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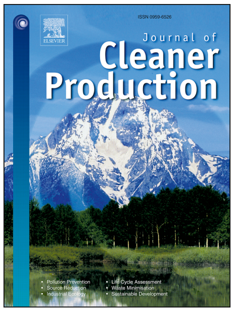

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Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize

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Abstract

Biomethane is a renewable gas that can be used in existing infrastructure to reduce dependency on natural gas and lower greenhouse gas (GHG) emissions. Policy incentives have promoted a rapid implementation of biomethane production facilities using anaerobic digestion (AD). A range of feedstocks are used in AD including crops which have a higher GHG burden than most wastes and residues. The purpose of this research is to characterise and assess GHG emissions from typical operational biomethane facilities. It is imperative that GHG savings are obtained therefore quantifying emissions using a robust methodology is paramount. This study uses maize as a case study utilising data from several farms and AD facilities. Results show that calculated emissions for biomethane production from maize are 33.8 gCO_2e/MJ of biomethane using the Renewable Energy Directive (RED) methodology. Key emission sources include N-fertiliser production, soil N_2O emissions, imported electricity use, and fugitive methane. Sensitivity analysis performed assessed key data inputs and demonstrates how input inventory parameters affect the GHG balance and highlights variability in results. For the desired GHG savings to be achieved it is important that operators minimise fertiliser use, use nitrogen inhibitors, minimise imported electricity, and undertake close management of methane loss. This paper shows that although biomethane is considered a renewable, low carbon fuel, the inputs need to be carefully managed in order to achieve this.

Highlights

- GHG emissions are characterised for typical biomethane production from maize
- Variability of GHGs is assessed using sensitivity analysis of key emission sources
- GHG emission hot-spots are fertiliser use, grid electricity and fugitive methane
- GHG balance increases with high N-fertiliser, imported electricity and methane loss
- Optimal GHG savings are only achievable when system inputs are minimised

Keywords: biogas, bioenergy, fugitive methane, GHG, LCA, sustainability

1. Introduction

Biomethane is a renewable fuel that can be produced from a wide range of different feedstocks, technologies and different scales for conversion. It is a versatile fuel that can be used as a substitute to natural gas (NG) which is increasingly an important resource for meeting the demand of heat, electricity and fuel in many countries (IEA 2016). Natural gas is a significant all-round energy carrier with an already well-developed infrastructure in many countries including pipelines (gas grids), filling stations and new infrastructure such as road transport via heavy duty vehicles or marine transport via tanker in the form of compressed natural gas (CNG) or liquefied natural gas (LNG) (IEA 2014). In locations with existing gas pipelines NG is easy to transport and has lower greenhouse gas (GHG) emissions in comparison to coal and oil (IEA 2017). Nonetheless NG is a non-renewable fossil fuel resource which releases fossil-derived carbon dioxide when combusted, hence there is growing interest in renewable low carbon gas.

Biomethane is defined as methane produced from biomass (ISO 16559:2014), with very similar properties to NG (ISO 2014). There are two main pathways to produce substitute NG:

- via thermo-chemical conversion (e.g. gasification and methanation) the methane-rich product gas is normally referred to as bio-based synthetic natural gas (bio-SNG) (National Grid, 2016); or
- via bio-chemical conversion when it is produced by biological processes, including anaerobic digestion (AD), landfills and waste water treatment, the initial product is raw biogas which must be cleaned and upgraded to reach a high methane content (referred to as biomethane) suitable for grid injection.

Bio-SNG and biomethane from upgraded biogas are essentially chemically identical and must meet the same technical specification to be injected into NG pipelines (Green Gas Grids, 2013a; IEA, 2014). Biomethane is now commonly implemented at a commercial scale in several countries including the UK and Germany (Horschig et al. 2016). In contrast bio-SNG is still at the R&D stage of development, has so far not achieved commercial status (DBFZ 2012); Green Gas Grids, 2016), and hence is not further considered in this paper.

In principal biomethane can be used for exactly the same applications as NG, if the final composition is in line with the different NG qualities on the market (Billig et al. 2017; Green Gas Grids, 2013b; IEA 2014). Therefore it can be used as a substitute for liquid transport fuels, to produce combined heat and power (CHP), heat alone and serve as feedstock for the chemical sector. In contrast to liquid biofuels such as biodiesel and bioethanol, biomethane and natural gas are fully interchangeable from an end-user perspective (IEA 2014).

The production of biomethane is a highly sophisticated industrial process that converts raw biomass into high valorisation gaseous fuel. One of the key drivers for developing biomethane is its potential to offer lower GHG emissions in comparison to NG. The use of wastes or residues as feedstock for AD offer the highest GHG savings, with crops also providing a low carbon conversion pathway for biogas production (JRC 2014b). Using crops for AD (and other bioenergy production pathways) has been subject to substantial debate, nonetheless Government incentives in many countries have supported the production of crop-based AD on the basis this is a low carbon renewable fuel (Cherubini & Strømman 2011; Horschig et al. 2016; Röder 2016). It is paramount that supply chain emissions are understood and minimised to optimise clean production of biomethane. This paper therefore focuses on the GHG emissions that can arise from the biomethane production chain including feedstock supply of crops, anaerobic digestion (via bio-chemical conversion, subsequent biogas cleaning and upgrading, and gas grid injection.

1.1. Crop-based anaerobic digestion

Maize (*Z. mays*) is the most common purposely grown crop used in countries with developed biomethane infrastructure, for example in Germany maize is used on more than 75% of the agricultural biogas plants (Rensberg et al., 2012), and in the UK in 2014 almost 30,000 ha of forage maize was used in England for AD (DEFRA, 2015), representing 0.7% of England's arable area. The

National Farmers Union predicts that an additional 125,000 hectares of maize will be grown for AD in England by 2020 (Soil Association 2015). To put this in context under a high growth scenario by 2020 approximately 0.5% of UK agricultural land could be used for AD crops (ADBA, 2016). The use of maize in Germany for AD is well publicised and whilst there are some similarities with the UK market, there are also some crucial differences. Firstly, the UK Government has introduced stringent biomass sustainability criteria (BSC) which restricts where maize can be grown and how intensively it is produced (OFGEM, 2016). Secondly, EU rules mean that effectively maize is required to be incorporated into crop rotations via the 'three-crop rule' (EC 2017a).

Maize is therefore used in this case study to highlight the key inputs and emission sources of annual energy crop cultivation and harvesting. The term 'energy crop' refers to biomass feedstocks which are cultivated especially for the purpose of energy production. For a farm system this involves sophisticated land management and crop husbandry regimes designed to maximise the biomass available from a given area of land. Purposely grown energy crops are an important feedstock for biogas plants offering a high level of energy generation. Whilst they can make a significant contribution to the economic and environmental sustainability of farming (Green Gas Grids, 2013a), the role of purposely grown crops in increasing the sustainability of agriculture in conjunction with use as a feedstock is often a delicate balance (Röder 2016; ADBA 2013).

Food versus fuel is the subject of ongoing debate which in simple terms is due competition for the limited land available to meet all human demands. Land is used for living, work and recreation space, and to produce the food, fuel and fibre that a growing human population requires. Whilst land use is acknowledged as an important issue, if AD provides an agricultural solution then land use change is of limited concern (Röder 2016). The impacts of land use change are not included within the scope of this paper for two reasons: i) land criteria provide a legal restriction on where crops can be grown, ii) indirect land use change (ILUC) is outside the scope of BSC, and would require a consequential rather than attributional approach. When assessing cleaner production it is important to use an attributional LCA (aLCA) approach so the results are meaningful at an individual operator level. It is therefore assumed in this study that the land used to cultivate crops is existing arable land.

