Technical University of Denmark

Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution

Møller, Jacob; Boldrin, Alessio; Christensen, Thomas Højlund

Published in:
Waste Management and Research

Link to article, DOI:
10.1177/0734242X09344876

Publication date:
2009

Document Version
Peer reviewed version

Accepted for publication in Waste Management & Research

Anaerobic digestion and digestate use: Accounting of greenhouse gases and global warming contribution

Møller, J., Boldrin, A. & Christensen, T.H.

Department of Environmental Engineering
Technical University of Denmark
Kgs. Lyngby, Denmark

A definitive version is published in Waste Management & Research, vol 27, pp 813-824, doi: 10.1177/0734242x09344876”

Abstract

Anaerobic digestion (AD) of source separated municipal solid waste (MSW) and use of the digestate is presented from a global warming (GW) point of view by providing ranges of greenhouse gas (GHG) emissions useful for calculation of global warming factors (GWFs), i.e. the contribution to GW measured in CO_2- equivalents tonne^{-1} wet waste. The GHG accounting was done distinguishing between direct contributions at the AD plant and indirect upstream or downstream contributions. GHG accounting for a generic AD plant with either biogas utilization at the plant or upgrading of the gas for vehicle fuel – in both cases the digestate was used for fertilizer substitution - resulted in a GWF from -375 (a saving) to 111 (a load) kg CO_2-eq. tonne^{-1} wet waste. This large range was a result of the variation found for a number of parameters. In descending order of importance these were: energy substitution by biogas, N_2O-emission from digestate in soil, fugitive emission of methane, unburned methane, carbon bound in soil and fertilizer substitution. GWF for a specific AD plant was in the range -95 to 28 kg CO_2-eq. tonne^{-1} of wet waste. The ranges of uncertainty, especially of fugitive losses of methane and carbon sequestration highly influenced this result. Compared to the few published GWFs for AD, the range of our data was much larger demonstrating the need to use a consistent and robust approach to GHG accounting and simultaneously accept that some key parameters are highly uncertain.

Key words: Global warming, greenhouse gas accounting, anaerobic digestion, digestate, MSW

1. Introduction

Anaerobic digestion (AD) is a waste management process for organic waste materials producing biogas and a stabilized residue, called digestate, that under certain conditions can be used on agricultural land. This paper focuses on anaerobic treatment of municipal solid waste (MSW). This includes source-separated organic household waste and garden waste; anaerobic digestion of farmyard manure is not addressed.

AD contributes to greenhouse gas (GHG) emissions, mainly from use of fossil energy at the facility, emissions from the bioreactor and combustion of biogas, and emissions from the digestate when applied to soil. Equally important, AD also has a large potential for global warming savings, especially from substitution of fossil fuel by the biogas, but also from carbon storage in soil and inorganic fertilizer substitution through use of the digestate as a fertilizer. Soil-improving effects reducing the need of fossil energy for ploughing, tilling and irrigation may also occur, but quantification of these effects is difficult and they are therefore not included in this paper. A conceptual overview of anaerobic digestion and digestate use is shown in Figure 1. Thus AD is important from a global warming point of view, and a consistent and robust way to do the GHG accounting for the technology should be employed.

According to the Kyoto Protocol, greenhouse gas emissions should for each nation be reported annually, and the 4th Assessment Report (Solomon et al. 2007) provides general guidelines on how annual greenhouse gas emissions from AD facilities can be estimated. In the present paper, we take a more in-depth approach and assume that data is available on the waste entering the anaerobic facility and that the degradation of organic carbon follows our general understanding of anaerobic processes.

The GHG accounting is done per tonne of wet waste (ww) received at the AD facility and according to Gentil et al. (2009). We distinguish between direct contributions at the facility and indirect upstream (e.g. provision of energy to the AD facility) or downstream contributions (e.g. energy substitution by biogas) from processes that are associated with waste management, but are not taking place at the AD facility. We also distinguish between fossil and biogenic CO_2 in the GHG accounting, and include carbon binding in soil from farmland application of digestate. From the GHG accounts we calculate the aggregated global warming factor (GWF) for anaerobic digestion and digestate use, namely the total contribution to GW measured in CO_2-equivalents tonne^{-1} wet waste.

In this paper only advanced large-scale anaerobic facilities are assessed. The data is based mainly on AD facilities situated in Europe because of lack of public data from other regions. The technologies can be arranged into a number of categories, e.g. one-step/two-step, wet/dry and mesophilic/thermophilic digestion and combinations thereof. We are not able to go into detail with all the possible combinations, but will provide ranges of data covering a generic anaerobic facility as well as an example of GHG accounting for a specific type of 'dry' thermophilic facility based on public available data supplemented with data from the generic facility.

The purpose of this paper is to describe anaerobic digestion of waste from a global warming point of view and provide information about data that is useful in GHG accounting and subsequent estimation of GWF (in CO_2-equivalents tonne^{-1} ww). We provide likely ranges for the contributions from the technology point of view and in this way identify the most important parameters and sub-processes contributing to global warming from anaerobic digestion of MSW.

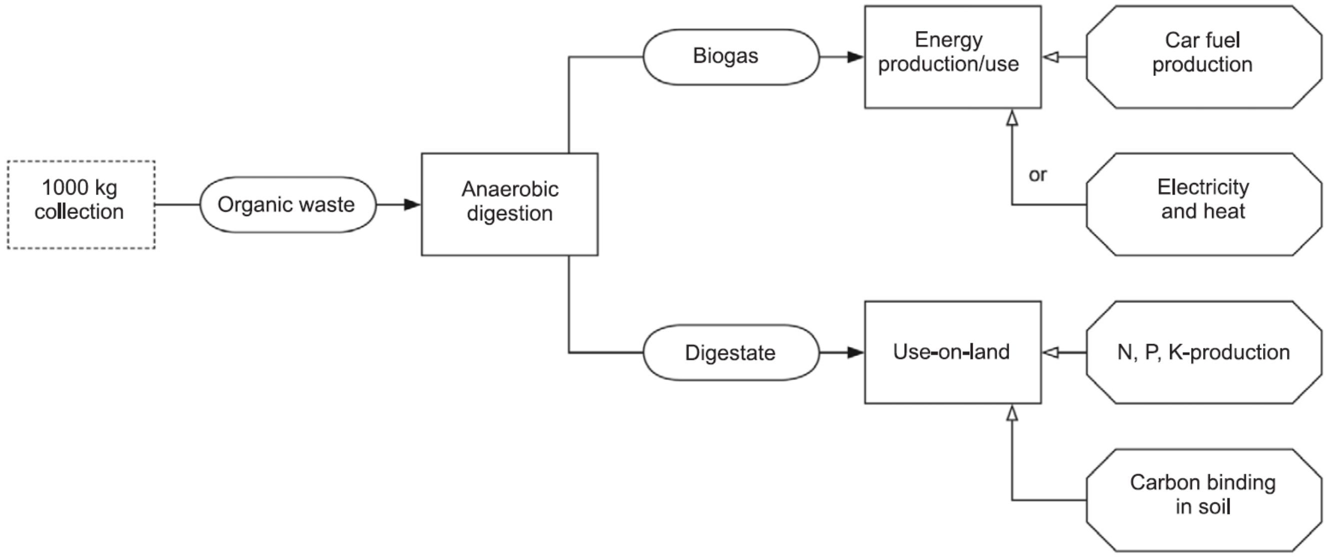

Figure 1 - Conceptual overview of anaerobic digestion (AD) and digestate use. Squares represent processes, ovals represent material flows and octagons represent substituted processes and avoided emissions.

