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Pathways to a renewable gas industry in Ireland

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Thesis submitted for the degree of Doctor of Philosophy to the National University of Ireland, Cork

Supervisors: Professor Jerry D. Murphy & Professor Brian Ó'Gallachóir

Head of School: Professor Liam Marnane

September 2017

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Declaration

I, Richard Seen Kong O'Shea, hereby declare that this thesis is my own work and that it has not been submitted for another degree, either at University College Cork (UCC) or elsewhere. Where other sources of information have been used, they have been acknowledged.

Signature: _____

Richard Seen Kong O'Shea

Date: _____

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Abstract

The use of renewable gas produced via the anaerobic digestion of biodegradable material has been mooted as a source of renewable energy in Ireland. The production of renewable gas in power to gas systems could also allow for the storage of significant quantities of excess renewable electricity in the form of methane gas, while demand driven biogas systems could act as a source of controllable and dispatchable renewable electricity. This work aims to assess the scale of these resource in Ireland.

The total theoretical resource of biomethane which could be produced via the anaerobic digestion of waste streams was found to be 12.5PJ equivalent to 6-7% of final energy consumption in transportation and final energy consumption in heat production. Most of this potential resource arose from cattle slurry and was concentrated in the southern and north-eastern regions of Ireland. Initial biomethane plants processing waste streams should use source separated household organic waste and should locate in regions where this resource is highest. Biomethane plants processing waste streams could produce 3.4-3.8 PJ of energy.

The total theoretical resource of biomethane associated with grass silage was found to be 128.4PJ, equivalent to 64% of energy consumption in transport and 72% of energy thermal energy consumption. The majority of the potential grass silage resource is located in western regions of Ireland. Biomethane plants processing grass silage and cattle slurry could provide 12.2PJ of energy. Plant scale, feedstock type, feedstock mixture, gate fees, feedstock price, and incentive value strongly influenced the quantity of biomethane that could be produced.

The use of decentralised anaerobic digestion systems can reduce the energy consumption and greenhouse gas emissions associated with the anaerobic digestion of wet feedstocks such as pig slurry by 21-22% and 18-19% respectively compared to a centralised anaerobic digestion system. This could increase the greenhouse gas emissions savings of biogas, allowing it to meet future stringent sustainability criteria.

Advanced sources of renewable gas such as microalgae (used in anaerobic digestion) and power to gas systems (converting excess renewable electricity into methane gas using biogenic sources of CO_2) could theoretically provide 1.8PJ and 1.4PJ of renewable gas respectively. These systems are technically less advanced, however, power to gas systems present an interesting opportunity for energy storage.

Feeding regimes for a demand driven biogas system to generate electricity at times of high demand, and biomethane outside of these periods were developed using lab scale trials and could inform the operation of full scale plants.

Thesis output

The following chapters have been published or are currently under review in peer-reviewed journals:

Chapter 3:

O'Shea, R., Kilgallon, I., et al., 2016. Quantification and location of a renewable gas industry based on digestion of wastes in Ireland. Applied Energy, 175, pp.229–239. Available at: http://dx.doi.org/10.1016/j.apenergy.2016.05.011.

Chapter 4:

O'Shea, R., Wall, D., Kilgallon, I., et al., 2016. Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise. Applied Energy, 182, pp.394–408. Available at: http://dx.doi.org/10.1016/j.apenergy.2016.08.063.

Chapter 5:

O'Shea, R., Wall, D.M., Kilgallon, I., et al., 2017. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Applied Energy, 188, pp.237–256. Available at: http://dx.doi.org/10.1016/j.apenergy.2016.11.121.

Chapter 6:

O'Shea, R., Wall, D.M. & Murphy, J.D., 2017. An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network. Applied Energy, 208, pp.108–122 Available at:

https://doi.org/10.1016/j.apenergy.2017.10.045

Chapter 7:

O'Shea, R., Wall, D.M. & Murphy, J.D., 2017. Assessing the biomethane resource of microalgae cultivated using carbon dioxide from thermal power stations in a temperate oceanic climate. Algal Research, (under review).

Chapter 8:

O'Shea, R., Wall, D.M., McDonagh, S., et al., 2017. The potential of power to gas to provide green gas utilising existing CO 2 sources from industries, distilleries and wastewater treatment facilities. Renewable Energy, 114, pp.1090–1100. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0960148117307243.

Chapter 9:

O'Shea, R., Wall, D.M. & Murphy, J.D., 2016. Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times. Bioresource Technology, 216, pp.238–249. Available at: http://dx.doi.org/10.1016/j.biortech.2016.05.050.

Contribution to papers

Chapter 3

I was the first author of the paper and was responsible for the data collection, processing, and interpretation of the results.

Chapter 4

I was the first author of the paper. I developed the optimisation model and associated thought process used in the paper and implemented it in MATLAB. I conducted analysis of the results and their interpretation.

Chapter 5

I was the first author of the paper. I determined the resource of grass silage and developed the optimisation mode and associated thought process. I analysed and interpreted the results.

Chapter 6

I was the first author of this paper. I proposed the assessment of the four scenarios of biogas production. I proposed and implemented the method used to assess each scenario.

Chapter 7

I was the first author of this paper. I proposed the design of the study and conducted the assessment. I was responsible for data collection and model implementation, as well as analysing the results.

Chapter 8

I was the first author of this paper. I proposed the study, collected the data required, and carried out the assessment. I interpreted results and presented the findings.

Chapter 9

I was the first author of the paper. I designed the experiment, and operated the laboratory trials, along with the associated monitoring of experimental parameters. Sample collection and preparation was conducted with the aid of my colleagues.

Thesis layout

This thesis has been split in two volumes to facilitate printing. Volume 1 contains Chapter 1 to Chapter 5. Volume 2 contains Chapter 6 to Chapter 10, plus Appendices A, B, C, and D.

1 Chapter 1: Introduction

1.1 Chapter overview

The aim of this chapter is to provide a background for this thesis and to highlight the requirement for indigenous renewable gaseous energy sources that can increase security of supply in the Irish energy system and reduce greenhouse gas (GHG) emissions. The consumption of energy and the emissions of GHGs in Ireland are summarised. The potential role of renewable gas is explored. A brief introduction to the production of renewable gas is included. The aims and objectives of the thesis are stated, and an outline of the chapters of the thesis and their link to one another is given.