1.2. Aims and Objectives

This paper has the primary aim of determining the main sources of GHG emissions from the production of biomethane via crop-based AD, characterising these emissions using aLCA, identifying key emission sources, and proposing best practice operation to minimise emissions. To achieve this aim the following objectives are established:

1. Characterise GHG emissions for biomethane supply chains utilising crop feedstocks to produce biogas via AD and subsequent upgrading to gas grid injection.
2. Assess variability and uncertainty in GHG emissions from biomethane production using a sensitivity analysis to assess key data inputs, methodology, and identify emission hotspots.
3. Propose best operational and management practice for minimising the net GHG balance of crop derived biomethane.

2. Materials and Methods

This section presents two main aspects relevant to the study. Firstly the methodological approach for quantifying greenhouse gas (GHG) emissions is described based on life cycle assessment (LCA) including the accounting methodology, functional unit, system boundary, materiality, emission factors, and allocation. Secondly the biomethane production process is described from crop cultivation through to AD, biogas upgrading, and grid injection (see section 2.2). Variability and uncertainty in the sensitivity analysis are also explained in the context of parameters that affect the characterisation of GHG emissions from biomethane production (see section 2.3).

2.1. Life cycle assessment methodology

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, 2010). GHG accounting therefore follows LCA methodology but is concerned only with the flow of GHG emissions within the system (Adams et al. 2015). LCA is structured, comprehensive and internationally standardised which follows a systematic and phased approach (ISO, 2006).

2.1.1. GHG accounting methodology

Whilst there are several potential decisions and approaches to GHG accounting methodology (Adams et al. 2015), the preferred method for this study is based on the EU Renewable Energy Directive (RED). This is selected as it is widely adopted throughout Europe and in the UK in particular every biomethane production facility is required to comply with this GHG accounting method. It therefore provides a robust and commonly accepted methodology to account for GHG emissions from crop-derived biomethane.

GHG calculations for this study follow the RED methodology to evaluate the life cycle GHG emissions from the supply chain. A description of the RED methodology is provided by EC (2010) with some of the GHG accounting challenges for biogas and biomethane assessed by (Adams et al., 2015).

2.1.2. Functional unit & system boundary

For this study the functional unit (FU) is defined as gCO_2e/MJ, where the energy value (MJ) is used to express the emissions associated with biomethane (MJ of biomethane). In accordance with the RED methodology, emissions are calculated using the lower heating value (LHV). This is in contrast to the gas industry that commonly measures gas using the higher heating value (HHV). It is important to note that this is the primary fuel and not the end-use as emissions are calculated up to the point of gas-grid injection. This FU is chosen as it is commonly used across Europe and makes sense given the many potential end-uses of gas.

The system boundary follows the RED methodology and starts at the cultivation of the crop, i.e. land preparation and seeding and includes all main crop cultivation processes, harvesting, transportation, silage production, AD, biogas upgrading & injection. Since the FU is the production of the primary fuel, the system boundary ends at the entry point to the gas grid. Consequently emissions from the gas network and end-use are outside the scope. Further description of the system boundary and diagrams are provided in section 2.2, below.

The system boundary does not incorporate the emissions associated with the manufacture of the plant, infrastructure, machinery and equipment used in bioenergy production and supply, as this is specifically omitted under the RED methodology (EC, 2009). In particular, the indirect energy consumed is not considered in the RED or when calculating GHG emissions for solid and gaseous biomass (EC, 2010). Biomass sustainability criteria (BSC) guidance requires that GHG emissions 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 2016). At an operator and policy level the GHG balance is calculated individually for each feedstock, hence it logically follows this paper adopts the same approach.

2.1.3. Materiality

Materiality is a concept used to assess the consequences of potential adjustments to inventory data and sensitivity analysis. Emission sources or physical inputs are material if their omission or misstatement could influence the results or stakeholder interpretation of the calculated GHG emissions. Quantitative materiality is a threshold applied to the calculated GHG emissions. If this threshold is exceeded then it is important that the inventory data is included within the system boundary. For this study a threshold of 1% has been selected for inclusion in the study, we define this as the 'inventory materiality threshold'. Quantitative materiality can also be applied to sensitivity analysis whereby if a threshold is exceeded in terms of total contribution to the GHG balance then it should be further assessed in the sensitivity analysis. We define this as 'sensitivity materiality threshold', for this study 5% of total emissions has been selected. Materiality thresholds are summarised in table 1:

Table 1: Materiality thresholds used in the GHG assessment

Materiality type	Threshold	Description
Inventory	1% of total GHG emissions	Where inventory data is not easily attainable, if the expected contribution to total life cycle GHG emissions is less than 1% then the item can be omitted from the inventory.
Sensitivity	5% of total GHG emissions	Where emissions from an individual source contribute 5% or more of the total life cycle GHG emissions, then this variable should be further assessed in the sensitivity analysis.

2.1.4. Emission factors

Emission factors used in this study are obtained from up to date sources as summarised in the inventory data. It is acknowledged that emission factors do have an influence on the calculated GHG balance, however it is important that some assumptions are made and that these are transparently referenced. To minimise the variability and uncertainty, emission factors from commonly used and well cited sources have been adopted. Nonetheless emission factors for any GHG assessment will be a potential source of variability and uncertainty (Whitaker et al., 2010).

2.1.5. Allocation

Co-product allocation is a continuous methodology choice for any LCA study, particularly bioenergy production pathways such as biomethane. This is due to more than one useful product being produced in the production system, for example digestate is co-produced with biogas, heat is co-produced in the CHP, and CO_2 can be captured in the biogas upgrading process. In LCA methodology it is necessary to choose an allocation method so that emissions can be divided between the co-products. For this study energy allocation is chosen for the simple reason that this has been adopted under the RED accounting methodology (EC, 2009; 2010). One exception to this is where useful heat is co-produced from CHP, in this case exergy allocation would be applied. Other options for allocating include mass, economic, giving credits, or avoiding allocation through system expansion, however they are not further considered in this study. It should be noted that for emissions to be allocated to digestate, the dry matter (DM) content needs to be sufficiently high, otherwise the LHV is zero.

2.2. Biomethane Production

To characterise GHG emissions from the biomethane production chain it is first necessary to describe each stage of the process. In this section the key processes and associated inputs and outputs are defined, alongside the potential variability and uncertainty aspects for each emission source. Figure 1 portrays a high-level system overview with a more detailed process flow of biomethane production provided in Figure 2. The following sub-sections outline each of the main production life cycle stages to describe the 'base case' and sensitivity cases.

Figure 1: Flow chart for the calculation of GHG emissions for biomethane production

Figure 2: Process flow of biomethane production using on-farm anaerobic digestion

2.2.1. Feedstock supply – crop cultivation & harvesting

As described in the introduction, the feedstock chosen for this paper is maize since it is the most commonly used purposely grown crop for AD. Whilst other crops are also used maize can be considered a typical crop and therefore provides a useful reference for the case study. Maize is an excellent crop for harvesting and storage in silage form as it has a low buffering capacity, high dry matter (DM) content and most importantly, a high water soluble carbohydrate content (Vervaeren et al., 2010). Maize is chosen by many farmers as it fits into existing crop rotations as a break crop between cereals and oilseeds, it grows well in many parts of UK and Europe, and offers reasonable economic returns.

