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Life cycle environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels.

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In this study, life cycle analysis (LCA) has been applied to evaluate the environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels, with a focus on Greenhouse Gas (GHG) emissions. The results demonstrate significant reductions in greenhouse gas emissions for the biogas as a fuel scenario due to the displacement of fossil petrol and diesel fuels (scenario 3), with savings of between 524 and 477 kg of CO₂ equivalent (per MWh of energy provided by the fuels). The utilisation of biogas for electricity generation saves around 300 kg of CO₂ equivalent per MWh of electricity injected into the grid (scenario 1), while Scenario 2, the upgrading of biogas to biomethane and its injection into the gas grid for heating saves 191 kg of CO₂ equivalent (per MWh of energy generated by the biomethane). The results emphasise the benefits of using life cycle analysis to provide an evidence based for

bioenergy policy. The limitations of the research are identified and recommendations made for future research priorities to further the use of LCA in the evaluation of bioenergy systems.

Key words:

Biogas, biomethane, life-cycle analysis, bioenergy.

1. Introduction

The coming into effect of the Paris Agreement under the United Nations Framework Convention on Climate Change in 4 November 2016, has seen increased actions from signatories throughout the world to reduce greenhouse gas (GHG) emissions (Nations, 2015). Within the European Union, the 20:20:20 package has set targets of 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables and 20% improvement in energy efficiency. In addition, member states have binding annual targets until 2020 for cutting emissions in sectors such as housing, agriculture, waste and transport (excluding aviation) (Commission, 2010). In 2014, Northern Ireland produced an estimated 20.3 million tonnes of CO₂ equivalent, and accounted for 4% of the total greenhouse gas (GHG) emissions in the UK, while only accounting for around 2.8% of the population of the UK. The agri-food sector in NI accounts for a much higher proportion of the economy than the UK average, as it is the region's largest employer and accounts for a much higher proportion of the regions total GHG emissions (29% as opposed to 9% in the rest of the UK (Committee, on, Climate, & Change, 2016)The second largest contributor to GHG emissions in Northern Ireland is the transport sector, which accounted for 21% of the emissions in 2014 (Department for Agriculture, 2018). In Northern Ireland, transport is closely linked to agriculture, with heavy duty vehicles used both by the agri-food industry, processors and retailers (Blades et al., 2017).

44

45 **Anaerobic digestion**

46 Anaerobic Digestion (AD) is a biochemical process involving the breakdown of organic materials
47 into biogas, comprising approximately 60% methane 40% carbon dioxide (along with trace gases
48 such as hydrogen sulphide and water) (AEBIOM, 2010) and a partially stabilised digestate
49 comprising microbial biomass and undigested feedstock from the digestion process with a range
50 of applications (Chen, Cheng, & Creamer, 2008). The high calorific value of biogas has seen its
51 potential highlighted as a central element of climate change and renewable energy policies in many
52 countries (N. Curry & Pillay, 2012) and also as way of mitigating GHG emissions from
53 farming/food production (J Bacenetti et al., 2016), and this in turn has led to increased levels of
54 research into the AD process itself, leading to steady progress in improving the efficiency of the
55 process (Jin, Li, & Li, 2016) (Zhen, Lu, Kato, Zhao, & Li, 2017).

56 Biogas production has developed rapidly over the last 10 years, particularly in Europe, with
57 Germany having 10,212 plants in operation in 2016 (International Energy Authority, 2016). In
58 Northern Ireland biogas production from AD has grown by over 2,000% in recent years, with 24
59 new plants being commissioned since 2015 and there are currently 103 AD sites either in
60 construction or already approved in the region (Anaerobic-digestion.com, 2018). Biogas can be
61 utilised in a number of ways, with the current most common use being in gas engines for combined
62 heat and power (CHP), with the electricity produced usually injected into the grid and a proportion
63 of the heat used on site (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009).

However, the biogas can also be upgraded for other utilisation options such as biomethane or biodiesel as part of a wider bioenergy system (Murphy, Devlin, Deverell, & McDonnell, 2014), or utilised for producing energy and chemicals within the biorefinery concept (Cherubini, 2010).

In Europe in 2013, more than 90% of biogas was used for electricity generation (IRENA, 2017).

However, utilisation options for biogas vary greatly between countries in Europe, with Sweden using 63% of its biogas production as automotive fuel in 2015 (International Energy Authority, 2016).

Upgrading of biogas to biomethane removes the CO₂ and impurities in biogas, bringing the methane content up to that of natural gas, making it interchangeable with natural gas as a fuel, and opening up a wider range of utilisation pathways such as injection into the grid (Starr, Villalba, & Gabarrell, 2015), use as Sustainable Natural Gas (SNG) in vehicles (IRENA, 2017) or integration with other biochemical conversion pathways for the production biohydrogen or biohythane (Han & Shin, 2004) (Ghimire et al., 2017). However, this divergence of utilisation pathways creates challenges for policy makers attempting to evaluate which of the pathways might be optimal for their conditions (Gonzalez-Salazar et al., 2016). To support the evaluation of these pathways and provide an evidence base for renewable energy policy, decision-support tools are needed, and one of the most commonly applied is life cycle analysis (McKone et al., 2011). Although data has been collected from an operating biogas plant in Northern Ireland for which the models have been built, the scenarios to be presented can also be applied in other regions having biogas plants as a source of energy and other product production.

Life cycle analysis

The rapid development and divergence of biogas utilisation pathways has seen an increased interest in the evaluation of the environmental performance of these systems. Life cycle analysis (LCA) is a method for evaluating the environmental performance of products processes or technological systems (Heijungs, Huppes, & Guinée, 2010). LCA quantifies the material and energy inputs and outputs over the entire life cycle of a product or process and has been widely used in the evaluation of bioenergy systems. A previous use of LCA for the evaluation of a bioenergy/bioeconomy system by the authors, demonstrated the reductions in GHG emissions which could achieved through the substitution of food wastes for traditional AD feedstocks and the very significant additional reductions from the diversion of the food waste from landfill (Pérez-Camacho, Curry, & Cromie, 2017).