2. Overview of anaerobic digestion technologies

At present more than 200 AD plants (in size from 2500 to 100,000 tonne year^{-1}) processing different types of organic waste are in operation worldwide – many of them situated in Germany (IEA, 2008). Sectoral figures, anyway, differ in a wide-ranging way due to whether or not sites operating co-digestion (e.g. with slurries, or sludge) are included or not. It is characteristic of anaerobic digestion plants that not one technology dominates; instead a number of different principles for construction and process control have been employed.

Regardless of the specific technology, the operation of an anaerobic digestion plant includes the following main stages: pre-treatment of the waste typically (for dry digesters) including grinding, shredding, screening and mixing; digestion of the waste including feeding and mixing in the reactor; gas handling including collection, treatment, storage and utilization and, finally, management of the digestate.

An anaerobic digestion (AD) facility or plant can be characterized according to the following options:

- Dry/wet digestion
- Thermophilic/mesophilic digestion
- One-stage/two-stage digestion
- One-phase/two-phase digestion

If the process is dry or wet depends on the moisture content in the reactor (dry: less than 75%, wet: more than 90%) and is to some extent a result of the moisture in the waste: processes treating garden waste tends to operate as dry processes. The biogas process can proceed at different temperatures, but are most often run at approximately 35°C (mesophilic) or at 53-55°C (thermophilic) temperature. The main technological difference results from the need to supply heat to the reactor to keep the correct operating temperature. Biogas production takes place in two microbiologically distinct stages: acidification and methanogenesis, with different optimum process conditions. The separation of these two stages increases methane yield, but also requires more technically complicated solutions. A further development is the separation of the reactor content into a solid and a liquid phase. Here, the solids left from the acidification process are routed back to the main reactor tank and the liquid phase undergoes methanogenesis separately.

Two-stage and two-phase systems are few due to technical difficulties. Most anaerobic digestion systems are characteristically one-stage, i.e. the whole digestion process takes place under the same process conditions, and one-phase, i.e., the entire process takes place in the same reactor.

Consequently, the majority of anaerobic digestion plants are adequately described as dry or wet and thermophilic or mesophilic plants.

3. Greenhouse gas emissions from anaerobic digestion and digestate use

The GHG emissions are grouped in terms of:

- Direct emissions which are emissions or avoided emissions directly linked to activities at the anaerobic digestion plant including combustion of fuel, fugitive gas losses from the reactor, emissions from utilization of biogas in a gas-engine at the plant or upgrading of biogas to motor vehicle fuel.
- Indirect emissions which are emissions or avoided emissions associated with the anaerobic digestion plant, but actually taking place outside the plant. Indirect emissions can be subdivided into:
    - Upstream emissions from provision of energy in the form of fuel, electricity and heat, and production of materials used on the plant and for the construction of the facility.
    - Downstream (avoided) emissions from the off-set of energy production (substitution) by the energy recovered at the plant, emissions from treatment of rejects, emissions from use-on-land of the digestate including transportation and application on land, emissions from the digestate itself, carbon sequestration in the soil and fertilizer substitution.

3.1 Direct emissions at the AD facility

Direct emissions from anaerobic digestion can be divided into three main categories: emissions from fuel combustion, fugitive gaseous emissions from the reactor and pipes and emissions associated with combustion of the biogas for energy recovery or emissions associated with upgrading biogas to motor vehicle fuel. Within this paper we are assuming that the AD facility has its own biogas-engine for energy production or biogas upgrading – in case biogas is exported from the AD facility the emissions from utilization of the gas should be categorized as indirect downstream emissions.

Direct emissions from fuel combustion are mainly from trucks and mobile machinery and other equipment for waste- and digestate handling, e.g. shredders and dewatering equipment.

Fugitive losses of GHGs at the AD facility occurs when the reactor is opened for maintenance, but also from pipes, valves and fittings in the system that lead the produced methane to the gas-engine or storage facility. Most important though, is intentional release of methane through valves due to over-pressure in the reactor.

On-site gas-utilization results in GHG emissions from the gas engine mainly in the form of biogenic CO_2, unburned methane and nitrous oxide (N_2O) produced during the combustion process. Emissions during the combustion of biogas, and especially the emission of methane, are dependent on the type of gas engine: lean-burn gas engines that are commonly used at AD facilities have the highest emission factors (EFs) for methane (Nielsen et al., 2008).

3.2 Indirect upstream emissions

Upstream contributions to GHG emissions from anaerobic digestion plants are related mainly to the provision of energy in the form of diesel oil and electricity. We here define "provision" as all emissions from extraction, transportation and refining of crude oil to diesel oil (transportation of diesel oil to the AD plant is not included), and all emissions from extraction/mining and transportation of the fuel to the power plant and subsequent production of electricity. GHG emissions from provision of water are of minor importance, but are included.

Provision of electricity for machinery for the treatment of waste and digestate, e.g. pumps and other equipment, are included, while provision of electricity for administration buildings is not.

The amount of electricity used at the AD facility can vary, depending on the digestion technology in consideration – wet technologies pump and transport larger amounts of digestate than dry technologies and, therefore, consume more electricity.

Few data is available on use of other materials at AD facilities (e.g. oil, detergents, lubricants, etc), but the contribution is considered small and the provision of these materials is not included in the GHG accounting. Likewise, we do not include emissions related to the construction of the AD facility.

3.3. Indirect downstream emissions

These can be divided in two main categories: avoided emissions from offsetting energy production by the energy recovered at the AD facility, i.e. energy and/or fuel substitution, and emission from the use of the digestate after it leaves the AD facility. Emissions from use of the digestate include provision of diesel oil and combustion of diesel in trucks for transportation and land application, emissions from the digestate during degradation in the soil, avoided emissions from carbon sequestration in the soil and avoided emissions from substitution of inorganic fertilizers.

Regarding substitution of energy production, the electricity is most often delivered to the grid. Gas engines at AD plants are usually not larger than a few MW and are often of the CHP-type, i.e. producing combined heat and power. In most cases the heat generated by the biogas engine is used internally at the AD plant to ensure mesophilic or thermophilic conditions in the reactor and to heat office areas and other facilities. This, it is important to stress, is not counted as a saving of externally provided fossil energy. In case the AD plant is connected to a district heating system or provides heat for nearby industries, the system is credited for substitution of other heat production.

An alternative for biogas utilization is its use as propellant in motor vehicles. To achieve that the biogas must be cleaned and upgraded, i.e. CO_2 removed, to obtain a biogas with low levels of contaminants and enriched in methane (>95 %). The typical operations for biogas preparation include compression, desulphurisation, decarbonisation and removal of halogens with activated carbon (Greater London Authority, 2008). The upgrading process could be performed within the anaerobic digestion facility or somewhere else: It is assumed in this paper that it is carried out at the AD plant. The upgrading sequence needs energy inputs and can result in some fugitive emissions of gas.