Maize fields are normally ploughed followed by seedbed preparation leaving a reasonably fine surface tilth. Sub-soiling is sometimes required if there is soil compaction below plough depth, although no sub-soiling is assumed in this study. Pesticide requirements for forage maize are generally lower than cereal crops, exact requirements will depend on field location and conditions (KWS, 2015). Fertiliser requirements for maize depend on the soil type and quality which are dependent on geographical location and previous land management among other factors. Typically N based fertiliser is applied pre-emergence to obtain maximum yield and quality, phosphorus (P) is applied prior to or at drilling as it is important for root growth, and potassium (K) is applied in the autumn or spring providing several roles including regulating the water content of the plant (PDA, 2015). From the review of operational biomethane facilities some variation was found in the amount of NPK fertiliser applied, therefore an average was taken to provide the most realistic data (see Table 2).

Direct and indirect N_2O emission rates attributed to nitrogen application to soil are calculated using the default data from the IPCC Guidelines for National Inventories (de Klein et al., 2006). It should be considered that these default figures are associated with a high degree of uncertainty, which can only be reduced by taking a more detailed modelling approach using site-specific soil and meteorological data (Brown et al., 2002, Yan & Boies, 2013).

As an annual crop, the lifespan of Maize is only 5-7 months depending on when it is established and harvested. Harvesting of maize generally occurs in September or October in the UK climate. Early harvesting can result in lower yields, lower dry matter, and a greater risk of clamp effluent, whereas late harvesting risks field losses, higher costs, and excessive dry matter (KWS, 2014). The timing of harvest is therefore important and earlier harvesting is preferable on heaver soils to prevent compaction and runoff (Soil Association 2015). A crop yield of 41.19 t/ha (13.18 tDM/ha) is assumed for this study based on the average of feedstocks supplying the biomethane facilities.

Forage harvesters collect and chop the plant material, and deposit it in the trailer of a tractor. Harvesters blow the chopped maize into the trailer through a chute at the rear or side of the machine. Precision chopping is necessary to achieve top quality maize silage, with the ideal chop length around 7-10 mm (KWS, 2014). Diesel is the main fuel used in cultivation and harvesting machinery with associated GHG emissions. Whilst some oil is required the GHG emissions are not material (<1%) and therefore not further considered here.

The main inputs to a farm system which result in GHG emissions include the use of fertilisers, pesticides, lime, herbicides, fuels combusted in farm machinery use, electricity, and irrigation (where used). The extent of GHG emissions depend primarily on the agronomic practice, i.e. how much and what type of fertilisers and other agro-chemicals are applied to the crop. Nitrogen-based fertiliser is the largest source of GHG emissions from crop cultivation due to the upstream use of natural gas in manufacturing ammonium based fertiliser and through soil N_2O emissions from fertiliser application (Fertilisers Europe 2015). A summary of the key inventory data for maize cultivation is provided in Table 2.

2.2.2. Transport & silage making

In general it is not economically viable to transport maize or other feedstocks over long distances due to relatively high moisture content. Therefore crops tend to be grown in close proximity to the biomethane facility. When maize is harvested it is collected in a tractor-trailer alongside the forage harvester and driven from the field to the biomethane facility over an assumed average distance of 20km. On arrival at site chopped maize is made into silage and stored in clamps. Biogas plants require continuous feeding whereas crops are harvested seasonally, hence crops require preservation with ensiling being the preferred method. When making silage for AD, the preservation of dry matter and energy during storage is the primary concern. To achieve high quality silage for AD the crop requires storage at optimum moisture content and particle size, an adequate storage system and proper management (from filling to feed out) (Bock 2017). Silage clamps are filled as quickly as possible to minimise oxygen intake, and compacted by using farm machinery driving over the clamp to push up and compress the material. Silage additives are often applied to suppress undesirable microorganisms, prevent heating up and fermentation failure, reduce dry matter losses and improve digestibility. Once silage clamps are full and compacted they are sealed manually using sheeting to prevent spoilage through oxygen ingress. The losses during the silage phase are estimated to be 11% from (Emery & Mosier, 2012).

For this study the main input considered is diesel used in transportation and making silage. Whilst silage additives and sheeting are important for the process they are not expected to have a material impact on GHG emissions. Similarly stored silage does not emit significant amounts of methane, which is primarily due to the low apparent pH. Fugitive emissions primarily occur when there are delays in delivery or processing. Liebetrau *et al.* (2010) found that the maximum methane measured was 0.008 gCH_4/kWh, which equals 0.004% of the methane converted (Liebetrau et al. 2010). Similarly the Baltic Biogas Bus project found the range of emissions from feedstock storage and feeding for existing plants is around 0-0.1% (Jonerholm & Lundborg, 2012). Table 2 summarises the main inventory data used for maize cultivation, harvesting, transportation and ensiling.

Table 2: Inventory and key assumptions for Maize

Detail	Parameter	Value	Unit	Data source
Crop	Moisture content at collection	68.00	%	Farm average
	Crop yield	41.19	tFM/ha	

	Existing land use	Annual cropland		Assumption
Fertiliser use	N fertiliser (24% N) - unspecified	108.00	kg/ha	Farm average
	Ammonium sulphate (26% N)	195.00	kg/ha	
	Urea (46% N)	96.00	kg/ha	
	P fertiliser – unspecified (P)	65.00	kg/ha	
	Muriate of potash (K)	300.00	kg/ha	
	Unspecified N emissions factor	4.57	$kgCO_2e/kg$	(Biograce, 2016)
	Unspecified P emissions factor	1.18	$kgCO_2e/kg$	
	Muriate of potash emissions factor	0.31	$kgCO_2e/kg$	
	Ammonium sulphate emissions factor	1.62	$kgCO_2e/kg$	
	Urea emissions factor	1.33	$kgCO_2e/kg$	
Seeds	Maize seeds	25	kg/ha	(E4Tech, 2014)
Pesticides	Pesticide application rate (active ingredient)	2.50	kg/ha	Farm average
	Pesticides emissions factor	13.90	$kgCO_2e/kg$	(Biograce, 2016)
Diesel	Cultivation fuel use (diesel)	70.70	L/ha	Farm average
	Harvesting fuel use (diesel)	62.73	L/ha	
	Maize silage fuel use (diesel)	1.00	L/t	(Emery et al., 2014)
	Diesel emissions factor	0.0876	$kgCO_2e/MJ$	(Biograce, 2016)
Losses	Efficiency of harvesting (e.g. losses)	100.00	%	(Emery et al., 2014)
	Maize silage losses	11.00	%	
Transport	Density of silage	613.00	kg/m^3	Farm average
	Distance transported	20	km	
	Energy intensity of transport	0.09	L/tkm	(E4Tech, 2014)
	Exhaust gas emissions	2.12	gCO_2e/km	

2.2.3. Anaerobic digestion of maize crop silage

Maize and other crop silages are stored in large silage clamps adjacent to the feed hoppers at AD facilities. Most operators will load the feed hopper 2-3 times a day using a telehandler powered by diesel. The feeding system is commonly designed to continuously feed the digester. In the digester the substrates are heated and the anaerobic digestion process takes place. Contents of the digester are stirred periodically to mix new substrate with the old substrate to improve the penetration of bacteria with the fresh substrate, to realise an even temperature in the digester, to prevent and disturb the build-up of sedimentary layers, to improve the metabolism of the bacteria by removing the gas bubbles and replacing them with fresh feedstock (Ecofys 2005). GHG emissions can arise from the digester only if gas can leaks, although generally modern digesters are gas-tight.

Gas holders and storage systems are designed to store gas and prevent leakage. The design of the AD plant can vary and gas storage units could be integrated with the digester itself or separate from it, leading to different methane loss into the atmosphere. Poorly maintained facilities can cause leaks and have the potential to suffer from large methane emissions. Gas storage is nonetheless expected to be a minor source of emissions with existing plants around 0-0.2% of biogas production (Jonerholm, K.;Lundborg 2012).

