate of the defined area source. The advantage of such measurements is the visibility of the overall emissions of a biogas facility over a long period of time. All emission sources are included in the measurement, and time variant emissions caused by specific operational situations as given in Figure 22 can be identified. The example shows a switch of compressor units (part of a biomethane grid injection installation), which releases immediately ca. 50 m³ of biogas. In parallel, the gas utilization was shut down, which caused pressure relief events. Such short and specific events are difficult to detect by means of on site evaluation based on cameras or portable gas detection systems. They are easy to detect by means of long-term analysis.

In case of no substantial single emission events, the method provides reproducible and normally distributed results. Figure 23 presents the distribution of results (ordered by size) of 4 measurement campaigns on one biogas plant. The reason for the variance in results can be either emission fluctuation or variance in the modelling.

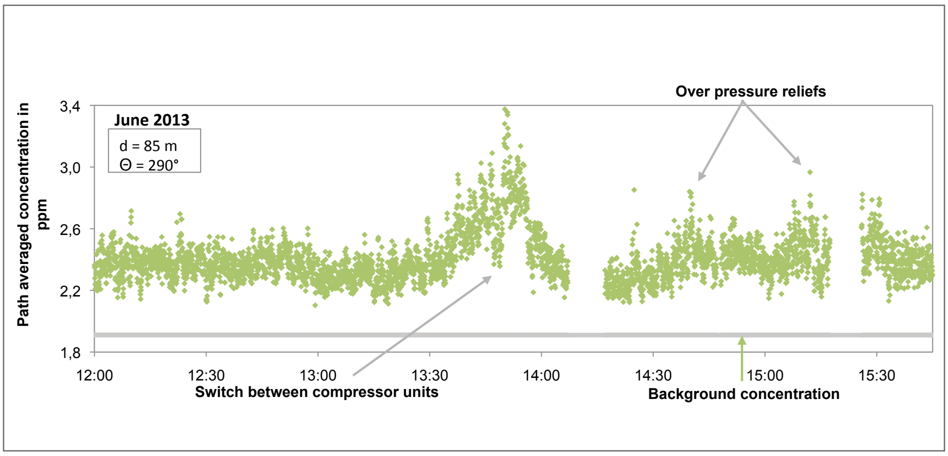

Figure 22: Open path readings on a biogas plant with pronounced emission events as release of pressure relief events (Westerkamp et al., 2014b)

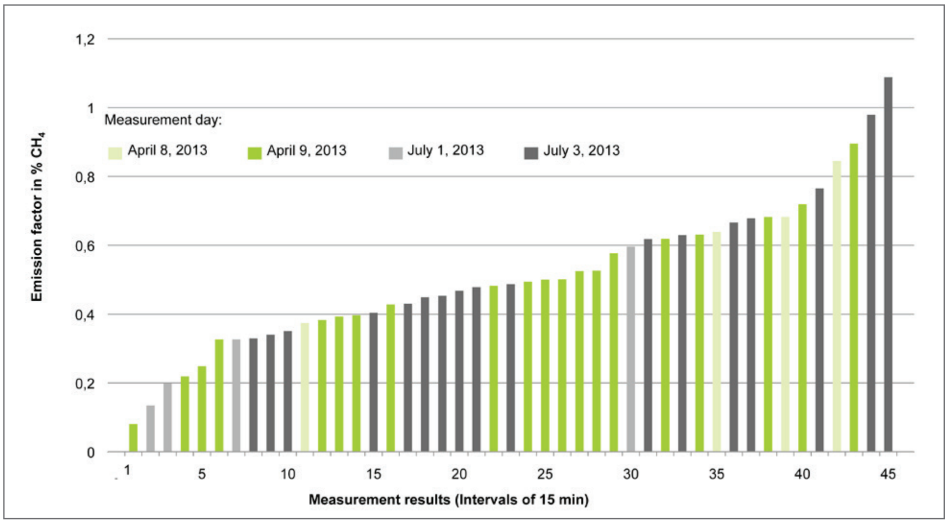

Figure 23: Emissions from a biogas plant based on open path readings (15 min average, sorted by size) and WindTrax based calculations, adopted from Westerkamp et al. (2014a).

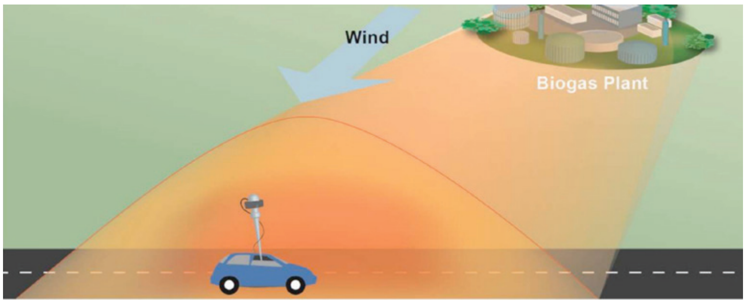

Figure 24: Schematic overview of the dynamic plume tracer dispersion method (Holmgren et al., 2015)

5.3 Other methods

Two methods, which have been published in recent years, are presented here. The authors do not claim to have covered all possible options for further methods.

5.3.1 Tracer dispersion method

The following description is derived from Mønster et al., (2014).

The analysis is based on a mobile tracer dispersion method, which combines a controlled release of tracer gas from the biogas facility with concentration measurements downwind of the facility by using a mobile high resolution analytical instrument. The base assumption is that the tracer gas, which is released at the source area (the biogas facility) has the same dispersion characteristics as the methane released from the facility. The concentration ratio of tracer and target gas remains constant along their atmospheric dispersion and the methane emissions can be calculated using Equation 3.

Equation 3

$$E = \frac{\int_{\text{plume start}}^{\text{plume end}} (C_{CH_4})dx}{\int_{\text{plume start}}^{\text{plume end}} (C_{tr})dx} \; \frac{MW_{CH_4}}{MW_{tr}}$$

The background needs to be considered as well. The tracer gas should have a sufficiently long atmospheric lifetime. Often gases such as N_20, Acetylene and SF_6 are used. The downwind plume concentrations are measured driving along transects with analytical equipment, which is fast and has high sensitivity towards the target gases down to ppb level. Often devices based on cavity ring down spectroscopy are used for that purpose. The measured concentration and the geographical location need to be logged. The correct simulation of the methane emitted from the source by means of the tracer gas is very important to obtain precise emission rates. The tracer gas should be released from the part of the plant where the most elevated methane concentrations are seen/expected (see Figure 24).

Compared to the open path method the tracer dispersion method requires a path or a street, where the measurement device can be transported. The results represent a discrete evaluation of every sampling point, a continuous observation without a gap of the plant is difficult to realize. The mobility of the measurements makes it easier to identify background sources than with the stationary laser system.

5.3.2 Charm – CH_4 airborne remote monitoring

The described method was used for a plant evaluation and the results have been published in (Wolf, Scherello, 2013). The method described here is taken from this publication.

The Charm® approach is carried out with a helicopter based laser measurement system, which was developed by a consortium around Open grid Europe GmbH in order to perform airborne tightness checks of natural gas transport pipelines. It was applied for the evaluation of an upgrading plant (Einbeck, Germany).

The principle of the measurement devices is based on a differential absorption LIDAR (Light Detection And Ranging). It compares two different laser signals, where one of them is influenced by the absorption of the target gas.

The plant is investigated by a ringlike flight (fenceline monitoring) around the plant. For the background assessment a ringlike flight upwind of the plant was taken. The emission rate is calculated based on the rectangular (to the ringlike measurement path) fraction of the wind and the average methane concentration. Based on this, the inflow- and outflow of the target gas into the ring can be calculated. The path average of the methane concentration (up to the flight altitude of the helicopter)

Table 6: Measurement results derived from the CHARM system at the biogas plant Einbeck

Measurement setup	Measured methane emission rate in $m^3 h^{-1}$	Released methane emission rate in $m^3 h^{-1}$
Background (upwind to the biogas plant)	0.0 ± 0.8	0
Biogas plant (without additional methane release)	2.07 ± 0.57	0
Biogas plant (with additional methane release in different rates)	4.86 ± 1.53	2.3
	9.43 ± 1.18	6.3
	12.27 ± 1.97	8.6

does not resemble the weather conditions, which are analysed in one height. According to the authors this might lead to a misinterpretation of the data. During the measurement flights methane was released in different rates in order to prove the recovery rate. Details of the measurement are included in Table 6.

Within the article the authors interpreted a portion of 0.5 $m^3 h^{-1}$ as a result from the exhaust of the upgrading facility. The additional 1.5 $m^3 h^{-1}$ have been declared as a nonpoint, fugitive source. An emission rate of 1.5 $m^3 h^{-1}$ represents 0.3 % of the methane produced at the investigated plant.

There is an uncertainty within the measurements and a deviation from the expected values too (Table 6). However, the linear increase of the measured emission rate (in the same manner as the additional release of methane) validates the method according to the authors of the article.

The method was transferred from leakage investigation of gas pipelines. It requires, as the other described remote evaluation methods, a certain topography and wind conditions. Additionally, the helicopter adds effort and costs. Last but not least, compared to the stationary open path system (see Chapter 5.2) the analysis of a longer period of time (e.g. several hours/days) does not seem practicable.

5.4 Emissions from open manure/digestate storage facilities

Emissions from open digestate or manure storage tanks have been analysed in several studies by means of chamber and remote sensing methods (Flesch et al., 2013; Gioelli et al., 2011; Hrad et al. 2015; Husted, 1994; Liebetrau et al., 2013a; Park et al., 2010; Ro et al., 2013).

The challenge of a precise determination of these emissions is the dependency of the emission rate to the gas potential of the digestate, the temperature within the digestate, the retention time in the storage tank and the non-even distribution of these characteristics in the tank.

The gas potential of the digestate might be quite constant over time given a constant substrate composition and feeding algorithm on the plant. The temperature of the digestate depends on factors like the design of the tank, potential covers (gas tight, covered but not gas tight, straw), topography of the surroundings and ambient temperature. Due to the lack of mixing the temperature is usually not evenly distributed within the storage tank. Consequently, the emissions from the surface are not evenly distributed over the surface area. The retention time of digestate depends on the times available for digestate application on agricultural land and might vary from year to year.

Several approaches have been taken to measure or estimate the emissions from storage tanks. In any case, short term measurements cannot consider the filling level and the long term temperature behaviour in the digestate storage and can therefore only give a very limited picture of the overall and long term emission situation.

Chamber method:

A chamber (open or closed) is placed on the surface and the emissions from the area covered by the chamber are used to calculate the overall emissions of the storage facility. The chamber might be placed on different spots on the surface or remain installed for longer periods of time to obtain reproducible results.

Emission potential (batch test of digestate at reduced temperature, e.g. 20°C):

A representative sample of the discharge of the last vessel connected to the biogas collection system is taken and incubated at reduced temperature to obtain the gas production potential at those temperatures. In the optimal case this temperature resembles the average annual temperature within the digestate storage (FNR, 2010; VDI, 2010). The result is used to describe an emission potential of the digestate, a determination of the real emissions is not possible with this method.

Open path method:

The area emission source analysed in this case is the digestate storage. Requirements on conditions are discussed in section 5.2.

Model based calculation based on batch tests:

The approach aims to simulate the digestate storage as a further digester and estimates the gas production according to the gas potential of the digestate (measured by batch tests), the degradation kinetics at different temperatures (also taken from batch tests), the temperature in the storage facility (which needs to be measured) and the retention time (calculated based on the filling level). This method includes most factors influencing the results.

A scientific comparison of these methods is as yet lacking. Table 7 gives a short evaluation of the methods.