1.2 The energy landscape in Ireland

1.2.1 Energy production and consumption

1.2.1.1 Primary energy

Total primary energy requirement (TPER) for Ireland in 2015 (the most recent data at the time of writing) was approximately 581PJ (Howley & Holland 2016), the primary energy requirement of each main energy source, along with the indigenous production of each is outlined in Table 1-1 (Howley & Holland 2016).

Table 1-1: Primary energy demand and indigenous production of main energy sources (Howley & Holland 2016)

Primary Energy Source	Demand	Share of overall energy demand	Indigenous Production	Indigenous share of primary energy source
	PJ	%	PJ	%
Coal	59.7	10.3	0.0	0.0
Peat	31.8	5.5	31.6	99.4
Oil	279.3	48.0	0.0	0.0
Gas	157.5	27.1	4.5	2.9
Renewable	48.1	8.3	42.9	89.2
Non-renewable waste	2.6	0.4	2.6	100.0
Electricity	2.4	0.4	0.0	0.0
Total	581.5	100	81.6	14.0

Indigenous primary energy supply in Ireland (14%) is relatively small, all the coal and oil used in Ireland is imported, 97.1% of natural gas used in Ireland is imported. The only significant indigenous sources of energy available in Ireland are peat, waste, and renewable energy resources. Total primary energy demand of fossil fuels (coal, peat, oil, and natural gas) and non-renewable waste account for 530.9PJ, equivalent to 91.3% of total primary energy requirement. TPER is the total quantity of energy used in a region, this incudes energy used in electricity generation and oil refining, losses in the conversion of chemical energy to electrical energy, and the transmission of electrical energy to an end user. TPER does not always reflect the final use of energy in a region.

1.2.1.2 Final energy

Final energy demand of each main energy source in Ireland is outlined in Table 1-2 (Howley & Holland 2016). Final energy demand (also known as total final consumption (TFC) is the actual quantity of energy consumed by energy end users.

Table 1-2: Final energy demand of the main energy sources in Ireland (Howley & Holland 2016)

Final Energy	**Demand**	**Share of TFC**
	PJ	%
Coal	13.1	2.8
Peat	8.4	1.8
Oil	266.4	56.8
Gas	72.1	15.4
Renewable	17.4	3.7
Non-renewable Waste	1.6	0.3
Electricity	90.3	19.2
Total	469.2	100.0

Oil dominates final energy demand (56.8%), all of which is imported. Electricity and natural gas are the next main contributors to final energy demand. A Sankey diagram outlining the flow of final energy demand to each main energy use sector (based on data in (Howley & Holland 2016)) can be seen in Figure 1-1.

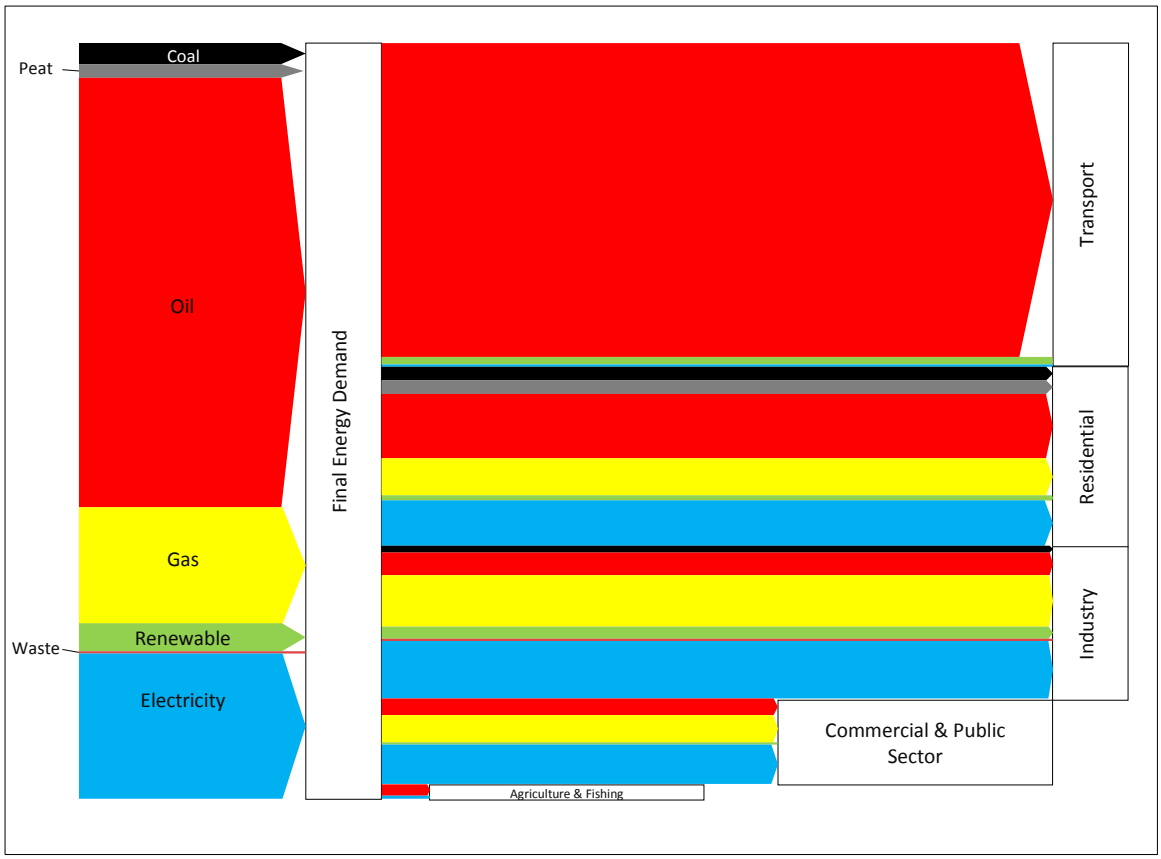


Figure 1-1: Sankey diagram of final energy demand in Ireland, 2015 (Howley & Holland 2016).

