BioGas to BioRefinery. Life Cycle Analysis of advanced utilisation options for anaerobic digestion using the anaerobic Biorefinery concept.

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Abstract

The BioGas to BioRefinery project is combining Life Cycle Analysis and Technology Evaluation to advanced utilisation options for anaerobic digestion using the Biorefinery concept. The projects primary aim is to identify optimal utilisation pathways for biogas and liquid effluent and digestate production and use. A further aim is to use the outputs of the research to provide an evidence-base for policy making by developing an evidence-based RoadMap for a biobased or bioeconomy for Northern Ireland. Using data from a regional anaerobic digestion feedstock evaluation, the research is modelling a range of advanced utilisation options for anaerobic digestion for both biogas production and use, and liquid effluent and digestate production and use. A particular focus of the project is potential synergies/symbioses between the common biorefinery building blocks. The usefulness of combining Life-Cycle thinking with the Biorefinery concept with a view to optimising policy development will be discussed, and future research priorities identified to support this important policy area.

Keywords: Biogas, biorefinery, anaerobic digestion, Life-Cycle Analysis

1. Introduction

One of the outputs on an ongoing programme of research into the Bioeconomy concept in Northern Ireland was the publication of a "Biogas Research Action Plan" in 2014, which included a "Quantification of Feedstocks for Anaerobic Digestion" which quantified the feedstocks available for biogas production on a regional basis. This present research builds upon and extends that previous work by applying the anaerobic Biorefinery concept to the data for feedstocks to include both biogas and digestate utilisation options, and evaluation of a selection of utilisation pathways using Life-Cycle Analysis.

1.1. Background

Anaerobic digestion (AD) is an established technology which involves the breakdown of organic materials by micro-organisms under controlled conditions in the absence of oxygen. The products of AD are biogas and digestate. Biogas typically consists of 55-70% CH_4, 45-30% CO_2 and some minor constituents, such as hydrogen sulphide (H_2S) and water. Methane energy in the biogas can be combusted as fuel and is commonly used for heat and/or electricity generation. Digestate, which consists of a suspended solid fraction and the other liquid fraction containing soluble nutrients, is the material that remains at the end of the AD process. Digestate can be used as an organic fertiliser and is reported to be more suitable than raw agricultural wastes (e.g. slurry, manure) for fertiliser use (Monson, Esteves, Guwy, & Dinsdale, 2007). A particularly active area for research is approaches to optimising the process to increase biogas yield and to look for economical uses for the digestate outputs (Smyth, Murphy, & O'Brien, 2009). One interesting approach is to place AD within the anaerobic Biorefinery, to allow an integrated approach which maximises synergies between them (Sawatdeenarunat *et al*., 2016). The use of the biorefinery concept allows the evaluation of both energy (electricity and heat) and chemical/material/nutrient management pathways in an integrated way and can contribute to the development of a RoadMap for a regional Bioeconomy (Vázquez-Rowe *et al*., 2015).

2. Methodology

The overall aim of the research is to build on and extend the outputs of the regional Quantification of Feedstock research through the application of the Biorefinery concept to both biogas and digestate outputs from the AD process. The following underlying objectives underpin these aims:

- To identify and quantify potential biogas and digestate production and utilisation pathways using the Biorefinery concept;
- To carry out a preliminary evaluation of the environmental impacts of these utilisation pathways using Life Cycle Analysis (LCA);
- To gain an understanding of the usefulness of the Biorefinery concept in informing decision making for resource management, the circular economy and the Bioeconomy; and
- To make recommendations for future research priorities in this important policy area.

Data from the NI Biogas Research Action Plan 2020 was be used to evaluate the potential amounts of biogas and digestate to be produced from organic wastes on a regional basis. Then, a review of the different output utilisation pathways was done to both products, biogas and digestate, and quantities are allocated to each of them. Biogas and digestate was explored using the Biorefinery concept, on the following utilisation options:

- Biogas (non-CHP);
- Digestate as a fertiliser;
- Digestate use for algae production; and
- Digestate use in hydrothermal processes (Gasification/pyrolysis).

The present article will focus on the uses of digestate after dewatering for both the liquid and solid components. The liquid fraction of the digestate, which is the primary component, can be used as a fertiliser and for algae production while the solid fraction can be used in hydrothermal processes such as pyrolysis and gasification. Potential feedstocks for anaerobic digestion: initial data. Based on the outputs of the quantification of feedstocks research, the following estimates for the quantities of organic waste were produced:

