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Biomass sustainability criteria: Greenhouse gas accounting issues for biogas and biomethane facilities

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Abstract

Biomass sustainability criteria were introduced in the UK following the EU Renewable Energy Directive. Criteria are now applicable to solid biomass and biogas, however because it is not mandatory criteria can be adapted by member states with the risk of different interpretation. Operators are required to report greenhouse gas (GHG) emissions for every MJ of energy produced. This paper provides a rigorous analysis of the current GHG emissions accounting methodology for biogas facilities to assess expected compliance for producers. This research uses data from operating CHP and biomethane facilities to calculate GHG emissions using the existing methodology and Government calculator. Results show that whilst many biogas facilities will meet GHG thresholds, as presently defined by Government, several operators may not comply due to methodological uncertainties and chosen operating practices. Several GHG accounting issues are identified which need to be addressed so the biogas industry achieves its reporting obligations and is represented objectively with other bioenergy technologies. Significant methodological issues are highlighted; including consignment definition, mass balance allocation, measurement of fugitive methane emissions, accounting for digestate co-products, fossil fuel comparators, and other accounting problems. Recommendations are made to help address the GHG accounting issues for policy makers and the biogas industry.

Highlights

- GHG accounting issues identified that affect potential compliance with legislation
- Appropriate recognition of digestate value is a key issue for biogas industry
- Fugitive methane emissions measurement is critical for sustainability criteria
- Chosen fossil fuel comparator value determines the potential GHG saving
- Rigorous analysis of GHG accounting methodology for biogas and biomethane systems

Keywords: Anaerobic digestion, biogas, biomethane, greenhouse gas, life cycle assessment, sustainability criteria.

Abbreviations:

AD	Anaerobic Digestion
ALCA	Attributional Life Cycle Assessment
BCC	Biomass Carbon Calculator
BSC	Biomass Sustainability Criteria
CCR	Carbon Capture and Replacement
CHP	Combined Heat and Power
CLCA	Consequential Life Cycle Assessment
CV	Calorific Value
DLUC	Direct Land Use Change
DECC	Department of Energy and Climate Change
DEFRA	Department of Environment, Food and Rural Affairs
DM	Dry Matter
EC	European Commission
EF	Emission Factor
FFC	Fossil Fuel Comparator
FIT	Feed in Tariff
FM	Fresh Matter
FQD	Fuel Quality Directive
FU	Functional Unit
GCV	Gross Calorific Value
GHG	Greenhouse Gas
GWP	Global Warming Potential
HHV	Higher Heating Value
ILUC	Indirect Land Use Change
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MC	Moisture Content
NI	Nitrogen Inhibitor
OFGEM	Office for Gas and Electricity Markets
RED	Renewable Energy Directive
RHI	Renewable Heat Incentive
RO	Renewables Obligation

1. Introduction

The Renewable Energy Directive (RED) (2009/28/EC) specifies a minimum set of sustainability criteria for biofuels and bioliquids, with a threshold of 35% savings of greenhouse gas (GHG) emissions with respect to fossil fuels they are compared to (EC, 2009a). Rules for calculating the GHG impact of biofuels, bioliquids and their fossil fuel comparators are also set in the Directive (JRC, 2014). The RED does not specify similar rules for biomass used for heating, electricity, and cooling. Nonetheless a European Commission (EC) report COM(2010)11 (EC, 2010a), makes recommendations on sustainability criteria and GHG accounting for solid and gaseous biomass pathways following a similar methodology to the RED and Fuel Quality Directive (2009/30/EC) (EC, 2009b). In contrast to the RED, the EC has not introduced binding criteria but has made non-binding recommendations to Member States (EC, 2014a). Out of all EU countries, the UK has adopted the most stringent of GHG savings requirements for Government supported solid and gaseous bioenergy projects (DECC, 2014b; EC, 2014a; OFGEM, 2014b).

The UK Government is committed to supporting sustainably produced biomass that delivers real greenhouse gas savings, and manages possible risks such as food security and biodiversity (DECC, 2012a). Bioenergy production is supported in the UK through different incentives and mechanisms. Biofuels production is promoted through the Renewable Transport Fuels Obligation (RTFO) (DfT, 2014). Biomass electricity is encouraged via Feed-in-Tariffs (FITs), the Renewables Obligation (RO), and Contracts for Difference (CfD) (OFGEM, 2014c). Biomethane and biomass heat generation are supported by the Renewable Heat Incentive (RHI), which is understood to be the world's first renewable heat scheme (DECC, 2013c).

As a consequence of EC policy, the UK has introduced biomass sustainability criteria (BSC) that facility operators receiving Government support are required to comply with. These sustainability controls for solid biomass and biogas go beyond those currently recommended or required in the EU and internationally (EC, 2014a). They reflect the principles of the UK Bioenergy Strategy and aim to support the development of sustainable biomass supply chains (DECC, 2012a). With the exception of FITs, each of these schemes has adopted sustainability criteria that include a requirement to meet both a GHG savings threshold and land use criteria.

1.1. Renewables Obligation (RO) and Contracts for Difference (CfD)

Reporting requirements on the use of biomass under the RO were introduced in 2009 (OFGEM, 2014b). The RED brought in mandatory sustainability criteria for bioliquids, which were incorporated into the RO (DECC, 2011). At the same time, the reporting requirements for solid biomass and biogas were expanded to require reporting against greenhouse gas (GHG) emissions criteria and land criteria, largely based on the sustainability criteria for bioliquids. Generators of over 50kW in size are now required to report whether the biomass they have used had been sourced from a type of 'protected land' and to provide details of the GHG emissions associated with its production and use (OFGEM, 2014b).

Following a consultation by DECC (2012b), the UK Government decided to make the sustainability criteria mandatory for support under the RO from April 2015, for stations of 1MW and above that use solid biomass or biogas (DECC, 2013b). GHG trajectories were tightened so that biomass power moves from 240kg CO_2e/MWh to a more stringent GHG emission lifecycle target of 200kg CO_2e/MWh from 2020, and tightens again to 180kg CO_2e/MWh from 2025 (OFGEM, 2014b). There is also a requirement for an independent audit report on compliance with the sustainability criteria for stations of 1MW and above using solid biomass and biogas.

Under the Electricity Market Reform it is intended that the forthcoming contracts for difference will follow the same approach as the sustainability criteria set under the RO. Where they differ it will be because of differences between the contractual approach taken in the CfD and the administrative approach via the RO (DECC, 2014a).

1.2. Renewable Heat Incentive (RHI)

In February 2013, DECC announced its intention to introduce sustainability criteria for biomass supported under the Renewable Heat Incentive (RHI) (DECC, 2013a). These criteria are broadly in line with those under the RO but reflect the smaller-scale nature of the heat market compared with the (large-scale) electricity market and that it is predicted most of the biomass supported under the

RHI will come from UK sources (DECC, 2013c). They will affect participants of the domestic and non-domestic RHI as well as producers and traders of biomass fuels. The criteria include (DECC, 2013a):

- Greenhouse gas criteria, under which biomass fuel used by RHI participants must meet a lifecycle greenhouse gas (GHG) emissions target of 34.8g CO_2e per MJ of heat. That is 60% GHG savings against the EU fossil fuel average.
- Land criteria, which will be in line with those under the RO

Land criteria include not sourcing biomass from land that since January 2008 was primary forest, designated for nature protection purposes, peatland, continuously forested, lightly forested area, or wetland. Since biogas crops are mainly grown on arable land the primary risk is converting grassland to cropland where a carbon stock calculation must be performed (OFGEM, 2014b). Further consideration of land criteria is outside the scope of this paper.

For biogas facilities producing heat, lifecycle GHG emissions are calculated using the conversion efficiency value, e.g. boiler efficiency. Biomethane producers are required to calculate emissions at the point of injection into the gas grid (DECC, 2014b).

Biomass sustainability criteria (BSC) under the RHI will not be grandfathered (DECC, 2011c, 2104b), which means all RHI scheme participants are subject to any changes in BSC, for example a reduction in the GHG criteria. This represents a significant risk for developers and investors and is in contrast to the RO which has opted to grandfather BSC (DECC, 2013b, 2013c; OFGEM, 2014b).

1.3. Feed In Tariffs (FITs)

There is currently no sustainability reporting requirements under the FIT, despite there being over 100 accredited anaerobic digestion (AD) facilities in operation (OFGEM, 2014c).

1.4. Renewable Transport Fuels Obligation (RTFO)

Sustainability requirements for the transport elements of the Renewable Energy Directive (RED) were implemented in the UK on 15 December 2011 (DfT, 2014). The RED is closely linked to the Fuel Quality Directive (FQD) and both directives include the same mandatory carbon and sustainability requirements that must be met if biofuel is to count towards European targets. The sustainability criteria are that (DfT, 2014):

- biofuels must achieve at least a 35% GHG emissions saving (this threshold will rise over time)
- biofuels may not be made from raw material obtained from land with high biodiversity value in or after January 2008;
- biofuels may not be made from raw material obtained from land with high carbon stock such as forests or land that was undrained peatland in January 2008 unless strict criteria are met.

Biogas is used for transport biofuels in many EU countries but this is not presently very common in the UK, therefore using biogas for transport fuel is not the focus of this paper.

1.5. Alternative methodologies for calculating GHG emissions from biogas

The EU methodology for calculating GHG emissions has been widely adopted by Governments and industry for bioenergy facility operators. This means that there is a consistent approach for approximating GHG emissions from different bioenergy pathways. However it should be noted that alternative methods and approaches do exist although these are more for policy-makers, researchers, and other industries rather than mandatory sustainability reporting for operators. For example, the RED and RTFO have been developed specifically for biofuels whereas the Publicly Available Specification 2008:2050 (PAS2050) is applicable to any product or service (Whittaker *et al*., 2011). These all have differences in their approach to measure GHG emissions.

Life Cycle Assessment (LCA) is defined by International Standards Organisation (ISO) and provides a framework for calculating GHG emissions and other potential environmental impacts (ISO, 2006). ISO standards can be interpreted in alternative ways hence there exists a wide range of GHG balances published in the literature. Results differ for various reasons including the methodological choice, system boundary definition, inventory data used, emission factors, and the question being asked (Adams *et al.*, 2013). Examples of alternative approaches to the RED for calculating emissions from biogas production include: Ravina and Genon (2015) who adopt the ISO/TS 14067 standards (2013); Patterson et al. (2011) which assesses biogas infrastructure at the regional scale; assessment of energy balances and emissions (Börjesson & Berglund, 2006, 2007; Pöschl *et al*., 2010); location specific LCAs of biogas (Buratti *et al*., 2013; Lantz & Börjesson, 2014; Wu *et al.,* 2015); assessments of specific feedstock or technology (Boulamanti *et al*., 2013; Mezzullo *et al.*, 2013; Starr et al., 2012); and consequential LCAs (Rehl *et al*., 2012; Styles *et al.*, 2014; 2015).