Transport has the largest final energy demand (ca. 200PJ) and accounts for 43% of final energy demand in Ireland. Final energy demand in transport is predominantly in the form of oil (97.2%), all of which is imported. Minor shares of renewable energy and electricity are also used in transport. All the electricity used in transport is consumed by rail passenger movements; electric vehicles are a minor consumer of electricity in transportation.

A breakdown of final energy demand in transportation can be seen in Figure 1-2. Final energy demand in transport is mainly in private cars (43%), 52% of private car energy consumption is sourced from diesel, 45% is sourced from petrol, and minor contributions are made by biofuels and liquid petroleum gas. Private car transport energy demand is supplied almost entirely by fossil fuels, ca. 96.8%. Road freight and light goods vehicles combined are responsible for 19% of final energy demand in transport, 96.3% of energy consumed by road freight and light goods vehicles is diesel. Public passenger services make up 2.9% of final energy demand in transport,

12% of energy consumed in public transportation is sourced from petrol (used mainly in taxis) and 85% of energy is sourced from diesel. Rail contributes 1.6% of final energy demand, 91% of which is sourced from diesel and 9% is source from electricity (the only major use of electricity in transport).

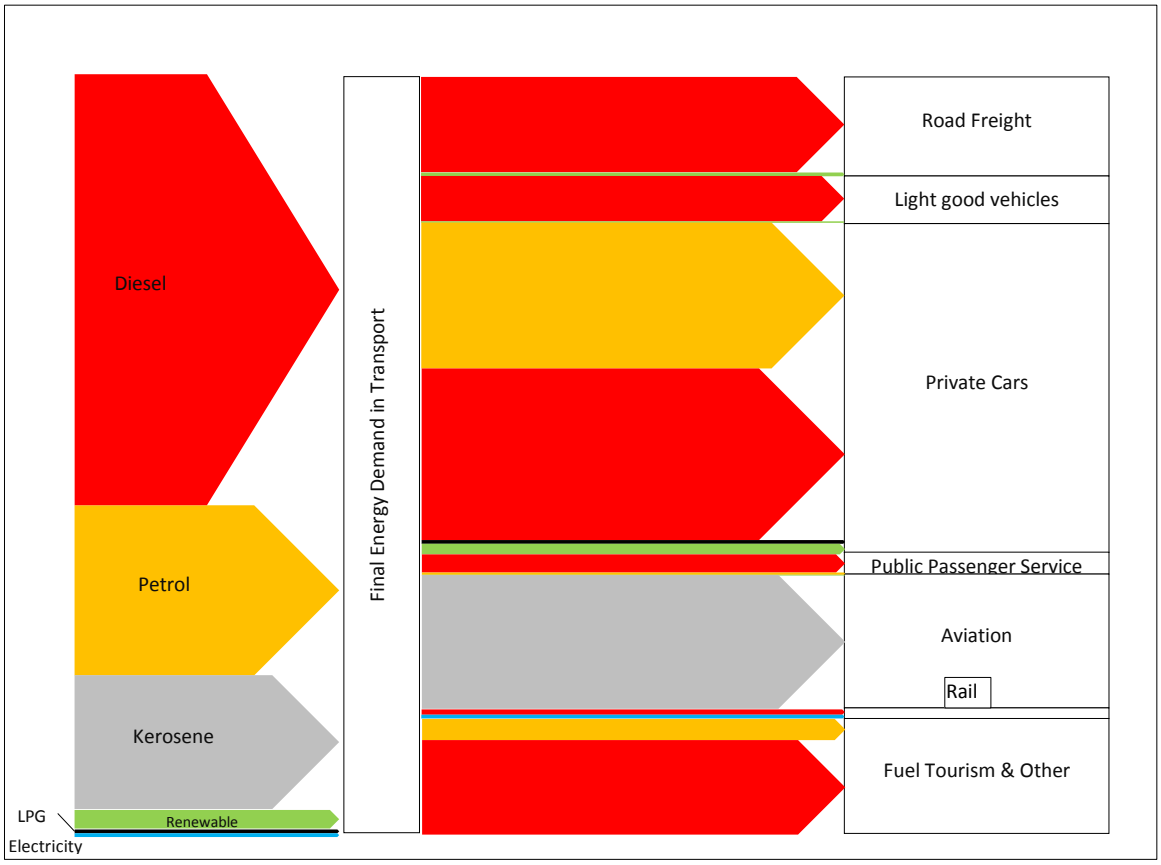


Figure 1-2: Sankey diagram of final energy demand in transport, 2015. Note: Electricity consumption and LPG consumption are enlarged to facilitate viewing. (Howley & Holland 2016)

Residential energy use is the next largest sector in terms of final energy demand (ca. 112PJ) accounting for 24% of final energy demand. Final energy demand in the residential sector is relatively evenly spread between; oil (36%), electricity (25%), natural gas (21%), with smaller contributions of coal and peat (15% combined), and renewable sources (3%). Non-electrical energy consumption in the residential sector was ca. 83PJ, this is primarily used to produce thermal energy for space and water heating. Thermal energy demand in the residential sector is mainly sourced from oil (48%) and natural gas (28%).

Final energy demand in industry (ca. 95PJ) is responsible for 20% of total final energy demand in Ireland. Industrial final energy demand is mainly in the form of electricity (37%) and natural gas (34%). Oil, renewable energy, coal, and non-renewable wastes are also used to meet final energy demand in the industrial sector, primarily for heat production. Industrial final energy demand per subsector can be seen in Figure 1-3. The largest subsectors of industrial energy use are basic metals and fabricated metal products (22%), and the food and beverage sector (20%). Final electrical energy demand in industry was ca. 35PJ corresponding to 37% of overall industrial final energy demand. The remaining non-electrical energy use, 60PJ, is used for the production of thermal energy[1]. Thermal energy demand in industry is mainly supplied by natural gas (54%) and oil (24%).