Provision and combustion of diesel for transportation and application of the digestate to farmland are dependent on the distance to the fields from the plant and, especially, if the digestate is from a wet or dry technology AD facility. Where dilute digestate is used on farmland without dewatering, substantial amounts of digestate has to be transported and applied to the soil.

Indirect downstream emissions resulting from agricultural use of digestate as soil conditioner and fertilizer substitute are difficult to predict based on the composition of the digestate alone. In addition knowledge of soil type, crop rotation and climate is required and the emissions can best be calculated by the use of an agricultural nutrient management model. Based on published data from such a model we supply emission coefficients for specific geographical areas regarding nitrous oxide (N_2O) and CO_2 (Bruun et al., 2006). If the application of digestate contribute to an increase of the carbon level in the soil at the end of the considered time frame (e.g. 100 years), it will represent an actual “long term” removal of carbon from the carbon cycle. This benefit is credited to the system as an avoided CO_2-emission (Marmo, 2008; Boldrin et al., 2009). We include this effect - carbon storage – in the downstream (avoided) emissions and use the numbers provided by Bruun et al. (2006) to estimate it. The digestate will to some extent substitute the use of inorganic fertilizer depending on the availability and amount of nutrients. The present paper follows Hansen et al. (2006) in assuming that the farmer will act rationally and comply with national legislation when using digestate as fertilizer substitution.

Beside savings of inorganic fertilizers and carbon binding, spreading of digestate on land can result in soil improvement (Boldrin, 2009), which leads to increased water retention of the soil (reduced irrigation), reduced herbicides/biocides requirements, improved soil structure, and reduced erosion. All these aspects could implicate some GHG savings, which are not quantified in this paper because of lack of data or of the high uncertainty related to that (i.e. local conditions, use, agricultural methods, etc). However, it is worth noticing that some estimates allocate an important part of benefits for GW coming from these induced effects on soils.

Indirect downstream emissions associated with incineration or landfilling of rejects from screened residues and the use of digestate in landscaping works are not considered in this paper. Generally, these emissions will be of minor importance, but if source separation of the waste is inadequate relatively large amounts of reject could be generated at the AD facility. In this case estimation of GHG emissions from treatment of the reject by landfilling or incineration could be carried out according to Manfredi et al. (2009) and Astrup et al. (2009).

4. Estimation of Global Warming Factors (GWFs) for anaerobic digestion and digestate use

We define the Global Warming Factor (GWF) as:

GWF= Emission Factor (EF) x Global Warming Potential (GWP) (equation 1)

Thus the global warming factors are obtained by multiplication of the emission factor for each emission by the global warming potential for that emission according to the IPCC and is used to characterize - in CO_2-equivalents - the potential contribution to global warming by each sub-process of anaerobic digestion and digestate use per characteristic unit, e.g. kg CO_2-eq. tonne waste^{-1}. When added together the aggregated global warming factor represents the total potential contribution to global warming by anaerobic digestion and digestate use per tonne of wet waste (ww).

Our approach to the estimation of the GWF for anaerobic digestion systems is based on the above definition of direct and indirect emissions associated with the anaerobic digestion technology and the subsequent use of the digestate. As a result of the type of waste, use of different anaerobic technologies and treatment of the digestate, the emissions will cover a rather large range, but in all cases the influence of the following emissions will be considered and included in the calculation of GWF:

- Emissions from fuel combustion at the AD facility
- Fugitive gaseous emissions from the anaerobic reactor and pipes
- Emissions associated with combustion of biogas
- Emissions from provision of energy in the form of fuel
- Emissions from provision of energy in the form of electricity
- Emissions from provision of water to dilute the waste
- Avoided emissions from substitution of energy production or use of upgraded biogas as vehicle fuel
- Emissions from combustion of diesel oil in connection with transportation and land application of digestate
- Emissions from digestate applied to land
- Binding of biogenic carbon in soil (C-storage)
- Avoided emissions from substitution of inorganic fertilizers

In the following paragraphs GWFs from direct and indirect emissions of GHGs are estimated per tonne of ww received at the plant and ranges of the emissions are provided when available. The GWF for each sub-process is calculated according to Equation 1. For fuel and energy the amount used per tonne of ww is multiplied by the EF (see Table 1) to give the GWF. For the emission of greenhouse gases other than CO_2 the amount per tonne of ww is multiplied by the GWP according to Solomon et al. (2007).

Regarding GWP of biogenic and fossil CO_2 we adopt the convention that GWP of $CO_{2,biogenic}$ is 0, GWP of stored biogenic carbon is -44/12 and GWP of $CO_{2,fossil}$ is 1 (Christensen et al., 2009).

4.1 Estimation of GWF from direct emissions

Fuel combustion

A typical value for fuel consumption at anaerobic digestion plants is 1.3 kg or approx. 1.6 litre of diesel per tonne of ww (Fisher, 2006). The EF for combustion of diesel oil is 2.7 kg CO2-eq/litre (Fruergaard et al., 2009) resulting in a GWF of fuel combustion at the plant of 4.3 kg CO_2/tonne of ww.

Estimation of methane production

Fugitive losses of methane as well as emissions from combustion of biogas are proportional to the amount of methane produced per tonne of ww. This is also the case for avoided emissions from substitution of energy production and to some extent carbon storage both described below under indirect downstream emissions. The amount of methane produced per tonne of ww is therefore a key parameter in order to estimate the GWF of anaerobic digestion.

If the amount of biogas produced and the percentage of methane in the biogas is known this can easily be converted to Nm^3 of methane per tonne of ww received at the plant. In case these data are not available, e.g. during decision-making or the planning phase of a new AD facility, methane production can be estimated using representative data on biogas production and percentage of methane in the biogas from existing AD facilities.

Biogas production from different types of waste varies, but for household waste, alone or mixed with garden waste, it is commonly in the range 80 – 130 Nm^3/tonne of ww received at the AD facility (Smith, 2001; Bjarnadottir, 2002; Hogg et al., 2002; Jansen & Svärd, 2002; European Commission, 2006). Biogas is a mixture of methane and carbon dioxide. The distribution of the carbon content in the waste into methane and carbon dioxide is dependent on process parameters such as temperature, pH and retention time in the reactor, but is usually in the range of 45 - 65 % methane and 55 – 35 % carbon dioxide (volume based percentage). If data on methane content in the produced biogas is missing values of 65 % methane and 35 % CO_2 can be used; this is representative for biogas production plants in Denmark (Nielsen et al., 2008). Methane production is thus often in the range of 50-85 Nm^3/tonne of ww received at the plant.