Table 7: Methods for emission evaluation at open digestate storages

Methods for emission evaluation at open digestate storages	Advantages	Shortcomings
Chamber method	Limited technical effort, easy to apply	Represents only a small fraction of the surface area in a limited period of time In case of area related non-even distribution of emissions and several storage tanks it is difficult to get representative results, Temperature and filling level related variations difficult to estimate
Emission potential (Batch test of digestate at reduced temperature, e.g. 20°C)	Easy to measure, can be combined with gas potential analysis, inter-plant comparison is easy to be made	No actual measured emission data, does not resemble filling level and different temperature situation appearing in reality
Open path method	Gives the overall emissions of the storage tanks (area)	Long measurement periods (e.g. weeks) result in large effort, separation of other sources in the background (e.g. biogas plant) might be difficult, high equipment costs
Model based calculation based on batch tests	If including temperature measurements at the plant and filling level it approaches the annual course of emissions	No actual measured emission data Annual measurement of filling level and temperature in the digestate is necessary (or adequate assumptions need to be made)

In general, it can be stated that there is no method available without major shortcomings. A proven method for a precise determination of the annual emissions from an open storage tank with a reasonable effort is currently not available, neither is there a valid means of comparing the different methods. However, there are several approaches, which can deliver reasonable results if the shortcomings and the assumptions to be made are considered. From the authors' perspective the "model based calculation method based on batch tests" tends to be the method which is most advantageous and with reasonable effort the most favourable.

5.5 Conclusions on measurement methods to quantify methane emissions from biogas plants

In terms of a brief overview, the measurement methods described are listed below:

- Source and leakage detection
  - Gas camera
  - Handheld laser
  - Gas concentration measurements based on gas samples
- Source quantification
  - Open chamber
  - Closed chamber
  - Estimation from flow observation (gas camera based)
  - In pipe measurements (flow and concentration)
  - Open path remote sensing methods
  - Tracer dispersion measurements

It should be mentioned that there are standards for the estimation of emissions as described in EN 15446:2008. They are based on concentration measurements in the vicinity of the leak and a factor based calculation of the emission rate. For the application within natural gas containing pipes, Dyakowska et al (2014) showed that there is no correlation between the EN 15446:2008 measured/calculated emission rate and the set emission rate within the test system. Obviously, many factors influence the concentration measurement close to the leak; therefore such a simple method cannot deliver precise results. Due to that, this method has not been considered within this report.

The previous chapters described some general methods to measure emissions from biogas plants.

There are many publications available, which describe measurements and measurement methods for the determination of methane emissions from biogas plants. Within the investigations, different measurement devices and different methodologies are used. Additionally, the methods used can vary in details, the plants and their operational status are different, ambient conditions can vary and have an impact on the results. A first comparative investigation presented in Holmgren et al., (2015) and Reinelt et al., (2017) where several teams analysed a biogas plant with different approaches and methods revealed a substantial impact on the results from the methods used, the necessity to identify and quantify the largest sources and last but not least the operational state of the plant. Another point was the importance of a careful evaluation of the background concentrations, which was even for the onsite measurements an important point.

While looking through literature it becomes clear that publications also differ in regards to consideration of sources. Some methods do not include certain sources; others have issues to separate (background) sources nearby as for instance barns or drainage ditches (Holmgren et al., 2015). There are publications, which lack a clear description of the methodology and differentiation of these facts, which makes the results difficult to compare to other publications.

In general, it needs to be stated that, since there is no standard available, even if each team applies the "same" method, it can have a slightly different approach and execution of the measurement and therefore different results. Because of this, the interpretation and comparison of the results of single measurements is difficult. An evaluation of a representative number of biogas facilities with a comparable approach is missing and therefore the deduction of a general emission estimate for the biogas sector as a whole is at current state not possible.

When discussing the use of emission data within GHG balances and life cycle assessments another important question arises. The measurement usually represents the emissions of a limited period of time representing a particular state of operation at the plant. There might be other states of operation (e.g. part load operation, shut down for maintenance, not all components operational, different filling level of gas storage, transition phases before and after maintenance measures), which result in different emissions. First investigations of pressure relief valves, for example, show that the operational status has an impact on emissions and cannot be neglected. From that perspective it is important to document, how the "representative operational state" has been defined and measured.

6. Results of methane emission measurements

The following chapter discusses some selected results referring to methane emissions. The overview is far from complete and does not include all available data. The idea is to give some trends and categorize the significance of the different components. Figure 25 gives an overview on the potential methane emission sources from components and processes applied within the biogas system including production and utilization.

6.1 Substrate storage and feeding systems

Biogas substrates are numerous and consequently the systems applied to store and handle these substrates are various. In general solid substrates do not tend to produce methane quickly on their own; since organic materials acidify during degradation and the resulting low pH prevents significant methane production.

The situation is different for manures and slurries. In particular cow manure will produce methane during storage due to methanogens already occurring in the manure. Another source of methane emissions can be the blending of fresh substrate with digestate (or liquids after solid/liquid separation) for the adjustment of characteristics necessary for the feed-in technology (mainly pumps). In case such a mixture is stored in an open tank, methane emissions are likely to occur.

6.1.1 Silage storage

In agricultural biogas plants silages, most often corn silage, are used as storable high quality substrate. In Germany corn silage has a percentage of about 75 % of the overall input of energy crops (Scheftelowitz et al., 2014). At biogas plants silages are normally stored in silage pits. The silage is covered by a foil and only the cut area is open to the atmosphere. On the surface of the cut area, emissions can be measured using the open chamber method Liebetrau et al., (2013a). In Liebetrau et al., (2013a) it is reported that only negligible amounts of methane are emitted from stored silage (averaged emissions of eight measured plants is 0.0007 % of the utilized CH_4). Due to the low pH-values (< 5) of silages caused by the lactic acid produced during the ensiling process (Yitbarek, Tamir, 2014) the methane formation process is safely suppressed during storage; methanogenic archaea need pH-values above 6.5. A review on emis-

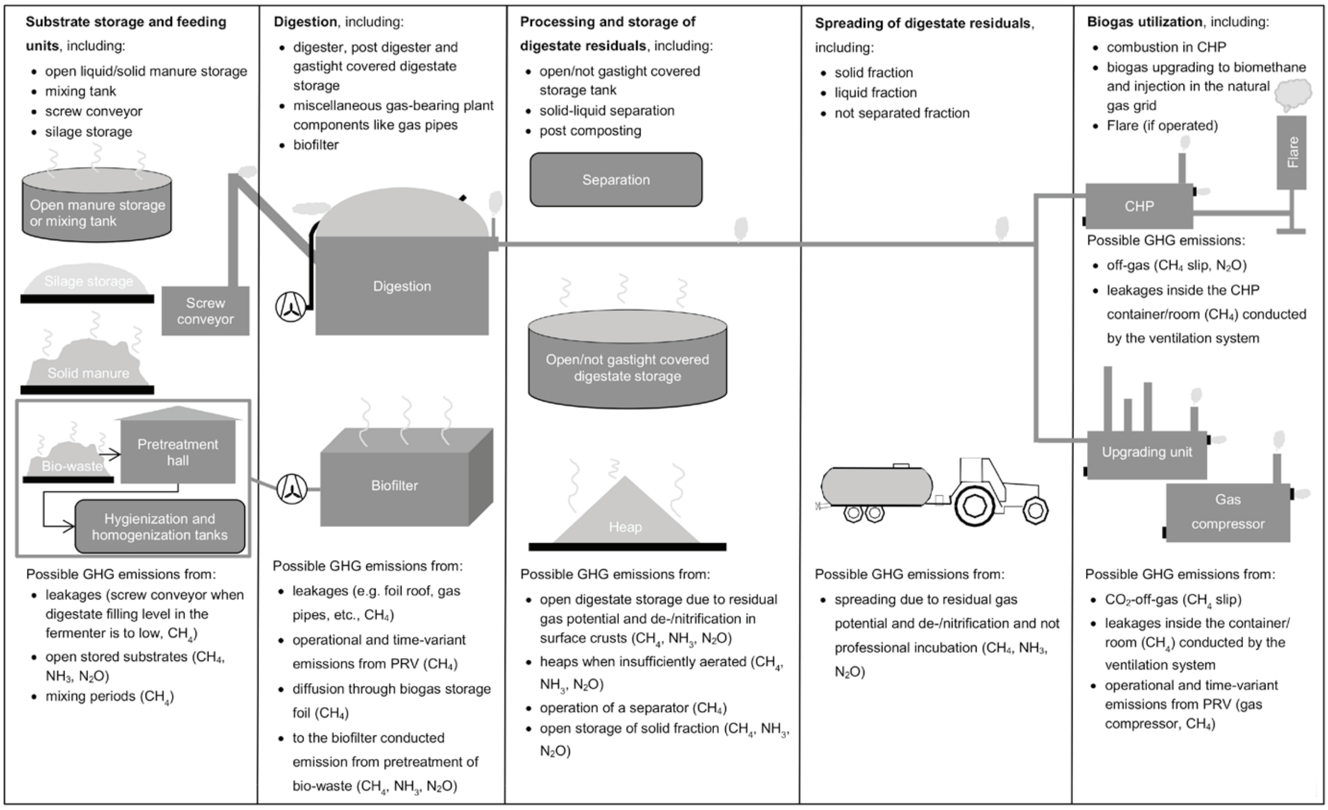

Figure 25: Overview about GHG emission sources from components and processes applied within biogas production and utilisation

sions of volatile organic compounds (VOC) from silage is provided by (Hafner et al., 2013). It is stated that alcohols (in particular ethanol) and acids (in particular acetic acid) contribute most to the overall VOC emission from corn silage. For biogas plants it is also important to abate such VOC emissions to reduce odour emissions. In summary methane emissions from stored silage are negligible.

6.1.2 Manure storage

Manure storage and in particular cow and pig manure is a well-known source of emissions. The retention of manure from animal husbandry within the barn installations and the subsequent storage until further application causes significant emissions. These are usually assigned to the animal husbandry within the agricultural sector. Using manure in a biogas facility reduces the emissions from storage and consequently this reduction is calculated as a credit in GHG balance. However, when storing manure or mixing manure with other substrates prior to feeding on-site of the biogas facility, the emissions need to be assigned to the biogas process.

6.1.3 Waste receiving hall and storage

The receiving area and the bunker for storage before further processing within waste processing plants are usually encapsulated, the collected air is then sent through a biofilter. In general the situation is similar to the silage storage – the substrates acidify or are already acidified rather than producing methane. Since the waste handling is somewhat uncontrolled in comparison to the ensiling process and the waste material is inhomogeneous, the occurrence of methane is more likely.

In Liebetrau et al. (2013b) several waste treating plants were investigated. The receiving and conditioning components emit methane (and VOCs); measured in the suctioned exhaust air of halls treated in the biofilter. However in comparison to other large sources, such as open handling and storage of digestate, post-treatment of digestate and emissions from CHP, the receiving, preconditioning and storage of waste is of secondary relevance.

6.2 Digestion process

6.2.1 Leakage identification and detection within gas bearing components

There are a few publications about the occurrence of leakages on gas-bearing plant components from biogas plants. In Schreier, (2011) by analysing ten investigated biogas plants it was shown that biogas losses from leakages are a relevant source. Eight plants had an overall number of 22 leakages and seven of them were evaluated

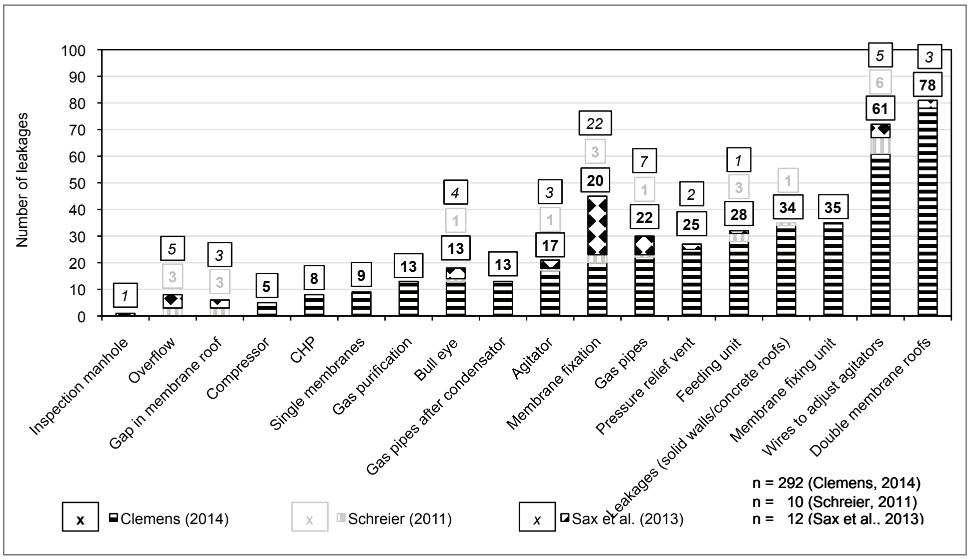

Figure 26: Identified leakages from biogas plants in Germany and Switzerland, data from (Schreier, 2011, Sax et al., 2013, Clemens, 2014)

as serious leakages. In Sax et al. (2013), 12 agricultural biogas plant were investigated. In Clemens (2014) a significant number of single biogas plants were investigated and the data were evaluated concerning the frequency of occurrence of the identified leakages. The summarized results from all three publications are shown in Figure 26.