Due to variability in the amount of fugitive methane emitted for different biogas plants and because this was not directly measured for this study, a default assumption of 1% methane loss for biogas production is used in this study. This is based on commonly used values in the UK and EU for operators that calculate GHG emissions using the RED methodology (Biograce 2013; E4Tech 2016; OFGEM 2016).

Biogas production requires some electricity which is normally obtained from a combination of imported grid electricity and biogas CHP. The selected source of electricity will depend on factors such as grid connection, cost, and availability. Electricity is required to power pumps, motor, stirrers, blowers, separators, control devices, and ancillary equipment. Depending on the parasitic load of a facility and source, electricity can influence net GHG emissions. In accordance with the RED, the emissions factor applied for imported electricity is based on the national electricity mix. This study uses the UK electricity mix emissions factor as this is where the biomethane facilities are located.

2.2.4. Biogas upgrading and cleaning

Biogas upgrading involves the removal of most of the carbon dioxide, water, hydrogen sulphide, and further purification of other trace gases (commonly referred to as gas cleaning) (IEA 2014). Biomethane can then be used directly in vehicles with gas engines or injected into the gas grid. In terms of GHG emissions biogas upgrading requires additional energy (usually electricity) and can require other inputs such as chemicals, water or membranes depending on the upgrading technology employed (Bauer et al. 2013; Sun et al. 2015). Methane emissions can also arise in the upgrading process. The increased energy requirement and methane loss can increase the GHG emissions from biomethane compared to biogas however it gives a more versatile high value fuel and can be used for a wider range of applications. Additionally the carbon dioxide stream can be captured and used in industrial processes such as in greenhouses or the food and drinks industry. Methane slip (which increases fugitive GHG emissions) can be reduced to almost zero by CO_2 capture or through the use of a thermal oxidiser. Production of biomethane can also have a nominally higher efficiency than biogas CHP since the electricity generation may waste heat.

Existing studies suggest a range of methane slip from biogas upgrading which is directly related to the technology employed, maintenance, and operation of the upgrading process. It can be observed that PSA and water scrubbing have higher emissions (1-3%) than chemical scrubbing (<0.5%), with membrane technology likely to be somewhere in between (Bauer et al. 2013; Avfall Sverige 2016; IEA 2014). For this study we use data obtained from the typical values at a biomethane upgrading facility where membrane technology is employed (see supplementary information for additional description). An assumed methane slip of 0.5% is used which is based on review of gas data and validated against manufacture technical specification.

2.2.5. Biomethane injection

Feeding upgraded biogas as biomethane into the natural gas grid is an efficient energy solution, even if the sites in which the gas is to be applied are far away from the sites at which it is produced (Biogaspartner 2011). Gas feed-in is facilitated via a compressor, a device raising the pressure level of the biomethane to that of the gas in the closed pressurised lines of the grid. Given European regulations, new gas producers have the opportunity to feed gas into the conventional gas grid. For purposes of injection, however, the gas must meet the quality specifications of the relevant legal provisions and may only deviate within the range of these quality standards (Biogaspartner 2011; Billig et al. 2017). Such standards are realised using technologies for reconditioning gas. Fugitive emissions of methane are the only potential source of direct GHG emissions, but can be minimised by ensuring pipes, joints and valves are not leaking.

Since a non-negligible quantity of energy is necessary for gas compression, the energy balance and the economic feasibility of the compression and feed-in process must be reviewed on a case-by-case basis. Depending on the amount required and the source of electricity, indirect GHG emissions associated with gas compression could be significant. For this case study we use the total electricity use from upgrading and injection combined. It is necessary to split this from electricity used in biogas production due to digestate co-product allocation, i.e. for upgrading and injection 100% of emissions are allocated to biomethane.

As biomethane typically has a gross calorific value (CV) of 36-38 MJ/m^3 (standard conditions) propane is usually required to be mixed to ensure the CV meets the minimum requirement of the gas grid. As this is added in the grid entry unit after the biomethane is produced it is considered outside the system boundary.

2.2.6. Digestate storage

Digestate is a co-product from the biogas production process which has useful nutrient content and agronomical benefits (Lukehurst et al., 2010). Digestate is produced throughout the year and must therefore be stored until the growing season, which is the only appropriate time for its application as a fertiliser, since its application is not allowed in winter. Digestate is stored in open or closed tanks, with closed storage additional biogas released is mostly recovered. Like manure, if liquid digestate is stored in open tanks, ammonia and methane gases (residual biogas) are released and therefore a potential source of GHG emissions (JRC 2014b). From the economic point of view, the operator is interested in attaining an as low as possible remaining gas potential in the digestate. An evaluation of biogas plants in Germany (Biogas-Messprogramm) revealed a gas potential of 1.5–3.5% remaining after digestion (Gemmeke et al., 2009). However, Liebetrau *et al.* found that in summer temperatures up to 10% of the total biogas production is generated in the digestate store. The determination of emissions occurring in reality is far from being simple, and depends on numerous variables such as the available substrate, temperature, mixing activities or weather conditions (Liebetrau et al. 2010). Moreover most modern biogas plants have secondary digestion so the residual gas in digestate is much lower.

Table 3 provides some examples of the impact open storage can have on GHG emissions, and demonstrates many biogas facilities could fail sustainability criteria if included within the system boundary. Open storage of digestate can result in GHG emissions of above 20 gCO_2e per MJ of biomethane (Buratti et al. 2013). These emissions are avoidable through covering the digestate storage, assuming no leakage of biogas. Best practice measures focus on the use of a protective layer over the liquid digestate to reduce emissions. Some European countries with a developed biogas sector (e.g. Germany, Denmark and Austria) now have financial incentives to establish covered digestate stores, with the main objective of reducing emissions (Grids 2013a). For the base case a default emission of 1% methane loss is assumed for biogas production (E4Tech, 2016). This includes emissions from closed digestate storage (see section 2.2.3). Low and high values are considered in the sensitivity analysis based on the variation shown in Table 3 (see section 2.3.6).

Table 3: Open digestate storage – examples of potential impact on GHG emissions (Adams et al. 2015)

GHG Emissions	Reference
0.44 gCH_4/ MJ of biogas 11.0 gCO_2e/ MJ of biogas	(JRC 2014b)

22.5 gCO_2e/ MJ of biogas	(Liebetrau et al. 2010)
15.1 gCO_2e/ MJ of biogas	(Boulamanti et al. 2013)
0.81 gCH_4/ MJ of biomethane 20.3 gCO_2e / MJ of biomethane	(Buratti et al. 2013)
15.2 gCO_2e / MJ of biogas	(Biograce 2013)

2.2.7. Inventory summary

A summary of the key inventory data is provided in Table 4. The inventory data has been obtained from a range of sources as indicated in the table, but primarily from operational biomethane facilities in the UK whom collaborated in the study. It is therefore based on realistic physical inputs for 'typical' production conditions.