Another approach is to estimate methane production from anaerobic plants based on pilot-scale experiments assuming that these data will be representative for full-scale operations as well. In this way Davidsson et al. (2007) measured methane production (methane yields) of 300-400 Nm^3 CH_4/tonne of volatile solid (VS) fed to the reactor from 17 different types of source-separated organic household waste in pilot-scale wet thermophilic digestion with a 15-day retention time. Methane production (Nm^3/tonne of ww) can be calculated as:

$$CH_{4,production} = VS_{input} \times CH_{4,yield} \qquad \text{(Equation 2)}$$

The amount of biogenic CO_2 (Nm^3/tonne of ww) produced by anaerobic digestion is most conveniently calculated from the percentage of methane in the biogas (%CH_4), obtained by direct measurements or from average data as reported above, as the ratio of methane to carbon dioxide in the produced biogas is difficult to predict directly from other parameters:

$$CO_{2,biogenic} = \frac{CH_{4,production}}{\%CH_4} \times 100 - CH_{4,production} \qquad \text{(Equation 3)}$$

Data for methane production in batch experiments with optimized process parameters and extended incubation periods may also be available. In this type of experiment maximum methane production, i.e., the methane potential can be achieved. In thermophilic wet batch-incubations of 50 days duration Davidsson et al. (2007) found methane potentials for source-separated organic household waste in the range of 298-573 Nm^3 CH4/tonne of VS fed to the batches. Because process conditions are not always optimal in full-scale production and as there is restriction on the retention time from economical considerations the methane production is never 100 % of the potential, but a lower value ($\%_{potential\_reached}$). On average the methane yield mentioned above corresponded to 70 % of the methane potential. Using this approach methane production (Nm^3/tonne of ww) can be calculated as:

$$CH_{4,production} = VS_{input} \times CH_{4,potential} \times \%_{potential\_reached} \qquad \text{(Equation 4)}$$

Methane production per tonne of ww received at the AD facility can, therefore, be estimated in the following ways:

- Directly from the actual biogas production, percentage of methane in the biogas and the amount of waste received at the AD facility.
- From existing full-scale AD facilities – often in the range 50-85 Nm^3 CH_4/tonne wet weight household waste mixed with garden waste.
- From pilot-scale experiments – representative methane yields for household waste are 300-400 Nm^3 CH4/tonne of VS fed to the reactor.
- From batch experiments – representative methane potentials are 300-600 Nm^3 CH4/tonne of VS fed to the batches. Seventy percent of this can probably be achieved in very well-operated full-scale AD facilities.

Fugitive emissions

The fugitive loss of methane is difficult to establish by measurements and probably highly variable from plant to plant. IPCC gives ranges between 0-10 % of the produced methane, but also states that "Where technical standards for biogas plants ensure that unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero" (Eggleston et al., 2006). Others have estimated the average fugitive loss to be about 3 % of the produced methane (Reeh & Møller, 2003). With methane production of 50-85 Nm^3/tonne a fugitive loss between 0 and 3 % corresponds to 0-2.6 Nm^3 of methane/tonne of ww received at the AD facility. At standard temperature and pressure (STP) methane weighs 0.718 kg/Nm^3 and the GWP for methane is 25 (Eggleston et al., 2006). The GWF from fugitive methane loss during anaerobic digestion is therefore in the range of 0-1.9 kg equal to 0-48 kg CO_2-eq/tonne of ww received at the AD facility.

Combustion of biogas

The EF for biogenic CO_2 from combustion of biogas in Denmark is 83.6 kg CO_2/GJ (Nielsen et al., 2008). This value depends on the percentage of methane in the biogas. Assuming an energy content of biogas (CH_4 and CO_2) of 23 MJ/Nm^3 (Nielsen et al., 2008) and a production of biogas of 80-130 Nm^3/tonne of ww the biogenic CO_2 emissions from combustion of biogas at the AD facility are in the range 154-250 kg CO_2/tonne of ww received at the AD facility.

During combustion in the biogas engine methane is converted to energy and CO_2, but as the combustion process is not 100 % efficient some methane is left unburned and in this way contributes to the GWF. On average the EF for lean-burn biogas engines (smaller than 25 MW) is 323 g CH_4/GJ biogas based on measurements at 13 Danish facilities (Nielsen et al., 2008). The EF for N_2O determined in the same investigation was 0.5 g N_2O/GJ biogas. Assuming an energy content of biogas of 23 GJ/1000 Nm^3 (Nielsen et al., 2008) and a production of biogas of 80-130 Nm^3/tonne of ww the emissions from combustion of biogas at the AD facility are 0.60-0.97 kg methane and 0.92-1.50 g N_2O/tonne of ww, respectively. Thus GWF from unburned methane is 15-24 kg CO_2 eq/tonne and from N_2O 0.3-0.5 kg CO_2 eq/tonne (GWP factor for N_2O: 298, Solomon et al. (2007)) of ww received at the AD facility.

Upgrading of biogas to vehicle fuel

The energy for treatment, upgrading and compression of biogas to be used as vehicle fuel is reported as 0.09 MJ/MJ fuel produced (Greater London Authority, 2008), i.e. 0.025 KWh/MJ fuel produced. The upgrade of 1.8-3.0 GJ of biogas produced per tonne of ww will therefore require 45-75 KWh/tonne of ww of electricity. Using EFs for electricity production reported in Table 1, the upgrading procedure will result in emissions of 4.5-68 kg CO_2-eq./tonne of ww.

Fugitive emissions of CH_4 during upgrading are estimated to be 0.2 %; this corresponds to 0.1-0.17 Nm^3 or 54-91 g of CH_4 lost, i.e. 1.4-2.3 kg CO_2-eq/tonne of ww.

4.2 Estimation of GWF from indirect upstream emissions

The emission from provision of diesel oil is assumed to be 0.4-0.5 kg CO_2-eq per litre (Fruergaard et al., 2009). The amount of diesel oil used at the AD facility is estimated to be approx. 1.6 litre/tonne of ww, therefore the GWF from provision of diesel oil is in the region of 0.6-0.8 kg CO_2-eq/tonne of ww received at the AD facility.

The GHG emissions from provision of water to dilute and mix with the waste is small. Data from Danish waterworks suggest it is approx. 0.15 kg CO_2-eq per m^3 (EDIP, 2004).

Data on GHG emissions from provision of electricity are highly variable from country to country since they are dependent on the fuel mix and whether electricity has been produced in combination with heat or not. Data for electricity provision is in the range 0.007-1.13 kg CO_2-eq/kWh (Fruergaard et al., 2009) - the high value representing rather inefficient coal based electricity production and the low value representing hydro-power production or some other non-fossil fuel based production. We do not use these extreme values, but have instead chosen representative data on low respective high CO_2-emission electricity. The low value of 0.1 kg CO_2-eq/kWh and the high of 0.9 kg CO_2-eq/kWh are representative of NORDEL (and hence average electricity in the Nordic countries) and CENTREL (average electricity in the Czech republic, Hungary, Poland and the Slovak republic), respectively (Fruergaard et al., 2009).

Electricity consumption for machinery, pumps etc. is typically in the range from 20 (Fisher, 2006) to 50 kWh/tonne of ww (Bjarnadottir et al., 2002). The provision of electricity, therefore, corresponds to a low range of 2-5 and a high range of 18-45 kg CO2-eq/tonne of ww received at the AD facility.

4.3 Estimation of GWF from indirect downstream emissions

Avoided emissions from substitution of energy production

Export of electricity to the grid result in GHG emission savings by avoided emissions from substitution of other electricity production. The amount of electricity produced from the biogas is dependent on the energy efficiency of the gas engine. Modern lean-burn gas engines can reach high total efficiencies for combined electricity and heat production of more than 80 % of the lower heating value of the biogas. Electricity production is reported in the range of 23.5-40.2 % with an average of 36 % of the lower heating value of the biogas (Nielsen & Illerup, 2003).

With a biogas production of 80-130 Nm^3/tonne of ww and an energy content of that biogas of 23 GJ/1000 Nm^3, electricity and heat production will be in the range 184-299 kWh and 810-1316 MJ/tonne of ww for engine efficiencies of 36 and 44 %, respectively.