However, this also demonstrates a challenge of applying LCA the to ‘multifunction’ systems, for example, those that include the dual function of waste management and secondary material or renewable energy production (Nakatani, 2014). In particular, the choice of functional unit (Heijungs & Guinée, 2007) (Reap, Roman, Duncan, & Bras, 2008), for utilising waste feedstocks to produce multiple energy pathways or energy carriers. This may go some way to explaining the variations in the reported environmental performance of systems, which may be attributed to the choice of functional unit (S Choudhary et al., 2014) differences in cultivation systems, location, feedstocks (Dressler, Loewen, & Nelles, 2012) (Ertem, Martinez-Blanco, Finkbeiner, Neubauer, & Junne, 2016) and/or final use of the energy and management systems for the digestate (Berglund & Börjesson, 2006) (Dressler et al., 2012). Czyrnek-Delêtre et al have highlighted the particular challenges in applying LCA to bioenergy systems and have made recommendations for addressing these, including that results should be reported using more than one functional unit (Czyrnek-Delêtre, Smyth, & Murphy, 2017).

108 **Aims and objectives.**

109 The aim of this study is to evaluate the life cycle environmental impacts associated with three
110 production and utilisation scenarios for biogas from anaerobic digestion, namely:

111 Scenario 1: biogas utilisation in CHP plant for electricity production;

112 Scenario 2: biogas upgrading and injection to gas grid for heating; and

113 Scenario 3: biogas upgrading for use as fuel in vehicles.

114 These three scenarios were chosen to reflect the divergence of utilisation pathways offered by the
115 upgrading of biogas to biomethane and the challenges this presents for the application of LCA to
116 evaluating bioenergy systems. In addition, the evaluation included two sensitivity analyses,
117 namely:

- 118 • Sensitivity analysis of a range of biogas upgrading technologies; and
- 119 • Sensitivity analysis of a range of fuel mixes in vehicles.

120 The following objectives underpinned this aim:

- 121 • To identify optimal utilisation pathways for biogas production and utilisation, with a focus
122 on GHG mitigation;
- 123 • To provide an evidence-base for the development of renewable energy policy at a regional
124 level; and
- 125 • To identify future research needs to further the use of Life Cycle Analysis in the evaluation
126 of bioenergy systems.

127 We believe that the analysis combines a number of novel elements including:

- Analysis based on an operational biogas/bioenergy facility, using primary data for both plant operation and feedstocks; and
- Analysis of vehicle fuel substitution based on operational dual-fuel HGV trials (Blades et al., 2017).

This article addresses issues of current interest to both researchers and policy makers. Work carried out as part of the Northern Ireland Biogas Research Action Plan has quantified the available feedstocks for AD in Northern Ireland and provided estimates of the biogas and energy potential of these feedstocks and possible reductions in greenhouse gas emissions from ‘traditional’ biogas to CHP (R. Curry et al., 2018). However, there has been significant recent research which has focussed on the potential for biomethane as sustainable transport biofuel in Ireland (Korres, Singh, Nizami, & Murphy, 2010), while research carried out for Ervia/Gas Networks Ireland, has highlighted the potential of biomethane in decarbonising domestic heating in Ireland (KPMG, 2018). As such, this article builds on and contributes to this debate by applying Life Cycle Analysis to evaluate the environmental costs and benefits associated with three biogas production and utilisation pathways, with the purpose of contributing to the evaluation of developing and diverging biogas utilisation pathways, providing an evidence base for renewable energy policy and contributing to the ongoing methodological development of the LCA methodology for the evaluation of bioenergy systems.

2. Materials and methods

2.1. Modelling scope of the study

Life cycle analysis (LCA) has been applied to evaluate the environmental impacts of three utilisation options for the biogas produced in an operational industrial anaerobic digestion plant

located in Northern Ireland. The study has been carried out following the ISO 14040/14044 standard (ISO, 2006). For modelling purposes of the LCA, SimaPro version 8.3 with Ecoinvent database 3.3 have been used. Details of the methodology, plant systems and assumptions are described in the following sections.

2.2.Goal and scope of the study

This study evaluates the environmental impacts of three utilisation scenarios for the biogas produced in the AD of organic wastes (with a feedstock of cattle slurry and grass silage), using life cycle analysis. The environmental impacts of the three systems are considered based on an operational industrial biogas plant in Northern Ireland. Scenario 1 represents the utilisation of the biogas in a CHP plant to produce electricity to inject into the grid (with some electricity used for plant operation); scenario 2 considers the upgrading of the biogas to biomethane for its injection into the gas grid for heating; scenario 3 considers the upgrading of the biogas to biomethane and its utilisation as a fuel for vehicles. Figure 1 illustrates the process flow diagram and system boundaries for the three scenarios.

Functional unit and system boundaries.

The functional unit (FU) chosen for the analysis is 1 MWh of energy. The rationale for this choice of FU is that the aim of the research is to evaluate the performance of three energy-carriers produced from anaerobic digestion of biogas, namely electricity, biomethane substituting for NG and biomethane substituting for vehicle fuel. Choudhary et al. demonstrated that the choice of FU can have a significant impact on the results of the evaluation of between different bioenergy systems (S. Choudhary et al., 2014) and other studies have chosen different functional units. K. S. Woon et al. who evaluated the three similar scenarios chose one tonne of feedstock as their functional unit (K. S. Woon, I. M. Lo, S. L. Chiu, & D. Y. Yan, 2016) while G. Fiorentino et al.

looking at the valorisation of municipal solid waste also used one tonne of waste (Fiorentino, Ripa, Protano, Hornsby, & Ulgiati, 2015). An interesting analysis by Dressler et al., used two different functional units (kg and kWh) (Dressler et al., 2012) to assess the environmental performance of biogas to CHP (see recommendations for future research priorities)

Description of the system

Figure 1 illustrates the system boundaries for the three scenarios considered where maize/grass silage and cattle slurry are used for the production of biogas which is then converted to electricity and heat in a combined heat and power (CHP) plant (scenario 1) or upgraded to biomethane (98% v/v of purity) for its injection into the gas grid (scenario 2) or its use as a fuel for an Iveco Stralis truck (scenario 3) (The Iveco Stralis truck was used as data from operational trials on dual-fuel usage was available upon agreement with the School of Mechanical Engineering (See acknowledgements) . The CHP produces enough electricity to cover the plant parasitic load and the remainder is fed to the electricity grid.