Apparently, leaks can be found at almost any component of the plant in sections containing biogas. The numbers show, that a frequent monitoring of the plant for leaks is absolutely necessary. The occurrence of a leak does not allow an interpretation of the amount of gas emitted there. The source “wires to adjust agitators” has for instance usually a minor flow rate.

The results of the presented investigations show that the rubber covers of digesters are very often a source of emissions. Either little leakages in the membrane itself occur, or the connection of the membrane to the digester is often the reason for methane losses.

It should be mentioned that the membranes used for the cover allow a certain diffusion of methane through the material. The interpretation and distinction of the measured emissions as diffusion or leak has to be done by means of a threshold for material related maximum allowed diffusion rates. The analysis of the membrane roof is easy in case of double membrane covers, since the inlet and the outlet of the air buffer can be evaluated for methane concentrations and flow rate and by doing so, the whole cover can be evaluated. The threshold of 1 L CH_4*(m²*bar*d)$^{-1}$ is given within the Safety Guidelines of the German Agricultural Employer’s Liability Insurance Association and used within the sector in Germany (SVLFG, 2016). It should be mentioned that the industrial tests for the characterization of the membrane material (DIN 53380-2:2006:11, 2006) are carried out under different conditions than the actual use of the membranes on site (different temperature, partial pressure of the gas, gas humidity etc.).

Figure 27 shows a variety of membrane roofs evaluated and it is obvious that some of them do not meet the limits for permeation and cannot be described as technically gas tight. It should be mentioned that due to the way these roofs are evaluated, it cannot be distinguished between a general increase of the diffusion through the foil and a potential minor leakage in the membrane. The question for the practical application is at which point the decision for a major maintenance needs to be made.

Single membrane covers are analysed in a different way. The diffusion rate of the material can be tested by means of a closed chamber installed on the membrane, however small leaks on the surface are next to impossible to detect since the whole membrane surface cannot be covered for the measurement process.

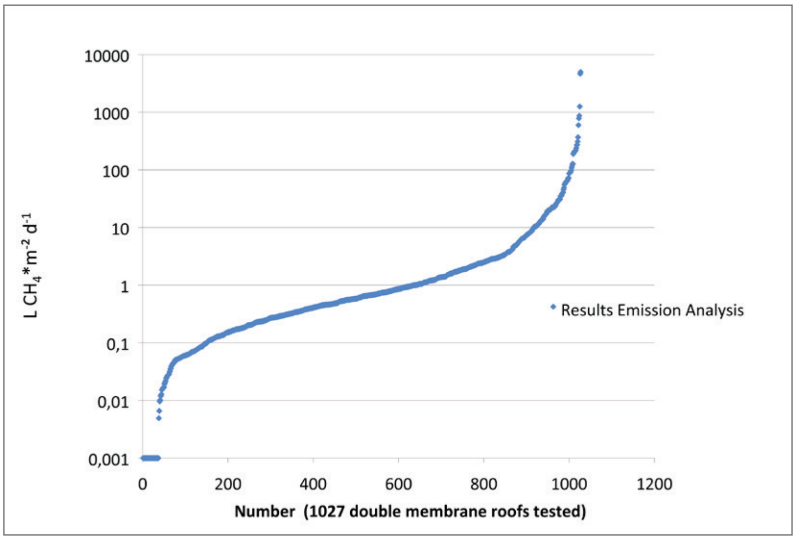

Figure 27: Methane emission through membrane covers based on measurement within air of air inflated double membrane roofs (1027 roofs measured, Clemens (2014))

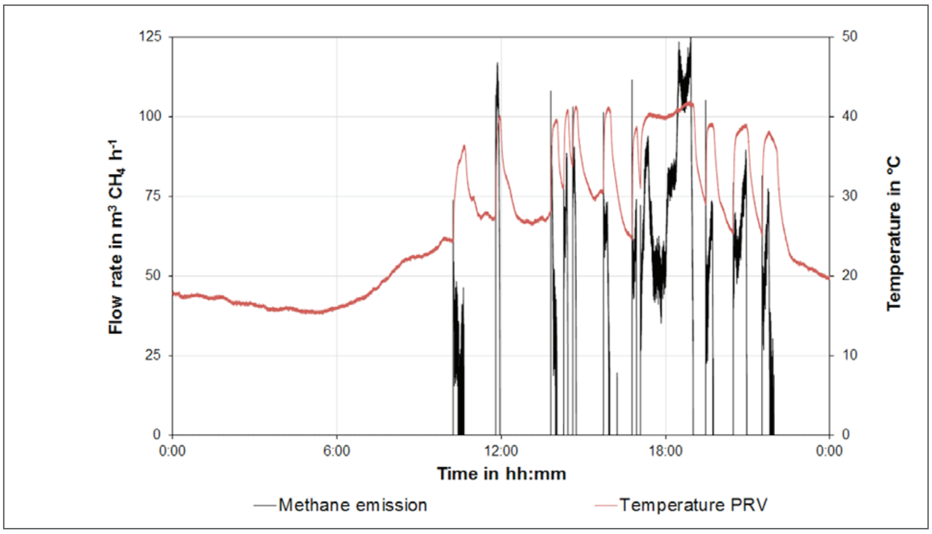

Figure 28: Opening time and flow characteristics of a pressure relief valve (Data from DBFZ).

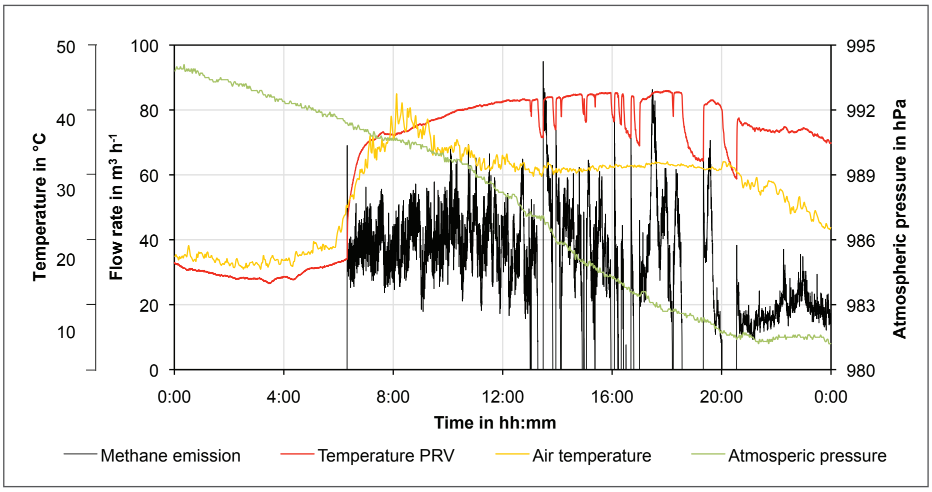

Figure 29: Influence of atmospheric conditions on the methane emissions from a PRV of a biogas plant, adopted from (Reinelt et al., 2016)

Leaks have been quantified separately in a few studies Liebetrau et al. (2013a), Westerkamp et al., (2014a), Reinelt et al. (2017). In Liebetrau et al., (2013a) the numerous little leaks emitted between 0.006 and 0.028 % of the methane produced at the facility. However, one major leak, which was a not properly closed maintenance opening, emitted 5 % of CH_4 utilized. In Westerkamp et al., (2014a) the leaks accumulated to between 0.001 and 0.055 % of total methane production, again as such may be described as rather minor leaks.

In Reinelt et al. (2017) all leaks were measured by different teams with levels below 0.044 %; the only exception was on PRV release which was measured at 0.73–1.11% of CH_4.

The general conclusion is that the majority of leaks are minor leaks with low flow rates. However, there are single cases of major leaks, which have not been recognized by the plant operators. Consequently a frequent screening of the plants for leaks is highly recommended.

6.2.2 Pressure relief valves

Hitherto the quantity and reasons for release of pressure relief valves (PRV) has been studied only sporadically. Therefore the emissions caused by this component are not very well quantified and understood. Figure 28 shows the behaviour of a flow meter and a temperature sensor installed at the very same pressure relief valves.

The opening events can easily be identified. It should be stated that since the monitoring devices have been installed and provided data, the operator was surprised about the releases, since they had no possibility to recognize the releases before.

For the purpose of plant optimization a simple logger for the recording of release events would be sufficient. This way the reasons for causing the release events can be identified and the occurrence can be reduced by adequate measures.

For the quantification of emission, flow rates and concentrations within the released gas need to be evaluated.

In Reinelt et al. (2016) a method for pressure relief valve investigation is presented and two biogas plants have been evaluated. Major reasons for the emission by pressure relief valve releases have been identified as:

- Unbalanced gas production and utilisation
- Activation of flare too late due to type of activation of the flare (manual or automated, connected to filling level in gas storage or CHP operation)
- Sudden changes in atmospheric conditions (see Figure 29)

An additional reason for PRV releases can be an improper gas management, in particular a hindered gas exchange between different gas storages or varying pres-

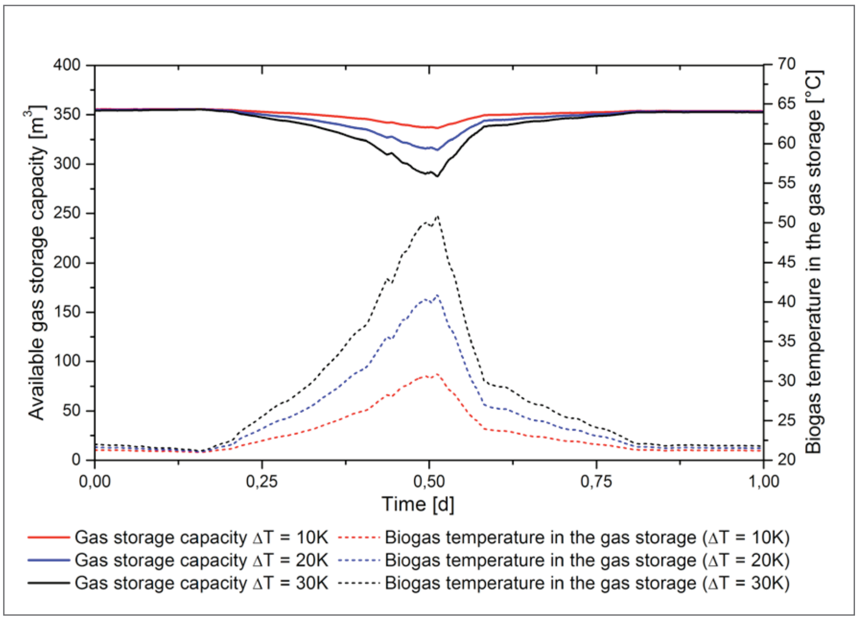

Figure 30: Temperature and gas storage capacity over time (adapted from Mauky et al. (2017))

Table 8: Change of gas storage capacity in relation to temperature change

Methods for emission evaluation at open digestate storages	Advantages Shortcomings		
Temperature change in K (Starting point 20.9 °C)	10	20	30
Volume change in % (based on the 20.9 °C scenario)	7 %	13 %	20 %

sure conditions within the system.

The temperature within the gas storage can change substantially due to solar radiation as the volume of the gas stored in the gas storage changes according to the ideal gas law. Moreover there is an additional water vapour uptake at higher temperatures which my further increase the volume/pressure. A change of 30 K in the gas storage is very likely on summer days in continental climates; this temperature change can result in a change of up to 20 % of the gas volume in the storage, which needs to be compensated by the available gas storage capacity (Figure 30 and Table 8).

Additionally it should be mentioned that the precision of most filling level indication systems for gas storage is insufficient and the gas transfer between different storage systems is uncontrolled. Consequently the options for exact gas management are limited, which can result in pressure relief vent release events.