Using the two EFs for electricity production of 0.1 and 0.9 kg CO_2-eq/kWh the GWF is in the range 18-30 or 166-269 kg CO2-eq/tonne of ww for avoided electricity production. Compared to electricity, data on heat production are fewer due to the fact that heat production in many countries is of only minor importance. We, therefore, employ a single representative EF for the heat production substituted by biogas utilization of 0.075 kg CO2-eq/MJ representing EU25 mixed heat production (Fruergaard et al., 2009). The amount of heat used internally is facility-specific and very variable. For mesophilic digestion it is reported in the range 70-180 MJ/tonne of ww (Berglund & Börjesson, 2006), but for thermophilic digestion it could exceed 25 % of the heat production (Anon., 2004) corresponding to 303 MJ/tonne of ww – this should be subtracted from the heat production to estimate the net heat export. Thus if the AD facility is exporting heat the maximum savings will be in the range 61-99 kg CO2-eq/tonne of ww for heat production.

Substitution of natural gas as vehicle fuel by upgraded biogas

If the energy content of biogas is 23 GJ/1000 Nm^3 (Nielsen et al., 2008) and the production of biogas is 80-130 Nm^3/tonne of ww, the energy recovered from the waste in the biogas is 1.8-3.0 GJ/tonne of ww. Assuming that biogas substitutes natural gas in vehicles 1:1 (on an energy basis) the amount of natural gas (with lower heating value of 0.0395 GJ/Nm^3 (Fruergaard et al., 2009)) replaced is 46-76 Nm^3/tonne of ww. This corresponds to 110-190 kg CO_2-eq/tonne of ww.

Transportation and application of digestate to agricultural land

In a wet anaerobic process with addition of water to the reactor to ensure complete mixing, the digestate may constitute several cubic metres per tonne of ww, but on average the relation may be in the range of 0.5 tonne of digestate produced per tonne of ww (e.g. Bjarnadottir et al., 2002; Crowe et al., 2002; Luning et al., 2003). Assuming that transportation takes place with large trucks a fuel consumption of approx. 0.03 litre diesel per tonne per km would be a typical value (Eisted et al. 2009). If the average transportation distance to the farmland is 20 km the diesel consumption will be 0.3-0.6 litre/tonne of ww. Fuel consumption for the application on land of the digestate was estimated in Berglund & Börjesson (2006) to be between 0.67 and 0.75 litre of diesel per tonne of digestate. We have adopted a value of approx. 0.5 litre diesel used for application of digestate per tonne of ww.

Including combustion as well as provision of diesel oil, the GWF of transportation will be in the range 0.9-1.9 kg CO_2-eq/tonne of ww. Regarding application of the digestate to soil we estimate the GWF to approx. 1.5 kg CO_2-eq/tonne of ww.

Use on land of digestate

Following land application biodegradation of the digestate will commence resulting in emissions of biogenic CO_2 and N_2O. Emission coefficients for these processes were taken from Bruun et al. (2006). To assess the full impact of a single application of digestate, emissions were modelled for a 100-year period and the emission coefficients, therefore, reflects the sum of emissions in that time-frame. It should also be noted that the emissions coefficients in Bruun et al. (2006) represent the difference between normal agricultural practice only using inorganic fertilisers and use of digestate supplemented with inorganic fertilisers according to Danish legislation. Emission coefficients for CO_2-

C and N_2O-N were in the range 0.86-0.96 of the C and 0.013-0.017 of the N applied to the soil, respectively, depending on climate, soil type and various other parameters related to agriculture. Carbon sequestered, i.e., carbon applied with digestate and not released as CO_2 during the 100-year period is thus in the range 0.04-0.14 of the applied amount of carbon. Concerning N_2O it is worth noticing that emissions are assumed to occur due to release of N from organic fertilisers during periods in which vegetation is not able to take up N. Some authors, though, reports the possibility of an overall reduction of N_2O from farmlands where compost is used, e.g. Favoino & Hogg (2008), but this is not included here.

The C, N, Phosphate (P) and Potassium (K)-content of pre-treated organic source separated household waste are in the range 45-52 %, 2.2-3.1%, 0.3-0.6 % and 0.8-1.3 % of the dry matter content, respectively (Davidsson et al., 2007). Assuming a dry matter content of 25 % the C-content of the waste is 113-130 kg/tonne and the nutrient content is 5.5-7.8 kg N/tonne, 0.075-0.15 kg P/tonne and 0.2-0.325 kg K/tonne of ww. As no nutrients are lost during the anaerobic digestion process itself the total nutrient content of the digestate equals the nutrient content of the waste, but some nutrient could be lost during storage or aerobic post-treatment of the digestate at the AD facility and with waste water – this is not considered here.

The carbon left in the digestate is calculated as carbon in the waste minus carbon escaped as biogas. The emission of biogenic CO_2 from combustion of the biogas was calculated above to 154-250 kg/tonne of ww corresponding to 42-68 kg of C/tonne of ww. The carbon content in the digestate is therefore in the range of 45-88 kg C/tonne of ww received at the plant. Using EFs of 0.86 to 0.96 of the carbon content, emission of biogenic CO_2 from the digestate is estimated to be 142-310 kg CO_2/tonne of ww. Coefficients for carbon storage of 0.04 to 0.14 of the carbon content in the digestate results in a GWF of -6.6 to -45 kg CO_2/tonne of ww.

Based on a nitrogen content of 5.5-7.8 kg N/tonne of ww and an EF for N_2O-N of 0.013-0.017 of the N applied to the soil the N_2O emission from the digestate is in the range 110-200 g N_2O/tonne of ww. This corresponds to a GWF between 33-60 kg CO_2-eq/tonne of ww.

As Hansen et al. (2006) we assume that the farmer complies with national regulation regarding use of organic fertilizers. In Denmark farmers are allowed to supplement the digestate with inorganic fertilizers to a certain level. Thus only 40 % of the nitrogen in the digestate is actually assumed to substitute inorganic N; regarding potassium and phosphorous the substitution rate is assumed to be 100 %. Avoided GHG-emissions from substitution of inorganic fertilizers can then be estimated from the nutrient content in the digestate in connection with inventories of fertilizer production. Using the average values for fertilizer production (Table 1) calculated from Boldrin et al. (2009) the GWF of fertiliser substitution is estimated to be in the range -20 to -28 kg CO_2-eq/tonne of ww.

5. Results and Discussion

Table 2 shows data for a generic anaerobic digestion plant with biogas utilization in a gas engine at the plant or upgrading of the biogas to vehicle fuel. The digestate is transported to nearby farms and used as fertilizer substitution. GHG accounting and calculation of GWFs are divided into three phases: direct emissions at the plant and upstream and down stream emissions outside the plant. Results are presented in Upstream-Operation-Downstream (UOD) tables. The ranges provided in the UOD table represent variations of the different parameters as explained in the text. The table is constructed by adding the lowest respective highest values in the ranges for the different emissions. For example, the lower limit of the GWF-interval for direct emissions at the AD plant (assuming combustion of the biogas at the AD plant) of 20 kg CO_2-eq/tonne ww in table 2 is calculated as 0.3 kg CO_2-eq from N_2O-emission plus 15 kg CO_2-eq from unburned CH_4 plus 4.3 kg CO_2-eq from diesel combustion plus 0 kg CO_2-eq from fugitive CH_4-loss. Thus the GWF-intervals do not represent a statistical entity, but are constructed to demonstrate the hypothetical span of the worst respective best case for the technology in question.