Figure 1.

The system boundaries of the electricity provided by the national grid include the emissions during the production of the respective energy sources. For natural gas usage and vehicle fuels, the emissions are from fuel combustion and exclude emissions associated with vehicle manufacturing, to facilitate comparison with the results of other studies which have excluded these (K. Woon, I. Lo, S. Chiu, & D. Yan, 2016)

The operational AD facility for the study uses grass/maize silage and cattle slurry (GS + CS) as feedstocks. The feedstock for the plant goes through the digester feed, the macerator and the solid

feeding system (Trioliet®) before it is pumped into 2 anaerobic digester tanks (maintained at mesophilic regime, 40°C).

For the purpose of the evaluation of the scenarios (S), biogas is either transferred to the CHP unit (S1) or to the biogas upgrading system (S2 and S3). If all the biogas is used for electricity generation, the average total electricity produced per day is 8880 kWh with a daily export to the grid of 6560 kWh and the rest (2320 kWh/day) used in the maintenance of the plant. This is equivalent to 26% of electricity output. There is an average daily heat production of 9052 kWh, of which 3017 kWh are used for maintaining the plant at 40°C.

Biogas upgrading.

The technology chosen for biogas upgrading is membrane separation which is a relatively new although it has recently gained a significant market application in recent years (IRENA International Renewable Energy Agency, 2017).

Fossil fuel alternative

To compare the biogas utilisation options, alternate scenarios were modelled into SimaPro 8.3 to calculate the environmental impact substituting for: electricity from the grid, natural gas grid and diesel and petrol as fuels for vehicles.

These routes compared the 1 MWh of electricity from the grid, 1 MWh provided by the natural gas grid or the fuel equivalent that provides 1 MWh of energy. This means the LCA study has been carried out, comparing (1) 1 MWh of electricity production from the grid or from the biogas CHP; (2) 1 MWh provided by the natural gas grid or the upgraded biogas (biomethane actually) equivalent gas amount and; (3) using the also equivalent 1 MWh of energy provided by a certain amount of fuel for vehicle utilisation (diesel/petrol or biomethane).

The data for modelling were taken from the Ecoinvent 3.3 database included in the SimaPro 8.3 software.

2.3.Life Cycle Inventory Data

The inventory data used to model the environmental impacts of the three biogas utilisation options, namely (1) AD electricity; (2) biomethane to grid and; (3) biomethane as a fuel are summarised in Table S1 of the Supplementary Information (SI) document. The data on plant operation was provided by the AD plant owner.

The biomethane balance was calculated using preliminary data from the AD plant owner while the energy consumption in the upgrading system was assumed as 0.4 kWh per m³ of biomethane, which was calculated from Patterson et al., 2011 (Patterson, Esteves, Dinsdale, & Guwy, 2011). The compression of biomethane was assumed to consume 0.35 kWh per m³ of biomethane (Smyth, Smyth, & Murphy, 2010). Others sources reviewed which provided similar values included (Evonik, 2016).

Additional inventory data have been provided on the allocation method followed within the biogas/digestate production (50:50); cattle slurry/milk production (3:97); and electricity/heat generation (75:25) within the CHP. The additional inventory data provides sources for all of the data and assumptions used to compile the inventory and an evaluation of these sources (See SI document).

2.4.Life Cycle Impact Assessment

The three scenarios for anaerobic digestion and biogas utilisation have been modelled using SimaPro LCA software, version 8.3. The impacts have been estimated using the ReCiPe method, Midpoint Hierarchical V1.13. 2017. (PRé, 2019). The ReCiPe method, at the midpoint level, was

followed to estimate the 18 impact categories which are addressed as follows: climate change, ozone depletion, terrestrial acidification, fresh water eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion and fossil depletion. The ReCiPe midpoint method and impact areas were chosen to allow the analysis to spotlight single impact categories which might be of interest to policy makers and other researchers (Huijbregts et al., 2017). For example, the choice of terrestrial eutrophication directly informs a key issue relating to biogas production in a region which is a Nitrate Vulnerable Zone (NVZ), that of potential run-off from digestate application to land.

3. Results

The environmental impacts related to the three scenarios considered in this paper are shown in next sections. Tables 2 to 4 in the SI document summarise the results for all the impact categories while Figures 3, 5 and 7 illustrate three impact categories: global warming potential (kg CO₂ eq), particulate matter formation (kg PM₁₀ eq) and terrestrial acidification (kg SO₂ eq) and two damage categories: freshwater and marine eutrophication (kg P eq and kg N eq respectively) as these categories were of particular interest in Northern Ireland as the entire region is designated as a Nitrate Vulnerable Zone (NVZ) under the Nitrates Directive (91/676/EEC) (Department of Agriculture, 2019).

3.1.Scenario 1: utilisation of the biogas for electricity production

Figure 2 illustrates scenario 1, where grass and maize silage and cattle slurries were anaerobically digested and the resultant biogas is used in a combined heat and power plant to produce electricity and heat.

Table S2 (SI document) summarises the emissions for all the impact categories considered in the ReCiPe method plus the savings for scenario 1. A negative value of the savings indicates that the emissions of the biogas utilisation option are lower than the avoided impacts resulting from the fuel replacement which provides an overall positive environmental performance for the scenario, and vice versa for a positive value.