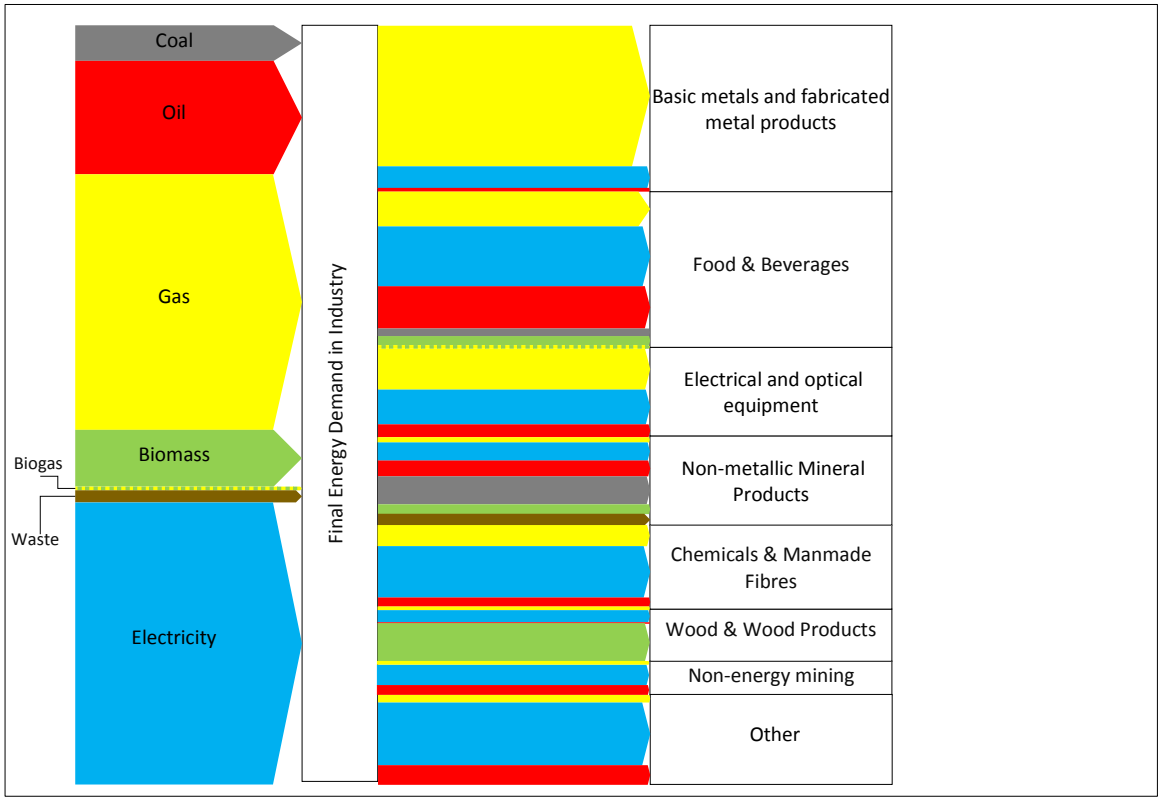


Figure 1-3: Sankey diagram of industrial final energy demand (2015). (Howley & Holland 2016).

[1] This is according to the method used to determine final thermal energy demand employed by the Sustainable Energy Authority of Ireland (SEAI). Final thermal energy demand is calculated as total final energy demand less transport final energy demand and electrical final energy demand

The commercial and public service sectors are responsible for 11% of final energy demand. This is mainly in the form of electricity (46%), followed by natural gas (31%), oil (19%), and renewable sources (3%). Final energy demand in agriculture and fishing contribute 2% of total final energy demand and is principally in the form of oil and electricity, these two sectors are the smallest in terms of final energy demand.

Final energy demand in all sectors in Ireland is chiefly in the form of non-renewable fossil fuels, nearly all of which are imported.

1.2.2 Renewable energy in Ireland

Ireland is legally obliged to ensure that 16% of gross final consumption is sourced from renewable sources in 2020, and must ensure that 10% of energy used in road and rail transportation comes from renewable sources in 2020 according to Directive 2009/29/EC (The European Parliament and the Council of the European Union 2009a). In order to achieve this goal national targets for; electricity from renewable sources (RES-E) of 40%, heat from renewable sources (RES-H) of 12%, and transport energy from renewable sources (RES-T) of 10% were outlined in the National Renewable Energy Action Plan (NREAP) in 2010 (Department of Communications Energy and Natural Resources 2010). As of 2015 RES-E was 25.3%, RES-H was 6.5%, and RES-T was 5.7% (when double weightings are applied to certain biofuels), the overall share of gross final energy consumption from renewable sources was 9.1% (Howley & Holland 2016).

1.2.2.1 Renewable Electricity

Renewable electricity production has increased rapidly in Ireland as a result of a large increase in the installed capacity of on shore wind farms from ca. 1,400MW in 2010 to 2,440MW in 2015 (Howley & Holland 2016). In 2015, 4.8PJ of renewable energy in the form of biomass and renewable waste, landfill gas, and biogas were used in electricity generation, 2.9PJ of electricity was sourced from hydroelectric schemes, and 23.7PJ of electricity was sourced from wind farms (Howley & Holland

2016). Renewable electricity from wind farms provided 21.1% of gross electricity consumption, electricity from hydroelectric schemes provided 2.5% of gross electricity consumption, and biomass and renewable waste, landfill gas, and biogas provided 1.7% of gross electricity consumption (Holland & Howley 2016). Renewable electricity production is likely to achieve the 40% RES-E goal outlined in the NREAP.

1.2.2.2 Renewable Heat

Heat sourced from renewable energy in 2015 was ca. 12PJ, total final thermal demand was ca. 178.8PJ, thus RES-H was ca. 6.7% in 2015 (reported as 6.5% in (Howley & Holland 2016)). The quantity of heat sourced from renewable sources has increased since 1990 from 4.5PJ to 12PJ in 2015, this pales in comparison to the increase in renewable electricity production from wind turbines over the same period (0PJ to 23.7PJ). The consumption of each source of renewable heat per sector is shown in Table 1-3.