The GWF from direct emissions at the plant is in the range 5 to 76 CO_2-eq/tonne of ww received at the plant. Fugitive losses of methane, combustion of diesel oil and emissions from combustion of biogas all contribute to the GWF with fugitive losses of methane being potentially the most important. Unburned methane from the biogas engine comes second – combustion of diesel at the plant and N_2O emission from the biogas engine are less important. The fugitive loss of methane is much smaller in connection with upgrading of biogas than by combustion in a gas engine at the AD facility.

The indirect upstream GWFs are in the range 3 to 149 CO_2-eq/tonne of ww with provision of electricity as the most important contributor. In most cases indirect upstream GWF will be in the same range as GWF from direct emissions at the plant irrespective of the type of electricity provided. The relative high electricity consumption for biogas upgrading has the effect that in that case indirect downstream emissions dominate over direct emissions at the plant. In contrast, the downstream GWF covers a much larger range from -47 to -414 kg CO_2-eq/tonne of ww. Here energy substitution is the most important factor. Added together electricity and heat substitution can provide GWF savings of up to 368 CO_2-eq/tonne of ww. Other savings come from carbon storage in soil and fertilizer substitution, but the impact of this is smaller – maximum savings are 45 and 36 CO_2-eq/tonne of ww, respectively. Nitrous oxide emission from the digestate in the soil is a very substantial source to indirect downstream GWF and is much larger than GWF from combustion of diesel fuel for transportation. It was assumed that the distance of transportation was only 10 km on average, but even if this was changed to 100 km N_2O-emission would still be the largest indirect downstream contribution to the GWF. However, as mentioned in section 4.3, some authors have suggested the possibility of a net reduction of N_2O-emisssion by use of digestate in agriculture related to replacement of mineral fertilisers by means of a slow-release N source. These conflicting results highlights the uncertainty associated with estimation of GWFs for anaerobic digestion and digestate use.

Totalling the indirect and direct emissions the generic anaerobic digestion facility could contribute to GWF in the range -375 to 111 kg CO_2-eq/tonne of ww received at the facility. If the AD facility has high biogas production, substitutes CO_2-heavy electricity and furthermore exports heat the result could be a substantial saving in GWF for anaerobic digestion of MSW. On the other hand low methane yield, in connection with upgrading of biogas to vehicle fuel and high emissions of . N_2O from the digestate for example, could turn anaerobic digestion into a net GWF load. This is partly in contrast to Smith et al. (2001) that estimated GWFs from anaerobic digestion of MSW in Europe. They included carbon sequestration, but not losses of methane and N_2O-emissions and depending on the energy mix the GWFs were in the range -246 to -51 kg CO_2-eq/tonne of ww treated. Fisher (2006) supplies GWFs for anaerobic digestion of kitchen waste in the UK. They divide the emissions geographically into 6.9 kg CO_2-eq/tonne of ww in the UK and savings of 2.3 kg CO_2-eq/tonne of ww taking place outside the UK – in total a GWF of 4.6 kg CO_2-eq/tonne of ww. This value falls in the range calculated in the present paper, but may represent only a number of possible outcomes of an estimation of GWF from anaerobic digestion of organic waste.

Table 3 shows GHG accounting and GWF of anaerobic digestion based on data from a dry, thermophilic, single stage anaerobic digester – the ABG facility in Jungo in Germany - treating a mixture of municipal biowaste and garden waste (Anon., 2004). The facility treats 40,000 tonne of waste per year and produces digestate used for agricultural applications. Methane production is 60 Nm^3/tonne of ww received at the facility. The biogas is combusted at the AD facility in a CHP gas engine and the generated electricity is exported to the grid; heat is not exported, but used internally. Where data was not provided we have used values from Table 2. Finally, we assume that the energy from biogas utilization substitutes an electricity mix representative of the country where the AD facility is situated, in this case Germany (see Table 1). The total GWF from this facility is in the range -95 to 28 CO_2-eq/tonne of ww received at the AD facility. The ranges of uncertainty of various parameters especially fugitive losses of methane and carbon sequestration highly influence the results and demonstrate that even using facility-specific data may not reduce the overall uncertainty substantially.

6. Conclusion

GHG accounting and calculation of GWF for anaerobic digestion in this paper have demonstrated that irrespective of the employed technology - as long as the produced biogas is utilized for energy substitution - the indirect downstream emissions are the most important factor. Direct emissions at the plant and indirect upstream emissions play less important roles. Furthermore, we have identified a number of key-parameters influencing GWF from anaerobic digestion in the form of savings or loads. In descending order of importance these are: energy substitution by biogas or substitution of natural gas in vehicles, N_2O-emission from digestate in soil, fugitive emission of methane at the plant, unburned methane during combustion, carbon bound in soil and fertilizer substitution.

The ranges of GWF from the different technologies in question are so extensive that knowledge of the specific facility is a precondition to estimate the GWF, but even in this case it may not be possible to determine the GWF of the facility with sufficient certainty. We suggest that GWF for anaerobic digestion should be carried out according to the scheme laid out in this paper, i.e., by collecting data at least of the above mentioned key-parameters for direct as well as and indirect emissions. In this way comparable and consistent GHG accounting and calculation of the GWF for anaerobic digestion and the use of digestate can be ensured.

7. References

Anon. (2004) Final Report. Anaerobic Digestion Feasibility Study for the Bluestem Solid Waste Agency and Iowa Department of Natural Resources. R.W. Beck, Seattle, WA, USA. Accessed September 2008 from: http://www.iowadnr.com/waste/policy/files/bluestem.pdf

Astrup, T., Møller, J. & Fruergaard, T. (2009) Incineration and co-combustion of waste: Accounting greenhouse gases and global warming contribution. Submitted to *Waste Management & Research*, Special Issue XXXX.

Berglund, M. & Börjesson, P. (2006) Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy*, **30**, 254-266.

Bjarnadottir, H.J., Fridriksson, G.B., Johnsen, T. & Sletnes, H. (2002) Guidelines for the Use of LCA in the Waste Management Sector. Nordtest Report TR 517. Nordtest, Espoo, Finland.

Boldrin, A., Andersen, J.K., Møller, J., & Christensen, T.H. (2009) Composting and compost utilization: Accounting of greenhouse gases. Submitted to *Waste Management & Research*, Special Issue XXXX.

Bruun, S., Hansen, T.L., Christensen, T.H., Magid, J., & Jensen, L.S. (2006) Application of processed organic municipal solid waste on agricultural land - a scenario analysis. *Environmental Modeling and Assessment*, **11**, 251-265.

Christensen, T.H., Gentil, E., Boldrin, A., Larsen, A.W., Weidema, B.P., & Haushild, M.Z. (2009) C balance, carbon dioxide emissions and global warming potentials in LCA-modeling of waste management systems. Accepted for publication in *Waste Management & Research*.

Crowe, M., Nolan, K., Collins, C., Carty, G., Donlon, B. & Kristoffersen, M. (2002) Biodegradable municipal waste management in Europe. 3v. EEA topic report, 15. EEA, Copenhagen, Denmark.