Table 4: Biogas and biomethane production inventory data and assumptions

Parameter	**Value**	**Unit**	**Data source**
Maize use per annum	40,000	t	Assumption for study
Maize biogas yield	190.5	m^3/tFM	Biomethane Potential (BMP) tests
Methane content in biogas	52	% CH_4	Laboratory feedstock analysis
On-site diesel use (e.g. telehandler)	0.24	L/tFM	Biomethane facility average
Biogas to CHP	12.4	% of total biogas	
Biogas flared	0.4	% of total biogas	
Biomethane upgraded	87.2	% of total biogas	
Electricity exported	0.0054	kWh/MJ of biogas	
Total net electricity use	0.0328	kWh/MJ of biogas	
Electricity imported	0.0187	kWh/MJ of biogas	
Electricity from biogas CHP	0.0141	kWh/MJ of biogas	
Electricity use in biogas production	45	%	
Electricity use in upgrading & injection	55	%	
Biogas CHP electrical efficiency	40.4	kWh_e/kWh of biogas	Biogas engine specification
UK grid electricity emissions factor	0.4943	$kgCO_2e$/kWh	(DECC, 2016a)
Heat demand	n/a		Supplied from CHP
Methane Losses from biogas production	0.2	gCH_4 /MJ of biogas	E4Tech, 2014
Methane Losses from biogas upgrading	0.1	gCH_4 / MJ of biomethane	Biogas upgrader specification
Digestate output – solid fraction	5,200	t	Mass balance – 13% of input
M.C. of digestate solid fraction	75	%	Oven test of D.M. at 25%

2.3. Sensitivity analysis

A sensitivity analysis was conducted as an integral part of the study. Through our review of operating biomethane facilities and existing GHG assessments it is apparent that variability exists in the input data due to different operational practices and plant design. Uncertainty also occurs due to scientific uncertainties and difficulties in measuring emissions sources such as field emissions and fugitive methane. The sensitivity variables were therefore selected based on those factors which have the larger influence on GHG results and through an assessment of current practice. To conduct the sensitivity analysis the 'base case' assumptions were kept the same with one variable changed for each sensitivity case. The variables considered for the sensitivity cases are summarised in Table 5, with additional description provided in the supplementary information.

Table 5: Sensitivity cases assessed for biomethane production GHG emissions

Sensitivity Case	Description	Sensitivity	Base Case
A	Low emission N-fertiliser	100 kg of Urea fertiliser	125 kg of N from different fertiliser types
B	High emission N-fertiliser	150 kg of Ammonium Nitrate	125 kg of N from different fertiliser types
C	Digestate N-fertiliser	125 kg of N derived from digestate	125 kg of N from different fertiliser types
D	Low crop yield	30.89 tFM/ha	41.19 tFM/ha
E	High crop yield	51.49 tFM/ha	41.19 tFM/ha
F	Low Soil N_2O emissions	0.46% of applied N	1% of applied N
G	Low Diesel use	-50% of each diesel use input	See tables 2 & 4
H	High Diesel use	+50% of each diesel use input	See tables 2 & 4
I	Electricity all derived from biogas CHP	0.0328 kWh/MJ of biogas electricity	0.0141 kWh/MJ of biogas electricity
J	Electricity all derived from import	0.0328 kWh/MJ of imported electricity (UK grid)	0.0187 kWh/MJ of imported electricity (UK grid)
K	Low methane loss (BP)	0.25%	1.0%
L	High methane loss (BP)	3.0%	1.0%
M	Low methane loss (U&I)	0.0%	0.5%
N	High methane loss (U&I)	2.0%	0.5%

3. Results and discussion

Results are presented in two sections, firstly the characterised GHG emissions of the 'base case' and secondly the variability and uncertainty assessment in the 'sensitivity analysis' cases. Best practice operational methods are described alongside the results.

3.1. Characterised GHG emissions of biomethane production

Based on the inventory data and accounting methodology described in section 2, the following GHG emissions from the biomethane production system have been calculated. Figure 3 shows the characterised GHG emissions for each emission source considered in the biomethane production life cycle. Total emissions have been calculated as 33.8 gCO_2e/MJ of biomethane which following the RED methodology represents a 61% GHG saving compared to the EU fossil heat average of 87 gCO_2e/MJ (EC, 2010). This fossil fuel comparator value is as applied in the EU for calculating GHG savings.

Figure 3: Characterised GHG emissions from biomethane production via AD using maize

The characterised emissions show that imported electricity, methane loss, and soil N_2O emissions are the biggest single sources of emission in the biomethane production supply chain. For feedstock supply, fertiliser production and crop yield influence net GHG balance, and diesel use in the different life cycle stages combined also adds up to a notable contribution. These emission sources are therefore further assessed in the sensitivity analysis below.

Table 6 further presents the absolute results with percentage contribution and rank. In addition a brief description of the potential variability and uncertainty that can arise is provided, which is assessed by the authors based on the literature and an assessment of calculated GHG emissions (see section 3.2).

Table 6: Biomethane production GHG emissions by source – characterised result, percentage contribution, rank, variability and uncertainty

Emission source	GHG emissions (gCO_2e/MJ of biomethane)	Contribution (%)	Rank	Variability	Uncertainty	Description
Seeds	0.06	0.2%	13	Low	Low	Seeds not material in total emissions but included for completeness. Uncertainty and variability low, therefore not further assessed.
Pesticides	0.27	0.8%	12	Moderate	Low	Pesticides not material in total emissions but included for completeness. Uncertainty is low but has moderate variability due to field differences. Not further assessed due to limited net impact on GHG balance.
Cultivation diesel	1.76	5.2%	7	Moderate	Low	Cultivation diesel can vary depending on field operations required, topology, and farm machinery used. Uncertainty is low but variability is moderate.
Fertiliser production	3.11	9.2%	5	High	Moderate	Fertiliser production can have a material impact on total GHG emissions. Uncertainty is moderate and variability is high due to the numerous fertiliser products available and differing agronomic

						requirements.
Soil N_2O emissions	6.02	17.8%	2	High	High	Soil N_2O released is one of the largest potential emission sources for crop cultivation. Variability is high due to local conditions such as soil and weather affecting crop nitrogen uptake. Uncertainty is high due to the difficulties in measurement.
Harvesting diesel	1.56	4.6%	9	Moderate	Low	Similar to cultivation, harvesting diesel use can vary depending on local conditions at harvest and machinery used.
Silage diesel	0.35	1.0%	11	Low	Low	Silage making diesel use is not expected to vary much and has low uncertainty. Nonetheless silage diesel is further assessed in combination with other diesel use.
Transport diesel	1.66	4.9%	8	Moderate	Low	Transport diesel is directly related to distance travelled so there is some variability expected, although uncertainty is low. Further assessed in combination with other diesel use.
Diesel use on site	0.80	2.4%	10	Low	Low	Diesel use on site is limited to movements of the telehandler to feed the feed hopper and is therefore similar to silage diesel.
Electricity import (BP)	4.74	14.0%	3	High	Moderate	Imported electricity demand is dependant on the amount of electricity produced from biogas on site and therefore has high variability. Uncertainty is moderate as the source of electricity can vary.
Methane loss (BP)	4.69	13.9%	4	High	High	Methane losses vary significantly and also have high uncertainty due to the difficulties in regular measurement.
Electricity import (U&I)	6.42	19.0%	1	High	Moderate	Electricity imported for upgrading and injection will depend on technology employed, compression required, and biogas electricity

						available, therefore variability is high.
Methane loss (U&I)	2.38	7.0%	6	High	Moderate	Methane loss varies depending on technology and operation. The uncertainty is moderate as it should be possible to regularly measure methane loss from the upgrading process.
Total	**33.82**					Total emissions can vary significantly as shown in the sensitivity analysis (see Figure 4)

3.2. Variability & Uncertainty (Sensitivity Analysis)

Variability and uncertainty in GHG emissions from biomethane production are considered here by conducting a sensitivity analysis as described in section 2.3. Sensitivity results portrayed in Figure 4 show that the GHG balance of biomethane can vary substantially depending on operational input values. Table 7 summarises the absolute values for each sensitivity case and percentage change from the base case.