1.6. Aims and Objectives

The methodology used for GHG accounting is now crucial for bioenergy facility operators. Not complying with the criteria means the withdrawal of financial support for projects that require several million pounds of capital investment. The primary aims of this study are to evaluate the GHG accounting methodology put in place for biogas and biomethane production facilities in the UK, highlight potential issues, assess possible implications of the chosen methodological approach, and make recommendations for improvements. Specific objectives of the study are:

i) Assess current GHG reporting methodology for biogas and biomethane facilities
ii) Present case studies from biomethane facilities to demonstrate GHG calculations and highlight key sources of GHG emissions
iii) Identify and describe GHG accounting methodology issues and assess the potential impact on results
iv) Discuss the potential impact of sustainability criteria and GHG accounting methodology on the biogas industry
v) Analyse the policy implications and make recommendations for addressing the key issues

2. Methods

A necessary starting point for the evaluation of GHG methodology for AD facilities is to outline the accounting methods and give an overview of the Biomass Carbon Calculator (BCC) which is provided by Government for reporting GHG emissions (OFGEM, 2014d). Section 2.1 gives a high-level overview of GHG accounting methodology and section 2.2 describes the BCC tool provided to operators. To analyse the current methodology for GHG reporting under the BSC, case studies using data from operating biogas facilities were used to calculate GHG emissions using the Government's existing methodology and calculator (see section 2.3). Results from the case studies are presented in section 3 to illustrate the implications of data, assumptions, and methodology on reported GHG emissions.

A sensitivity analysis was performed to evaluate the impact of different assumptions and methods on the final results. From this assessment several potential GHG accounting issues were identified with the impact of these discussed in section 4. Policy implications of these issues and recommendations for improving the methodology are proposed in section 5. Figure 1 provides a graphical summary of the approach adopted in this paper.

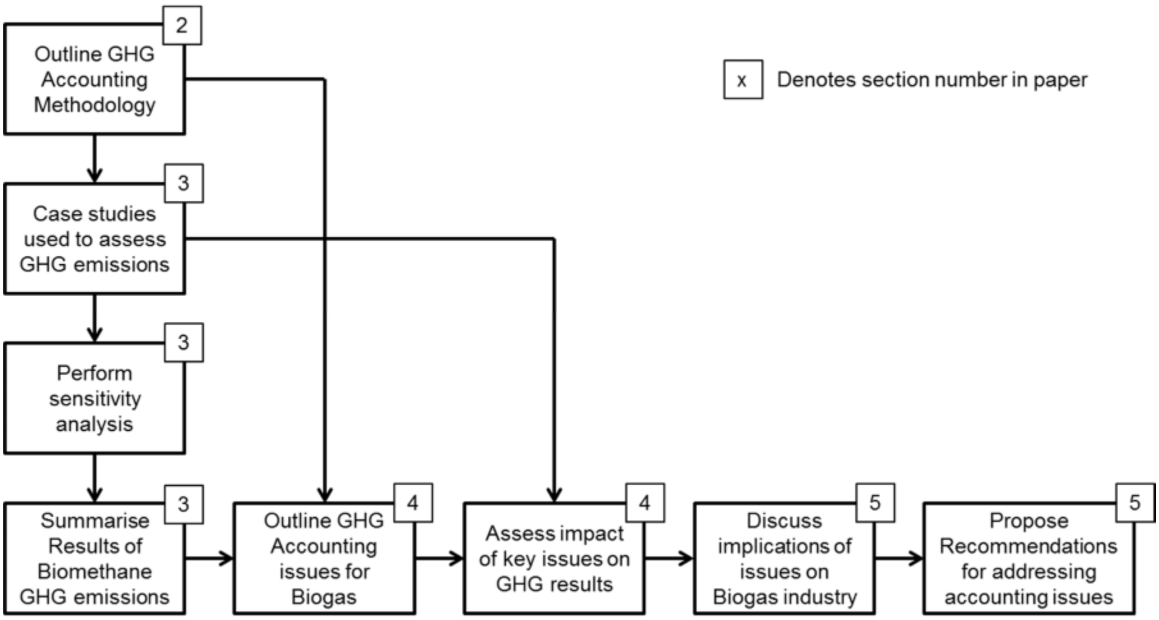

Figure 1: Summary of approach adopted in this paper

2.1. Methodology for calculating GHG performance of solid and gaseous biomass

Life Cycle Assessment (LCA) is considered to be the appropriate method to evaluate the Greenhouse Gas (GHG) performance of bioenergy compared to that of fossil alternatives (EC, 2010a). GHG accounting therefore follows LCA methodology but is concerned only with the flow of GHG emissions within the system. LCA is a structured, comprehensive and internationally standardised which follows a systematic and phased approach (ISO, 2006). Nonetheless there are aspects of LCA methodology that require choices as described within this paper.

GHG emissions from a given biomass energy application differ depending on the type of feedstock used, carbon stock changes due to land use, transport, processing, and the efficiency of conversion into electricity, heating and/or cooling (Adams *et al.*, 2013; EC, 2014a). The assessment of GHG emissions within BSC is based on a simplified methodology contained in the European Commission report on biomass sustainability (EC, 2010a), which uses the following formula:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}, \qquad \text{[Eq. 1]}$$

Where

E = total emissions from the use of the fuel before energy conversion;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualised emissions from carbon stock changes caused by land use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the fuel in use, that is greenhouse gases emitted during the combustion of solid and gaseous biomass;

e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} = emission savings from carbon capture and geological storage;

e_{ccr} = emission savings from carbon capture and replacement.

The functional unit is defined as gCO_2e/MJ, where the energy value (MJ) can be used to express the emissions associated with the fuel (MJ_{fuel}) or energy produced (MJ_{elec} or MJ_{heat}). This methodology does not incorporate the emissions associated with the manufacture of the machinery and equipment used in bioenergy production and supply. In particular, the indirect energy consumed is not considered in the RED or when calculating GHG emissions for solid and gaseous biomass (EC, 2009a, 2010a).

BSC guidance requires that GHG emissions must be calculated and reported on a 'per consignment' basis. This essentially means that each feedstock with different 'sustainability characteristics' needs to be reported individually rather than as a mix of feedstocks that produced the biogas (OFGEM, 2014b). GHG performance are expressed as 'savings' relative to a fossil fuel comparator (FFC) given as the EU average of fossil electricity, heating or cooling (EC, 2010a):

$$\text{GHG 'Saving'} = (E_{FFC_{h,el,c}} - E_{h,el,c})/E_{FFC_{h,el,c}} \qquad \text{[Eq. 2]}$$

Where $E_{h,el,c}$ = total emissions from the heat, cooling or the electricity; and

$E_{FFC_{h,el,c}}$ = total emissions from the fossil fuel comparator for heat, cooling or electricity.

It should be noted that the definition of the GHG methodology involves policy choices and this paper assesses the methodology adopted by the UK Government.

2.2. Biomass Carbon Calculator

The UK Solid and Gaseous Biomass Carbon Calculator (BCC) has been developed for calculating the carbon intensity and GHG saving of solid biomass and biogas used for electricity and heat generation (E4Tech, 2014). The BCC incorporates the calculation methodology set out in the RED (EC, 2009a), taking account of the recommendations set out by the EC in their report on sustainability requirements for solid and gaseous biomass (EC, 2010a). The tool is designed to assist in calculating the final GHG emission saving that should be reported to Ofgem, who regulate both the RO and RHI schemes (OFGEM, 2014a, 2014b). It therefore allows the user to model GHG emissions of individual feedstock (consignments). The primary aim of the software is to facilitate the use of actual data collected directly from the supply chain to calculate fuel chain carbon intensity. Users are required to enter input data to the BCC, which then uses this information to apply conversion efficiencies and emission factors, to calculate the GHG emissions from the fuel chain. An example fuel chain for biomethane is presented in Figure 2.

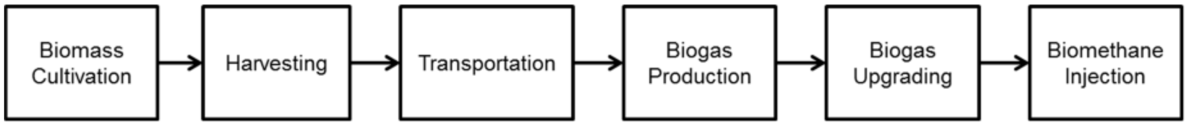

Figure 2: Example fuel chain for biomethane production (adapted from (E4Tech, 2014; OFGEM, 2014d))

As many of the assumptions and results in the tool are hidden, for this research an excel spreadsheet was developed which follows the same methodology as the BCC (see supplementary information). Using the BCC does not allow for full transparency and it is also difficult to address some of the accounting issues identified in this paper. The excel spreadsheet in the supplementary information therefore allows for a clear method and the ability to perform different modelling. Results from case studies were checked against the BCC to ensure consistency in the calculations.

2.3. Case Study Details

A case study is used to illustrate the potential GHG performance of common biogas facilities and highlight accounting issues using actual data. Energy crops are most likely to be affected by BSC as wastes are exempt, and residues are only required to calculate emissions from the point of collection onwards (OFGEM, 2014b). Maize is currently the most commonly used energy crop substrate for biogas (DEFRA, 2014a), and is therefore the primary focus here. Four scenarios for the cultivation of maize and production of biogas are considered. Scenario A assumes that all of the cultivation nutrient requirements are met with inorganic fertilisers. Scenario B has 30,000kg of digestate applied during cultivation with the remaining nutrients supplemented with inorganic fertiliser. Scenario C has the same assumptions as scenario A except that the biogas plant yield is lower due to biogas supplying CHP, whereas A and B assume electricity is supplied by the UK grid. Scenario D has the same assumptions as scenario B except for the use of biogas CHP. Table 1 outlines the main assumptions in performing the GHG calculations for the maize scenarios A, B, C & D and manure/slurry.

Table 1: Main assumptions used in GHG calculations for biomethane from maize scenarios and manure/slurry (using site data and Buratti et al., 2013; KWS, 2012; OFGEM, 2014d)

Parameter	Unit	Maize A	Maize B	Maize C	Maize D	Manure/ Slurry
		UK Grid electricity		Biogas CHP electricity		UK Grid
		Inorganic	Digestate	Inorganic	Digestate	
Cultivation						
Crop Yield	t_{FM}/ha	40	40	40	40	-
Moisture Content (MC)	% wet basis	70	70	70	70	90
Fertiliser Inputs						
N	kg (nutrient) / ha	150	60	150	60	-
P	kg (nutrient) / ha	60	24	60	24	-
K	kg (nutrient) / ha	250	42	250	42	-
Digestate	kg	0	30,000	0	30,000	-
Pesticides	kg (nutrient) / ha	0.57	0.57	0.57	0.57	-
Maize Seeds	kg/ha	29	29	29	29	-
Diesel	l/ha	60	60	60	60	-

Harvest, haul & clamp						
Diesel	l/ha	94	94	94	94	-
Silage loss	%	10	10	10	10	-
Biogas Production						
Biogas Plant Yield	MJ_{HHV}/t_{FM}	3,922	3,922	3,432	3,432	432
Electricity	MJ_{elec}/MJ_{biogas}	0.05	0.05	0.05	0.05	0.05
Electricity source		UK Grid	UK Grid	Biogas	Biogas	UK Grid
Methane losses	gCH_4/MJ_{biogas}	0.2	0.2	0.2	0.2	0.2
Biogas Upgrading						
Efficiency	$MJ_{biomethane}/MJ_{biogas}$	0.99	0.99	0.99	0.99	0.99
Electricity	$MJ_{elec}/MJ_{biomethane}$	0.01	0.01	0.01	0.01	0.01
Methane losses	$gCH_4/MJ_{biomethane}$	0.1	0.1	0.1	0.1	0.1
Biomethane Injection						
Electricity	$MJ_{elec}/MJ_{biomethane}$	0.01	0.01	0.01	0.01	0.01

Cattle manure/slurry is also considered in the case study to provide a commonly used agricultural residue. Whilst waste is exempt from GHG criteria, residues like manures are required to report from the point of collection (OFGEM, 2014b). This substrate is included as most AD facilities use mixed feedstocks and is useful to illustrate accounting issues. Similar biogas plant operating conditions to maize A are considered (see Table 1), e.g. electricity use, methane losses, biogas upgrading and injection efficiencies, with additional data provided in Table 2.