Figure 2.

There are 7 out of the 18 impact categories where the electricity from the AD plant has a lower environmental impact than the electricity from the national grid while in other 7 the impact is of a similar value. Only 4 impact categories showed a higher impact for the AD electricity, with the most significant being agricultural land occupation.

Figure 3 shows five of the most relevant environmental impact categories considered for the production of 1 MWh of electricity: climate change, terrestrial acidification, freshwater and marine eutrophication and particulate matter formation.

Figure 3.

In the climate change impact category, the results of the GHG emissions are expressed in kg of CO₂ eq (carbon dioxide equivalent), with GWP values over a 100-year time horizon (Intergovernmental Panel on Climate Change, 2006). Terrestrial acidification is expressed in kg of SO₂ eq, freshwater and marine eutrophication as kg of P and N eq respectively and particulate matter formation as kg of PM₁₀ eq (Intergovernmental Panel on Climate Change, 2006).

The production of 1 MWh of electricity injected into the grid from AD, generates 302 kg of CO₂ eq which is lower than the value of the electricity from the grid (597 kg of CO₂ eq). The utilisation of electricity from AD could then save 294 kg of CO₂ eq per MWh of electricity injected into the grid. This result was compared to other studies although direct comparisons are difficult due to feedstock and functional unit variations. Other authors using the same functional unit found similar results, for example, Dressler et al. studied biogas production from maize and its conversion to electricity obtaining emissions of 248 to 281 kg of CO₂ eq per MWh of electricity generated (Dressler et al., 2012). Studies performed in Italy for the anaerobic digestion of maize silage and pig slurry produced values ranging from 294 to 350 kg CO₂ eq per MWh of electricity produced (J. Bacenetti, Negri, Fiala, & Gonzalez-Garcia, 2013).

As set out in Figure 3 and Table S2 (SI document), electricity from the grid has similar terrestrial acidification potential (2.75 vs 2.54 kg of SO₂ eq) and freshwater eutrophication (0.19 vs 0.11 kg of P eq). Marine eutrophication (0.1 vs 0.35 kg N eq). Particulate formation PM₁₀ are similar in both cases, being slightly higher for electricity from biogas (1 vs 0.8 kg of PM₁₀ eq). Fusi et al., reported lower acidification and eutrophication potential for grid electricity due to the maize cultivation which contributes significantly to these impacts (Fusi, Bacenetti, Fiala, & Azapagic, 2016), however, they did not report on particulate matter impact (PM₁₀). Woon et al. reported higher values of particulate matter formation for the electricity from the AD of food waste (K. S. Woon et al., 2016), although the possible origin was not identified.

3.2.Scenario 2: upgrading of the biogas to natural gas standards to use as gas to grid for heating

The system boundaries for scenario 2 are illustrated in Figure 4. In this case, the biogas produced in the AD of grass/maize silage and cattle slurry is upgraded to biomethane using membrane

separation technology. The system uses the electricity needed for upgrading from the electricity generated in the CHP plant. The environmental impact of both upgraded biomethane and natural gas are compared and shown Figure 4 and Table S3 (SI document).

Figure 4.

In Table S3 (SI document), the comparison between the environmental impacts of natural gas and biomethane and the savings from the utilisation of biomethane are summarised. The production and utilisation of 1 MWh equivalent of biomethane from AD, generates 259 kg of CO₂ eq which is lower than the value of fossil natural gas (450 kg of CO₂ eq). Biomethane could then save 191 kg of CO₂ eq per MWh of biomethane. Natural gas from the grid has lower freshwater eutrophication (0.00 vs 0.05 kg P eq), marine eutrophication (0.02 vs 0.016 kg of N eq) than biomethane. Particulate matter formation and terrestrial acidification are higher for natural gas from the grid. Jury et al. reported that biogas has a higher contribution to human health and ecosystem quality damages than natural gas but lower contribution to global warming potential and consumption of resources. A higher contribution to aquatic acidification and eutrophication from biogas production is likely to be due to the ammonia emissions from farming, and possibly digestate storage (Jury, Benetto, Koster, Schmitt, & Welfring, 2010). Similar effects were found by Styles et al. (Styles, Dominguez, & Chadwick, 2016). Figure 5 shows five of the most relevant environmental impact categories considered for the production of 1 MWh of electricity: climate change, terrestrial acidification, freshwater and marine eutrophication and particulate matter formation.

Figure 5.

3.3.Scenario 3: upgrading of the biogas for its utilisation as a vehicle fuel

The system boundaries for scenario 3 are illustrated in Figure 6.

Figure 6.

Table S4 (SI document) summarises the 18 impact categories considered in the ReCiPe method, Midpoint Hierarchical used in SimaPro while Figure 7 illustrates the most relevant impact categories.

The utilisation of biomethane as fuel for vehicles saves around 500 kg of CO₂ eq per MWh equivalent compared to petrol or diesel, with the savings slightly higher for diesel fuel. The particulate matter formation is of the same order of magnitude for diesel and petrol and much lower for biomethane. Figure 7 shows five of the most relevant environmental impact categories considered for the production of 1 MWh of electricity: climate change, terrestrial acidification, freshwater and marine eutrophication and particulate matter formation.

Figure 7.

The results are in accordance with Woon et al. (K. S. Woon et al., 2016) who found the scenario of fuel utilisation as having the greatest impact in terms of GHG emissions reductions, although they obtained lower values for terrestrial acidification savings (-0.210 kg SO₂ eq/ tonne food waste) and higher values (+0.25 kg PM₁₀ eq/ tonne food waste) for particulate matter formation, we had more reduction of terrestrial acidification (-1.98 kg SO₂ eq/ MWh of diesel which is equivalent to -0.680 kg SO₂ eq/ tonne food waste and -0.80 kg PM₁₀ eq/ MWh of diesel equivalent to -0.275 kg PM₁₀ eq/ tonne food waste). Our numbers have been converted from Woon et al., 2016 by taking a production of 17.2 MWh/day of biomethane minus 1.316 MWh/day used for upgrading and compression being produced from 46.2 tonne of food waste per day.