6.3 Open/not gastight covered digestate storage tanks

The issues with measurement of open digestate storage tanks have been discussed above. It should also be highlighted that any type of cover other than a gas tight cover is not efficient in the perspective of reduction of methane emissions.

As already mentioned the temperature of the digestate during storage has a large impact on gas production. Figure 31 shows the results of a plant survey in Germany (FNR 2010), where the gas potential of the digestate has been evaluated at different temperatures. It is obvious and well known that there is a significant difference of the gas potential of digestate measured at 37 and 20 to 22°C (in the survey 20°C and 22°C were used). However the temperature (and filling level) in digestate storage tanks is far from constant (e.g. Muha et al., 2015 and Figure 31) and therefore the precise estimation of the emissions from digestate requires the inclusion of temperature and filling level.

The storage of digestate within the digestion of manure has a particularly interesting aspect due to the fact that it reduces the emissions from the otherwise

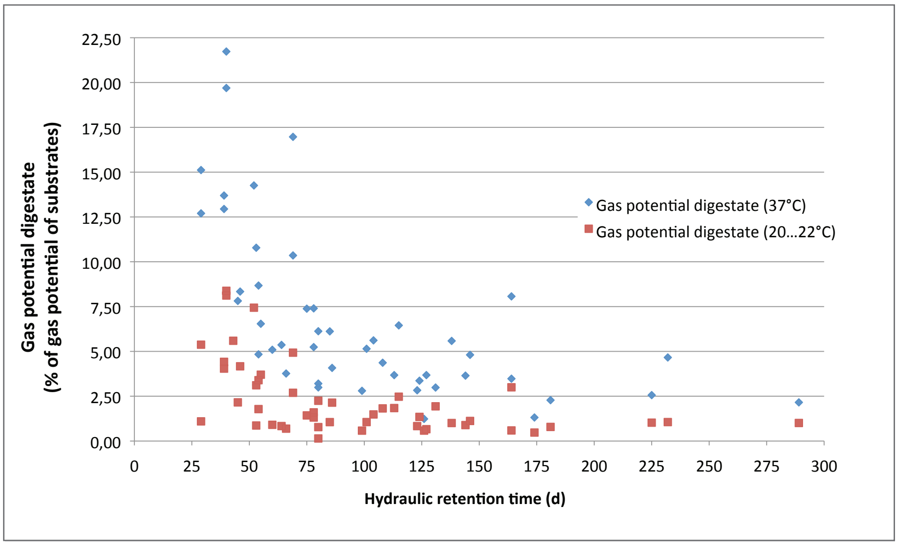

Figure 31: Gas potential of digestates at different temperatures (Data from FNR (2010))

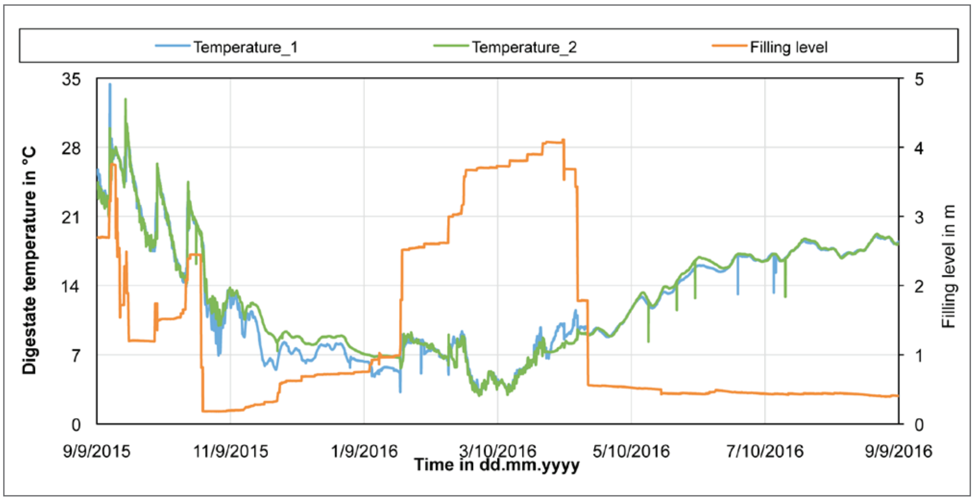

Figure 32: Temperature and filling level inside of an open digestate storage tank (temperature measured 0.5 m below the digestate surface) (DBFZ)

conventional storage of manure. This is usually integrated in GHG balances by giving the manure digestion a credit. These credits have a significant impact on the GHG balance of manure digestion. Assuming that the situation in a manure lagoon is similar to a digestate lagoon, the emission factors for manure storage could be used as indicator for the emissions from digestate storage. The assumed emission factors vary for different animal species, animal husbandry systems (or management systems) and storage temperatures. They range widely for liquid/slurry, from 17–80 % of the methane potential of the manure, depending on temperature and type of management system (IPCC 2006). In many cases the amount of manure available on site is not sufficient to make the digestion process a viable business. In such a case one solution is the addition of other energy rich substrates in order to increase the overall capacity of the plant and achieve a better economic output of the plant. Manure based plants, in particular with high water content, have a high throughput and a low specific gas production. The gas tight operation of all vessels, in particular the digestate storage, is often cost intensive. The question under which conditions the digestion of manure has an environmental benefit, even with open digestate storage and with addition of energy rich substrates is addressed in chapter 7.

In case of co-digestion of manure with energy rich substrates, such as energy crops, the impact of the credit on the emissions decreases with increasing share of energy crops. First of all, the energy crops contribute to the biogas production much more than the manure, so in relation to the overall energy output, the credit quickly diminishes with increasing shares (in wet mass) of energy crops. Second – if assuming open digestate storage after digestion, the digestate may, at a certain point depending on the amount of energy crops- emit more methane than the methane avoided by digesting the manure within the substrate. At this point the digestate storage is not compensated by the manure credit any more (under the assumption that the methane conversion factor is equal for manure and digestate).

Within Figure 32 the situation is depicted comparing several co-digestion scenarios and different retention times. No other emissions or credits are considered (e.g. provision of energy crops). It should be mentioned that the methane conversion factor (MCF), which represents the emission potential of the manure, is 10 % (of the gas potential of manure). According to IPCC this is quite conservative, their values range from 10 % at average temperature of 10°C to 50 % at 28°C. Assuming a 20 % MCF all values in the graph would double. The interesting fact to be seen here is the high impact of the portion

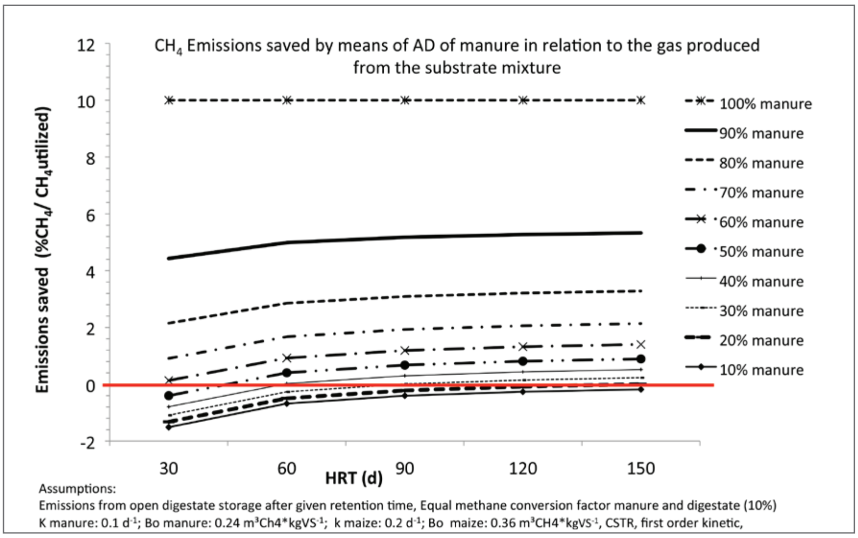

Figure 33: The methane emissions saved by means of manure credits in a co digestion scenario manure/maize.

of energy rich substrates on the relative emission savings and the low impact of the retention time. Maize is quickly degraded and therefore the retention time has no large impact on the emission potential in the digestate. Since the graph shows the emission savings in relation to the methane utilized, the emission savings are, for the manure only plant, constant. Higher degradation due to higher retention times results in less emissions from the digestate and therefore in higher credits but also proportionally higher gas production. Therefore the ratio of both stays constant. In absolute numbers the longer retention times are of course favourable.

Measurements of open digestate storages have been carried out for example in Liebetrau et al. (2013a); Hrad et al. (2015); Gioelli et al. (2011). The emissions (% CH_4 (of utilized methane)) are given in the range of 0.2 – 11.2 for a variety of measured vessels (Liebetrau et al., 2013a); Values of 1 (open storage tank from biogas plant 1 from Hrad et al., 2015), 1.8 and 4.4 have been measured (calculated from Gioelli, 2011 for non-separated and liquid fraction of digestate) respectively.

6.4 Gas utilisation

Gas utilisation is another major GHG emission source that occurs on biogas plants. There are basically two different options for utilizing the produced biogas. The first one is the combustion in a CHP unit to generate electrical and thermal energy. In CHP units methane emissions can occur due to leakages at the engine or the surrounding gas tubes, but this kind of emission source is usually negligible in comparison to the methane slip (portion of uncombusted methane) in the exhaust of CHP plants. The methane slip appears due to incomplete combustion in the engines that depends amongst others on the design of the combustion chamber, the adjustment of the lambda value (Oxygen fuel ratio, mostly used to control efficiency and NOx emissions), the maintenance of the unit, and the capacity utilisation of the unit (Aschmann, 2014). Concerning the resulting methane emissions in the literature some results are given in Figure 34 of the produced gas, the median of the given results is 1.65 %, the average 1.89 %. There are some units, which have a substantial higher slipage (see Figure 34), which is usually caused by poor maintenance of the CHP unit.

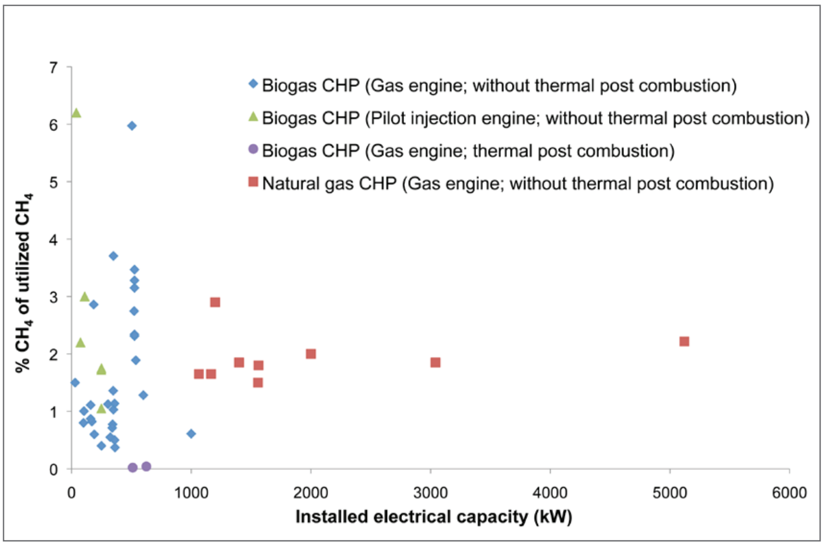

Figure 34: Methane emissions from CHP units operated with biogas and natural gas (Liebetrau et al., 2013a; Aschmann, 2014, Kretschmann et al., 2012; van Dijk, 2012)

It appears to be obvious that size has no relation to the emissions within this data set.

Aschmann (2014) states that gas-spark ignition engines emit about 1 % CH_4 whereas compression ignition engines emit 2 – 3 % CH_4 because of the higher gas compression which increases the energy efficiency. For the reduction of these emissions several options are available and/or under research.

Catalysts are not able to reduce the methane, since under lean operation conditions, and the apparent exhaust gas temperatures currently available, noble metal oxidation catalysts cannot oxidize the methane emissions with a sufficient lifetime.

According to the current state of the art methane emissions from CHP can be reduced by application of a selective catalytic reduction (SCR) catalyst (assuming regulations require a lean operation for NO_x reduction), however, there may be a trade off with GHG emissions as an incomplete reduction of NOx may lead to the production of N_2O. A quantification of this effect needs further investigation.