Davidsson, Å., Gruvberger, C., Christensen, T.H., Hansen, T.L. & Jansen, J.l.C. (2007) Methane yield in source-sorted organic fraction of municipal solid waste. *Waste Management*, **27**, 406-414.

European Commission (2006) Integrated Pollution Prevention and Control – Reference Document on Best Available Techniques for the Waste Treatments Industries. JRC, Sevilla, Spain.

EDIP (2004): Environmental Design of Industrial Products. Lifecycle-assessment database developed by the Danish Environmental Protection Agency in 1996, 2nd update, Copenhagen, Denmark.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 5 Waste. IPCC National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan. Accessed February 2009 from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/

Eisted, R., Larsen, A.W, & Christensen, T.H. (2009). Collection, transport and transfer of waste: Accounting of greenhouse gases. Submitted to *Waste Management & Research*, Special Issue XXXX.

Favoino, E. & Hogg, D. (2008). The potential role of compost in reducing greenhouse gases. *Waste Management & Research*, **26**, 61-69.

Fisher, K. (2006) Impact of Energy from Waste and Recycling Policy on UK Greenhouse Gas Emissions - Final Report. Prepared by Environment Resource Management (ERM) for Department for Environment, Food and Rural Affairs (DEFRA), Oxford, UK. Accessed February 2009 from: http://randd.defra.gov.uk/Document.aspx?Document=WR0609_5737_FRP.pdf

Fruergaard, T., Astrup, T., Møller, J., Ekvall, T., & Christensen, T.H. (2009) Energy use and recovery in waste management and implications for GHG counting. Submitted to *Waste Management & Research*, Special Issue XXXX.

Gentil, E., Aoustin, E., Crawford, G., & Christensen, T.H. (2009) Greenhouse gas accounting and waste management. Submitted to *Waste Management & Research*, Special Issue XXXX.

Greater London Authority (2008) Greenhouse gas balances of waste management scenarios. Greater London Authority, London, UK.

Hansen, T.L., Bhander, G.S. & Christensen, T.H. (2006) Life cycle modeling of environmental impacts of application of processed organic municipal solid waste on agricultural land (EASEWASTE). *Waste Management & Research*, **24**, 153-166.

Hogg, D., E. Favoino, N. Nielsen (2002) Economic analysis of options for managing biodegradable municipal waste. Final report to the European Commission. Eunomia Research and Consulting, Bristol, UK.

IEA (2008) International Energy Agency Task 37: Energy from Biogas and Landfill Gas. International Energy Agency. Accessed February 2009 from: http://www.iea-biogas.net

Jansen, J. la Cour. & Svärd, Å. (2002) Survey of operational experiences from European biogas plants for treatment of household waste. Lunds Tekniska Högskola, Lunds Universitet, Lund, Sweden.

Luning, L., van Zundert, E.H.M., & Brinkmann, A.J.F. (2003) Comparison of dry and wet digestion for solid waste. *Water Science and Technology*, **48,** 15–20.

Manfredi, S., H. Scharff, M. Barlaz, D. Tonini, & Christensen, T.H. (2009) Landfilling of waste: Accounting of greenhouse gases. *Waste Management & Research*, Special Issue XXXX.

Marmo, L. (2008) EU strategies and policies on soil and waste management to offset greenhouse gas emissions. *Waste Management*, **28**, 685-689.

Nielsen, O.-K., Lyck, E., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Illerup, J.B., Sørensen, P.B. & Vesterdal, L. (2008) Denmark's National Inventory Report 2008 - Emission Inventories 1990-2006 - Submitted under the United Nations Framework Convention on Climate Change. NERI Technical Report no. 667. National Environmental Research Institute, University of Aarhus, Denmark. Accessed February 2009 from: http://www.dmu.dk/Pub/FR667.pdf

Nielsen, M. & Illerup, J.B. (2003) Emissionsfaktorer og emissionsopgørelse for decentral kraftvarme. Eltra PSO projekt 3141. Kortlægning af emissioner fra decentrale kraftvarmeværker. Delrapport 6. (Emission factors and emission accounting for decentralised combined power and heat production. Eltra PSO project 3141. Mapping of emissions from decentralised combined heat and power plants. Sub-report 6). NERI Technical Report no. 442. National Environmental Research Institute, University of Aarhus, Denmark. Accessed February 2009 from: http://www.dmu.dk/1_viden/2_Publikationer/3_fagrapporter/rapporter/FR442.pdf

Reeh, U. & Møller, J. (2001) Evaluation of different biological waste treatment strategies. In: Proceedings of NJF Seminar No. 327, Urban areas - rural areas and recycling - the organic way forward? The Royal Veterinary and Agricultural University of Denmark. Aug. 20-21, 2001. NJF, Stockholm.

Smith, A., Brown, K., Ogilvie, S., Rushton, K. & Bates, J. (2001) Waste Management Options and Climate Change. Final report to the European Commission, DG Environment. Office for Official Publications of the European Communities, Luxembourg.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (eds.) (2007) Climate Change 2007. The physical science basis. Contribution of working group 1 to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK.

Tables

Table 1: Emission factors (EFs) relevant in GHG accounting for anaerobic digestion and use-on-land of digestate.

Type of process/emission	Emission factor	Reference
Provision of diesel oil	0.4-0.5 kg CO_2-eq/l diesel	Fruergaard et al. (2009)
Combustion of diesel oil	2.7 kg CO_2-eq/l diesel	Fruergaard et al. (2009)
Provision and combustion of natural gas	2.4-2.5 kg CO_2-eq./Nm^3	Fruergaard et al. (2009)
Combustion of Danish biogas in lean-burn gas engine <25 MW	83.6 kg CO_2/GJ 323 g CH_4/GJ 0.5 g N_2O/GJ	Nielsen et al. (2008)
Provision of electricity	NORDEL: 0.1 kg CO_2-eq/kWh CENTREL: 0.9 kg CO_2-eq/kWh Germany: 0.35 kg CO_2-eq/kWh	Fruergaard et al. (2009)
Provision of heat (EU25)	0.075 kg CO_2-eq/MJ	Fruergaard et al. (2009)
Provision of water from waterworks	0.15 kg CO_2-eq/m^3	EDIP (2004)
Production of N fertilizer	8.9 kg CO_2-eq/kg N	Average value calculated from Boldrin et al. (2009)
Production of P fertilizer	1.8 kg CO_2-eq/kg P	Average value calculated from Boldrin et al. (2009)
Production of K fertilizer	0.96 kg CO_2-eq/kg K	Average value calculated from Boldrin et al. (2009)

Table 2: Greenhouse gas accounting and global warming contribution (GWF's) for anaerobic digestion and digestate use. Energy production from the biogas or upgrading takes place at the plant. The digestate is used in agriculture and substitutes inorganic fertilizers. Values are expressed per tonne of wet waste (ww) received at the plant.