Table 2: Additional assumptions for manure/slurry in GHG calculations (OFGEM, 2014d)

Parameter	Unit	Value
Moisture Content	% wet basis	90
Density of dry product	t/m^3	0.25
Energy intensity of transport	MJ_{fuel}/tkm	1.01
Distance transported	km	10
Diesel for transport	MJ_{fuel}/t	10.1
Biogas Plant Yield	MJ/t_{FM}	432

Data used for this case study obtained from industry is generic rather than providing explicit facility details. This is because the focus is on the methodology rather than the specific results. Tables 1 and 2 summarise the primary data in a format that is consistent with the BCC. Figure 3 illustrates the key inputs, operations, energy and carbon flows of a typical biomethane system.

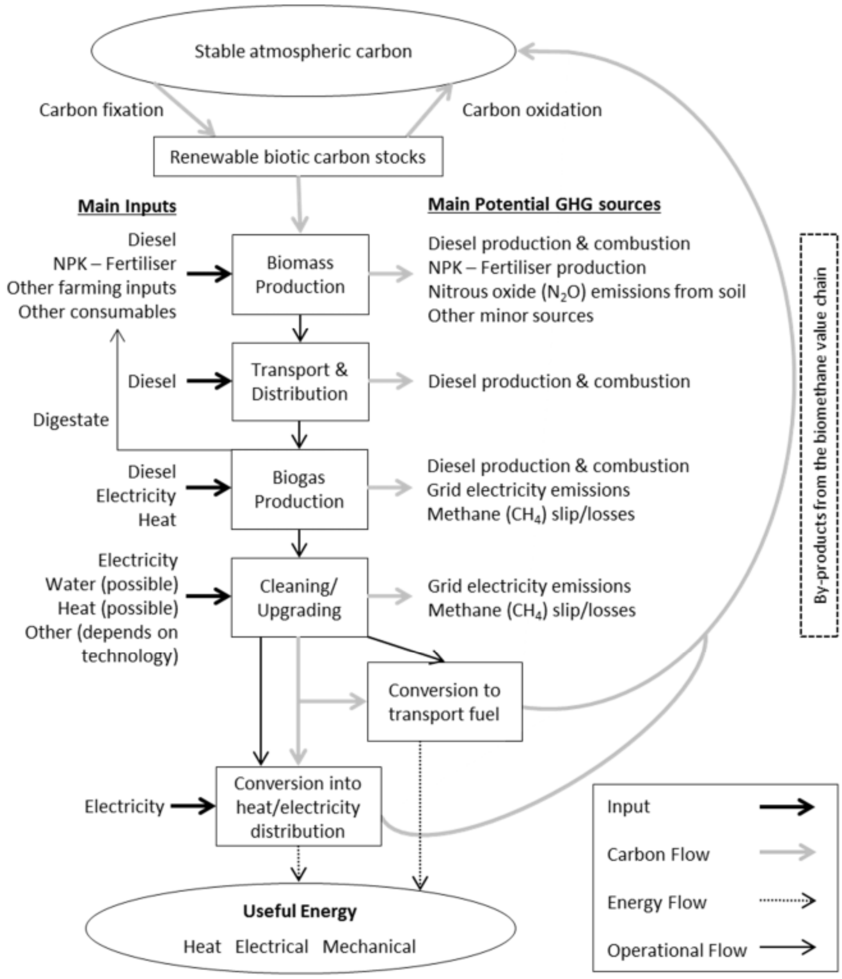

Figure 3: Flow chart for the calculation of GHG emissions for biomethane production (adapted from IEA Bioenergy Task 38 (IEA, 2013) and Korres, 2013)

2.4. Sensitivity Analysis

A limited number of sensitivity cases (for maize only), shown in Table 3, are assessed for the larger emissions sources. Whilst fertiliser inputs also have a large influence on results; these are evaluated in the 4 scenarios so are not included as sensitivities. Crop yield influences the relative impact of cultivation and harvesting, with lower yields resulting in greater emissions per tonne. Methane losses are uncertain due to difficulties in measurement and variations in operation (Liebetrau *et al.,* 2010). Electricity use can vary due to the plant operation performance and the conversion, upgrading, and injection technologies employed (Mezzullo, 2010; Thrän *et al.* 2014). Other sensitivity cases were considered but are outside the scope of this paper.

Table 3: Sensitivity cases considered for maize scenarios

No.	Sensitivity Case	Stage	Low	High
1	Crop Yield	Cultivation	$30t_{FM}$/ha	$50t_{FM}$/ha
2	Methane losses	Biogas production Upgrading/injection	0.1 gCH_4/MJ_{biogas} (~0.5%) 0 $gCH_4/MJ_{biomethane}$ (0%)	1.0 gCH_4/MJ_{biogas} (~5%) 0.6 $gCH_4/MJ_{biomethane}$ (~3%)
3	Electricity use	Biogas production Upgrading/injection	0.025 MJ_{elec}/MJ_{biogas} 0.005 $MJ_{elec}/MJ_{biomethane}$	0.075 MJ_{elec}/MJ_{biogas} 0.030 $MJ_{elec}/MJ_{biomethane}$

3. Results

3.1. GHG emissions of Biomethane facility case study scenarios

GHG emissions were calculated for each of the four maize scenarios and manure based on the methodology and assumptions described in section 2. Results are displayed in Table 4 and Figure 4, with GHG emissions for maize varying depending on the selected operation of the biomethane facility. For maize the two stages of the fuel chain with the largest emissions are cultivation and biogas production. Emissions from cultivation vary depending on the type and amount of fertiliser applied, Maize B has the lowest emissions due to the modelling assumption that digestate has zero emissions associated with production (OFGEM, 2014d). Nonetheless, N_2O emissions from soil are higher with maize B due to the larger emissions factor for organic N (IPCC, 2006). Maize C has the highest emissions from cultivation because the biogas plant yield is lower and therefore more feedstock is required. Harvesting, haulage and storage in silage clamps is 6-8% of the total emissions in all 4 maize scenarios and therefore a relative minor source. For manure, emissions from collection are not significant but account for 16% overall.

Table 4: GHG Emission Results ($gCO_2e/MJ_{biomethane}$) for four maize scenarios and manure/slurry

Life cycle stage	Maize A	Maize B	Maize C	Maize D	Manure/Slurry
	UK Grid electricity		Biogas CHP electricity		UK Grid
	Inorganic	Digestate	Inorganic	Digestate	-
Cultivation	15.8	13.1	18.1	14.9	0
Harvest, haul & clamp (collection)	1.9	1.9	2.2	2.2	2.1
Biogas Production	11.3	11.3	6.8	6.8	6.0
Biogas upgrading	3.6	3.6	3.6	3.6	3.6
Biomethane injection	1.7	1.7	1.7	1.7	1.7
Total	**34.3**	**31.6**	**32.4**	**29.2**	**13.4**

GHG emissions from the biogas production stage depend on the plant yield, the amount and source of electricity, and any methane losses. The plant yield will depend on the substrates used, the dry matter content, efficiency of biogas conversion, and other factors (Andersons, 2010; KWS, 2012; Thrän *et al.* 2014). For biogas production, Maize C & D has lower emissions as biogas CHP provides the electricity. The source of electricity is an important parameter because the emission intensity of the electricity grid is much higher than biogas (OFGEM, 2014d). Methane slip accounts for 4.6gCO_2e/MJ_{biogas} in each scenario using the default value (~1% loss), so all methane losses are assumed to be the same.

3.2. Sensitivity Analysis

Three sensitivity cases with low and high input values are considered for maize only based on the larger emissions sources. Results were calculated by changing the assumptions shown in Table 3, and reveal that GHG emissions can vary substantially from base case results, see Figure 5. These additional results are helpful to portray the GHG accounting issues described in section 4. Note that the low/high cases are chosen to illustrate variation rather than specifically showing the expected extreme values.

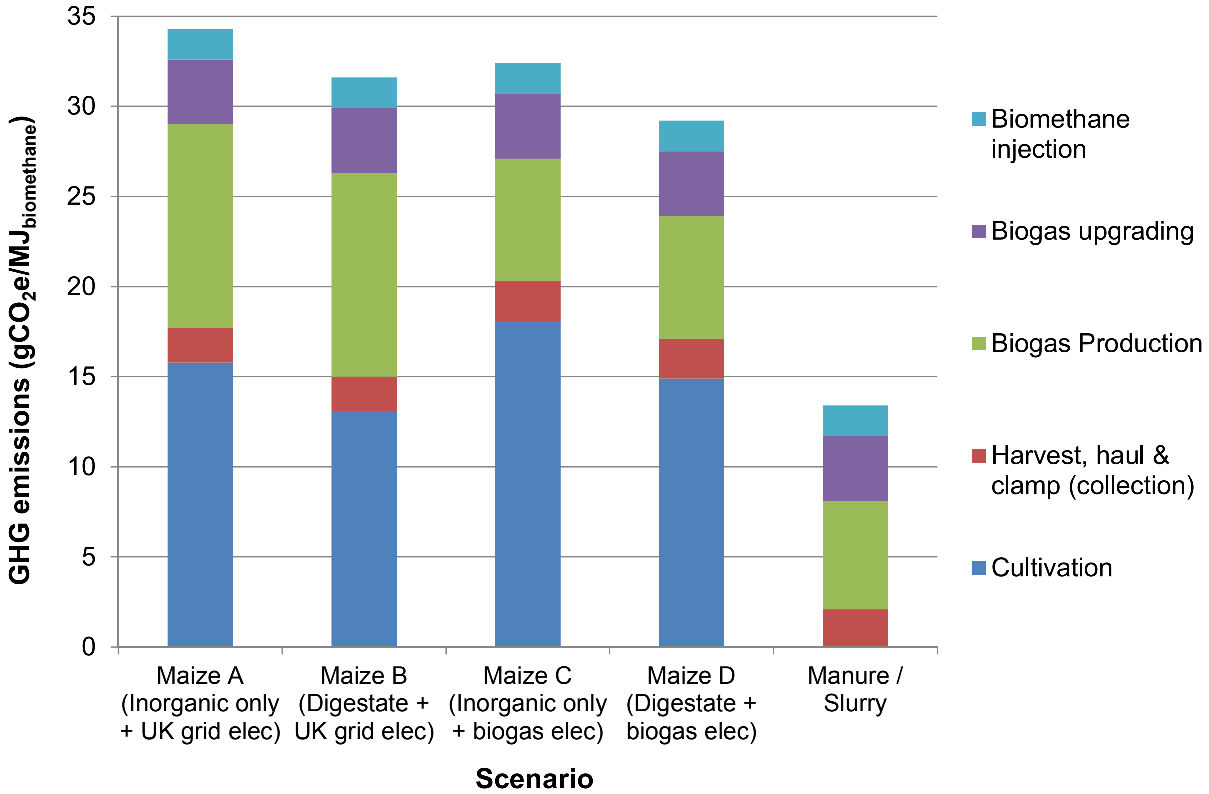

Figure 4: GHG Emission Results ($gCO_2e/MJ_{biomethane}$) for four maize scenarios and manure/slurry