Figure 4: Sensitivity analysis results for the GHG emissions of different cases

Table 7: Sensitivity analysis results – absolute and change from base case

Sensitivity Cases		**GHG balance (gCO_2e/MJ)**	**Change from Base Case (gCO_2e/MJ)**	**Change from Base Case (%)**
Base	Base Case	33.8	-	-
A	Low N-fertiliser	32.0	-1.8	-5%
B	High N-fertiliser	41.0	7.2	21%
C	Digestate fertiliser	32.3	-1.5	-4%
D	Low crop yield	38.1	4.3	13%
E	High crop yield	31.2	-2.6	-8%
F	Low soil N_2O	30.5	-3.3	-10%
G	Low diesel use	31.7	-2.1	-6%
H	High diesel use	36.0	2.2	7%
I	Biogas electricity	26.8	-7.0	-21%
J	Import electricity	37.6	3.8	11%
K	Low CH_4 loss (BP)	30.2	-3.6	-11%
L	High CH_4 loss (BP)	43.9	10.1	30%
M	Low CH_4 loss (U&I)	31.6	-2.2	-7%
N	High CH_4 loss (U&I)	40.7	6.9	20%

Sensitivity cases A-C show that the type and amount of N-fertiliser are key determinants in emissions from feedstock supply. Operators should therefore aim to minimise N inputs and look to use fertiliser products with low embodied emissions from production. In this example Urea has a much lower GHG impact than Ammonium Nitrate, although these emission factors can vary (Fertilisers Europe 2015). Using digestate (case C) does reduce net emissions but since N_2O emissions from soil are expected to increase the GHG saving is only marginal. These results show that there is a high variability in emissions from fertiliser production with a moderate uncertainty as manufacturers increasingly publish the carbon footprints of fertiliser products.

Crop yield directly impacts the emissions from feedstock supply with high crop yields (case E) being preferable to low yields (case D). Clearly this is logical as the inputs are the same, however it should be considered that in many cases higher crop yields require additional N-fertiliser hence there is a trade-off between increased yields and the amount of N-fertiliser applied. Farmers should therefore be aware of optimising both crop yields and balancing this with N inputs so the net emissions are not increased. As crop yields are measured using calibrated weighbridges the uncertainty is low, whereas variability is moderate due to external factors such as weather and local geography.

Soil N_2O is an area of ongoing research with only limited long term studies performed on the emissions from N-fertiliser application in different regions, crops, and rates. As the differences between the two studies referenced here show there is a high variability in emissions from soil, the uncertainty is also high (see case F). Due to the uncertainties it is recommended that further research and measurement is undertaken of soil N_2O emissions from a range of different crops in different regions. Best practice measures for farmers include the use of Nitrogen inhibitors which can mitigate and slow down the release of N to air and increase the uptake by the crop (EC 2001).

For all of the feedstock supply sensitivity cases (A to F), emissions from biogas production, upgrading & injection remain unchanged. Diesel use is used in both the feedstock supply and biogas production, therefore changing this in the sensitivity analysis impacts both these life cycle stages. Two extreme cases were considered being a low diesel input (case G) and a high diesel input (case H). Reducing diesel inputs by 50% saved a total of 2.1 gCO_2e/MJ (6.2%), whereas increasing inputs by 50% increased emissions by 2.2 gCO_2e/MJ (6.5%). This shows that minimising diesel use is important and overall can have a material impact on results, however these sensitivity cases are quite extreme and the individual inputs are unlikely to be material (<5%) in a sensitivity analysis. To a certain extent diesel use in the crop production supply chain is unavoidable and alternative energy sources for farm machinery are limited. Potential options for reducing emissions from on-farm diesel use include using biodiesel (if sufficient supply is available), precision agriculture (JRC 2014a), or genetic engineering innovations which have facilitated no-till or low-till cultivation (Islam & Reeder 2014; Camargo et al. 2013). Nevertheless crop-based AD is expected to have much higher emissions from diesel use than waste or residue supply chains.

Electricity use was found to have notable impact on the overall GHG balance with biogas CHP (case I) being preferable to imported electricity (case J). There are GHG savings to be made by avoiding emission intensive electricity supply even when there is a lower biomethane output as a result. For individual operators best practice is to use renewable or low carbon electricity sources where possible. In reality this is not always practical due to plant configurations and grid connectivity. Additionally economics are important in decision-making as the relative cost of electricity compared to the biomethane output is assessed by operators.

The final sensitivity cases considered were methane losses. Case K assumed that biogas production had a low CH_4 loss of 0.25% which is achievable based on recent research (Avfall Sverige 2016; Energiforsk 2015). This saves approximately 3.6 gCO_2e/MJ (11%) compared to the base case of 1% loss. In contrast the high case L of 3% loss increases emissions by 10.1 gCO_2e/MJ (30%) and would mean operators struggle to achieve the necessary GHG savings required to receive Government support. For upgrading and injection a methane loss of 0% is achievable with the best available technology such as carbon capture or a regenerative thermal oxidiser (RTO). Case M assumes zero CH_4 loss which saves 2.2 gCO_2e/MJ (7%) compared to the base case of 0.5% loss, whereas case N has a high loss of 2% increasing emissions by 6.9 gCO_2e/MJ (20%). It is not in the operators' interest to lose methane, therefore best practice management includes regular methane leak detection, periodic external measurement, utilising efficient technologies for upgrading.

3.3. Comparative GHG results

To provide context to the results it is useful to compare a selection of GHG assessments of alternative bioenergy technologies. Results from other studies should always be interpreted with caution though as functional units, system boundaries, transparency, scale, location, data assumptions, and emission factors (among other factors) can vary. Table 8 provides a summary of GHG results for alternative bioenergy systems:

Table 8: Comparative GHG emissions from alternative bioenergy technologies and feedstocks

Technology	Feedstock	Functional Unit	GHG Result (gCO_2e/MJ)	Description	Ref
Biomethane	Wheat, sugar beet, barley	1 MJ of biomethane	59.0 – 64.0	This is a mix of the 3 feedstocks used in AD and upgraded to biomethane	(Power & Murphy 2009)
Biomethane	Corn, sorghum, triticale	1 MJ of biomethane	26.1 – 62.7	Higher results assume uncovered digestate storage	(Buratti et al. 2013)
Biomethane	Grass	1 MJ of biomethane	41.0	Assumes energy allocation	(Thamsiriroj & Murphy 2011)
Biomethane	Liquid Manure	1 MJ of biomethane	-71.3 – -44.2	Negative emissions achieved through avoided methane leakage from storage	(JEC 2014)
Biomethane	Maize	1 MJ of biomethane	40.4 – 85.7	Emissions higher due to assumptions on fertiliser crop yield and operating parameters	(JEC 2014)
Biomethane	MSW	1 MJ of biomethane	11.3 – 18.1	Supply chain emissions excluded as waste	(JEC 2014)
Biodiesel	Oilseed rape	1 MJ of biodiesel	48.0	Assumes energy allocation	(Thamsiriroj & Murphy 2011)
Biodiesel	Tallow	1 MJ of biodiesel	40.0	Assumes energy allocation	(Thamsiriroj & Murphy 2011)
Biodiesel	Oilseed rape	1 MJ of biodiesel	37.3 – 58.7	Range due to different energy sources and use of co-products	(JEC 2014)
Biodiesel	Waste cooking oil	1 MJ of biodiesel	13.6 – 13.9	Supply chain emissions excluded as a waste	(JEC 2014)
Bioethanol	Wheat, sugar beet, barley	1 MJ of bioethanol	60.0 – 69.0	This is a mix of the 3 feedstocks used to in fermentation	(Power & Murphy 2009)
Bioethanol	Wheat	1 MJ of bioethanol	54.1 – 86.0	Range due to different energy sources and use of co-products	(JEC 2014)
Bioethanol	Straw	1 MJ of bioethanol	9.1 – 9.2	Wheat straw is a residue under the RED	(JEC 2014)
Combustion heat	Birch wood	1 MJ of heat	22.2 – 30.6	Managed forest used for feedstock supply	(Solli et al. 2009)
Combustion electricity	Rice husk	1 MJ of electricity	60.4	Supply chain emissions are high for rice cultivation	(Shafie et al. 2014)
Combustion electricity	Forest residue	1 MJ of electricity	3.1 – 3.9	Supply chain emissions excluded as a residue	(Thakur et al. 2014)
Combustion electricity	Willow	1 MJ of electricity	134.0	High result due to fertiliser use, low crop yield and low electrical conversion facility	(Goglio & Owende 2009)
Gasification CHP	Forest residue	1 MJ of electricity 1 MJ of heat	8.8 – 10.5 2.4 – 2.8	Supply chain emissions excluded as a residue	(Guest et al. 2011)
Gasification CHP	Wood waste	1 MJ of electricity 1 MJ of heat	1.9 – 4.2 0.8 – 1.9	Supply chain emissions excluded as a waste	(Adams & McManus 2014)