4. Sensitivity Analysis

Two sensitivity analyses were performed, the first looked at was the variation in the energy use of upgrading technologies (electricity) and the second sensitivity analysis evaluates the environmental impacts of different utilisation rates of biomethane to petrol and diesel in the dual fuel vehicle. The approach used for the sensitivity analysis of energy use for upgrading was to use the range of estimates for electricity use from the literature, while for analysis of fuel utilisation ratios, a range of hypothetical scenarios were adopted (see below).

4.1.Sensitivity analysis on biomethane upgrading technologies.

The upgrading of biogas to biomethane can be achieved via a range of technologies which include adsorption being pressure swing adsorption the most common (PSA); absorption with water (water scrubbing), polyethylene glycol (organic physical scrubbing) and mono ethanol amine, MEA (chemical scrubbing); by permeation or membrane separation; and cryogenic separation (Persson, Jonsson, & Wellinger, 2006), (Petersson & Wellinger, 2009), (Pertl, Mostbauer, & Obersteiner, 2010) and (Patterson et al., 2011).

A key consideration when selecting the technology to use for the upgrading of biogas is the electricity consumed at this stage. The performance related to electricity consumption for each of the technologies considered is summarised in Table 5. According to the electricity consumption for each technology, a sensitivity analysis was carried out. The electricity requirement for each technology has been taken from a summary of energetic requirements of biogas upgrading from Patterson et al. (Patterson et al., 2011).

The results from the sensitivity analysis are summarised in Table S6 (SI document). A key point from the sensitivity analysis is that the variations in electricity use for each technology are not reflected in variations in the GHG emissions. For example, the electricity use ranges from 0.26 to

0.47 kWh/m³ of biomethane, however, the variation in, for example, GHG emissions (climate change) only vary from 255.51 to 261.59 kg CO₂ eq/MWh of biomethane obtained. One possible explanation for this is that the upgrading process is only a small part of overall plant electricity use and also that the electricity is coming from plant parasitic load. While beyond the scope of this analysis, an additional factor with upgrading processes is differing levels of CH₄ slippage, which could affect the environmental impacts, particularly with respect to GHG-eq.

4.2.Sensitivity analysis on fuel rates.

A sensitivity analysis to illustrate the environmental effect of a dual fuel vehicle utilisation with different rates of biomethane to diesel was performed. The cases studies were the utilisation of ratios of biomethane to diesel (bioM: diesel) of 100: 0 (which is the baseline considered in scenario 3); 70: 30; 50: 50; 30: 70 and 0: 100 (case where only diesel was used).

Table S7 (SI document) shows the results from the calculation with SimaPro 8.3. This analysis showed higher environmental impact in all categories as the rate of diesel fuel increases in the total fuel combination of the dual fuel system vehicle.

5 Discussion and conclusions

The environmental impacts of three utilisation scenarios for biogas from anaerobic digestion have been evaluated using life cycle analysis. The results of the analysis have been summarised in Figures 7, 8 and 9 and Table S8 (SI document).

Figure 7

Figure 8.

Figure 9.

The aim of this study was to evaluate the life cycle environmental impacts associated with three production and utilisation pathways for biogas from anaerobic digestion, with the underlying objectives of identifying optimal utilisation pathways (with a focus on GHG emissions reductions), informing renewable energy policy development and identifying future research needs. While all three of the scenarios demonstrate reductions relative to the non-renewable alternative, the upgrading of biogas to biomethane substituting for petrol or diesel use in transport provides the greatest reductions in environmental impacts, both in terms of GHG emissions, but also particulates.

These results are in line with the results from similar studies, for example, Murphy et al. found that biomethane from grass achieved a reduction of 75% compared to diesel for transport (Korres et al., 2010), compared to a percentage reduction from this study in the range of 73% to 75%.

Research by Poschl et al. demonstrated that the energy efficiency of the system improved by up to 65% when natural gas was substituted instead of electricity and also that energy efficiency could be further enhanced by 5.1–6.1% through recovery of residual biogas from enclosed digestate storage units (Pöschl, Ward, & Owende, 2010). Evangelisti et al. make the important point that a critical factor in optimising utilisation pathways is the quantity and quality of the energy substituted and it therefore important to define the energy system within which the plant is embedded (Evangelisti, Lettieri, Borello, & Clift, 2014).

While the focus of the LCA has been GHG mitigation, it has also quantified the reductions in particulate emissions associated with the substitution of biomethane for petrol and diesel fuels, demonstrating reductions of around 73/74%. While some sources claim almost zero particulate

emissions for Compressed Natural Gas (CNG) (Ireland, 2018), it is likely that these claims relate solely to the combustion of the fuel. However, while some of the particulate material occurs from incomplete combustion of Hydrocarbons (HCs) in fuel, lubricating oil and brake and clutch use also contributes to particulate emissions (Heywood, 2018). Additionally, the LCA modelling would include any particulate emissions associated with raw material acquisition and vehicle manufacture (MacLean & Lave, 2003).

The sensitivity analysis of biogas upgrading technologies indicated that variations in the energy (electricity) requirements for upgrading were not reflected in significant variations in GHG emissions. Possible explanations for this include upgrading being only a small part of overall plant electricity use or that the electricity is coming from plant parasitic load.