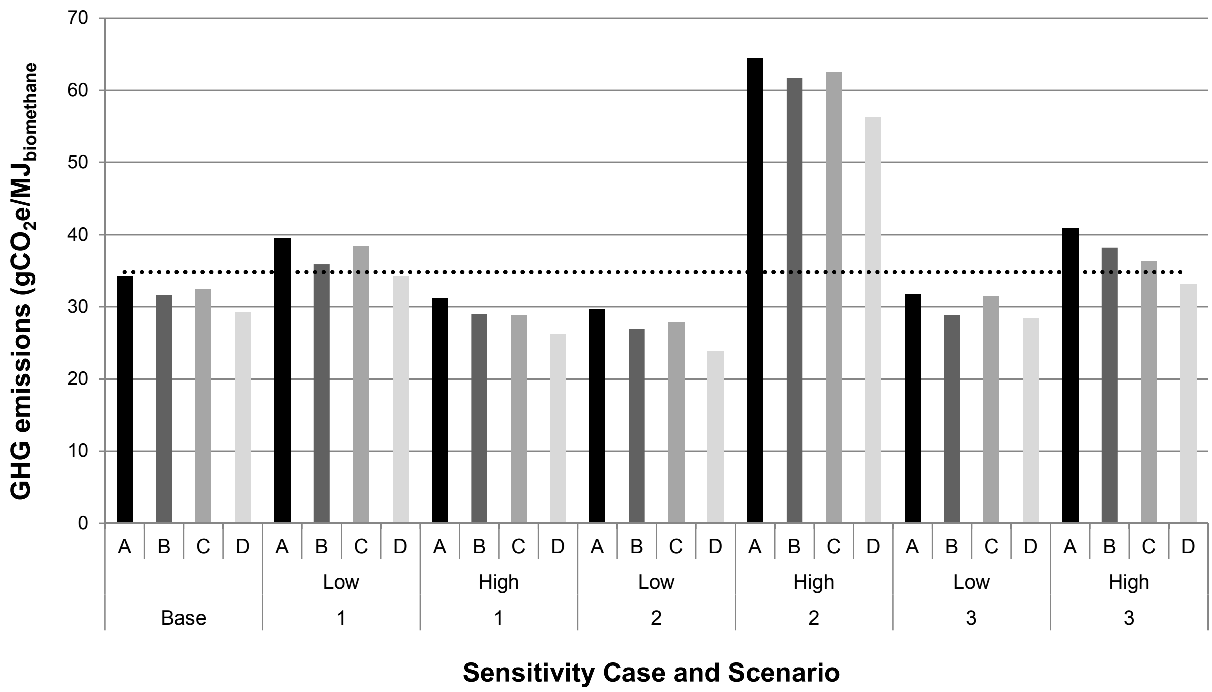

Figure 5: Sensitivity analysis results for different scenarios

4. Discussion

Several issues associated with accounting for GHG emissions have been identified during the development and application of the Government methodology for biogas. This section discusses the key problems using examples from the case study.

4.1. Digestate co-product allocation

A useful co-product from the AD facility is digestate which can be used as an organic fertiliser, replacing artificial fertilisers to realise several environmental benefits (Chambers & Taylor, 2013; Lukehurst *et al*., 2010; Vaneeckhaute *et al*., 2013; WRAP, 2011). When accounting for GHG emissions of co-products there are different approaches that produce varying results depending on the method applied. In the UK Government methodology and Biomass Carbon Calculator (BCC) the default approach currently taken is to assume zero emissions associated with digestate production, i.e. the co-product is considered a waste (or zero energy content) so 100% of emissions are allocated to biogas. GHG emissions do arise when digestate is applied to soil which is accounted for in the BCC.

The methodology proposed in the RED and COM(2010)11 are to allocate co-products in proportion to their energy content, except where heat is the co-product when the Carnot efficiency should be used (see section 4.7) (EC, 2010a). Other options for allocating include mass, economic, exergy, giving credits, or avoiding allocation through system expansion (Adams & McManus, 2014; EC, JRC & IES, 2010; Jungmeier *et al*., 1998; Manninen *et al*., 2013; Whittaker, 2015; WRI, 2011). For this study different approaches to energy allocation are analysed as this is the approach adopted in the EU and UK.

When digestate is produced it can either be used as an organic fertiliser on AD feedstocks, used on other crops, or a combination of both. This can be accounted for in two ways (see Figure 6):

(1) Zero emissions from production, effectively treated as a recycled product in a closed loop system, as described above, this is how the BCC by default calculates GHG emissions (OFGEM, 2014b).
(2) Allocate emissions between biogas and digestate based on energy content, as proposed in the RED and COM(2010)11, and adopted for the RO [EC 2009a, 2010a; OFGEM, 2014b].

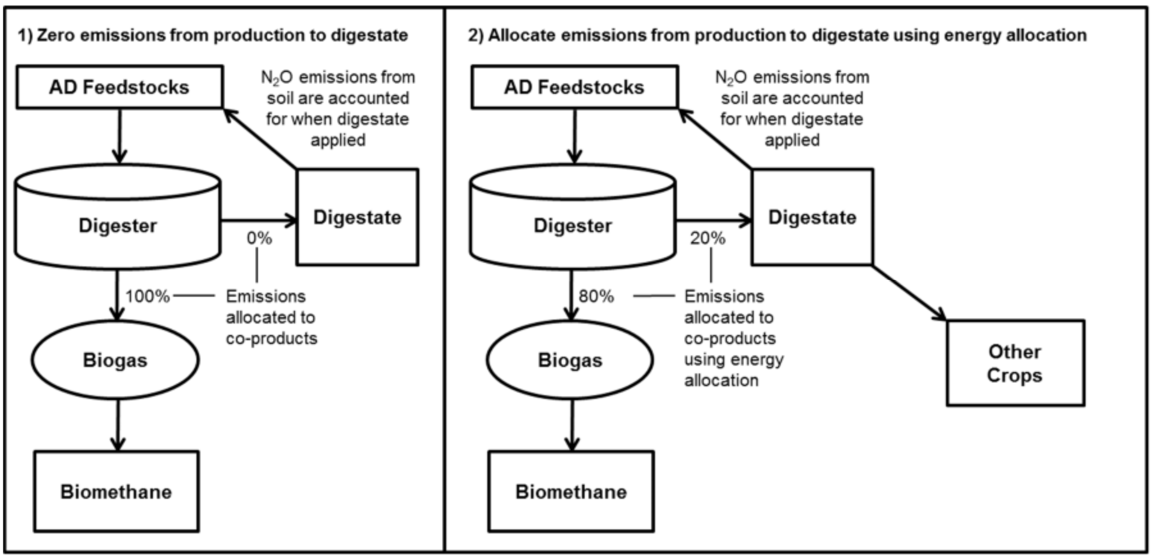

Figure 6: Two different approaches for energy allocation of emissions between biogas and digestate

Using (1) there is a GHG saving from avoided inorganic fertiliser production, i.e. Maize B results apply to Maize A. With (2) energy allocation uses the lower heating value (LHV) of both co-products to allocate emissions which should reduce the GHG emissions allocated to biogas and assign a GHG value to digestate. When digestate is used on other crops (2) should be used otherwise no benefit is recognised from the organic fertiliser produced because this would be outside the biogas system boundary. Difficulties may arise when digestate is used on a combination of both AD feedstocks and other crops as (1) is not appropriate and (2) calculates the digestate emissions factor, which could lead to double accounting, i.e. emissions from biogas/digestate co-production include digestate as an upstream input.

Farmers often cannot use all digestate produced on AD feedstocks, indeed this may not also be the optimal use in terms of GHG savings, nutrient recycling, and fertiliser avoidance. It is therefore likely that digestate will be used on other crops or exported from the farm for use elsewhere. With approach (1) or using the LHV there is no recognition of the valuable co-product (digestate) hence there is no benefit to the facility operator in terms of reduced GHG emissions. This does not properly account for GHG emissions attributed to biogas, is illogical, and could lead to policy that doesn't encourage the most efficient use of digestate, a valuable resource.

Using data in Table 5 from an operational crop-based biogas facility, it is possible to allocate emissions to digestate using energy allocation based on higher heating value (HHV). This simple example shows that for every 1,000kg of feedstock, 700kg of digestate is produced with an assumed calorific value of 975MJ. The solid and liquid fraction CVs were calculated using literature data of 15.0MJ/kg (9.9% MC) for digestate (Kratzeisen *et al*., 2010), and the biogas output is taken from Table 1. The results show that for every tonne of input 4,897MJ of output are obtained, which allocates 20% (i.e. 975/4897) of emissions to digestate. This method is not perfect as the mass of the main product should be known, but this makes limited sense when this is a gas. It should also be noted that the approach here does not consider the enthalpy of vaporisation (Çengel & Boles, 1998) which is not included as digestate is not used a fuel. If incorporated it effectively places zero value to digestate due to the high MC as shown in approach (1). HHV or fertiliser credits are therefore more appropriate.

Table 5: Mass and energy inputs and outputs for biogas and digestate production

	Mass	Gross Calorific Value
Feedstock input (dry basis)	1,000 kg	-
Total Digestate output	**700 kg**	**975 MJ**
Solid fraction (27% DM)	130 kg	591 MJ
Liquid fraction (4% DM)	570 kg	384 MJ
Biogas output	**-**	**3,922 MJ**

Using the maize scenarios A & B the impact of the 2 different approaches for energy allocation are assessed. If (1) is used on case A and B, then the result is the same as this is the logic followed by the BCC model, i.e. zero emissions to digestate. If (2) is used (assuming HHV for digestate) then the results change as shown in Table 6.

Table 6: Results for Maize A (inorganic fertiliser) & Maize B (digestate) when energy allocation (using HHV) is applied to co-product production

Scenario	Result ($gCO_2e/MJ_{biomethane}$)	Comments
Base		
Maize A	34.3	See table 4
Maize B	31.6	See table 4
100% of digestate applied to AD feedstocks:		
Maize A	28.5	Case A would reduce inorganic fertiliser use for the next crop, but the emissions allocated to digestate (20%) from production would then be an input to the AD feedstocks. The biogas produced would have a lower GHG value (80%).
Maize B	31.6	Case B would have increased emissions from digestate production due to co-product allocation (20%), however the emissions from biogas produced would have a lower GHG value (80%). Overall the result would be the same.
100% of digestate applied to other crops:		
Maize A	28.5	Case A would have lower emissions up to biogas production due to allocation between biogas/digestate.
Maize B	n/a	Case B is not applicable as it assumes digestate is used on AD feedstocks.

In summary, with approach (1) no benefit is recognised if digestate is used on 'other crops' and has no impact if digestate used on 'AD feedstocks'. With (2) case A would achieve lower GHG emissions regardless of where the digestate is used, and case B gives the same result if applied to 'AD feedstocks'. By not providing simple guidance or an appropriate allocation option, this could disincentive the appropriate use of digestate on AD feedstocks and other crops (see section 5.1). Moreover, it is apparent that energy allocation is not appropriate for digestate particularly if the LHV is determined including the latent heat of vaporisation.

4.2. Mass balance approach

Traditionally in LCA a functional unit (FU) is defined to provide a reference to which the inputs and outputs are related (ISO, 2006). For biogas production which often uses several co-substrates this would usually be 1 m^3 or 1 MJ of biogas and take account of all of the feedstocks used within the system. However, bioenergy facility operators are required to report on a 'per consignment' basis which effectively means having a FU for each feedstock type, i.e. $1MJ_{biomethane}$ from maize, $1MJ_{biomethane}$ from manure, etc. Consignment reporting is logical so that sustainability characteristics of different biomass feedstocks can be individually assessed. This is relatively straightforward to account for solid and liquid biomass fuels using a mass balance approach (OFGEM, 2014b). For gaseous fuels it is more difficult as several substrates are often mixed together with the resulting energy content not necessarily directly proportional to the combined energy content of each feedstock (Biograce, 2015). It is crucial to know the energy generated for each substrate so that GHG emissions are attributed to each feedstock on a per MJ basis.