Gasification electricity	Willow	1 MJ of electricity	16.7	Absolute number but no breakdown of LCI data	(Thornley et al. 2015)

These comparative results show that the use of waste and residue feedstocks are preferable in terms of lower GHG emissions. However when compared to alternative crop-derived fuels such as biodiesel and bioethanol, biomethane from maize is preferable both in terms of GHG balance and in the versatility of end-uses. Previous studies show wide variability in results which shows the importance of obtaining actual data from facility operators, otherwise there is a risk of incorrect modelling assumptions.

When results are compared to different conversion technologies gasification, in theory, has lower GHG balance primarily because woody feedstock have lower supply chain emissions, and because of no assumed fugitive emissions. However biomethane from AD is commercially available and has widespread deployment which is due to its application on farms. In contrast gasification has several operational and commercial issues and is therefore unlikely to be deployed on farms. Additionally agricultural feedstocks are better managed through AD due to the integration in farm management and the wider benefits such as digestate and farm waste management.

It is difficult to compare results to electricity generation due to the different functional unit, which is an important consideration. Biomethane injected into the gas grid could be used for electricity. In this case a CHP generator is preferable, otherwise there is a loss of efficiency in conversion.

4. Conclusions

This paper has characterised GHG emissions from a representative biomethane production system that upgrades biogas produced from the anaerobic digestion of maize, which is the most common feedstock used for biomethane in the UK and Germany (ADBA, 2016; Rensberg et al., 2012). The inventory data used has been collected from operational biomethane facilities and farms in the UK to provide a realistic assessment of GHG emissions from a ‘typical’ production process. It has been shown that variability exists in potential emission sources throughout the supply chain for reasons including geography, weather, farming practice, soil quality, methodological and measurement uncertainty, biomethane facility design and operation, and other factors. Key emission sources for biomethane produced from crops include fertiliser production, soil N_2O emissions from fertiliser application, crop yield, methane loss, electricity use, and diesel use. It is therefore important that each of these sources is closely managed to ensure crop-derived biomethane can be considered a low carbon fuel. For cleaner production of biomethane the following operational best practice methods are proposed:

- Low emission fertilisers should be used, minimising the use of Nitrogen fertiliser where possible and applying at the correct time to optimise yields and minimise emissions.
- Optimising crop yields through effective crop management with consideration of optimal N use balancing emissions from N application against changes in crop yield, i.e. ensure farming inputs achieve the best yields but without compromising the net GHG balance.
- Nitrogen inhibitors can be applied to reduce N_2O emissions from soil (Misselbrook et al., 2014).
- Precision farming and improved farm machinery can help to reduce the need for diesel and optimise where farming inputs (fertilisers and pesticides) are applied.

- Ensure electricity use on site is minimised and wherever possible operators should use low carbon electricity such as biogas CHP. Imported electricity will commonly increase the GHG balance as this is based on the regional electricity mix.
- Optimise biogas yields through regular monitoring of feedstocks and sampling of substrates in the digester. Additives or changes in feedstock mix may be required to increase biogas outputs which helps to reduce GHG emissions,
- Minimise methane losses from both biogas production and upgrading through regular monitoring and leak detection.
- Implement technologies that minimise methane loss from biogas upgrading such as carbon capture or regenerative thermal oxidisers.

Unless closely managed the GHG emission savings achievable from biomethane may not meet the minimum requirements of policy-makers and other conversion technologies could be preferred, therefore best practice methods should be followed. Further research and analysis is required into several aspects of emission quantification to improve the accuracy of calculated GHG balances, this includes:

- Measurement of N_2O emissions from soil from different crops using varied fertiliser inputs and grown in different locations.
- Long term assessments of the potential emission savings from the use of Nitrogen inhibitors.
- Losses from silage clamps (feedstock storage loss).
- Methane loss from biogas and biomethane production systems.
- Lower emission alternatives to diesel for providing the mechanical energy in farm machinery.
- Additional understanding of the emissions associated with digestate application.

A final consideration for crop-based biomethane is that ultimately the biomass resource is limited by the available land, therefore farmers and operators need to continuously follow best practice guidance particularly around crop rotations and land management (ADBA 2013). Future development of the biomethane sector is anticipated to focus more on the use of wastes and residues (EC, 2017), nonetheless crops will continue to play an important role in energy generation and farm management so optimising their usage is crucial to the sustainable development of the sector.