Another reliable but expensive option for the reduction of hydrocarbons is post-combustion systems. Post combustion systems reduce methane emissions to negligible values, but have extensive additional investment and operational costs.

Thresholds for methane (or total C) emissions from CHP are under discussion. In the Netherlands there is already a limit given by the authorities (1,200 mg/m³) and

Table 9: Methane contained in the off gas of upgrading facilities (FNR 2012)

	Pressure swing adsorption	Water scrubber	Physical absorption	Chemical absorption	Membrane
Methane contained in the off gas of the upgrading process (% of treated methane)	1–5	0.5–2	1–4	0.1	2–8 (0.5)*

*Different emissions for membranes are given as the technology is developing; 0.5 % CH_4 is given by Steentjes (2013) and Bauer et al. (2013) for the use of membranes (SEPURAN®) from the company EVONIK and gas recirculation. It should be mentioned that after feeding into the grid the final utilisation of the gas (e.g. as fuel or in CHP) might also cause emissions, which need to be considered for a GHG balance.

in Germany values from 1–1.3 g m^{-3} are discussed currently. In any case, a frequent monitoring and a reasonable limit can help to ensure an operation of the CHP units, which is according to the state of the art and prevents large emissions from poorly designed or maintained units.

Upgrading of biogas to biomethane can also cause emissions. Every technology for separating the methane from the biogas leaves a percentage of methane in the off gas. National regulations define the amount of methane to be released to the atmosphere. In case of a proper post-treatment of the off gas, the amount of methane emitted can be reduced to negligible values. However, the post treatment needs to be maintained and monitored for proper functioning otherwise large emissions can occur.

6.5 Post composting after anaerobic digestion

Composting of digestates or separated solids from digestate is a common practice within solid waste treatment to ensure hygienisation and a defined quality of the end product. Digestates are rich in methanogenic activity and in the case of anaerobic conditions the methane production will continue. A crucial part of any post-treatment is the sufficient supply of oxygen to the material, which is ensured by sufficient structure in the heap and oxygen supply by active aeration or frequent turn over. In case of insufficient operation significant methane emissions will occur.

Figure 18 shows the results presented in Daniel-Gromke et al. (2015). It should be mentioned that post-composting refers to open composting, which was separately measured. Emissions from composting within a building with air collection are included in “Emissions after Biofilter”. The variation of the results is high and shows how difficult it is to give a representative answer on the emission situation. But as in the case of PRV release events – the operation of the facility has a large impact on the emissions. If post treatment of the digestate is poorly managed and the oxygen supply for the process is insufficient, the resulting methane emissions can be very high.

Table 10: Emission results from on-site measurements

Approach	Plant type (Number of investigated plants)	Measured methane emission rate	Reference
On-site method (leakage detection, standard methods, dynamic and static chambers)	Agricultural biogas plants (8) Biogas plants with upgrading unit (2)	1.1 – 13.7 % CH_4 (1.9 – 24.5 g CH_4 kWhel^{-1})	Liebetrau et al. (2013a)
	Biowaste treatment plants (10)	15 – 295 kg CO_2eq Mg^{-1}Waste	Daniel-Gromke et al. (2015)
On-site method (leakage detection)	Agricultural biogas plants (292)	(no quantification available, only qualitative leak evaluation)	Clemens (2014)
On-site method (permanent monitoring of PRVs)	Agricultural biogas plants (2)	Plant A 0.1 % CH_4 Plant B 3.9 % CH_4	Reinelt et al. (2016)
On-site method (leakage detection, standard methods, dynamic and static chambers, High volume sampling) Remote sensing approach (IDMM and TDM)	Biowaste treatment plant (1)	0.6 – 2.1 % CH_4 0.6 – 3.0 % CH_4	Holmgren et al. (2015) Reinelt et al. (2017)

Table 11: Emission results from remote sensing methods

Remote sensing approach	Biogas plant				Investigation period	CH_4-Emission		Reference
	Digestate storage	Methane production (m^3 h^{-1})	Substrates	Gas utilisation (kWel)		in kg h^{-1}	in % CH_4-loss	
DIAL + Fenceline Monitoring	Gastight covered digestate storages	500	Energy Crops	Biogas upgrading to biomethane	1 hour	1.49	0.4	Wolf et al. (2013)
IDMM	Gastight covered and open digestate storage	370	Not mentioned	CHP 889 + 526	1 day	10.1	4	Groth et al. (2015)
IDMM	Open digestate storage	70 – 225	Dry manure	CHP 1 000	25 days within a year	3.66 (3.80; 3.54; 2.60; 2.74)	3.1 (2.9; 2.7; 5.2; 1.7)	Flesch et al. (2011)
IDMM	Plant 1: Gastight covered and open digestate storages		Pig slurry (40 %) and energy crops (60 %)	CHP 2x 526	7 days (filled digestate storage) 6 days (emptied digestate storage)	7.2 (filled digestate storage) 5.4	4.0 (filled digestate storage) 3.0	Hrad et al. (2015)
IDMM	Plant 2: open digestate storage		Energy crops	CHP 526	2 days	2.7 – 4.8	3.2 – 5.5	Hrad et al. (2015)
IDMM	Plant 3: open digestate storage		Cattle slurry (40 %) and energy crops (60 %)	CHP 526	2 days	2.7 – 3.1	3.4 – 3.8	Hrad et al. (2015)
IDMM	Plant 4: Gastight covered digestate storage		Bio-waste	CHP 360 + 250	2 days	2.3 – 4.2	2.8 – 5.2	Hrad et al. (2015)
IDMM	Plant 5: Gastight covered digestate storage		Bio-waste	CHP 580	2 days	2.2 – 3.2	1.6 – 1.9	Hrad et al.(2015)
IDMM	Plant 1: Gastight covered digestate storages	500 – 600	Energy Crops	Biogas upgrading to biomethane	4 days		0.5 ± 0.2	Westerkamp et al. (2014a)
IDMM	Plant 2: Not gastight covered digestate storages	1 700 – 1 900	Energy Crops	Biogas upgrading to biomethane	10 days		2.0 ± 0.8	Westerkamp et al. (2014a)
IDMM	Plant 3: Gastight covered digestate storages	1 500 – 3 000	Agricultural residual material	Biogas upgrading to biomethane	9 days		0.22 ± 0.12	Westerkamp et al. (2014a)
IDMM	Open digestate storage	1 180	Bio-waste	Biogas upgrading to biomethane	3 days	4.9 – 13.9	0.6 – 1.7	Reinelt et al. (2017)
TDM	Open digestate storage	1 180	Bio-waste	Biogas upgrading to biomethane	3 days	17.9; 24.5	2.2; 3.0	Reinelt et al. (2017)

6.6 Overall emissions from biogas plants

It is obvious that the published overall emissions from biogas plants have the same restrictions as the methods used to measure them. All the publications from different groups have varying assumptions and methods used to evaluate the emissions, and therefore it is difficult to compare these numbers. The need for harmonization of the methods has been described before. Table 10 and Table 11 give an overview of the results published, according to the issues mentioned above; they cannot be put into relation to each other.

In general, the single source method will deliver fewer emissions since the method cannot assess all leaks. The plants evaluated have very different design and consequently different emissions. Apparently the variety of the amounts emitted is high; therefore the results do not allow a general assessment of the technology. The use of standard values to make an analysis of the sector is questionable considering these results.

For single plants a plant analysis is recommended and if needed followed by adequate measures to reduce the emissions. For the sector a method harmonisation and a data acquisition is required to get a comprehensive estimation of the emission situation.

6.7 Remarks for construction and operation for emissions minimization

The presented results and trends within the emissions, lead to a number of emission reduction measures. Many of them are measures within the operation of biogas plants and can be integrated in daily routines without installations or additional investment. Major measures and/or routines are briefly described below.

Gas tight digestate tank or complete degradation:

Emissions from digestate storage should be minimized since they are one of the major sources. Either the digestate tank should be covered (gas tight with gas utilisation) or the degradation of the substrate should reduce the emission potential extensively. German technical guidelines set limit values for remaining emission potential (measured at 20°C) at 1–1.5 % (of gas produced) (VDI, 2010).

CHP unit:

The exhaust of the CHP can contain high methane concentrations due to incomplete combustion. Frequent control and documentation of motor settings and frequent maintenance and control of methane concentrations can help to minimize these emissions. The results presented in Figure 34 have a median of 1.65 % of the utilized gas.

Further reduction can be achieved by means of post combustion of the exhaust, but this is an expensive solution. There are no catalysts for methane emission reduction available at the market under lean operation conditions. However, SCR catalysts are also discussed as an option for optimising the emissions from CHP.

Frequent leakage control surveys:

The biogas containing components should be frequently monitored to identify leakages. This includes surveys with leakage detection systems such as methane cameras and handheld lasers. Such a survey should be carried out dependent on the status (age and number of leaks found) of the plant every 1 to 3 years. Monitoring for elevated methane concentrations within the exhaust streams from air inflated double membrane roofs should be included in routine measures.

Gas management:

Gas management should aim at avoidance of PRV releases (and flaring events) in order to minimize emissions and losses in general. This includes the automatic operation of the flare linked to the filling level of the gas storage. This requires a stationary flare, which is operational in parallel to the CHP and kicks in before the PRV opens. The filling level of the gas storage should, during normal operation, be well below 80 % (in order to compensate weather and operation induced changes); a value of around 50 % is recommended. The level indicators need to be capable of delivering precise measurements in any range of filling level. Connected membrane gas storage systems need to be adjusted to each other in order to allow controlled filling levels and pressure conditions in all vessels under all process conditions. Accordingly, gas transfer between several gas storage systems needs to be controllable in order to avoid unbalanced filling levels as well as pressure ratios, which might lead to PRV release in one vessel although other vessels have spare capacity. Adequate dimensions of pipes, blowers in the gas pipes and controllable air pressure in the air inflated roofs are measures to achieve well balanced filling levels.

The gas management system can also include the adjustment of feeding during shutdown of the gas utilisation or periods of reduced load of the CHP. In case flare operation does not avoid PRV release events under certain circumstances, a monitoring system for PRV in order to get records for number and duration of release events is recommended.

Avoidance of open handling and storage of digestate under anaerobic conditions:

As soon as the digestate leaves the process its emission potential needs to be minimized. In case the digestate is used to condition substrate for better handling, this should happen within encapsulated units and the produced gas should be treated.

Any aerobic post-treatment should include a sufficient oxygen supply in order to avoid methanogenic activity. The measurement of oxygen supply (or methanogenic activity) within the process is recommended.

Upgrading facilities:

Depending on the applied upgrading technology methane emissions via the off gas varies. An exhaust treatment is recommended in case of significant emissions. Frequent function control and monitoring of the performance of such devices is necessary.

7. Greenhouse gas balance for assessment of significance of methane emissions

The aim of this chapter is to put the methane emissions, measured or modelled in the previous chapters, into context, in order to assess their significance. An analysis of the main factors influencing the GHG balance will be performed and the most efficient approaches for the emission reduction will be identified and recommended. Besides the methane emissions, heat utilization, parasitic electricity consumption and the substrate used were varied in order to show their impact on the GHG balance.

7.1 Principles and framework of GHG balance

The overview should help to understand the impact of methane emissions on the GHG balance and give some guidance for the evaluation of plant concepts in respect of impact on the environment. Based on the results, the technical concepts and measures necessary to reach certain reduction targets are identified. The methodology recommended by the International Standardisation Organisation for the assessment of the environmental impacts of any product or service is Life Cycle Assessment (LCA) (ISO 14040; 2006). LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or environmental areas of concern can be identified and possibly avoided. In LCA, with the focus on environmental impacts, economic and social aspects and impacts are, typically, left outside the scope of the LCA.

When, in an LCA study, only the impacts on climate change are analysed (in particular only GHG emissions) the study is called a carbon footprint, and specific recommendations are available at international level (ISO 14067, 2013). The advantages of a carbon footprint, instead of a full LCA (which would include all relevant environmental impacts) are the simplification of the data collection and analysis, however, as a drawback, there are limitations in the conclusions that can be drawn, as possible trade-off among different environmental impacts cannot be identified.