Guidance originally issued suggested that the heating value (or energy content) of the feedstock should be used to calculate the energy produced by each substrate. This implies using the lower heating value (LHV) of the feedstock, which is logical where the biomass is used for combustion as the primary energy content is proportional to the end use based on conversion efficiency. It is however not correct to use the LHV for gaseous fuels as substrates such as maize and manure have very different biogas productivities and GHG emissions are calculated on the basis of biogas (energy) produced (JRC, 2014). To illustrate this, Table 7 shows typical LHV and CH_4 yields for maize and manure based on literature, with the differences in allocation percentages given.

Table 7: Typical LHV, CH_4 yields, and allocation percentages for maize and manure

Feedstock	Maize	Manure	Ref
LHV (MJ/kg) – dry basis	18	10	(OFGEM, 2014b)
CH_4 yield (m^3/t) – fresh basis	105	12	(KWS, 2012)
Allocate on LHV	64.3%	35.7%	
Allocate on CH_4 yield	89.7%	10.3%	

To apply the GHG emissions calculated for single substrates to co-digested multiple substrates a simple weighted average for energy produced is applied, this assumes no significant synergies exist among the different substrates in the digester and is within the accuracy of the results needed for these calculations (JRC, 2014). Using the data in Table 4 and assumptions for maize A and manure shows different GHG emissions are calculated depending on the energy allocation approach applied (see Table 8). It can be seen that using the LHV for energy allocation results in lower energy produced allocated to maize and therefore the emissions are higher. In contrast using the CH_4 yield gives very similar results to single substrates with no allocation. In recognition of this issue, OFGEM subsequently commissioned a biogas apportioning tool that allocates relative productivity for different substrates (JRC, 2014), based on each individual feedstock biogas yield.

Table 8: GHG emission results for maize and manure using different energy allocation methods

Allocation Method	Parameter	Unit	Maize A	Manure
No Allocation	Biogas Plant Yield	MJ/tFM	3,922	432
	GHG emission	**$gCO_2e/MJ_{biomethane}$**	**34.3**	**13.4**
LHV (64.3% maize, 35.7% manure)	Biogas Plant Yield	MJ/tFM	2,800	1,554
	GHG emission	**$gCO_2e/MJ_{biomethane}$**	**41.4**	**11.9**
CH_4 yield (89.7% maize, 10.3% manure)	Biogas Plant Yield	MJ/tFM	3,906	448
	GHG emission	**$gCO_2e/MJ_{biomethane}$**	**34.4**	**13.3**

4.3. Definition of consignment

In the UK, the RO orders do not define 'consignment' yet they are clear that a determination of what constitutes a consignment should be based on the 'sustainability characteristics' of the material (OFGEM, 2014b). Figure 7 provides a simple example of different consignments entering an AD facility. Clearly diverse feedstocks are produced, collected, and processed differently hence GHG emissions will vary between consignments. Given the reason for BSC is to ensure biomass feedstocks are sustainably produced, reporting by consignment makes sense. However with the mass balance approach described in section 4.2, it is difficult to attribute emissions accurately once consignments are mixed. The issue here is therefore two-fold, firstly how to define a consignment, and secondly how to ensure emissions are assigned accurately between different consignments when they are often mixed differently in storage and in the digester.

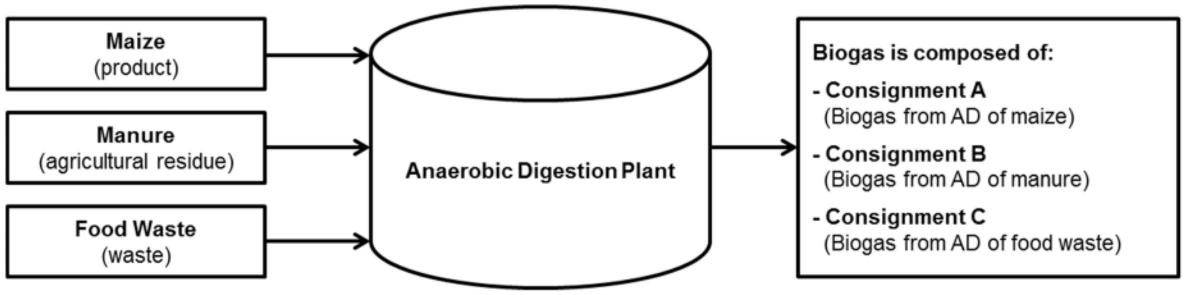

Figure 7: Illustration of determining different consignment for biogas from AD (adapted from OFGEM, 2014b)

4.4. Chain of custody

Following the mass balance and consignment definition issues, a further problem arises when assessing the chain of custody. That is where different consignments are traced through the biomass supply and biogas production system. For many AD facilities the collected feedstock will be received during a few weeks of the year (e.g. during harvest season). Several feedstocks could be ensiled and mixed together in large silage clamps, which means that although the operator may know the total amount of feedstock received at the facility, it may not be possible to accurately know which feedstock is producing biogas at a given point in time. Feedstock mixing is common in AD, therefore an issue arises in determining the chain of custody for calculating emissions on a consignment (or individual feedstock) basis. Estimation or a robust method for stock taking is therefore required by facility operators.

4.5. Methane slip

Methane slip is a potential issue for many different biogas facilities, the severity of which will depend on how the plant is operated (Boulamanti *et al*., 2013; Liebetrau *et al*., 2010; Thrän *et al*. 2014). Fugitive emissions arise in both the production of biogas (through anaerobic digestion) and in the scrubbing and upgrading process to produce biomethane (Petersson, 2012). The introduction of BSC provides the framework and methodology to be able to encourage operators to minimise fugitive methane emissions. For instance, a small methane slip ~1% (0.2gCH_4/MJ of biomethane) can contribute 20% or more of total GHG emissions (Buratti *et al.*, 2013; OFGEM, 2014d). Despite being a fundamental and potentially significant issue it is difficult to accurately measure fugitive methane loss and there is no clear guidance from regulators on this issue, therefore many operators will be required to use a default value currently given as 0.2gCH_4/MJ (~1%) (OFGEM, 2014d). This could result in better operators being penalised whereas operators with lower standards could benefit, i.e. if emitting a lot of fugitive methane but using a default value. In contrast, those operators with lower methane leakage do not benefit as there is presently no clear guidance or incentive to demonstrate lower methane loss.

Apart from the environmental aspect, there are also other reasons to avoid methane emissions (Petersson, 2012). Primarily there is the economic incentive as a loss of methane is a loss of income. Safety is also an important consideration as methane can form explosive mixtures with air, and odour problems may cause issues (Holmgren, 2009). Literature and longer-term research on methane losses is limited with the best example being the Swedish Voluntary scheme (Petersson, 2012). The scheme is set up in two parts, internal routines for leak detection, and emission measurements performed once every 3 years by an external consultant. A standardised approach is provided with a detailed description of how to measure and calculate methane slip (Holmgren, 2011). Recent results from the voluntary agreement are shown in Table 9 (Holmgren, 2012).

Table 9: Results from methane loss measurements in the Swedish voluntary agreement (Holmgren, 2012)

	1st round 2007-2009	Rolling average 2007-2012
Biogas production	1.6 %	1.9 %
Biogas upgrading	2.7 %	1.4 %

An outstanding issue is that methane slip from surfaces such as uncovered digestate tanks can be hard to quantify (Boulamanti *et al.*, 2013; JRC, 2014; Liebetrau *et al.*, 2010; Manninen *et al.*, 2013; Petersson, 2012). Once collected, digestate is stored prior to field application, however the digestion process continues in storage and the gases released can have an important impact on GHG emissions (JRC, 2014; Liebetrau *et al.*, 2010). Digestate is stored in open or closed tanks. With closed storage additional biogas released is mostly recovered, with open storage the methane is released to the atmosphere (JRC, 2014). Table 10 provides some examples of the impact open storage can have on GHG emissions, and demonstrates many crop and waste biogas facilities could fail BSC if included within the system boundary.

Table 10: Open digestate storage – examples of potential impact on GHG emissions

Source	Maize	Manure	Reference
Joint Research Centre (JRC)	0.44gCH_4/ MJ_{biogas} 11.0gCO_2e/ MJ_{biogas}	2.0gCH_4/ MJ_{biogas} 50.0gCO_2e/ MJ_{biogas}	(JRC, 2014)
Liebetrau *et al.* – summer (mean)	22.5gCO_2e/ MJ_{biogas}		(Liebetrau *et al.*, 2010)
Boulamanti *et al.*	15.1 gCO_2e/ MJ_{biogas}	45.9gCO_2e/ MJ_{biogas}	(Boulamanti *et al.*, 2013)
Buratti *et al.*	0.81 gCH_4/ $MJ_{biomethane}$ 20.3gCO_2e / $MJ_{biomethane}$	-	(Buratti *et al.*, 2013)
Biograce	15.2gCO_2e / MJ_{biogas}	78.2gCO_2e / MJ_{biogas}	(Biograce, 2014)

4.6. Farming inputs and Nitrous Oxide emissions from soil

Not all farming inputs are presently considered in the GHG accounting methodology, for example the use of nitrification inhibitors (NIs) (Burzaco *et al.*, 2013; DEFRA, 2014b). Since cultivation represents potentially the largest source of emissions for crop-based biogas (OFGEM, 2014d), then farming inputs and emissions need to be as accurate and complete as possible. NIs have the potential to reduce direct and indirect Nitrous Oxide (N_2O) emissions (DEFRA, 2014b). Research into the effect of NIs is ongoing, but it is likely that reductions in GHG emissions will be achieved through their use. It is perhaps too early to quantify the effect these have and many factors such as geology and weather can influence this. Nonetheless, this should be considered in the GHG methodology as a potential method for mitigating potent GHGs from cultivation.

Precision farming techniques for cultivation including different ploughing, seeding, and fertiliser application methods can have an influence on GHG emissions (ADBA 2014; Soffe, 2003). These are not currently recognised in the BCC or methodology which could limit the promotion of more sustainable agriculture.

4.7. Biogas combined heat and power (CHP)

Co-product allocation is a potential issue as different methods produce variable results (Adams & McManus, 2014). The methodology presented by EC (2010a) recommends allocation of the total GHG emissions based on the exergy content of heat and electricity. This means as heat utilisation increases, the GHG savings associated with electricity generation increases. The exergy allocation approach is sensible and adopted in Europe. Potential issues for operators include the calculation of the Carnot efficiency, and how useful heat is defined and measured. Another problem is that biogas CHP is not included in the BCC for biomethane, which means the emission factor for biogas electricity needs to be calculated outside of the model.

4.8. Carbon capture and replacement (CCR)

CCR is employed by some biogas facilities to make use of the carbon dioxide (CO_2) emitted from combustion or removed from biogas upgrading. Examples include the use of CO_2 in greenhouses to improve growing conditions for fruit and vegetables, and the production of industrial gas. EC (2010a) recognises emission savings from CCR (see section 2.1), this is limited to emissions avoided through the capture of CO_2 of which the carbon originates from biomass and which is used to replace fossil-derived CO_2 used in commercial products and services. The BCC includes the option to incorporate savings from CCR, nonetheless there is no clear guidance or examples on the calculation method, and it is not apparent what evidence is required to support this.