Table 1-3: Renewable heat consumption in 2015 (Howley & Holland 2016)

Sector	**Energy consumption (PJ)**				
	Biomass & non-renewable waste	Biogas	Solar	Geothermal	Total
Industry-Food and Beverage	1.1	0.1	0.0	0.0	1.3
Industry-Wood and wood products	4.8	0.0	0.0	0.0	4.8
Industry- Other non-metallic mineral products	1.2	0.0	0.0	0.0	1.2
Residential	1.4	0.0	0.5	1.3	3.2
Commercial	0.7	0.2	0.0	0.6	1.5
Total	9.2	0.4	0.5	1.9	12.0

From a sectoral perspective, 60.8% (7.3PJ) of all renewable heat is used in industry, with 98% of this arising from the use of biomass and non-renewable wastes, and 2% arising from the use of biogas in the food and beverage sub sector. The bulk of renewable energy in industry is used in the wood and wood products subsector, this accounts for 66.2% of all renewable heat used in industry and was sourced entirely from biomass and non-renewable wastes which arose in the wood and

wood products industry. The residential sector has the second largest renewable heat consumption accounting for 26.7% of renewable heat use, 43.8% of renewable heat use in the residential sector is sourced from biomass and non-renewable waste. The commercial and public services sector consume the remaining 12.6% of renewable heat in Ireland, again the majority (46.7%) of this renewable heat is sourced from biomass and non-renewable waste.

In terms of renewable heat sources, biomass and non-renewable wastes are responsible for 76.7% of renewable heat in Ireland, geothermal heat supplies 15.8%, solar thermal supplies 4.5%, and biogas supplies 3.1%. Recent work by the Sustainable Energy Authority of Ireland (SEAI) has found that Ireland is likely to miss the 12% RES-H target by 1.256 - 10.676PJ in 2020, equivalent to 1 - 5 percentage points of a shortfall (Clancy 2015). The lack of significant renewable heat use in sectors other than the wood and wood products industry (in which biomass and renewable wastes are an easy to source by-product) shows that little progress has been made in promoting the wider adoption of renewable heat in Ireland.

1.2.2.3 Renewable Transport

Energy from renewable sources used in transport amounted to ca. 5.4PJ in 2015, this corresponds to 3.3% RES-T on an energy basis (Howley & Holland 2016). Second generation biofuels (originating from wastes and non-food sources) and third generation biofuels (algae) are allocated double their contribution in terms of energy content in the calculation of the progress to the 10% RES-T target. Taking this into consideration the RES-T share increased to 5.7% (Howley & Holland 2016). Double weighting does not apply in the calculation of progress to the overall target of 16% of gross final energy consumption from renewable sources.

Within Ireland the Biofuel Obligation Scheme (BOS) mandates that fuel suppliers ensure that a certain percentage of the fuel they sell by volume is classified as a renewable fuel, for 2016 this was 6% (Byrne Ó'Cléirigh & LMH Casey McGrath 2017). As a result of BOS much of the fuel purchased at garage forecourts is a blend of fossil fuel and a liquid biofuel. Progress toward meeting the 10% RES-T goal is

satisfactory, however, as can be seen in Figure 1-4 (adapted from (Byrne Ó'Cléirigh & LMH Casey McGrath 2016)) Ireland is achieving this progress through the use of imported liquid biofuels.

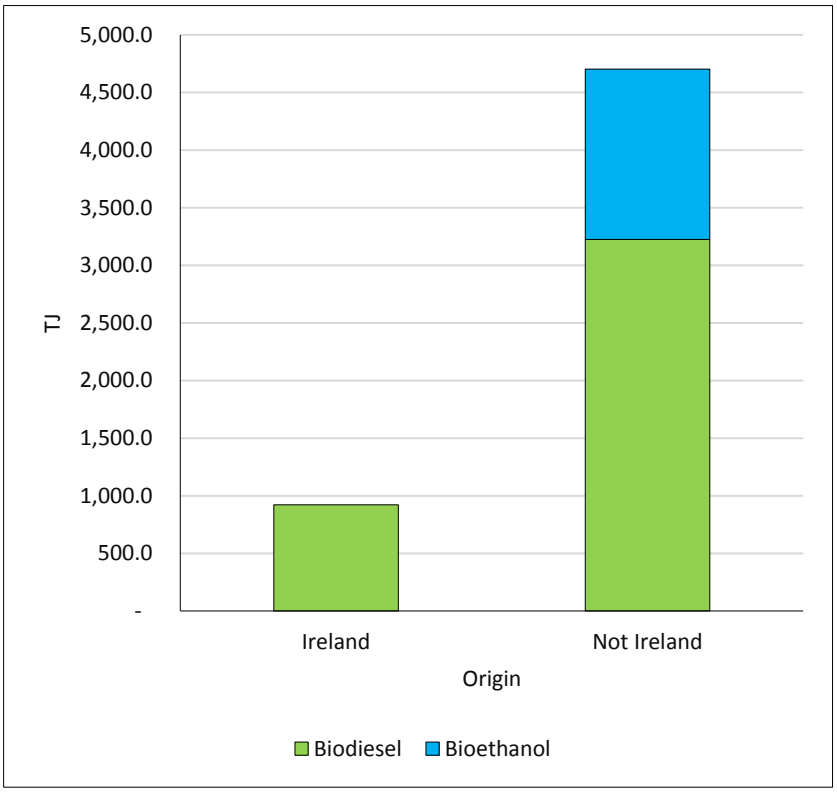


Figure 1-4: Origin of liquid biofuel used in Ireland, 2015 (Byrne Ó'Cléirigh & LMH Casey McGrath 2016)

The total quantity of liquid biofuels used in Ireland in 2015 was ca. 195,987m^3 consisting of 70,379m^3 of bioethanol (all of which was imported) and 125,607m^3 of biodiesel (27,905m^3 produced in Ireland from used cooking oil and tallow) (Byrne Ó'Cléirigh & LMH Casey McGrath 2016). Using an energy content of 21$MJ.L^{-1}$ for bioethanol and 33$MJ.L^{-1}$ for biodiesel as per directive 2009/28/EC (The European Parliament and the Council of the European Union 2009a) the total energy sourced from liquid biofuels was 5.6PJ (1.5PJ of bioethanol and 4.1PJ of biodiesel), this is slightly higher than the values reported in (Howley & Holland 2016).

Indigenous biofuel production accounted for 22.2% of biodiesel consumption and 16.4% of total biofuel consumption in 2015 (on an energy basis). Ireland is meeting

the requirement for renewable transport fuel through the use of imports while producing a limited amount of biofuel from indigenous wastes.

1.3 Irish greenhouse gas production

1.3.1 Total greenhouse gas production

The total emissions of greenhouse gases in Ireland for 2015 was ca. 58.5MtCO_2eq, disaggregated Irish GHG emissions can be seen in Figure 1-5 (Adapted from (Duffy et al. 2017) and data from the Common Reporting Format (United Nations Framework Convention on Climate Change 2017)).