Indirect: Upstream	**Direct: Waste Management**	**Indirect: Downstream**
GWF (kg CO_2-eq/tonne ww): **Combustion of biogas:** **High CO_2 electricity: 19 to 46** **Low CO_2 electricity: 3 to 6** **OR** **Upgrading of biogas to vehicle fuel:** **High CO_2 electricity: 50 to 149** **Low CO_2 electricity: 6 to 18**	**GWF (kg CO_2-eq/tonne ww):** **Combustion of biogas:** **20 to76** **OR** **Upgrading of biogas to vehicle fuel:** **5-9**	**GWF (kg CO_2-eq/tonne ww):** **Combustion of biogas:** **High CO_2 electricity: -197 to -414** **Low CO_2 electricity: -49 to -175** **OR** **Upgrading of biogas to vehicle fuel:** **-47 to -304**
CO_2- equivalents (kg/tonne ww): ▪ Provision of electricity: High: 18 to 45 Low: 2 to 5 ▪ Provision of diesel: 0.6 to 0.8 ▪ Provision of water: 0 to 0.5 ▪ Provision of electricity for biogas upgrading: High: 31 to 103 Low: 3.5 to 11.5	CO_2- equivalents (kg/tonne ww): Operation of plant: ▪ CH_4 fugitive loss: 0 to 47 (GWP: 25) ▪ CO_2-fossil from diesel combustion: 4.3 (GWP: 1) Combustion of biogas: ▪ CO_2-biogenic: 0 (GWP=0) ▪ CH_4-unburned: 15 to 24 (GWP: 25) ▪ N_2O: 0.3 to 0.5 (GWP: 298) OR Upgrading of biogas to vehicle fuel: ▪ CH4 fugitive loss: 1.0 to 4.7 (GWP: 25)	CO_2- equivalents (kg/tonne ww): Transportation of digestate ▪ CO_2-fossil from provision and combustion of diesel: 0.9 to 1.9 (GWP: 1) Land application of digestate: ▪ CO_2-fossil from provision and combustion of diesel: 1.5 (GWP: 1) ▪ CO_2-biogenic from digestate: 0 (GWP=0) ▪ N_2O from digestate: 33 to 60 (GWP: 298) ▪ C bound in soil: -45 to -7 (GWP=-44/12) ▪ Substituted fertilizer: -36 to -26 Energy recovery from biogas: ▪ Substituted electricity: High: -166 to -269 Low: -18 to -30 ▪ Substituted heat: -61 to -99 OR Upgrading of biogas to vehicle fuel: ▪ Substituted natural gas: -77 to -258
Accounted (unit/tonne ww): ▪ Provision of electricity: 20 to 50 kWh ▪ Provision of diesel: 1.6 l ▪ Provision of water: 0 to 2 m^3 ▪ Provision of electricity for	Accounted (unit/tonne ww): Operation of plant: ▪ CH_4 fugitive loss: 0 to 2.6 Nm^3 ▪ Use of diesel : 1.6 l ▪ Use of electricity 20 to 50 KWh ▪ Use of water 0 to 3 m^3	Accounted (unit/tonne ww): Transportation of digestate ▪ Use of diesel: 0.3 to 0.6 l Land application of digestate: ▪ Use of diesel: 0.5 l ▪ CO_2-biogenic from digestate:

biogas upgrading: 35 to 115 KWh	Combustion of biogas: ▪ CO_2-biogenic: 154 to 255 kg ▪ CH_4 unburned: 0.6 to 1.0 kg ▪ N_2O from combustion process: 0.9 to 1.5 g OR Upgrading of biogas to vehicle fuel: ▪ Use of electricity: 35 to 115 KWh ▪ CH_4 fugitive loss: 39 to 187 g	142 to 310 kg ▪ N_2O from digestate: 110 to 200 g ▪ C bound in soil: 1.8 to 12 kg ▪ Substituted fertilizer: N: 2.2 to 3.1 kg, P: 0.075 to 0.15 kg, K: 0.2 to 0.325 kg Energy recovery from biogas: ▪ Substituted electricity: 184 to 299 kWh ▪ Substituted district heat: 810 to 1316 MJ OR Upgrading of biogas to vehicle fuel: ▪ Substituted natural gas: 39 to 131 kg
Not accounted: ▪ Transportation of waste to plant ▪ Provision of materials for construction of plant ▪ Provision of lubricants etc. ▪ Provision of heat for offices etc.	Not accounted: • Construction of plant • Emissions from stored waste and digestate	Not accounted: ▪ Transportation and treatment of reject ▪ Treatment of waste water

Table 3: Greenhouse gas account and global warming contribution (GWF) for a one-step, one-phase, dry, thermofilic anaerobic digestion plant in Germany. Based on data from Anon. (2004) supplemented with values from Table 2. Values are expressed per tonne of wet waste (ww) received at the plant.

Indirect: Upstream	**Direct: Waste Management**	**Indirect: Downstream**
GWF (kg CO_2-eq/tonne ww): 5.7 to 9.2	**GWF (kg CO_2-eq/tonne ww): 4.8 to 42.6**	**GWF (kg CO_2-eq/tonne ww): -105 to -23.4**
CO_2- equivalents (kg/tonne ww): ▪ Provision of electricity: 5.3 to 7.7 ▪ Provision of diesel: 0.4 to 1.5	CO_2- equivalents (kg/tonne ww): Operation of plant: ▪ CH_4 fugitive loss: 0 to 32.4 ▪ CO_2-fossil from diesel combustion: 2.7 to 8.1 ▪ Combustion of biogas: ▪ CO_2-biogenic: 0 (GWP=0) ▪ CH_4-unburned: 1.8 (GWP=25) ▪ N_2O: 0.3 (GWP=298)	CO_2- equivalents (kg/tonne ww): Transportation of digestate ▪ CO_2-fossil from provision and combustion of diesel: 0.4 to 0.6 (GWP: 1) Land application of digestate: ▪ CO_2-fossil from provision and combustion of diesel: 1.5 (GWP: 1) ▪ CO_2-biogenic from digestate: 0 (GWP=0) ▪ N_2O from digestate: 33 to 60 (GWP: 298) ▪ C bound in soil: -51 to -7 (GWP=-1) ▪ Substituted fertilizer: -36 to -26 Energy recovery from biogas: ▪ Substituted electricity: -52.5
Accounted (unit/tonne ww): ▪ Provision of electricity: 15 to 22 kWh ▪ Provision of diesel: 1 to 3 l	Accounted (unit/tonne ww): Operation of plant: ▪ CH_4 fugitive loss: 0 to 1.8 Nm^3 ▪ Use of diesel : 1 to 3 l ▪ Use of electricity 15 to 22 kWh Combustion of biogas: ▪ CO_2-biogenic: 187 ▪ CH_4 unburned: 0.7 kg ▪ N_2O: 1 g	Accounted (unit/tonne ww): Transportation of digestate ▪ Use of diesel: 0.14 to 0.18 Land application of digestate: ▪ Use of diesel: 0.5 l ▪ CO_2-biogenic from digestate: 158 to 348 kg ▪ N_2O from digestate: 110 to 200 g ▪ C bound in soil: 2 to 15.8 kg ▪ Substituted fertilizer: N: 2.2 to 3.1 kg, P: 0.075 to 0.15 kg, K: 0.2 to 0.325 kg Energy recovery from biogas: ▪ Substituted electricity: 150 kWh
Not accounted: ▪ Transportation of waste to plant ▪ Provision of materials for construction of plant ▪ Provision of lubricants, detergents etc. ▪ Provision of heat for offices etc.	Not accounted: • Construction of plant • Emissions from stored waste and digestate	Not accounted: ▪ Transportation and treatment of reject ▪ Treatment of waste water