Limitations of the research. One area previously identified as a potential limitation is the choice of functional unit in multi-function systems, such as biogas production using waste feedstocks and a range of utilisation pathways. While most LCA researchers provide a clear rationale for their choice of functional unit, the decision will largely be driven by aim or purpose of the LCA. For example, researchers evaluating use of waste feedstocks are likely to choose 1 tonne of waste as their functional unit, (Gentil et al., 2010) (Cherubini, Bargigli, & Ulgiati, 2008), whereas researchers wishing to evaluate bioenergy systems will chose an energy or energy carrier functional unit (Stephenson et al., 2010). Cherubini offers a useful classification system for functional units by defining them by on the basis of input and output FU's (Cherubini & Strømman, 2011). Recent research from the EC Joint Research Centre (JRC) has made recommendations for dealing with 'multi-functionality, problems, and warning that without a clear and systematic basis for these choices "solving multi-functionality problems are likely to produce divergence results' (Pelletier, Ardente, Brandão, De Camillis, & Pennington, 2015) p75, and this and a range of other

methodological issues are addressed in the Product Environmental Footprint (PEF) guide, published by the JRC (Manfredi, Allacker, Chomkamsri, Pelletier, & de Souza, 2012). An additional possible limitation is ‘static’ nature of the scenarios when modelling. Heijungs and Guinée have highlighted the dangers of using ‘what-if’ scenarios when applying LCA to multi-functional systems (Heijungs & Guinée, 2007). Finally, as with all LCA studies, the issue of how to deal uncertainty arises. The authors hope that the provision of all of the inventory data used in the modelling, combined with the sensitivity analysis will go some way to addressing this (Igos, Benetto, Meyer, Baustert, & Othoniel, 2018).

Recommendations for future research priorities.

The aims of this study combined the evaluation of the sustainability of three production and utilisation pathways with identifying future research needs to further the use of LCA in the evaluation of bioenergy systems. One of the key issues is what has been referred to as the changing nature of life cycle assessment, which is challenging traditional LCA classification systems (McManus & Taylor, 2015). For example, this research combined a retrospective analysis of an existing bioenergy system, with prospective analysis of two hypothetical utilisation pathways. As such, it does not fit comfortably within the convention of classification of LCA as attributional or consequential (Styles et al., 2016), and may more accurately be described as dynamic life cycle assessment (Pehnt, 2006).

The authors have previously recommended as a priority research into guidance on the application of LCA to biogas/bioenergy systems, and believe that the recommendations set out by Czyrnek-Delêtre et al. provide a useful platform for future research (Czyrnek-Delêtre et al., 2017), and we would recommend that future LCA’s of bioenergy systems should include sensitivity analyses of both input and output FU’s. We would further recommend that all researchers carrying out LCA’s

of biogas/bioenergy systems should provide all underlying Inventory data as Supplemental Information (SI). In addition, while GHG emissions reduction is often the focus of policy-makers, it is important that a full range of impact areas is reported, to avoid burden shifting, particularly when the purpose of the evaluation is to inform policy (Sala, Reale, Cristobal-Garcia, Marelli, & Pant, 2016). With the growing divergence of bioenergy utilisations pathways, it is becoming increasingly important that the evaluation of these systems includes other bioenergy technologies such as gasification/pyrolysis/fermentation/algae, to enable potential synergies to be identified, and we believe the use of the biorefinery concept offers a useful framework for this (Pérez-Camacho et al., 2017). The authors hope that the issues identified and discussed in this paper can provide insights for other researchers and help set out the priorities for research to support this important research and policy area.

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Figure 1. System boundaries for the three main scenarios considered. Scenario 1: biogas utilisation in a CHP plant for electricity and heat production. Scenario 2: Gas to grid for heating. Scenario 3: Biogas as a fuel for vehicles.

Figure 2. System boundaries for scenario 1: biogas utilisation in a CHP plant for electricity and heat production.

692

693 Figure 3. Environmental impacts of 1 MWh of electricity production into the grid from NI grid (■) and AD
 694 of maize/grass silage and cattle slurry (■).

Figure 4. System boundaries for scenario 2: gas to grid.

697

698 Figure 5. Environmental impacts of 1 MWh of gas production into the grid from natural gas grid (■) and
 699 biogas to grid (■).

Figure 6. System boundaries for the scenario 3: biogas as a fuel for vehicles.

702

703 Figure 7. Environmental Impacts of 1 MWh of utilization of different fuels for vehicles: petrol (■); diesel
 704 (■); and biomethane (■).

Figure 8. Summary GWP for the 3 scenarios considered.

Figure 9. Summary of CO₂ emission savings for the 3 scenarios considered.

Supplementary Information (SI). Tables and Data Inventory.

Tables

Table 1. Summary of data and data sources for modelling scenarios 1, 2 and 3.

Data	Amount	Source
Inputs to AD plant		
Cattle slurry	26.4 tonne per day	AD plant owner
Maize/Grass silage	19.8 tonne per day	AD plant owner
Heat (from CHP)	3017 kWh per day	AD plant designer
Electricity (from CHP)	2320 kWh per day	AD plant owner
Outputs from AD plant/CHP plant		
Biogas	3498 m ³ /day	AD plant owner
Digestate	5494.4 m ³ over 3.5 months	AD plant owner
Option 1: CHP/ AD Electricity		
Electricity total	8880 kWh per day	AD plant owner
Electricity to grid	6560 kWh per day	AD plant owner
Heat	9052 kWh per day	AD plant owner
Option 2: Biogas to NG Grid		
Biomethane	1755.16 m ³ (17200 kWh per day)	AD plant owner
Mix of gases	1742.84 m ³	AD plant owner
Electricity used (upgrading)	705.1 kWh per day	(1)
Option 3: Biogas as a Vehicle Fuel		
Biomethane	1755.16 m ³ (17200 kWh per day)	AD plant owner
Mix of gases	1742.84 m ³	AD plant owner
Electricity used (upgrading plus compression)	1316.37 kWh	(2)

(1)(Patterson et al., 2011) (2)(Patterson et al., 2011), (Smyth et al., 2010).

Table 2. Environmental impacts of 1 MWh of electricity production into the grid for scenario 1 using grid electricity and AD electricity.