4.9. Consequential LCA (CLCA)

CLCA is a modelling approach that generally should be used by policy-makers and not by individual facility operators, who adopt attributional LCA (ALCA) (Brander & Wylie, 2011; Plevin *et al.,* 2013; Whittaker, 2015). However, the two are now often inextricably linked. There are issues with the inappropriate use of CLCA when incorrectly incorporated into facility-level reporting (Brander *et al.*, 2009). Examples that adopt CLCA within the RED include cereal residues which are not allocated GHG emissions from cultivation, and exported electricity is awarded a credit based on similar electricity generation from the same source (Whittaker, 2015). This can substantially impact on the calculated GHG savings.

With the ALCA approach GHG emissions are directly attributable to the production and use of bioenergy nonetheless there are valid examples where CLCA could be applied. For instance a biogas facility that uses local feedstocks rather than transporting long distances to a large scale bioethanol plant could be given credit for displacing a less efficient bioenergy pathway. In reality, using CLCA in combination with ALCA is bad practice and could lead to inconsistent approaches and difficult to administer.

4.10. Indirect Land use change [ILUC]

Emissions from direct land use change (DLUC) are within the methodology but operators do not currently need to report against ILUC (EC, 2010a, 2010b). Emissions from ILUC are difficult to calculate, predict and validate, and require complex modelling (Bauen *et al.,* 2010). EU policy includes the possibility of introducing adjusted estimated ILUC factors into sustainability criteria (EC, 2014b).

4.11. Fossil fuel comparator and GHG savings

The choice of a fossil fuel comparator (FFC) determines the level of GHG savings a bioenergy system can make (Adams *et al*., 2013). Current legislation defines FFC values of $198gCO_2e/MJ_{electricity}$ and $87gCO_2e/MJ_{heat}$ (EC, 2010a), and adopted in the UK a minimum 60% GHG saving against these values is required (DECC, 2014b; OFGEM, 2014b). The FFC is a policy choice and one that has a significant impact on which bioenergy conversion routes are preferable. Incorrect policy choices risk leading to less efficiency forms of bioenergy being incentivised.

4.12. System boundary

What is included within the system boundary has a direct impact on GHG results. The choices made affect the consistency and appropriateness of the reporting methodology. An obvious example of emissions which are currently not included is open digestate storage, see section 4.5.

4.13. Emission factors

Emission factors (E.F.) are crucial in estimating the GWP of a given quantity of released emissions. For consistency, operators are required to use standard E.F. such as those provided in Biograce (2014). There are however some E.F. which are not available, for example multi-nutrient fertilisers commonly used on crops are not all within the BCC or guidance (OFGEM, 2014b; 2014d). Other issues include recent research highlighting methane may have a GWP of 34, which could have a significant impact on GHG results for biogas (Myhre *et al*., 2013). N_2O emissions from soil is another issue as the actual emissions will depend on the local environment and how fertiliser or digestate is applied (IPCC, 2006; Nicholson *et al*., 2013).

5. Conclusions and Policy Implications

Sustainability criteria sets challenging GHG emission targets for biogas plants that are achievable and consistent with expectations of facility operators. Providing a robust, consistent, and logical methodology is crucial for the confidence of industry, investors and future development of the sector. This section provides conclusions and assesses the policy implications of the foremost methodological issues discussed in section 4.

5.1. Digestate co-product allocation

Recognition of the fertiliser value of digestate is crucial to a viable, long term biogas industry. Policy needs to be developed that incentives both renewable gas and nutrient-rich organic fertiliser. Unless digestate is appropriately valued, biogas facilities may struggle to achieve BSC. The current methodology does recognise digestate as a co-product, nonetheless with the BCC default models 100% of emissions are effectively allocated to biogas (OFGEM, 2014d). Moreover there is no clear guidance from policy-makers on how to perform the allocation calculations, or valid justification on why energy allocation is appropriate. This is an issue for many operators who will distribute digestate to different farms for use on a variety of both food crops and AD feedstocks.

An additional complication is how to assign an energy value to digestate. Using the LHV is required by legislation, but this approach doesn't value the nutrient content and potential yield improvements of digestate application (WRAP, 2012). Policy-makers have not provided guidance on how to calculate the LHV of digestate, whether to include the enthalpy of vaporisation, or given a default value.

The use of LHV is more appropriate for energy co-products as digestate has limited primary energy value, particularly in liquid form (OFGEM, 2014d). It could be more suitable to use a credit for synthetic mineral fertiliser displaced, in a similar approach to credits for excess co-generated electricity or CCR (EC, 2009a, 2010a; OFGEM, 2014b). Fertiliser credits could be determined by using the nutrient content and availability of digestate and would remove the need to perform allocation by assigning a value to digestate based on the ability to offset synthetic mineral fertilisers. It is concluded that energy allocation is not appropriate for allocating emissions to digestate.

5.2. Mass balance and 'consignment' definition

Reporting by consignment poses problems for operators in both its definition and practical implementation. The mass balance approach for biogas is not perfect but can be applied using biogas production apportioning between consignments. Another approach to BSC would be to allow the mixing of consignments, for example maize and manure, which have different sustainability characteristics. This blended feedstock is the reality of the biogas actually being produced, rather than the theoretical methane yields. The advantage is that it may encourage more use of wastes so GHG intensive feedstocks can be averaged out. The disadvantage would be that it allows less sustainable feedstocks to be used where individually they may fail BSC.

The UK Government are clear that wastes and residues should be encouraged for AD (DEFRA, 2011). As wastes are currently exempt from GHG criteria, there is not a clear incentive to use them alongside crops. Allowing the mixing of feedstocks and averaging of GHG emissions could promote more use of wastes and residues (EC, 2014a; JRC, 2014), although there is then a risk this encourages less sustainable substrates. However, a recent report indicates that 70% GHG savings are only possible when maize and manures are mixed (JRC, 2014).

It is inevitable that some consignments may fail BSC due to issues such as poor weather and low crop yields. The averaging of GHG emissions across the year has been implemented under the RO in order to recognise that some consignments of biomass could through no fault of the generator exceed the GHG threshold (DECC, 2014a). This is subject to the provision that the consignment of biomass must not exceed an overall ceiling, i.e. an upper GHG limit. Figure 8 explains how this is implemented and shows that a similar approach could be adopted for the RHI. By introducing a ceiling and averaging it is possible to limit the use of consignments with high GHG emissions, whilst still encouraging overall emissions to be below the average threshold.

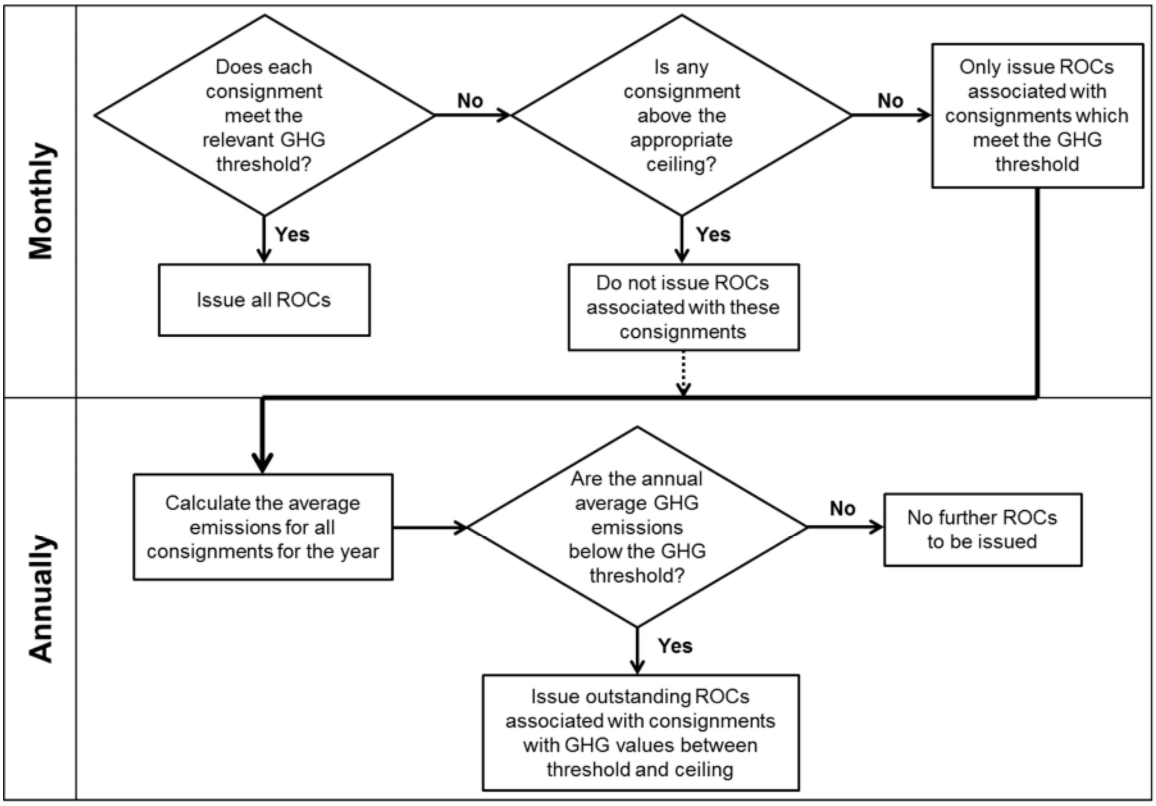

Figure 8: Flow chart showing approach to annual averaging of GHG emissions for issue of Renewable Obligation Certificates (ROCs) (DECC, 2014a)

5.3. Methane slip

The challenge with methane measurements is the precise determination of emissions because there is no standard method available for this purpose for all sources in a biogas facility (Liebetrau *et al.*, 2010). Current UK guidance has no clear mention of methane losses yet this could be a major source. Some international standards do exist such as EN ISO 25140:2010 measuring stationary source emissions by a Flame Ionization Detector (ISO, 2010), and EN ISO 25139:2011 using gas chromatography (ISO, 2011). Emission measurements are described further in the Swedish voluntary scheme, however methane slip from large surfaces such as uncovered digestate tanks are difficult to quantify (Petersson, 2012).

Guidance is required from Government so operators understand best practice and can measure and mitigate methane loss. Many biogas facilities need to report using actual data and therefore will need to have processes in place to quantify and evidence methane slip. Where this data is not available then the use of default values is required. However there is a wide variety of losses published and limited long term studies undertaken which makes it difficult to determine an appropriate default value (see section 4.5). The loss used in the BCC is given as 0.2gCH_4/MJ (~1%) (OFGEM, 2014d), this appears to have been selected based on Biograce (2014). A value of 1% for biogas production and 1% for upgrading can have a big impact and therefore the default value for methane slip needs to be based on robust literature and research.

5.4. Soil Emissions from Crop Production

It is acknowledged that the production of feedstock is amongst the highest contributors to the overall GHG emissions of biomethane production. Although a significant portion of the emissions can be abated through the use or organic N, around 50% of the emissions from cultivation are linked to soil emissions (OFGEM, 2014d). Typically these are divided into direct and indirect N_2O emissions.

Direct Nitrous Oxide emissions occur when Nitrogen is applied to the soil resulting in denitrification. Indirect N_2O emissions are attributed to leaching of nitrate to ground water and surface water and from the deposition of volatilised ammonia. DEFRA has funded a scientific research programme looking at 'potential for nitrification inhibitors (NIs) and fertiliser nitrogen application timing strategies to reduce direct and indirect Nitrous Oxide emissions from UK agriculture' (DEFRA, 2014b).

The use of NIs can reduce direct Nitrous Oxide emissions, whilst also reducing losses through leaching of nitrate. In their project brief, DEFRA has highlighted previous work carried out on NIs on New Zealand pastureland showed up to 90% reduction in Nitrous Oxide emissions and nitrate leaching losses (DEFRA, 2014b).