The 4 phases of an LCA study, which represent the sections of this chapter, are:

1. Goal and scope definition: the goal is the intended application and the reasons for carrying out the study.
2. Life Cycle Inventory: the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
3. Life Cycle Impact Assessment: the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
4. Life cycle interpretation: the phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

7.2 Goal and scope of the GHG balance

The goal of this study is the assessment of the relevance and significance of methane emission from biogas plants. The systems analysed are biogas plants digesting several feedstocks (and combinations of feedstocks) with different technological implementations and operational practices. The functions of the product systems analysed is the production of electricity and heat. The functional unit is 1 MJ of electricity. In case of multifunctionality (co-production of heat and electricity), allocation will be performed by exergy.

In the previous chapters the potential sources of methane emissions from biogas plants were identified and the corresponding methane losses were quantified. In this chapter, the methane emissions are treated as the variable sum of all emissions occurring, without component specific considerations. Given the high variability of the total methane emissions from biogas plants, in this section the significance of these emissions is analysed by putting them into their context within a GHG balance of the whole plant.

One of the main drivers of producing biofuels and bioenergy is the reduction of GHG emissions, to counteract climate change. It is therefore of paramount importance that the production of biofuels and bioenergy contributes, significantly, to the reduction of GHG emissions. In this context, the European Union has set ambitious objectives in its policy for a sustainable energy system, with the Renewable Energy Directive (RED 2009). Together with the targets the EU has defined sustainability criteria, which include the reduction of GHG emissions in comparison to a fossil fuel comparator (FFC).

To prove that the biofuel produced complies with the emission limit the European Commission has also defined, with the Renewable Energy Directive (RED, 2009), a simplified methodology for GHG emission accounting and a set of default values for the most common biofuels, including biogas and biomethane. In 2010 the EC has recommended to the member states to use the same approach for the sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling (COM 11, 2010). However, the legislation went into force only for biofuels. The input values and the methodology for GHG accounting were further updated in 2014 with the SWD 259 (2014). The same approach is presented in the proposal for a recast of the Renewable Energy Directive (RED) presented with the ‘Winter Package’ in Nov. 2016 for the period 2021–2030 (RED recast, 2016), where mandatory sustainability criteria for solid and gaseous bioenergy are being considered.

The default values used in EU policies are supposed to be representative of common biofuel and bioenergy pathways and represent an average of the whole continent. Therefore the input values used in SWD 259 (2014) and published in (Giuntoli et al. 2015,) are applied to put the methane emissions from biogas plants into context without using specific case studies, but the theoretical and simplified pathways modelled by the Joint Research Centre (JRC) of the European Commission for the default values calculation. The three substrates used in the in the JRC report Giuntoli et al. (2015,) are manure, silage maize and biowaste.

The environmental impact assessment is limited to the category of climate change. The selected methodology for the impact assessment is IPCC AR4. The only GHG included in the analysis are non biogenic CO_2 and methane emissions. N_2O emissions are not included in the analysis. As the goal of this study is limited to the assessment of methane emissions from biogas plants, the upstream emissions are taken as constant (emissions occurring during the appropriation / cultivation of the feedstock) and are those reported in SWD 259 (2014) and Giuntoli et al. (2015).

System boundaries are depicted in Figure 35. It is assumed that the alternative fate of manure would be

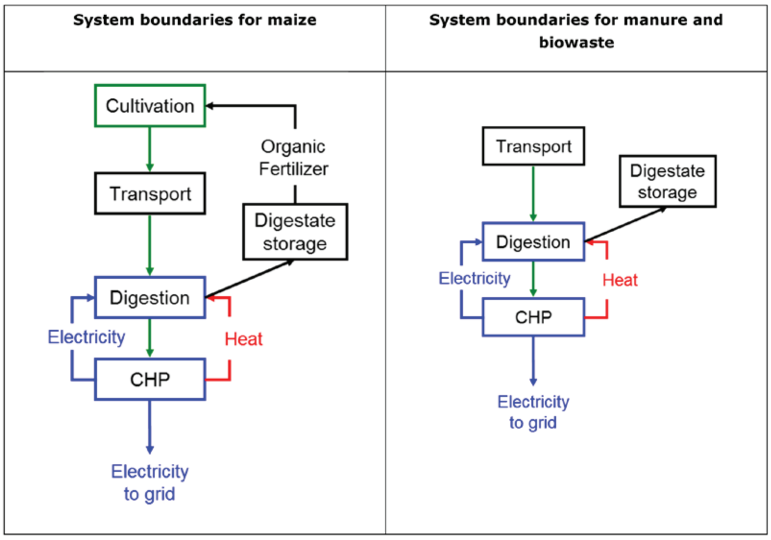

Figure 35: System boundaries for the biogas plant concepts analysed

storage in open tanks, therefore, the comparison among system is carried out allocating credits for avoided GHG emissions to the manure based pathways. Plants concepts are highly individualized and it is impossible to really define "representative plant concepts". However, the objective of this study is to allow a general evaluation of the biogas plants concepts modelled and give an idea which concepts are able to fulfil certain emission reduction targets considered the methane emission described in the previous chapters.

7.3 Inventory analysis

All the component and source specific CH_4 emissions from the plant are considered within the analysis as a sum parameter. This sum of all methane emissions is varied, in % of the total amount of methane provided to the CHP, from 0 to 7, to facilitate the understanding of the relevance of CH_4 emissions from biogas plants. The % of methane emitted to the atmosphere is to be considered comprehensive of all the emissions: digestate storage, CHP methane slip, pressure relief valves, leakages and diffusion of the membrane gas storage units, leaky gas pipes etc. Distribution of digestate on land is not included in the analysis.

The main parameters defining the pathways to produce biogas from the substrate analysed are reported in Table 12.

The common agricultural practice for manure management is storage in open tanks, where anaerobic digestion naturally occurs, and methane is emitted, together with other gases and odours. Anaerobic digestion of manure in biogas plants avoids such emissions. Therefore, credits for avoided methane emissions are added to the GHG accounting of manure biogas pathways. Credits for such avoided emissions are equal to 17.5 % of the produced methane (equivalent to 14.6 % of biomethane potential of manure VS = 70kg/ton, Biomethane potential $B_0 = 0.24$ $m^3CH_4*kgVS^{-1}$; yield = 0.2 $m^3CH_4*kgVS^{-1}$). Further details are reported at pg. 59 in Giuntoli et al. (2017) and Giuntoli et al (2015).

The credits are also applied to the fraction of manure digested in co-digestion with maize according to SWD 259 (2014) and Giuntoli et al. (2015).

As N_2O emissions from the plant (digestate, engine etc.) are not included in the analysis, for reasons of consistency, the N_2O credits, which derive from the avoided emissions from raw manure storage, have not been considered. According to IPCC, the N_2O emissions from

Table 12: Parameter for GHG balances

	Maize	Manure	Biowaste
Cultivation	Yield = 40.76 t FM/ha Diesel = 104.32 l/ha $N_{applied}$ = 63.24 kg/ha Moisture = 65% $K_{applied}$ =3 8.52 kg K_2O/ha	n.a. moisture = 90% credits for avoided raw manure storage: 17.5% of methane produced (if related to the methane potential of the used manure it equals 14.6 %)	n.a. moisture = 76.3%
Ensiling	Losses = 10% DM Diesel = 0.56 l /t $_{maize}$	n.a.	n.a.
Transport	20 km	5 km	20 km
Digestion	VS content = 33.6% VS reduction = 72% yield = 345 l CH_4/kg VS	VS content =7% FM VS reduction = 43% Yield = 200 l CH_4/kg VS	VS content 21.7% Yield = 438 l CH_4/kg VS

Source: Giuntoli et al. (2015)

manure or digestate storage are about ¼ of the emissions of methane, in terms of CO_2eq.

The impact of parasitic electricity consumption by varying it from 5 to 15 % of the electricity produced has been analysed in order to assess the significance of electrical efficiency on the GHG performances of biogas plants. Another parameter analysed was the influence of sensible heat export. To do so we have used the allocation approach recommended in EU policies COM 11 (2010).

The formula used is:

$$EC_{el} = \frac{E}{\eta_{el}} \left(\frac{C \cdot \eta_{el}}{C \cdot \eta_{el} + C_h \cdot \eta_{el}} \right)$$

Where:
EC_{el} = Emissions allocated to electricity
E = total emissions
C_{el} = Fraction of exergy in the electricity, or any other energy carrier other than heat, set to 100 % (Cel = 1).
C_h = Carnot efficiency of heat at 150 °C (423 Kelvin), which is: 0.3546
η_{el} = electrical efficiency, η_h = thermal efficiency

The methodology set in COM11 (2010) sets a lower limit for the Carnot factor at 150°C. If the heat is exported at temperatures lower than 150°C, the heat can use the same Carnot factor as if it were at 150°C. For higher temperatures, which is not common for biogas plants, the Carnot factor is calculated as $C_h = (T_h - T_0)/Th$. Where T_h (°K) is the temperature of the exported heat and T_0 (°K) is the environment temperature, set at 273 °K.

As it is very common that biogas plants digest manures with other substrates, with a higher content of volatile solids, such as energy crops or other residues, to improve the performances of the plants, we have modelled the co digestion of manure and maize with different percentages of mixture (20, 40 and 70 % maize within substrate mixture, fresh matter (FM) mass based).

To understand the significance of the GHG emissions resulting from the modelling exercise, the total GHG emissions deriving from the supply chain emissions and the biogas plant losses are presented together with the Fossil Fuel Comparator (FFC) for electricity used in EU policies.

The used FFC is taken from SWD 259 (2014) and it is equal to 186 g CO_2eq. per MJ of electricity (this equals 669.6 g CO_2/kWh) and it is based on the following power mix: 50 % natural gas fired CCGT plants (with gas sourced from a mixture of sources, from short/long distance as well as LNG), 25 % coal fired IGCC plants, and 25 % conventional coal.

It should be noted that the FFC is not meant to actually represent what is replaced by producing electricity with biogas, but rather as an arbitrary term of comparison to understand the significance of the GHG emissions of a given system.

The same document recommends, for bioenergy installations, a 70 % emission reduction target in comparison to the FFC. We therefore plot the results together with 30 % of the FFC, which corresponds to 55.8 gCO_2/MJ (200.9 gCO_2/kWh).

It should be mentioned that the average emissions for electricity for specific countries can differ from this value substantially. However, to ensure consistency and comparability of greenhouse gas savings in different Member States, the EU has considered it appropriate to apply a fossil fuel comparator based on average Union emissions (RED recast, 2016). Another point is the type of utilization of biogas. If used in other sectors the FFC for heat or natural gas are according to Giuntoli et al. (2015):

FFC heat = 80 g CO_2 eq. / MJ_{heat}
FFC natural gas = 72 g CO_2 eq./ MJ_{NG}
(no gas utilization is considered here)

7.4 Results and interpretation

The following section compares the impact of substrate used, parasitic energy use, heat utilization and methane emissions on the GHG balance of biogas plants concepts.

Substrates used are maize, manure and biowaste. External heat utilization is varied at 0 – 20 – 40 % of the overall energy content of the biogas utilized. Parasitic electrical demand of 5 – 10 – 15 % of the produced electricity has been analysed. To point out what is the methane emissions target for each system analysed which allows GHG emissions lower than 30 % of the FFC, methane emissions are assessed from 0 to 7 % of utilized methane.

Not all combinations of the variables are shown for a clearer arrangement; only those that were considered relevant to show the general trends have been selected.

Figure 36 and Figure 37 show the results of the emission calculations for maize and biowaste. The area with the blue and white pattern in graphs a, c and e represents the GHG emitted with the production of 1 MJ of electricity by anaerobically digesting maize, while the area with the orange and white pattern in graphs b, d and f represents the GHG emissions of biowaste. The yellow area represents 30 % of the EU FFC.

In Figure 36 the impact of different levels of internal electricity consumptions is analysed, while in Figure 37, the impact on emissions of different levels of export of useful heat is analysed according to the rules set in SWD 259 (2014) and Giuntoli et al. (2015) for allocation.

The radii in the graph represent the different level of methane losses expressed as a percentage of the total biogas provided to the CHP. They vary from 0 to 7 %.

Three levels of internal electricity consumption are considered for the calculation in Figure 36: 5, 10 and 15 % of the total electricity produced by the CHP. This share of internal consumption is supposed to include all the electric systems and devices used by the whole biogas plant, and therefore includes: CHP internal consumption; pumps, mixing and stirring devices; pre-treatments; digestate handling; control units and so on. Compared to the methane emissions the parasitic electricity consumption has only minor impact on the overall GHG balance.