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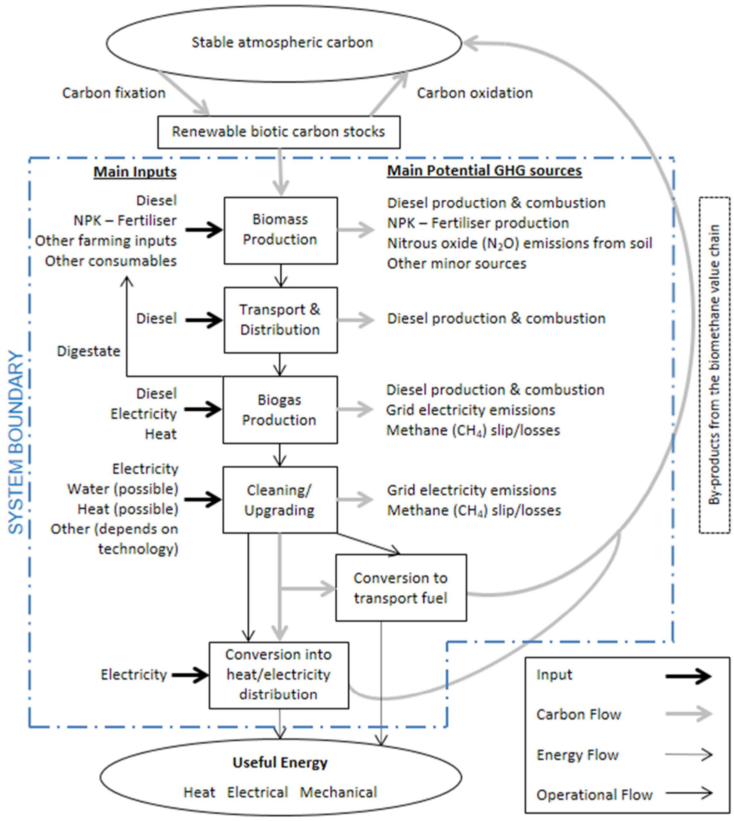
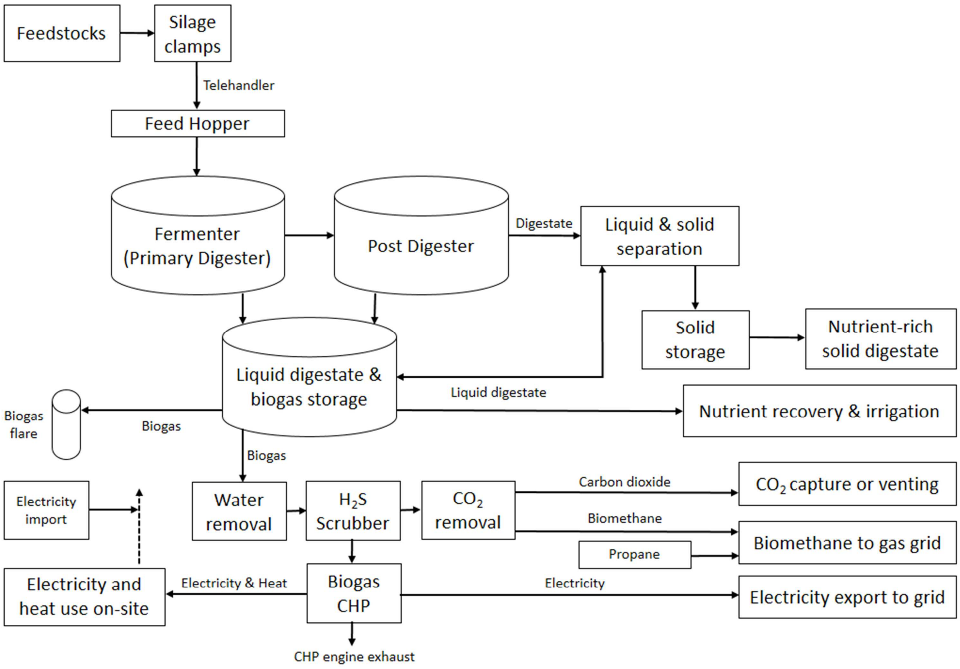
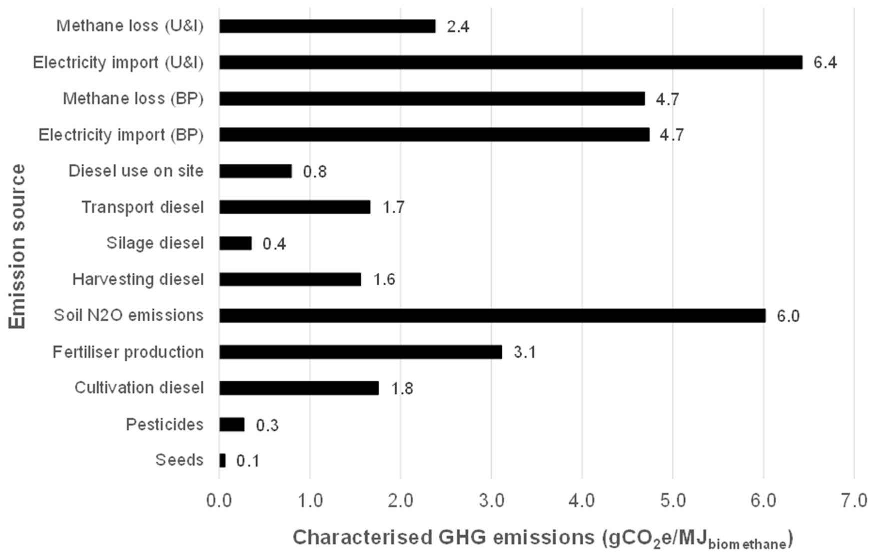
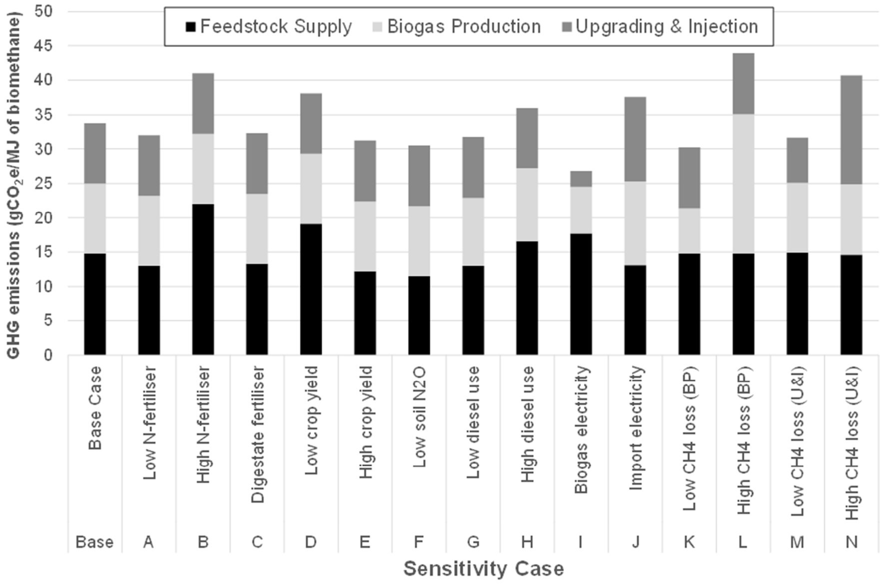

Stable atmospheric carbon
Carbon fixation
Carbon oxidation
Renewable biotic carbon stocks
Main Inputs
Main Potential GHG sources
Diesel
NPK – Fertiliser
Other farming inputs
Other consumables
Biomass Production
Diesel production & combustion
NPK – Fertiliser production
Nitrous oxide (N2O) emissions from soil
Other minor sources
Diesel
Transport & Distribution
Diesel production & combustion
Digestate
Diesel
Electricity
Heat
Biogas Production
Diesel production & combustion
Grid electricity emissions
Methane (CH4) slip/losses
Electricity
Water (possible)
Heat (possible)
Other (depends on technology)
Cleaning/ Upgrading
Grid electricity emissions
Methane (CH4) slip/losses
Conversion to transport fuel
Electricity
Conversion into heat/electricity distribution
SYSTEM BOUNDARY
By-products from the biomethane value chain
Useful Energy
Heat Electrical Mechanical
Input
Carbon Flow
Energy Flow
Operational Flow


Feedstocks
Silage clamps
Telehandler
Feed Hopper
Fermenter (Primary Digester)
Post Digester
Digestate
Liquid & solid separation
Solid storage
Nutrient-rich solid digestate
Liquid digestate & biogas storage
Liquid digestate
Nutrient recovery & irrigation
Biogas flare
Biogas
Biogas
Electricity import
Water removal
H_2S Scrubber
CO_2 removal
Carbon dioxide
CO_2 capture or venting
Biomethane
Biomethane to gas grid
Propane
Electricity and heat use on-site
Electricity & Heat
Biogas CHP
Electricity
Electricity export to grid
CHP engine exhaust



Methane loss (U&I)
Electricity import (U&I)
Methane loss (BP)
Electricity import (BP)
Diesel use on site
Transport diesel
Silage diesel
Harvesting diesel
Soil N2O emissions
Fertiliser production
Cultivation diesel
Pesticides
Seeds
2.4
6.4
4.7
4.7
0.8
1.7
0.4
1.6
6.0
3.1
1.8
0.3
0.1
Emission source
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Characterised GHG emissions (gCO2e/MJbiomethane)



GHG emissions (gCO2e/MJ of biomethane)
Feedstock Supply
Biogas Production
Upgrading & Injection
50
45
40
35
30
25
20
15
10
5
0
Base Case
Low N-fertiliser
High N-fertiliser
Digestate fertiliser
Low crop yield
High crop yield
Low soil N2O
Low diesel use
High diesel use
Biogas electricity
Import electricity
Low CH4 loss (BP)
High CH4 loss (BP)
Low CH4 loss (U&I)
High CH4 loss (U&I)
Base
A
B
C
D
E
F
G
H
I
J
K
L
M
N
Sensitivity Case