Initial findings from the project have shown direct N_2O emissions can be reduced between 40% and 70%, with a mean, non-significant reduction of 56% (Misselbrook *et al.*, 2014). Although these types of NIs should be promoted across the whole of the Agricultural sector, it is possible to achieve GHG emission savings of up to 25% overall crop-production for biomethane.

5.5. Recommendations for addressing GHG accounting issues

It is possible to improve the existing methodology and biomass carbon calculator (BCC) through policy development and enhanced modelling, although there is not always a perfect solution as variability exists in LCA. Recommendations are proposed for addressing the issues identified:

- Allow the BCC to include digestate nutrient values, solid/liquid fraction volumes, and energy content, to accurately perform co-product allocation. Adding a user input for digestate outputs would improve the BCC and further encourage appropriate use of organic fertiliser. A policy change away from energy allocation for digestate is required.
- Consider giving credits to synthetic mineral fertiliser offset to account for avoided GHG emissions. AD differs from other bioenergy conversion technologies such as burning wood, where there is limited direct benefit to soil quality, nutrient recycling, or improvements in soil carbon and structure, hence these savings are real and should be incentivised.
- Provide default values for LHV of different types of digestate. Currently there are no default values (OFGEM, 2014b), which makes energy allocation difficult.
- Allow the BCC to include Nitrification Inhibitors following the successful findings from a DEFRA (2014b) study (Misselbrook *et al.*, 2014).
- Ensure mass balance is based on the average share of biogas produced (methane yield) by each feedstock (JRC, 2014).
- Consider increasing excess electricity credits based on UK grid GHG emission intensity rather than avoided emissions from biogas electricity-only.

- Government should provide clear guidance on the measurement of fugitive methane emissions as this is not currently included (OFGEM, 2014b).
- Consider introducing mandatory methane detection tests and rewarding better performance through tiered support tariffs.
- Include open digestate storage within the system boundary (JRC, 2014)
- Include biogas CHP within the biomethane chains in the BCC so emissions from biogas electricity can be easily calculated within the tool.
- Recognise additional farming inputs such as nitrogen inhibitors.

5.6. Concluding Remarks

Delivering biogas is essential for decarbonisation of the electricity, heat and transport sectors, in addition to increasing energy security and providing a versatile fuel. AD offers farmers an organic nutrient rich soil improver (digestate) that can reduce dependency on synthetic mineral fertilisers. Introducing biomass sustainability criteria (BSC) is a positive step forward for industry and policy-makers. It encourages future progressive development of the sector. Difficulties arise in having a methodology that applies consistently to all pathways, impacts different bioenergy systems fairly, and produces appropriate results. As BSC is nascent, teething problems are expected. Over the next twenty or more years of support schemes, BSC will develop as policy-makers, regulators, and operators learn by doing. This paper has analysed some of the key methodological issues associated with accounting for GHG emissions for biogas and biomethane pathways.

Significant methodological issues identified in GHG reporting for biogas operators include co-product allocation, accounting for digestate, mass balance and consignment definition, chain of custody, measurement of methane losses, nitrous oxide emissions from soil, biogas CHP allocation, carbon capture and replacement, fossil fuel comparators, system boundary definition, emission factors, grandfathering, use of consequential LCA, and land use change. These issues were described in sections 4 and 5 using case study results from section 3 to assess potential impacts on GHG results.

Methodological decisions for LCA effect the measurement of the GHG performance of biogas as there are multiple choices. The LCA methodology in the RED is endorsed by the EU legislator and has been adopted in the UK. Whilst it makes sense to use the same methodology for all types of bioenergy, some improvements could be made (EC, 2014a; JRC, 2014). Using a comprehensive, accurate, and functional model is necessary to ensure consistency between operators and different bioenergy systems. There is a balance between encouraging developers, providing certainty for investors, mitigating GHG emissions, increasing renewable energy production and security of supply without introducing over-burdensome reporting requirements. In certain instances highlighted in this paper, there is an apparent inconsistency between different bioenergy pathways and incentives. This could limit a level playing field and may lead to incentivising less appropriate or inefficient forms of bioenergy. The definition of a GHG methodology is a policy choice that should be used to support multi-functional sustainable bioenergy systems and encouraging best operational practice.

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References

Adams, P. & McManus, M., 2014. Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation. Sustainable Energy Technol. Assess. 6, 129-140. DOI: 10.1016/j.seta.2014.02.002

Adams, P., Bows, A. Gilbert, P., Hammond, J., Howard, D., McNamara, N., Thornley, P., Whittaker, C., Whitaker, J. 2013. Understanding the greenhouse gas balances of bioenergy systems. Supergen Bioenergy Hub, Tyndall Centre for Climate Change Research, University of Manchester, UK. Available from: http://epsassets.manchester.ac.uk/medialand/supergen/Publications/GHG_balances.pdf [accessed 24.11.14]

ADBA, 2014. Voluntary guidelines on best practice for crop feedstocks in anaerobic digestion. ADBA; London. Available from: http://adbioresources.org/wp-content/uploads/2014/09/cbp-a5_Web.pdf [accessed 20.03.15]

Andersons, 2010. A detailed economic assessment of anaerobic digestion technology and its suitability to UK farming and waste systems. 2nd Edition. Project No. NNFCC 10-010; York.

Bauen, A., Chudziak, C., Vad, K., & Watson, P. 2010. A causal descriptive approach to modelling the GHG emissions associated with the indirect land use impacts of biofuels. Final report. A study for the UK Department for Transport. E4Tech; London.

Biograce, 2014. Biograce II – Harmonised Greenhouse Gas Calculations for Electricity, Heating and Cooling from Biomass. Intelligent Energy Europe. Netherlands Enterprise Agency, Utrecht. Available from: http://www.biograce.net/app/webroot/biograce2/ [accessed 25.03.15]

Biograce, 2015. Biograce II – Methodological Background Document, version 2. Netherlands Enterprise Agency, Utrecht. Available from: http://www.biograce.net/app/webroot/biograce2/ [accessed 25.03.15]

Börjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems – Part I: Fuel-cycle emissions, Biomass Bioenergy, 30, 469–485. DOI: 10.1016/j.biombioe.2005.11.014

Börjesson, P., Berglund, M., 2007. Environmental systems analysis of biogas systems – Part II: The environmental impact of replacing various reference systems, Biomass Bioenergy, 31, 326–344. DOI: 10.1016/j.biombioe.2007.01.004

Boulamanti, A., Maglio, S.D., Giuntoli, J. Agostini, A. 2013. Influence of different practices on biogas sustainability. Biomass Bioenergy, 53, 149-161. DOI: http://dx.doi.org/10.1016/j.biombioe.2013.02.020

Brander, M., & Wylie, C. 2011. The use of substitution in attributional life cycle assessment. Greenhouse Gas Meas. Manage., 1 (3-4), 161–166. DOI:10.1080/20430779.2011.637670

Brander, M., Tipper, R., Hutchison, C., & Davis, G. 2009. Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels (Technical Paper No. TP-090403-A). Ecometrica; Edinburgh, UK.

Buratti, C., Barbanera, M. & Fantozzi, F. 2013. Assessment of GHG emissions of biomethane from energy cereal crops in Umbria, Italy. Appl. Energy, 108, 128-136. DOI: http://dx.doi.org/10.1016/j.apenergy.2013.03.011

Burzaco, J., Smith, D. & Vyn, T. 2013. Nitrous oxide emissions in Midwest US maize production vary widely with band-injected N fertilizer rates, timing and nitrapyrin presence. Environ. Res. Lett., 8, 035031. DOI:10.1088/1748-9326/8/3/035031

Chambers B. & Taylor, M. 2013. The use of digestate as a substitute for manufacture fertilizer, in: Korres, N., O'Kiely, P., Benzie, J., West, J. (Eds.), Bioenergy production by anaerobic digestion using agricultural biomass, Earthscan, Abingdon, pp. 359-374.

Çengel, Y.A. & Boles, M.A., 1998. Thermodynamics – An engineering approach, third ed. McGraw-Hill, New York.

Dept. for Energy & Climate Change (DECC), 2011. Renewables Obligation (Amendment) Order 2011. Available from: http://www.legislation.gov.uk/uksi/2011/984/note/made [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2012a. UK Bioenergy Strategy. Available from: https://www.gov.uk/government/publications/uk-bioenergy-strategy [accessed 05.10.14].

Dept. for Energy & Climate Change (DECC), 2012b. Consultation on proposals to enhance the sustainability criteria and to ensure affordability for the use of biomass feedstocks under the Renewables Obligation (RO) (September 2012). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66519/6339-consultation-on-biomass-electricity--combined-hea.pdf [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2013a. Government Response to 'Providing Certainty, improving performance' July 2012 consultation (February 2013). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/128679/Gov_response_to_non_domestic_July_2012_consultation_-_26_02_2013.pdf [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2013b. Government Response to the consultation on proposals to enhance sustainability criteria for the use of biomass feedstocks under the Renewables Obligation (RO) (August 2013). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/231102/RO_Biomass_Sustainability_consultation_-_Government_Response_22_August_2013.pdf [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2013c. Non-Domestic Renewable Heat Incentive, Improving Support, Increasing Uptake, 4 December 2013. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/265855/Non-Domestic_Renewable_Heat_Incentive_-_Improving_Support_Increasing_Uptake_-_PUBLISHED.pdf [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2014a. Consultation on adjustments to sustainability and reporting provisions for biomass (June 2014). Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/320567/biomass_sustainability_consultation.pdf [accessed 05.10.14]

Dept. for Energy & Climate Change (DECC), 2014b. Non-Domestic Renewable Heat Incentive (RHI) Biomass & Biomethane Sustainability. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/370604/Non-domestic_RHI_-_Biomass_and_Biomethane_Sustainability_November_2014.pdf [accessed 04.11.14]

Dept. of Food, Environment & Rural Affairs (DEFRA), 2011. Anaerobic digestion strategy and action plan, DEFRA: York. Available from: https://www.gov.uk/government/publications/anaerobic-digestion-strategy-and-action-plan [accessed 05.01.15]

Dept. of Food, Environment & Rural Affairs (DEFRA), 2014a. Area of Crops Grown For Bioenergy in England and the UK: 2008-2013. Government Statistical Service, DEFRA: York. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/377944/nonfood-statsnotice2012-25nov14.pdf [accessed 05.12.14]

Dept. of Food, Environment & Rural Affairs (DEFRA), 2014b. Potential for nitrification inhibitors and fertiliser nitrogen application timing strategies to reduce direct and indirect nitrous oxide emissions from UK agriculture. Project Ref: AC0213. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=16481&FromSearch=Y&Publisher=1&SearchText=nitrification%20inhibitors&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description [accessed 23.02.15]

Dept. for Transport (DfT), 2014. Renewable Transport Fuels Obligation (RTFO), Part 2: Carbon and Sustainability Guidance Year 7 version 7.0. Available from: https://www.gov.uk/government/publications/rtfo-guidance [accessed 05.10.14]

E4Tech, 2014. UK Solid and Gaseous Biomass Carbon Calculator User manual for the Solid and Gaseous Biomass Carbon Calculator, Version 2.0, April 2014. Available from: https://www.ofgem.gov.uk/ofgem-publications/87062/manualforcarboncalculator.pdf [accessed 05.10.14]

EC, JRC & IES, 2010. International Reference Life Cycle Data System (ILCD) Handbook – General guide for life cycle assessment – detailed guidance, EUR 24708 EN, 1st Ed, March 2010, European Commission (EC), Joint Research Centre (JRC), Institute for Environment and Sustainability (IES), Luxembourg, Publications Office of the European Union.