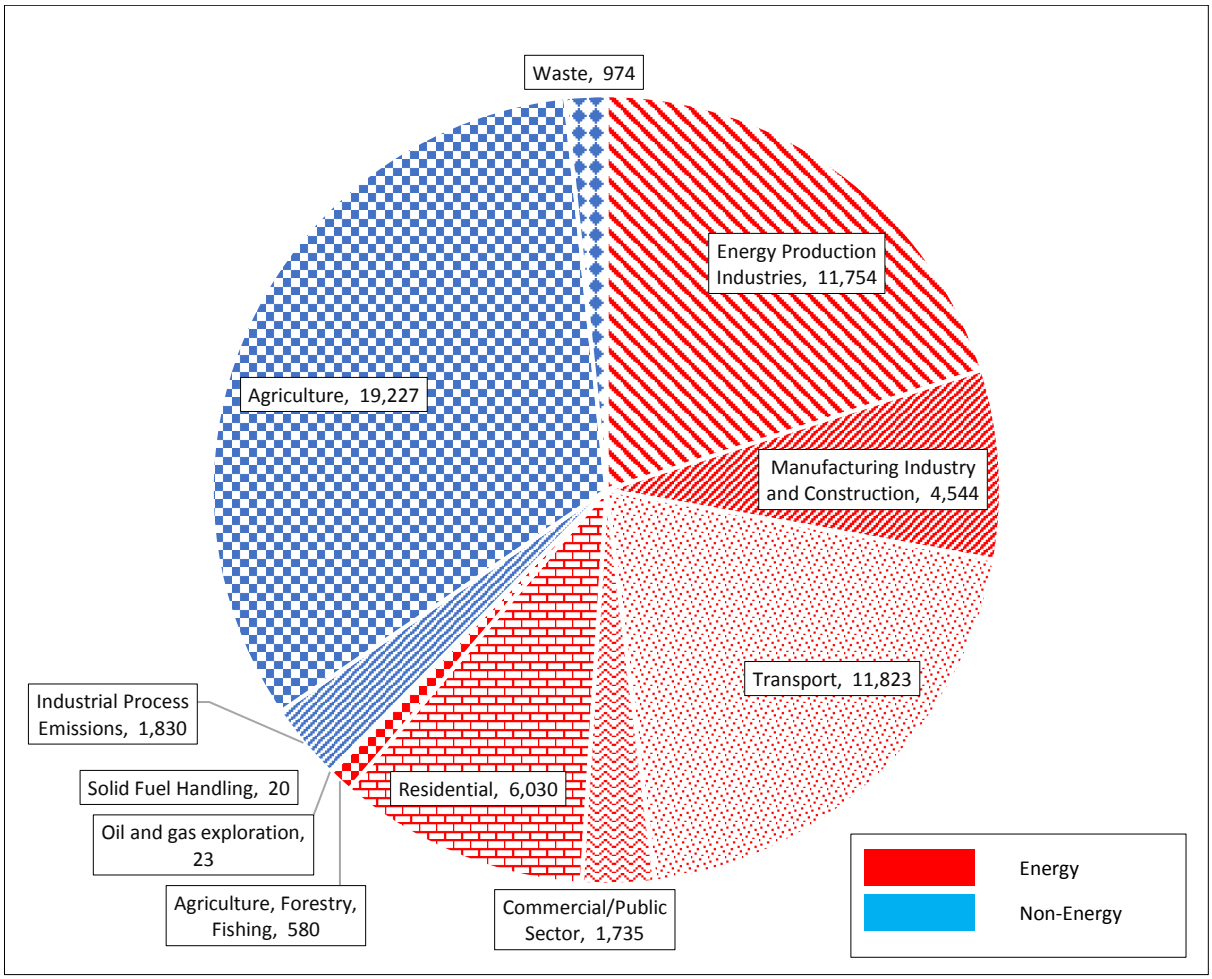


Figure 1-5: Total greenhouse gas emissions in Ireland, 2015. Units are ktCO_2eq, (United Nations Framework Convention on Climate Change 2017)

Energy related activities were responsible for 62% of GHG emissions in 2015, the largest contributors to energy related CO_2eq emissions were transportation (32% of energy related GHG emissions) and energy production industries[2] (32% of energy related GHG emissions). Residential energy consumption was responsible for 17% of energy related GHG emissions while manufacturing was responsible for 12% of energy related GHG emissions. Non-energy activities were responsible for 38% of total GHG emissions in 2015 and agriculture was responsible for 87% of all non-energy GHG emissions in 2015.

In terms of total GHG emissions agriculture was the single largest emitter, responsible for 33% of all GHG emissions in 2015. Transportation and energy production industries were the next largest emitters of GHG in Ireland, responsible for 20% of total GHG emissions respectively.

1.3.2 Greenhouse Gas Reduction Requirements

According to the Doha Amendment to the Kyoto protocol (Directive 2015/1339), Ireland is required to emit 20% fewer GHGs in 2020 than was emitted in the base year of 1990 (European Council 2015). Within Ireland, certain sources of GHGs are under the remit of the European Union Emissions Trading System (EU ETS), these emitters of GHGs are legally obliged to reduce their GHG emissions by 21% relative to 2005 by 2020, Directive 2009/29/EC (The European Parliament and the Council of the European Union 2009b).

The total verified GHG emissions by installations under the remit of the EU ETS in 2015 was ca. 16,829.7 ktCO_2eq (adapted from (European Commission 2017)). Facilities participating in the EU ETS include those in the energy production industry, large energy users in the manufacturing industry, and aviation operations. The total verified GHG emissions in 2015 from facilities participating in the EU ETS in the energy production industry were 11,546 ktCO_2eq (adapted from (European Commission 2017)), this represents ca. 98% of total emissions from the energy

[2] Energy production industries include electricity production at large power stations, oil refining, and the manufacturing of solid fuels (primarily peat derived products).

production sector. As such, GHG emissions in the energy production sector are almost fully under the remit of the EU ETS and their reduction is the responsibility of facility owners.