MSW:	484,000
Manures:	10.8 million
Grass silage	1.94 million
Total:	13.2 million

3. Potential utilisation pathways for the anaerobic Biorefinery

3.1. Biogas (non-CHP)

Biogas has traditionally been considered to be the main product in the anaerobic digestion of organic residues (AEBIOM, 2010). Its most commonly use is in a biogas engine for the production of electricity and heat (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009). Usually, industrial plants producing biogas are able to use part of the produced electricity for self-consumption and inject the rest of the production into the national electricity grid. However, the biogas can also be upgraded to natural gas quality and be used as biomethane 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). If the aim is the production of biomethane, the biogas from AD must first be upgraded and further purified after the initial H_2S removal stage. A range of technologies exist to do this including water scrubbing pressure swing adsorption and amine scrubbing. The most extensively use process for large scale systems (>100 Nm^3 biogas per hour) is water scrubbing (Yliopisto, 2010). Standards have been developed for the upgrading of biogas to allow it to be used as a substitute for natural gas (Bright, Bulson, Henderswon, Sharpe, & Pickering, 2011). This option is gaining the interest of policy makers in traditional gas markets such as the UK, the Netherlands and Germany. Targets for its production are being included in some national renewable plans and bio-methane is also attractive to gas companies as a low carbon energy source.

3.2. Digestate production

Digestate is the general term used to designate the material left after the anaerobic digestion process. It is comprised of undigested solids and the liquid fraction digester feedstock. Between 90 to 95% of the feed to the digester will remain as digestate (Tampio, Marttinen, & Rintala, 2016) Depending on the feedstock the percentage of dry matter will vary. The reported values of dry solids can vary from 4.33% for food-based digestate to 8.22% for manure-based digestate, while the value used for grass silage digestate was 6.6%. Table 1 sets out the estimates for digestate production in Northern Ireland.

Table 1. Production of digestate per year in Northern Ireland.

Solid fraction (tonne/year)	Liquid fraction (tonne/year)
935,558.68	11,024,586.72

3.2.1. Digestate as a fertiliser

The liquid fraction of the digestate can be upgraded to enhance its use as a fertiliser. Tampio *et al*., compared the potential of four digestate liquid treatment in a theoretical AD plant using food waste to produce fertilisers with low water content and high nutrient value and provided estimates of the conversion efficiency of each. Using these values, estimates have been made from the for the potential production of fertiliser from the liquid fraction of digestate, based on the assumption that 50% of total liquid digestate (5.5 mill. tonne LD/y) arisings will be used in this process and the results are set out in Table 2. *3.2.2. Digestate use for algae production* Research done by Xia and Murphy have demonstrated in a case study how 1 m^3 of liquid digestate could be used for the nutrient source of microalgae cultivation, producing 14.6 kg volatile solids (VS) of microalgae.

Table 2. Fertiliser production potential from the liquid fraction of the digestate.

Feedstock for fertilizers (liquid fraction of digestate) = 5.5 mill. tonnes per year		Estimation	
Fertiliser production technology	wt% of fertiliser*	Fertiliser produced (tonnes per year)	Fertiliser produced (millions of tonnes/year)
S1 (Stripping)	79%	4,354,711.76	4.35
S2 (Stripping + Reverse Osmosis)	26%	1,433,196.27	1.43
S3 (Evaporation + Reverse Osmosis	16%	881,966.94	0.88
S4 (Evaporation + Stripping + Reverse Osmosis)	20%	1,102,458.67	1.10

*Using efficiencies from Tampio *et al*.

Table 3. Algae and biodiesel production from liquid digestate.

Liquid digestate as a feedstock= 5.5 mill. tonnes per year	
Algae production (mill. tonne of VS of microalgae per year) *	80.3
Biodiesel production (mill. m^3 per year) **	53.6

*Using microalgae yield from Xia and Murphy (Xia & Murphy, 2016).

**Using yield from literature (Gnansounou & Kenthorai Raman, 2016).

For the purposes of this study, we have estimated how much biodiesel could be produced from the microalgae previously produced using liquid digestate as a nutrient source, based on yield estimates from Xia and Murphy (Xia & Murphy, 2016) and (Gnansounou & Kenthorai Raman, 2016).

3.2.3. Digestate for hydrothermal processes (Gasification/Pyrolysis)

Monlau *et al*. coupled pyrolysis with anaerobic digestion to close the loop like in a proposed Biorefinery (Monlau, Sambusiti, Antoniou, Barakat, & Zabaniotou, 2015) and provided estimates for the quantities of Biochar, Bio-oil and Syngas which be produced and the estimates used in this research is based on their yield factors. Based on a review of potential processing options and products, the following product options were selected for the estimation of product quantities from hydrothermal processes:

- Biochar;
- Bio-oil; and
- Syngas.

The results for the estimation of the products from the pyrolysis of the solid fraction of the digestate is shown in Table 5.

4. Results

The initial LCA analysis was focused on the performance of the upgrading of biogas, relative to conventional CHP utilisation: Scenario 1: Biogas utilisation for Combined Heat and Power (CHP); Scenario 2: Biogas Gas-to-Grid (GtG); andScenario 3: Biogas to Vehicle Fuel. The system boundaries for the analysis are shown in Figure 1.

Table 4. Product estimation potential from the pyrolysis of the solid fraction of digestate.