European Commission (EC), 2009a. Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the promotion of the use of energy from renewable sources. Official Journal of the European Union 2009, 16-62, Brussels.

European Commission (EC), 2009b. Fuel Quality Directive (2009/30/EC) of the European Parliament and of the Council of 23 April 2009*,* Official Journal of the European Union 2009, 88-113, Brussels.

European Commission (EC), 2010a. COM(2010) 11, Sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling, EC: Brussels.

European Commission (EC). 2010b. COM(2010) 811 final, Report from the Commission on indirect land-use change related to biofuels and bioliquids, EC: Brussels.

European Commission (EC), 2014a. SWD(2014) 259 final, State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU, EC: Brussels.

European Commission (EC), 2014b. Proposal on indirect land-use change: Council reaches agreement. Press release 7550/14, Council of the European Union, Brussels.

Holmgren, M.A., 2009. Frivilligt åtagande – inventering av utsläpp från biogas – och uppgraderingsanläggningar. U2007:02. Reviderad 2009.

Holmgren, M.A., 2011. Handbok metanmätningar. Swedish Gas Centre, report no 227.

Holmgren, M.A., 2012. Sammanställning av mätningar inom frivilligt åtagande 2007-2012. Avfall Sverige, report no U2012:15.

International Energy Agency (IEA), 2013. Climate change effects of biomass and bioenergy systems. IEA Bioenergy Task 38, Armidale, NSW, Australia. Available from: http://task38.org/ [accessed 12.04.15]

International Standards Organisation (ISO), 2006. Environmental management – life cycle assessment – principles and framework. EN ISO 14040. 2nd ed. ISO: Geneva.

International Standards Organisation (ISO), 2010. Stationary source emissions – Automatic method for the determination of the methane concentration using flame ionisation detection (FID). EN ISO 25140:2010. ISO: Geneva.

International Standards Organisation (ISO), 2011. Stationary source emissions – Manual method for the determination of the methane concentration using gas chromatography. EN ISO 25139:2011. ISO: Geneva.

International Standards Organisation (ISO), 2013. Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification and Communication. ISO/TS 14067:2013. ISO: Geneva.

IPCC, 2006. Chapter 11 - N_2O emissions from managed soils and CO_2 emissions from lime and urea application, in 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change (IPCC), Geneva. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf [accessed 15.03.15]

Joint Research Centre (JRC), 2014. Solid and gaseous bioenergy pathways: input values and GHG emissions, Report EUR 26696 EN, JRC: Ispra, Italy.

Jungmeier, G., Resch, G., & Spitzer, J., 1998. Environmental burdens over the entire life cycle of a biomass CHP plant, Biomass Bioenergy, 15, 311-323. DOI: 10.1016/S0961-9534(98)00039-7

Korres, N., 2013. Life cycle assessment as a tool for assessing biomethane production sustainability, in: Korres, N., O'Kiely, P., Benzie, J., West, J. (Eds.), Bioenergy production by anaerobic digestion using agricultural biomass, Earthscan, Abingdon, pp. 317-358.

Kratzeisen, M. Starcevicb, N., Martinovc, M., Maurera, C., Müllera, J., 2010. Applicability of biogas digestate as solid fuel. Fuel, 89, 2544-2548. DOI: 10.1016/j.fuel.2010.02.008

KWS, 2012. Biogas in Practice. KWS: Thriplow, Hertfordshire, UK. Available from: http://www.kws-uk.com/global/show_document.asp?id=aaaaaaaaaaloymt&download=1 [accessed 26.02.15]

Lantz, M. & Börjesson, P. 2014. Greenhouse gas and energy assessment of the biogas from co-digestion injected into the natural gas grid: A Swedish case-study including effects on soil properties. Renew. Energy, 71, 387-395. DOI: 10.1016/j.renene.2014.05.048

Liebetrau, J. Clemens, J., Cuhls, C., Hafermann, C., Friehe, J., Weiland, P., Daniel-Gromke, J. 2010. Methane emissions from biogas-producing facilities within the agricultural sector. Eng. Life Sci. 2010, 10, No. 6, 595–599. DOI: 10.1002/elsc.201000070

Lukehurst, C., Frost, P. & Al Seadi, T. 2010. Utilisation of digestate from biogas plants as biofertiliser. IEA Bioenergy Task 37. Available from: http://www.iea-biogas.net/technical-brochures.html [accessed 05.02.15]

Manninen, K. Koskelaa, S., Nuppunenb, A., Sorvaria, J., Nevalainenb, O., Siitonenb, S. 2013. The applicability of the renewable energy directive calculation to assess the sustainability of biogas production. Energy Policy, 56, 549-557. DOI: http://dx.doi.org/10.1016/j.enpol.2013.01.040

Mezzullo, W. G. 2010. An Interdisciplinary assessment of biogas production and the bioenergy potential within the South West of England, PhD Thesis, University of Bath, Bath. Available from: http://opus.bath.ac.uk/22984/ [accessed 12.01.15]

Mezzullo, W. G., Mcmanus, M. C. and Hammond, G. P. 2013. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste, Appl. Energy, 102, 657-664. DOI: 10.1016/j.apenergy.2012.08.008

Misselbrook, T.H., Cardenas, L. M., Camp, V., Thorman, R.E., Williams, J.R., Rollett, A.J. & Chambers, B.J. 2014. An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environ. Res. Lett. 9 (2014) 115006 (11pp). Available from: http://iopscience.iop.org/1748-9326/9/11/115006/pdf/1748-9326_9_11_115006.pdf [accessed 25.02.15]

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis.

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nicholson, F.A., Bhogal, A., Chadwick, D., Gill, E., Gooday, R.D., Lord, E., Misselbrook, T., Rollett, A.J., Sagoo, E., Smith, K.A., Thorman, R.E., Williams, J.R., Chambers, B.J., 2013. An enhanced software tool to support better use of manure nutrients: MANNER-NPK. Soil Use Manage. 29 (4). 473-484. DOI: 10.1111/sum.12078

OFGEM, 2014a. Non-Domestic Renewable Heat Incentive (RHI). Office for Gas and Electricity Markets (OFGEM). Available from: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-renewable-heat-incentive-rhi/policy-and-regulations [accessed 05.10.14]

OFGEM, 2014b. Renewables Obligation: Sustainability Criteria Guidance. Office for Gas and Electricity Markets (OFGEM), 1st June 2014. Available from: https://www.ofgem.gov.uk/environmental-programmes/renewables-obligation-ro [accessed 05.10.14]

OFGEM, 2014c. Feed-in-Tariff (FIT) scheme. Office for Gas and Electricity Markets (OFGEM). Available from: https://www.ofgem.gov.uk/environmental-programmes/feed-tariff-fit-scheme [accessed 05.10.14]

OFGEM, 2014d. The UK Solid and Gaseous Biomass Carbon Calculator (14th August 2012). Office for Gas and Electricity Markets (OFGEM). Available from: https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator [accessed 20.10.14]

OFGEM, 2015. Feed-in Tariff: Central FIT Register. Office for Gas and Electricity Markets (OFGEM). Available from: http://www.renewablesandchp.ofgem.gov.uk/ [accessed 23.03.15]

Patterson, T., Esteves, S., Dinsdale, R. & Guwy, A. 2011. Life cycle assessment of biogas infrastructure options on a regional scale, Bioresour. Technol., 102, 7313–7323, DOI: http://dx.doi.org/10.1016/j.biortech.2011.04.063

Petersson, A., 2012. The Swedish Voluntary system for control of methane emissions. May 2012, IEA Bioenergy Task 37.

Plevin, R., Delucchi, M. & Creutzig, F. 2013. Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers, J. Ind. Ecol., 18 (1), 73-83. DOI: 10.1111/jiec.12074

Pöschl, M., Ward, S. & Owende, P. 2010. Evaluation of energy efficiency of various biogas production and utilization pathways, Appl. Energy, 87, 3305–3321. DOI: 10.1016/j.apenergy.2010.05.011

Ravina, M. & Genon, G. 2015. Global and local emissions of a biogas plant considering the production of biomethane as an alternative end-use solution, J. Clean. Prod. 102, 115-126. DOI: 10.1016/j.jclepro.2015.04.056

Rehl, T., Lansche, J. & Müller, J. 2012. Life cycle assessment of energy generation from biogas—Attributional vs. consequential approach. Renew. Sustain. Energy Rev. 16 (6), 3766–3775. DOI: 10.1016/j.rser.2012.02.072

Soffe, R., 2003. The Agricultural Notebook. 20th Edition. Blackwell Science, Oxford.

Starr, K., Gabarrell, X., Villalba, G., Talens, L. & Lombardi, L. 2012. Life cycle assessment of biogas upgrading technologies, Waste Manag., 32, 991–999, DOI: 10.1016/j.wasman.2011.12.016

Styles, D. Gibbons, J., Williams, A., Stichnothe, H., Chadwick, D. & Healey, J. 2014. Cattle feed or bioenergy? Consequential life cycle assessment of biogas feedstock options on dairy farms. GCB Bioenergy. DOI: 10.1111/gcbb.12189

Styles, D., Gibbons, J., Williams, A., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D. & Jones, D. 2015. Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation. GCB Bioenergy. DOI: 10.1111/gcbb.12246

Thrän et al. 2014. Biomethane – status and factors affecting market development and trade. IEA Task 40 and Task 37 Joint Study. September 2014. Available from: http://www.bioenergytrade.org/downloads/t40-t37-biomethane-2014.pdf [accessed 23.03.15]

Vaneeckhaute, C., Meers E., Michels, E., Buysse, J. & Tack, F. 2013. Ecological and economic benefits of the application of bio-based mineral fertilizers in modern agriculture. Biomass Bioenergy, 49, 239-248. DOI: http://dx.doi.org/10.1016/j.biombioe.2012.12.036

Wu, X. F., Yang, Q., Xia, X. H., Wu, T. H., Wu, X. D., Shao, L., Hayat, T., Alsaedi, A. and Chen, G. Q. 2015. Sustainability of a typical biogas system in China: Emergy-based ecological footprint assessment, Ecological Informatics, 26, 78-84. DOI: 10.1016/j.ecoinf.2014.06.006

Whittaker, C., 2015. Life cycle assessment of biofuels in the European Renewable Energy Directive: a combination of approaches? Greenhouse Gas Meas. Manage., DOI: 10.1080/20430779.2014.998442

Whittaker, C., McManus, M. & Hammond, G. 2011. Greenhouse gas reporting for biofuels: A comparison between the RED, RTFO and PAS2050 methodologies. Energy Policy, 39 (10), 5950-5960. DOI: http://dx.doi.org/10.1016/j.enpol.2011.06.054

WRAP, 2011. Digestates: Realising the fertiliser benefits for crops and grassland. Waste and Resources Action Plan (WRAP) project no. OAV036-210. September 2011. Available from: http://www.wrap.org.uk/sites/files/wrap/Farmer%20guidance%20final%20-%20Cymru.pdf [accessed 20.01.15]

WRAP, 2012. Using quality anaerobic digestate to benefit crops. Waste and Resources Action Plan (WRAP). Available from: http://www.wrap.org.uk/content/using-quality-digestate-benefit-crops-0 (accessed 20.01.15)

WRI, 2011. Product life cycle accounting and reporting standard, Greenhouse Gas Protocol, World Resources Institute (WRI) and World Business Council for Sustainable Development. Available from: http://www.ghgprotocol.org/ [accessed 23.03.15]