The outcome to be seen in the graphs of Figure 36, Figure 37 and Figure 38 is the fact that the variation of methane emissions from the biogas plant in the chosen order of magnitude is the main parameter influencing the GHG emissions. In fact, in all the systems analysed, the GHG emissions are lower than the 30 % of FFC when the methane emissions are zero or close to 0, while with increasing methane emissions from the plant most systems emit more GHG than the 30 % FFC limit, and therefore have GHG savings lower than 70 % of the FFC.

The impact on maize based plants is most pronounced, as it is the only substrate, which includes a cultivation process, which generates upstream emissions. The additional emissions deriving from the cultivation process allow biogas from maize to have GHG emissions lower than 30 % of the FFC only with methane losses lower than 1 %. Consequently, the second main parameter influencing the GHG emissions is the substrate used.

As set in the EU directive (RED and RED2 proposal), wastes and residues have 0 GHG emissions till the point of collection, therefore biowaste, without emissions from the biogas plant (when methane emissions are set to 0), has only emissions from the transport process, which are very close to 0. The percentage of methane losses which causes GHG emissions higher than 30 % of the FFC start at about 4 %, with 5 % internal electricity consumption. This drops to about 3.5 % with 15 % of internal electricity consumption (Figure 37: b, d and f). Average parasitic electricity consumption of agricultural biogas plants amounted in FNR (2010) to 7.9 %.

In Figure 37 the GHG emissions of biogas plants with 10 % internal electrical consumption are reported with different levels of heat export. The percentage of useful heat exported are set to 20 and 40 % of the energy content of the biogas produced, in terms of Lower Heating Value (LHV); they do not include the heat used internally to warm the digesters.

In the case of maize, (Figure 37: a, c and e) the percentage of methane losses which cause GHG emissions higher than 30 % of the FFC start from about 0.5 % with no heat export, to about 1 % with 20 % heat export, up to about 2 % when the amount of useful heat exported is 40 % of the total energy content of the biogas produced. It can be concluded that a biogas plant, which does not export the heat and uses solely maize cannot meet the reduction target in case the technology adopted for electricity production in the CHP results in 1–2 % methane emissions (not considering any other emissions).

For biowaste (Figure 37: b, d and f) the methane losses resulting in GHG emissions higher than the 30 % FFC start from about 3.5 % when there is no heat export, to about 4.5 % with 20 % of the heat is exported, up to about 5.5 % when 40 % of the energy content of the biogas produced is exported.

These results show that methane emissions are still the most relevant parameter in determining the GHG emissions of biogas systems, however, the export of useful heat significantly contributes to the reduction of the GHG emissions per MJ of electricity produced by allocating part of the emissions to the heat exported.

The anaerobic digestion of animal manures and slurries is, correctly, seen as one of the most effective methods to reduce GHG emissions from manure handling (Battini et al., 2014). In fact, anaerobic digestion in biogas plants allows avoidance of the methane emissions that would otherwise take place during the storage of the raw slurries.

In Figure 38, some example of calculations, based on Giuntoli et al. (2015) are reported with the same approach of removing all the methane losses from the plants and adding a variable loss of methane, from 0 to 7 %, to the JRC data. Figure 38 a clearly shows that the methane emissions are negative, and, even if 7 % of the methane produced is lost in fugitive emissions, the GHG emissions are not higher than -150 g CO_2 eq/MJ electricity produced when 5 % of the electricity produced is used for internal consumption. The results are obvious

GHG emissions (g CO_2eq MJel^{-1})

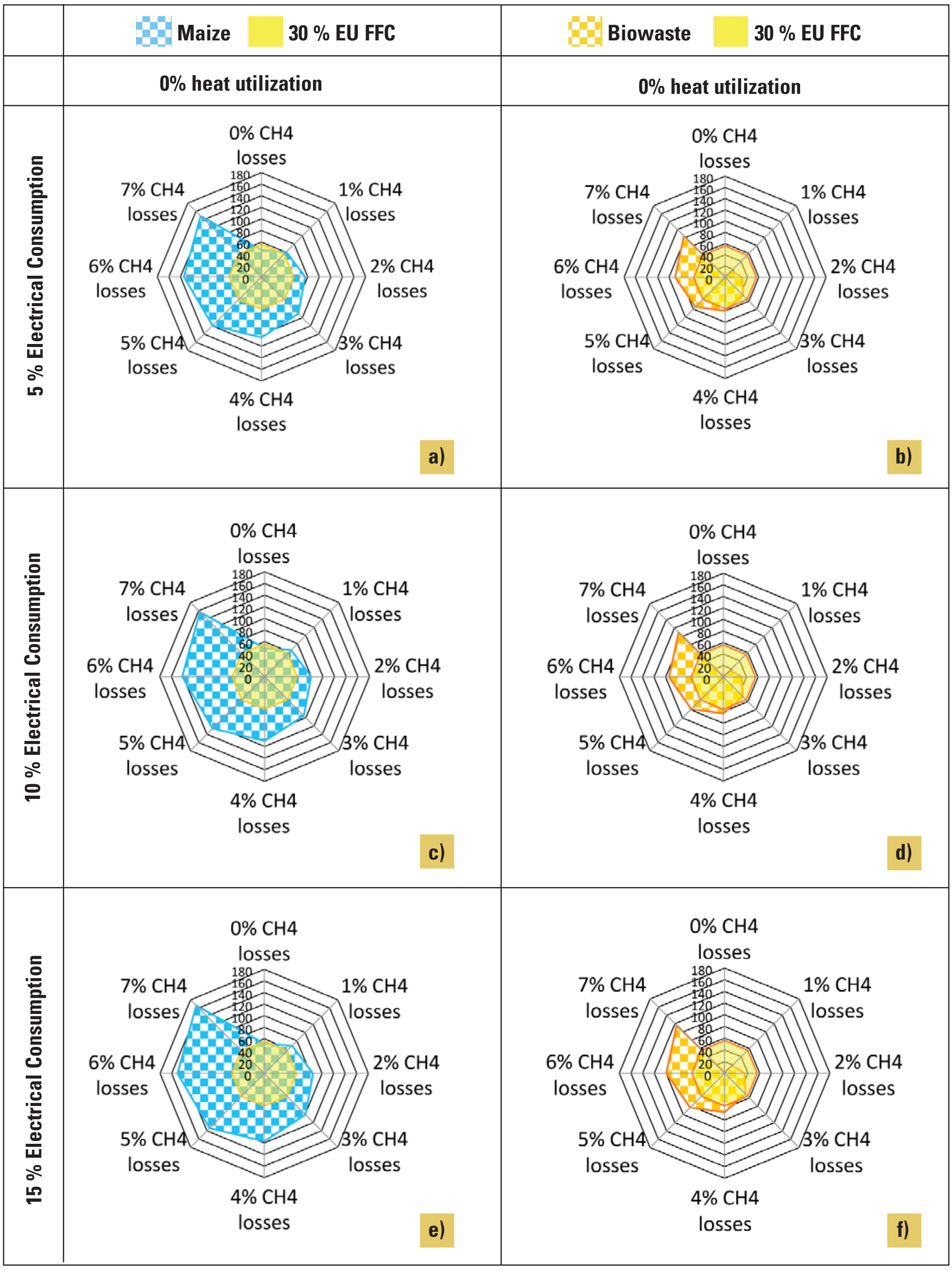

Figure 36: Impact of electricity consumption and substrate on GHG emissions; plants based on maize and biowaste

since the credit for digesting the manure represents 17.5 % of the produced methane.

By increasing the internal electrical consumption, the emissions actually decrease (Figure 38c), down to about -155 g CO_2 eq/MJ with 7 % methane loss, as a larger amount of manure is needed to produce 1 MJ electricity, therefore there are higher credits. Surprisingly, also if the efficiency of the plant is improved by exporting part of the heat the emissions increase (Figure 38e). Although it may seem anti-intuitive, it is correct, because part of the emissions are allocated to the heat, as well as part of the negative emissions (due to the credits) are allocated to the heat. Since the credit has a higher impact on the result, the outcome is higher emission of

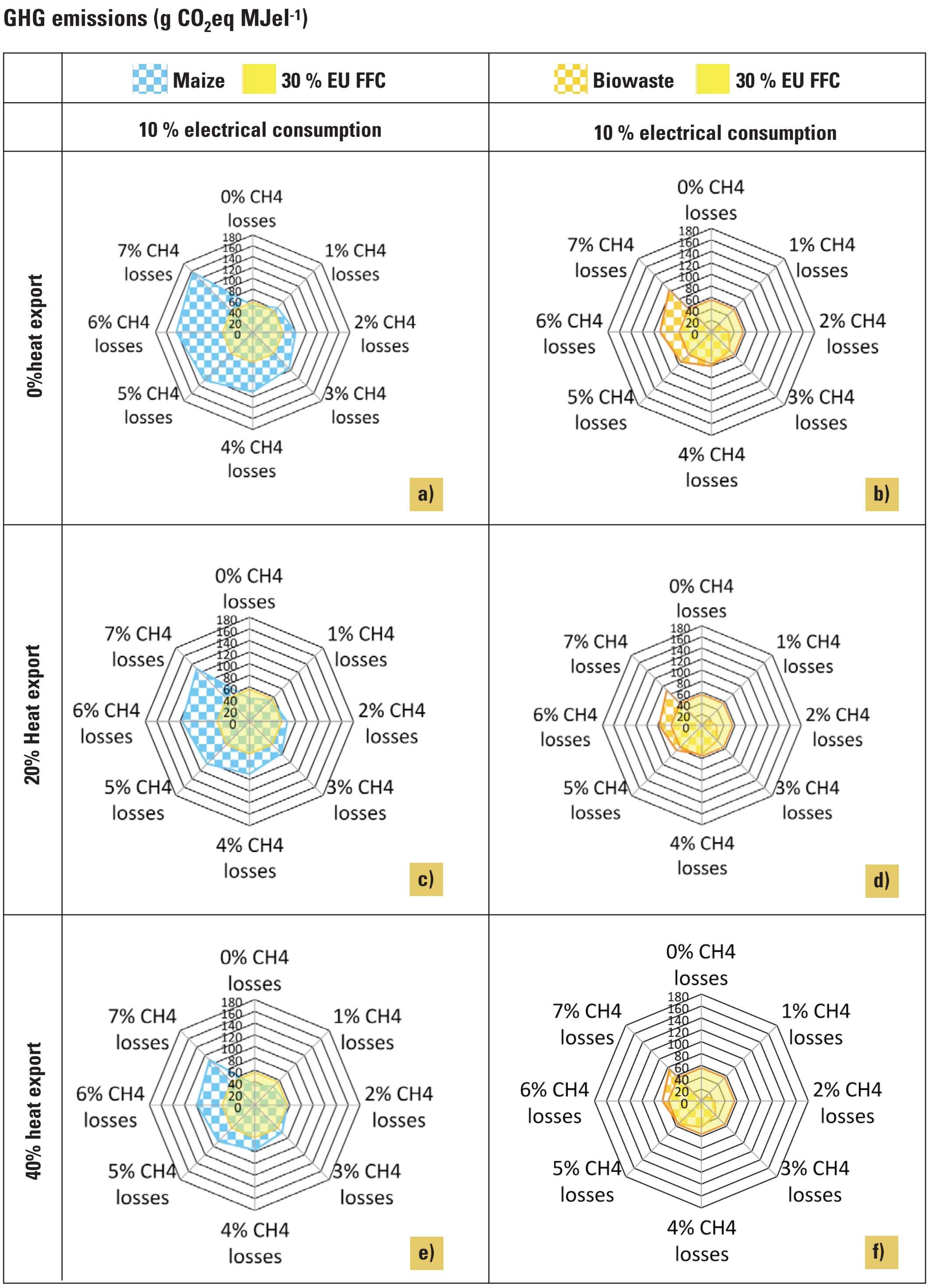

Figure 37: Impact of heat utilization and substrate on GHG emissions; plants based on maize and biowaste

GHG per MJ of electricity produced.

It must be said that although the emissions increase, they go from about -155 to about -130 g CO_2 eq/MJ in the worst case, with 7 % methane loss, it can be concluded that in any case manure digestion is an effective method to capture the methane emission that would otherwise occur with the open storage of raw slurry and valorise energetically the methane produced.