1.3.3 Non Emissions Trading System Emissions

Subtracting the ETS emissions from total GHG emissions in 2015 results in non-ETS sector emissions of ca. 41,710.2ktCO_2eq, this is 3% lower than the value for non-ETS emissions supplied by the Irish Environmental Protection Agency (EPA) of 43,037ktCO_2eq for 2015 (Environmental Protection Agency 2017). The non-ETS sector in Ireland is predominantly comprised of agriculture (46%), transport (28%), and the residential sector (14%). By 2020 Ireland as a nation is required to reduce non-ETS GHG emissions by 20% relative to 2005, Directive 406/2009/EC (European Parliament and the Council of the European Union 2009). Opportunities to reduce GHG emissions in agriculture are limited owing to the nature of GHG emissions in Irish agriculture as outlined by Figure 1-6.

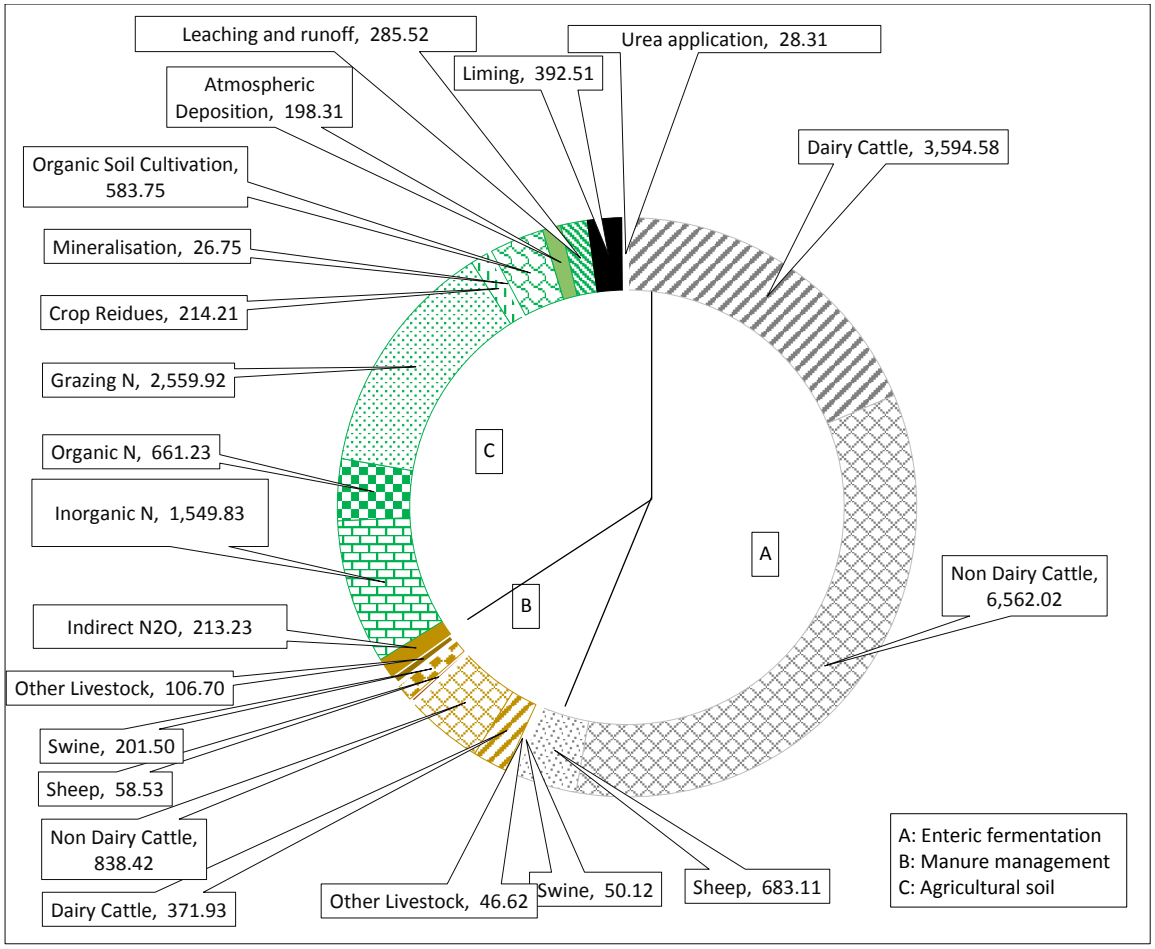


Figure 1-6: Greenhouse Gas Emissions in Agriculture, 2015. Units are $ktCO_2eq$. Adapted from (United Nations Framework Convention on Climate Change 2017).

The main source of GHG emissions in agriculture is enteric fermentation in ruminants (57% of agricultural GHG emissions), these emissions are primarily in the form of methane (CH_4) and are a result of the digestion of carbohydrates by livestock. Limited opportunities exist for to reduce enteric methane emissions from ruminants, recent research has indicated the potential of dietary supplements to reduce CH_4 production in ruminants, specifically cattle. Alteration of cattle feed intake to reduce CH_4 emissions may include; increasing grain consumption, supplementation with lipids, supplementation with dried distiller's grains, and the addition of macroalgae to diets (Beauchemin 2009; Machado et al. 2014). Issues remain with ensuring that alteration of diet to reduce CH_4 production does not impede cattle feed conversion efficiency (Beauchemin 2009).

The next largest contributor to GHG emissions in agriculture are agricultural soils which contribute 32% of total GHG emissions in agriculture. The main sources of GHGs from agricultural soils are nitrous oxide (N_2O) emissions associated with nitrogen contained in urine and faeces deposited by grazing livestock, inorganic fertiliser application, and organic fertiliser application. Little can be done to reduce GHG emissions associated with nitrogen deposited by livestock while grazing. Manure management results in the emission of GHGs during the storage of animal manures and slurries in slurry pits and is responsible for ca. 9% of GHG emissions in agriculture. The use of manures and slurries in anaerobic digestion to produce a renewable gaseous energy source is a potential method to alleviate some of the GHG emissions associated with manure management.

Owing to the limited opportunities to reduce GHG emissions in agriculture inspection of GHG emissions airing in transportation is warranted. Greenhouse gas emissions (non-ETS) from transportation in 2015 are outlined in Figure 1-7.