No.	Impact category	Unit	(a) NI Grid	(b) GS+CS	Savings
1	Climate change	kg CO ₂ eq	597.11	302.77	-294.34
2	Ozone depletion	kg CFC-11 eq	0.00001	0.00033	0.00032
3	Terrestrial acidification	kg SO ₂ eq	2.75	2.54	-0.21
4	Freshwater eutrophication	kg P eq	0.19	0.11	-0.08
5	Marine eutrophication	kg N eq	0.09	0.35	0.26
6	Human toxicity	kg 1,4-DCB eq	123.73	106.12	-17.61
7	Photochemical oxidant formation	kg NMVOC	1.23	1.52	0.29
8	Particulate matter formation	kg PM10 eq	0.80	1.00	0.20
9	Terrestrial ecotoxicity	kg 1,4-DCB eq	0.01	0.13	0.11
10	Freshwater ecotoxicity	kg 1,4-DCB eq	3.40	2.63	-0.77
11	Marine ecotoxicity	kg 1,4-DCB eq	3.39	2.44	-0.95
12	Ionising radiation	kBq U235 eq	35.71	40.80	5.09
13	Agricultural land occupation	m ² a	55.97	1094.75	1038.79
14	Urban land occupation	m ² a	4.56	2.80	-1.77
15	Natural land transformation	m ²	0.09	0.17	0.08
16	Water depletion	m ³	1.47	1.97	0.50
17	Metal depletion	kg Fe eq	4.79	19.64	14.85
18	Fossil fuel depletion	kg oil eq	158.06	190.24	32.18

Table 3. Environmental impacts of 1 MWh of NG/biomethane production into the gas grid for scenario

2.

No.	Impact category	NG Grid	Biogas to Grid	Savings
1	Climate change [kg CO ₂ eq]	450.71	259.67	-191.04
2	Ozone depletion [kg CFC-11 eq]	0.00000	0.00016	0.00016
3	Terrestrial acidification [kg SO ₂ eq]	3.80	1.14	-2.66
4	Freshwater eutrophication [kg P eq]	0.00	0.05	0.05
5	Marine eutrophication [kg N eq]	0.02	0.16	0.14
6	Human toxicity [kg 1,4-DCB eq]	82.68	49.97	-32.72
7	Photochemical oxidant formation [kg NMVOC]	0.71	0.69	-0.02
8	Particulate matter formation [kg PM10 eq]	0.83	0.45	-0.37
9	Terrestrial ecotoxicity [kg 1,4-DCB eq]	0.00	0.06	0.06
10	Freshwater ecotoxicity [kg 1,4-DCB eq]	1.09	1.24	0.15
11	Marine ecotoxicity [kg 1,4-DCB eq]	1.00	1.15	0.15
12	Ionising radiation [kBq U235 eq]	0.00	18.95	18.95
13	Agricultural land occupation [m ² a]	0.00	515.93	515.93
14	Urban land occupation [m ² a]	0.00	1.32	1.32
15	Natural land transformation [m ²]	0.00	0.08	0.08
16	Water depletion [m ³]	0.00	0.91	0.91
17	Metal depletion [kg Fe eq]	0.00	9.26	9.26
18	Fossil fuel depletion [kg oil eq]	170.82	87.21	-83.62

Table 4. Environmental impacts of 1 MWh of petrol/diesel/biomethane fuel for scenario 3.

No.	Impact category	Petrol Fuel	Diesel Fuel	Biomethane Fuel	Savings respect petrol	Savings respect diesel
1	Climate change [kg CO ₂ eq]	701.82	654.91	178.35	-523.48	-476.56
2	Ozone depletion [kg CFC-11 eq]	1.72E-06	1.34E-06	0.00E+00	-1.72E-06	-1.34E-06
3	Terrestrial acidification [kg SO ₂ eq]	2.88	2.67	0.69	-2.19	-1.98
4	Freshwater eutrophication [kg P eq]	0.00	0.00	0.00	0.00	0.00
5	Marine eutrophication [kg N eq]	0.17	0.17	0.05	-0.12	-0.12
6	Human toxicity [kg 1,4-DCB eq]	11.83	9.60	2.20	-9.63	-7.40
7	Photochemical oxidant formation [kg NMVOC]	4.56	4.43	1.27	-3.29	-3.16
8	Particulate matter formation [kg PM10 eq]	1.06	1.08	0.28	-0.78	-0.80
9	Terrestrial ecotoxicity [kg 1,4-DCB eq]	0.04	0.04	0.01	-0.03	-0.03
10	Freshwater ecotoxicity [kg 1,4-DCB eq]	0.05	0.04	0.01	-0.04	-0.04
11	Marine ecotoxicity [kg 1,4-DCB eq]	0.42	0.40	0.06	-0.36	-0.33
12	Ionising radiation [kBq U235 eq]	2.09	1.63	0.00	-2.09	-1.63
13	Agricultural land occupation [m ² a]	2.12E-03	2.11E-03	0.00E+00	-2.12E-03	-2.11E-03
14	Urban land occupation [m ² a]	0.00	0.00	0.00	0.00	0.00
15	Natural land transformation [m ²]	0.00	0.00	0.00	0.00	0.00
16	Water depletion [m ³]	0.01	0.06	0.00	-0.01	-0.06
17	Metal depletion [kg Fe eq]	0.15	0.16	0.00	-0.15	-0.16
18	Fossil fuel depletion [kg oil eq]	201.76	210.24	0.00	-201.76	-210.24

Table 5. Summary of upgrading technologies energy requirements and data for sensitivity analysis calculations.

Scenario	Upgrading technology	Electricity used (KWh/m ³ of biomethane) ¹	Total electricity consumed (kWh/day)	Electricity left for grid injection (kWh/day)
1	PSA (Pressure Swing Adsorption)	0.41	723.1	5836.9
2	Water scrubbing	0.39	700.7	5859.3
3	Organic physical scrubbing	0.47	819.7	5740.3
4	Chemical scrubbing	0.26	457.2	6102.8
5	Cryogenic separation	0.42	737.2	5822.8
Baseline	Membrane separation (baseline)	0.40	705.1	5854.9

Table 6. Sensitivity analysis LCA results for the different biogas upgrading technologies considered.