Feedstock for pyrolysis (solid fraction of digestate) = 820,000 tonnes per year		Estimation	
wt% averages for each product*		Products (tonnes per year)	Products (kt/y)
Biochar	34%	318,089.95	318
Bio-oil	53.50%	500,523.89	500
Syngas	12.50%	116,944.84	116

*(Monlau *et al*., 2016).

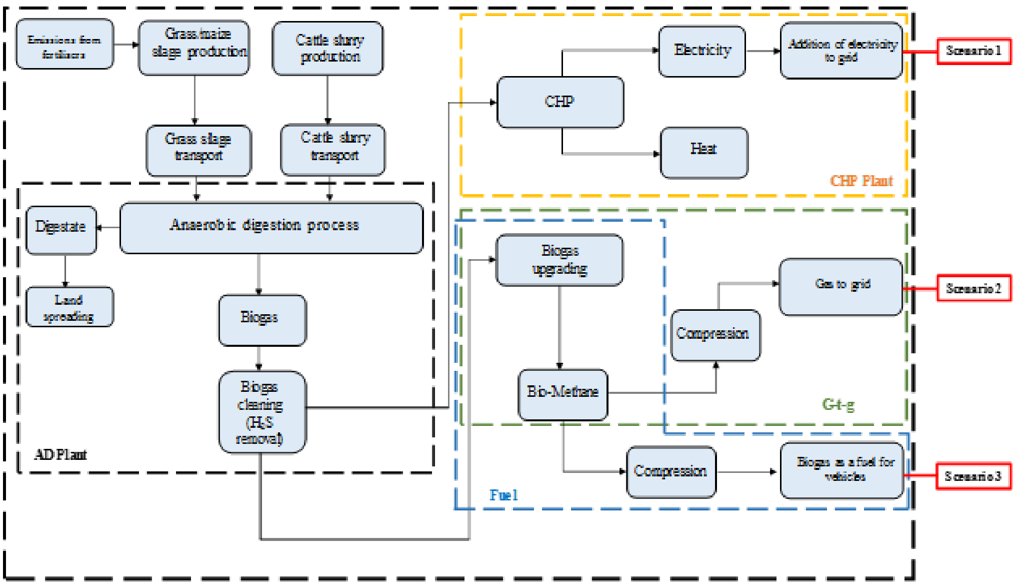
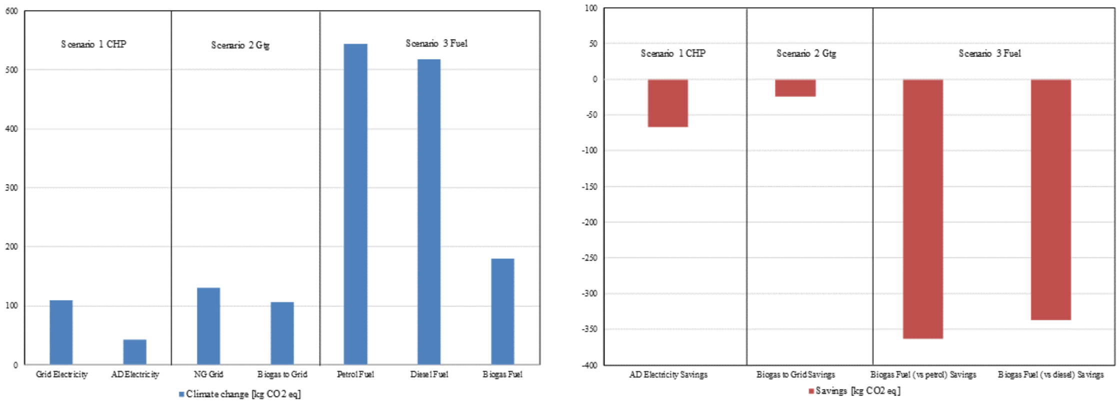


Figure 1. System Boundaries for Biogas Utilisation Options.

Table 5. Summary GWP for all the Scenarios.

	Grid electricity	AD Electricity	NG Grid	Biogas Grid	Petrol Fuel	Diesel Fuel	Biogas Fuel
Climate change [kg CO_2 eq]	110.15	43.01	130.53	106.59	543.36	517.59	180.29
Savings [kg CO_2 eq]	N/A	67.14	N/A	23.94	N/A	N/A	363.07 337.3



Figures 2 (a) Climate Change Impact and **2 (b)** CO_2-eq savings for Biogas Utilisation Options.

5. Discussion, conclusions and next steps

We have presented the preliminary outputs of the project to evaluate advanced utilisation options for Biogas use, against conventional CHP. The digestate production and utilisation pathways are currently being evaluated using Life Cycle Analysis (LCA). The main conclusion to be drawn from the research at this stage is that the use of the anaerobic Biorefinery concept provides a useful framework for identifying biogas and digestate production and utilisation pathways on a regional basis and providing a framework for the environmental benefits and costs of these to be evaluated.

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