In Figure 38b,d and f, the GHG emissions of the co-digestion of manure and maize with different percentages of maize (20, 40 and 70 % in fresh matter mass) are shown.

In Figure 38b it can be noted that the GHG emissions per MJ of electricity go from negative values up to

GHG emissions (g CO_2eq $MJel^{-1}$)

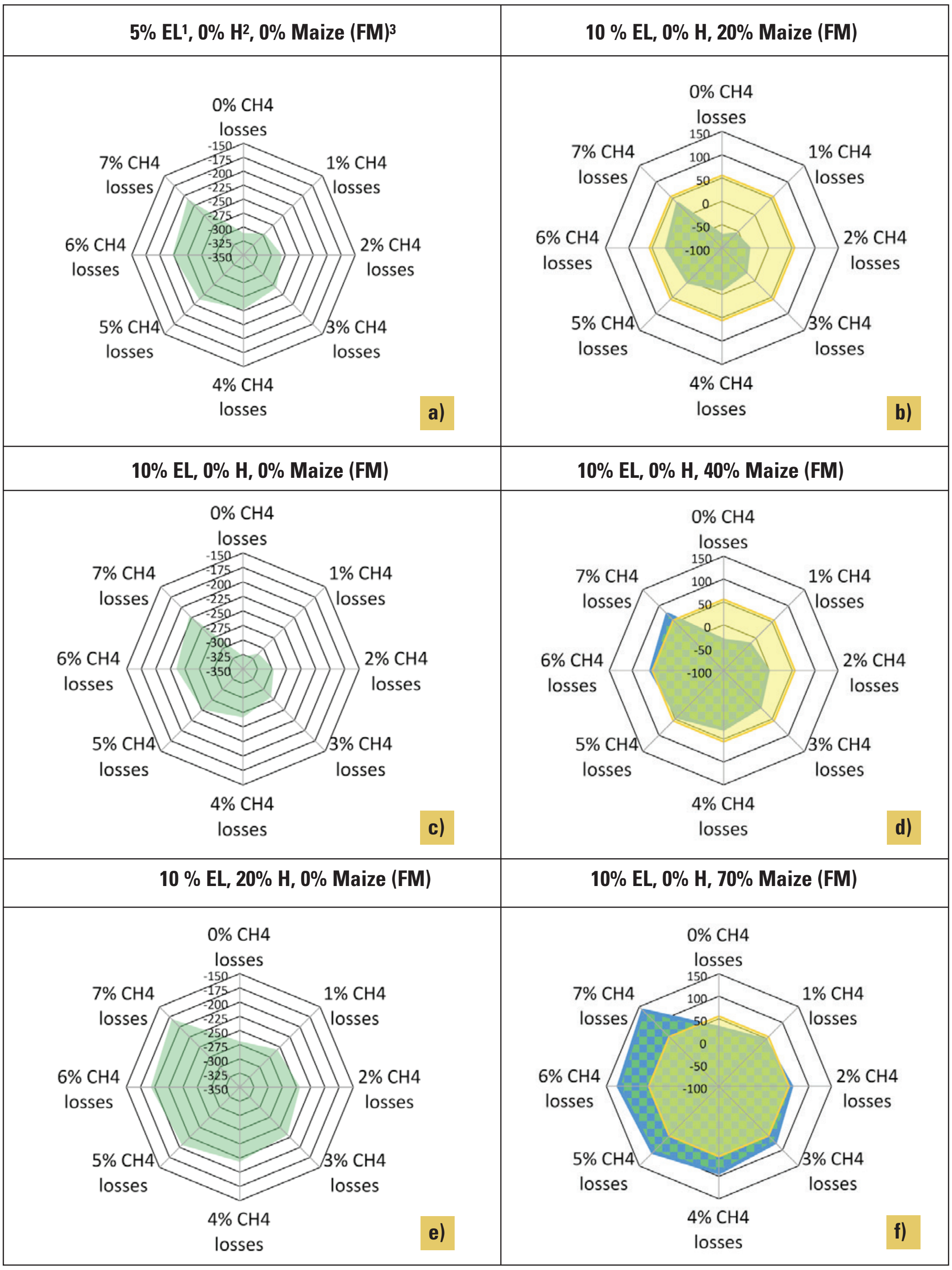

Figure 38: Impact of manure on GHG emissions; plants based on co-digestion of manure with Maize

[1] EL = Electrical internal consumption as a percentage of the total electrical production
[2] Maize FM= share of maize as fresh mass
[3] H-Share of heat utilization over the total energy content of the biogas reaching the CHP
[*] The yellow area represents 30 % of the FFC

the 30 % FFC, with 7 % methane losses, when manure is co-digested with 20 % maize silage. With 40 % maize, at 5 % losses from the plant we have emissions higher than the 30 % FFC limit (Figure 38d). In case the mixture is made of 70 % maize, by fresh matter, (Figure 38f) the methane emissions from the plant must be kept at values lower than 2 % of the methane produced to have total GHG emissions lower than 30 % of the FFC. The manure credit has in such a configuration only minor impact on the GHG balance of the plant.

7.5 Limitations of the Analysis

For a correct interpretation of the results of any LCA assessment, the limitations of the approach used should be identified and reported. The limitations of this study were identified as:

- Single environmental impact category used: the lack of information on other environmental impacts reduces the significance and robustness of the results and does not allow the identification of trade-offs among environmental areas of concern.
- Attributional modelling approach: the results obtained, relative to 1 MJ of electricity, do not provide information on the impacts deriving from market mediated effects (scale effects are neglected) therefore the results should not be used to support policy aimed at changing the installed capacities (e.g. Indirect Land Use Change for maize).
- N_2O emissions are not accounted for: as N_2O is a powerful GHG, the results lose robustness.

7.6 Conclusions from the GHG Balance

The results of this modelling exercise confirm that methane losses from the biogas plants are the most significant parameter affecting the GHG emissions of biogas plants running on energy crops or biowaste. In fact, in all the pathways modelled, with the increase of the methane losses, the GHG emissions go from lower to higher than the 30 % FFC limit, therefore the pathways would go from sustainable to unsustainable, according to the EC methodology.

The on-site parasitic electrical demand has a very low impact on the GHG performances of biogas plants if compared to methane emissions from the plant. Thermal efficiency has a limited impact on the GHG performances of biogas pathways as well, however it may contribute in increasing the maximum allowed methane loss from the plant to more feasible amounts for energy crops and biowaste.

In fact, if maize is digested alone, and 40 % of the heat is exported the 30% FFC limit is reached with 2 % methane emissions. It should be mentioned that some plant systems come with emissions, which are difficult to avoid. Any on site CHP unit for instance will result in uncombusted methane emissions from the combined heat and power unit in that order of magnitude (see Figure 34). Even with all other sources reduced to negligible levels, this inevitable emission will occur and need to be considered.

On the other hand, manure digestion guarantees negative emissions owing to the credits for avoided methane emissions from the manure storage, even if 7 % of the methane produced is lost (in case of 100 % manure digestion). Furthermore, co-digestion of manure and energy crops may create synergies thanks to the combination of the positive aspects of both substrates, the excellent environmental results of manure digestion and the economic, logistic and technical performances of maize, but only a limited share of maize can be allowed as to be seen in Figure 33 and reported also in Agostini et al. (2015).

It should be added that due to high water content and low biogas yields manure based plants have much higher volumes of substrate to be treated than energy crop based plants. Open digestate storage may contribute to significant methane emissions if retention times are too short. Consequently, the gas tight storage of digestate becomes a crucial factor for the economics and GHG reduction. (Agostini et al. 2016) showed that there are cases in which the costs of covering digestate are rapidly paid back. The outcome of such analysis is highly dependent on the tariffs for the electricity produced, the necessary storage capacity, the gas potential of the digestate etc. In particular the retrofit of existing installations might be limited due to construction limits.

The addition of energy crops to manure might be necessary to increase plant capacity to a scale which is economically feasible. Particular attention must be paid to plant configuration, retention time and digestate storage with increasing portions of energy crops, to ensure minimal methane release and to ensure emissions less than 30 % of the FFC.

The biogas plants modeled in this assessment are to be considered conceptual plants originally built to represent common technologies in Europe. Actual biogas plants concepts are highly individualized and it is impossible to really define “representative plant concepts”. However the methane emission situation given above should allow a general evaluation of the GHG performances of the different concepts and give an idea which concepts are able to fulfill certain emission reduction targets.

8. Conclusion and outlook

Methane emission quantification within the biogas sector is a new topic, which will be of significant interest to the scientific and industry communities in assessing sustainability of biogas systems. For example, according to EU legislation, operators must prove that the biogas system provides a certain reduction in GHG emissions as compared to a potential fossil fuel displaced on a whole life cycle analysis. The methodologies (including the FFCs) and the interpretation and evaluation of the results obtained, which are still under development, must be standardized to allow the industry and policy to proceed.

The methodology for methane emissions evaluation from biogas plants has been developing over recent years. Currently several methods are in use and a variety of data sets have been provided from different international teams. In the future the methods used and in particular the documentation and reporting of the results needs to be harmonized in order to obtain comparable and representative results. When comparing results particular attention should be paid to the limitations of the methods used, the duration of measurement (in order to cover time variability of specific emission sources), the completeness of plant components measured and potential sources included but not belonging to the biogas facility (e.g. barns) and the operational mode of the plant. For a representative emission factor of the average emissions during operation, all aspects need to be sufficiently considered for a sound result.

The parameters most affecting the quantity of methane emissions were identified as structural (the technologies deployed) and operational (e.g. gas management). It was found that open storage of digestate, the CHP engine, leaks and the PRV were the most important sources. In some cases large quantities of methane emissions have been reported caused by single large leaks or long lasting pressure relief events.

The application of specific monitoring and/or technologies can reduce these emissions. A crucial part of any operation should be a monitoring plan and in particular frequent monitoring of any potential emission sources on site. Some of the potentially larger sources (CHP, PRV and large leaks) are dependent on operation and time variant and therefore need to be routinely monitored. In case of increasing emissions they should be substantially reduced by operational or technical measures.

It is very difficult to give general, average numbers for emissions from components or complete biogas plants. Firstly, the results given in literature have large differences due to the variations within the methodology as mentioned above. For example CHP emissions show a substantial variability, although the methods for quantification are well defined and engine construction and operation should lead to similar emissions. Secondly the plants are highly individualized and any comparison needs to be done in relation to the plant design and plant operation in order to obtain a general emission factor.

Thirdly - methane emissions need to be seen in context with other factors influencing the overall GHG balance. Looking at the methane emission alone will not allow assessment of the full impact of the plant on GHG emissions related to the energy provided or waste treated.

Assessing methane emissions in the context of a GHG balance it becomes obvious that beside the methane emissions, other important factors (in decreasing order) on the overall GHG balance are: the substrate used; the heat utilization; and the parasitic energy demand. In case of a clear reduction target the plant design needs to be chosen carefully, since some components (such as CHP unit, open digestate storage) cause inevitable emissions once in operation.

Assuming a 30 % FFC limit as a target for the operation, it becomes apparent that energy crop based plants will have difficulties to reach this reduction target without specific measures (such as heat utilization, gas tight digestate storage and exhaust treatment at the CHP) since the energy crops come with a GHG burden associated with the production of the crops. On the other hand, manure digestion reduces significantly emissions from manure storage (in the absence of a biogas plant); manure digestion significantly reduces GHG emissions of co-dogestion systems.

The major task for the future is an improvement of precision, reproducibility and representativeness of the methods used for emission quantification. A method harmonization or at least a defined protocol will be necessary to compare results from different measurements. An important aspect of the documentation is the definition of the status of the plant and how highly time variant emissions (such as PRV release events) are included in a long-term reference time period. Only comparable results in combination with a sufficient number of plants analyzed will lead to a better understanding of the emissions from the whole sector.

The results presented show a variety in the amount of emissions from biogas plants. There are not sufficient data for a general assessment of the sector, but trends indicate which components should be monitored and which measures are useful to minimize the amount of released methane.

A general task for the future is to raise awareness within the plant operators and plant manufactures on this issue. Only if the industry is sensitive to the subject, can emissions be further reduced.

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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 work of IEA Bioenergy Task 37: Energy from Biogas.

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