No.	Impact category	(1) PSA	(2) Water scrubbing	(3) Organic physical scrubbing	(4) Chemical scrubbing	(5) Cryogenic separation	Membrane separation (baseline)
1	Climate change [kg CO ₂ eq]	259.97	259.67	261.59	255.51	260.21	259.67
2	Ozone depletion [kg CFC-11 eq]	0.000156	0.000155	0.000157	0.000151	0.000156	0.000155
3	Terrestrial acidification [kg SO ₂ eq]	1.15	1.14	1.16	1.11	1.15	1.14
4	Freshwater eutrophication [kg P eq]	0.05	0.05	0.05	0.05	0.05	0.05
5	Marine eutrophication [kg N eq]	0.16	0.16	0.16	0.16	0.16	0.16
6	Human toxicity [kg 1,4-DCB eq]	50.07	49.97	50.64	48.51	50.16	49.97
7	Photochemical oxidant formation [kg NMVOC]	0.69	0.69	0.69	0.66	0.69	0.69
8	Particulate matter formation [kg PM10 eq]	0.45	0.45	0.46	0.44	0.45	0.45

No.	Impact category	(1) PSA	(2) Water scrubbing	(3) Organic physical scrubbing	(4) Chemical scrubbing	(5) Cryogenic separation	Membrane separation (baseline)
9	Terrestrial ecotoxicity [kg 1,4-DCB eq]	0.06	0.06	0.06	0.06	0.06	0.06
10	Freshwater ecotoxicity [kg 1,4-DCB eq]	1.24	1.24	1.26	1.21	1.25	1.24
11	Marine ecotoxicity [kg 1,4-DCB eq]	1.15	1.15	1.16	1.11	1.15	1.15
12	Ionising radiation [kBq U235 eq]	18.99	18.95	19.21	18.39	19.02	18.95
13	Agricultural land occupation [m²a]	517.02	515.93	522.88	500.90	517.88	515.93
14	Urban land occupation [m²a]	1.31	1.31	1.34	1.28	1.32	1.32
15	Natural land transformation [m²]	0.08	0.08	0.08	0.08	0.08	0.08
16	Water depletion [m³]	0.91	0.91	0.93	0.89	0.92	0.91
17	Metal depletion [kg Fe eq]	9.19	9.21	9.38	8.99	9.29	9.26
18	Fossil fuel depletion [kg oil eq]	86.53	86.76	88.41	84.60	87.54	87.21

Table 7. Sensitivity analysis LCA results for the different fuel rates considered in the dual fuel vehicle.

No.	Impact category	BioM: Diesel 100:0	BioM: Diesel 70:30	BioM: Diesel 50:50	BioM: Diesel 30:70	BioM: Diesel 0:100
1	Climate change [kg CO ₂ eq]	178.35	318.87	414.88	510.89	654.91
2	Ozone depletion [kg CFC-11 eq]	0.00E+00	4.02E-07	6.70E-07	9.37E-07	1.34E-06
3	Terrestrial acidification [kg SO ₂ eq]	0.69	1.27	1.67	2.07	2.67
4	Freshwater eutrophication [kg P eq]	0.00	0.00	0.00	0.00	0.00
5	Marine eutrophication [kg N eq]	0.05	0.08	0.11	0.13	0.17
6	Human toxicity [kg 1,4-DCB eq]	2.20	4.39	5.87	7.36	9.60
7	Photochemical oxidant formation [kg NMVOC]	1.27	2.20	2.84	3.48	4.43
8	Particulate matter formation [kg PM10 eq]	0.28	0.52	0.68	0.84	1.08
9	Terrestrial ecotoxicity [kg 1,4-DCB eq]	0.01	0.02	0.02	0.03	0.04
10	Freshwater ecotoxicity [kg 1,4-DCB eq]	0.01	0.02	0.03	0.03	0.04
11	Marine ecotoxicity [kg 1,4-DCB eq]	0.06	0.16	0.23	0.30	0.40
12	Ionising radiation [kBq U235 eq]	0.00	0.49	0.81	1.14	1.63
13	Agricultural land occupation [m ² a]	0.00	0.00	0.00	0.00	0.00
14	Urban land occupation [m ² a]	0.00	0.00	0.00	0.00	0.00
15	Natural land transformation [m ²]	0.00	0.00	0.00	0.00	0.00
16	Water depletion [m ³]	0.00	0.02	0.03	0.04	0.06
17	Metal depletion [kg Fe eq]	0.00	0.05	0.08	0.11	0.16
18	Fossil fuel depletion [kg oil eq]	0.00	63.07	105.12	147.17	210.24

Table 8. Summary GWP and emission savings for the 3 scenarios.

Per MWh of energy	Grid electricity	AD Electricity ¹	NG Grid	Biogas Grid ²	Petrol Fuel	Diesel Fuel ³	Biomethane Fuel ⁴
Climate change [kg CO ₂ eq]	597.11	302.77	450.71	259.67	701.82	654.91	178.35
Savings [kg CO ₂ eq]	N/A	294.34	N/A	191.04	N/A	N/A	523.48
							476.56

Notes for table 8:

1. Avoided GHG emissions from AD Electricity (Table 2: $597.11 - 302.77 = 294.34$ kg CO₂ eq)
2. Avoided GHG emissions from Biogas to Grid (Table 3: $450.71 - 259.67 = 191.04$ kg CO₂ eq)
3. Avoided GHG emissions from Biomethane to Petrol Fuel (Table 4: $701.82 - 178.35 = 523.48$ kg CO₂ eq)
4. Avoided GHG emissions from Biomethane Diesel Fuel (Table 4: $654.91 - 178.35 = 476.56$ kg CO₂ eq)