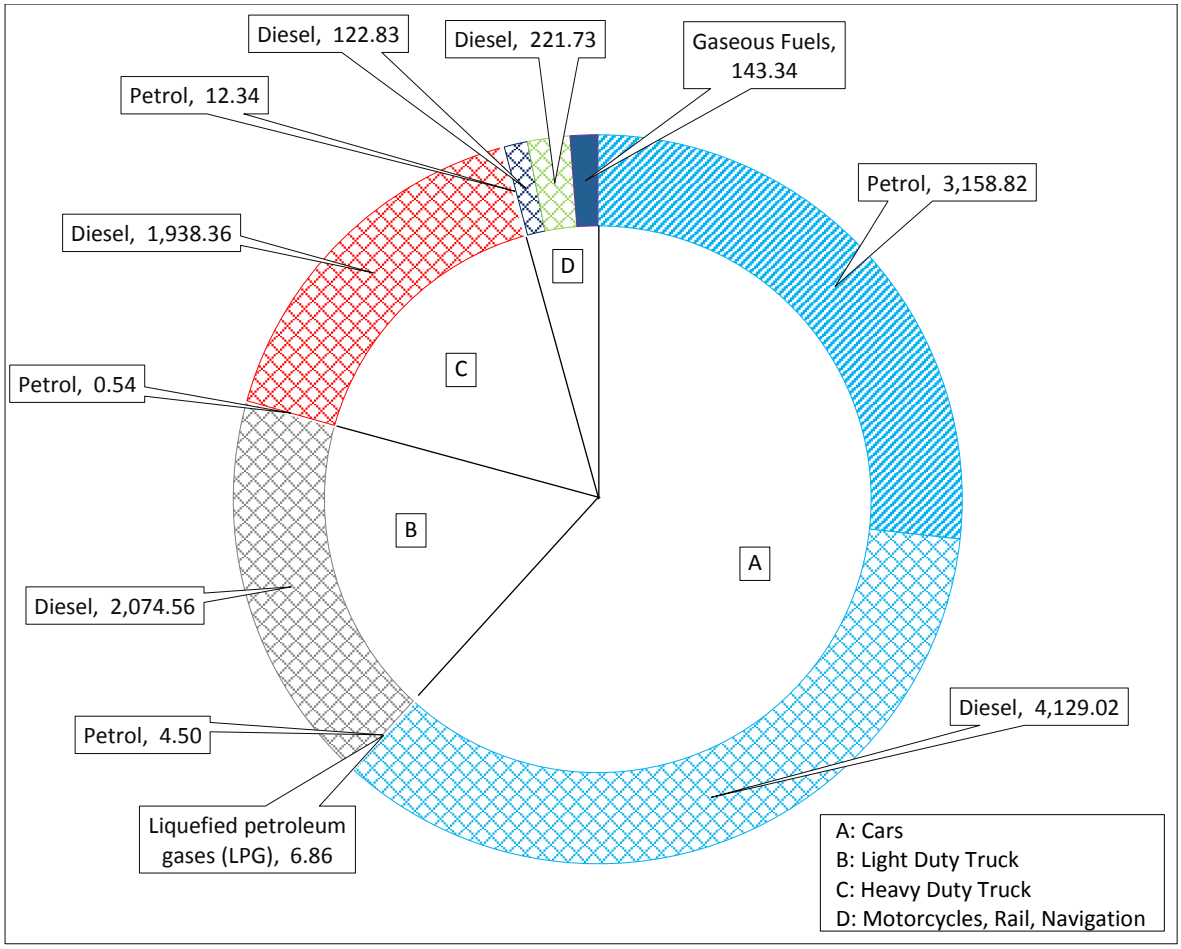


Figure 1-7: Non-emissions trading scheme greenhouse gas emissions in transport (2015). Units are $ktCO_2eq$. Adapted from (United Nations Framework Convention on Climate Change 2017).

Cars are responsible for 62% of non-ETS transport emissions in Ireland, light duty trucks and heavy duty trucks are responsible for 18% and 16% of non-ETS transport emissions in Ireland. A minor share of emission arises from the use of motorcycles, rail, and waterway navigation. Regarding fuels used in transportation, petrol is responsible for 27% of emissions in transportation and is only a major contributor to GHG emissions from cars. The majority (73%) of GHG emissions in transportation are a result of diesel consumption, 51% of diesel emissions originate from cars, 49% of diesel emissions originate from light and heavy duty trucks combined. Reduction in GHG emissions from transportation is required if Ireland is to meet the 20% reduction in non-ETS emissions in 2020 relative to 2005. The requirement for GHG reductions in energy related non-ETS sectors is compounded by the large quantity

of GHG emissions arising in agriculture and the limited opportunities to reduce these.

1.4 The role of renewable energy in future energy systems

The prior sections detailed the current state of play in the Irish energy system in relation to renewable energy use. A key driver of the growth of renewable energy use is the commitment by the EU to reduce GHG emissions by 80-95% compared to 1990 levels (European Commission 2011).

Based on this commitment a number of studies were conducted at a pan European level in order to assess possible pathways to achieving this reduction in GHG emissions (Capros et al. 2012b; Capros et al. 2012a; Capros et al. 2014). Results of the work showed that achievement of the 80% GHG reduction target at a European scale was possible with the largest part of emission reductions resulting from the shift toward carbon free energy sources such as renewables, the overall consumption of oil and gas were found to reduce by 80% and 60% respectively (Capros et al. 2012a; Capros et al. 2012b). The use of renewable energy sources was found to increase in all sectors, with the highest increase modelled in the transportation sector, predicated by the use of biofuels especially in long distance road transport of freight owing to the difficulty of electrifying this mode of transport. Renewable energy sources was also found to increase markedly in the generation of electricity (51% of generation in 2050) and in the production of thermal energy (Capros et al. 2012b). Within the power generation sector surplus renewable electricity production was converted to hydrogen in power to gas systems as this was found to be the cost-effective use of excess renewable electricity. The resulting hydrogen was blended with natural gas and enabled for emission reductions to be realised in sectors where substitution with non-gaseous renewable fuels was difficult (Capros et al. 2012a).

At a national level work by Chiodi et al. found that in order for Ireland to achieve an 80% reduction in GHG emissions the sectors that require the greatest degree of GHG emission reduction are transportation (97.6% reduction), power generation (83.4% reduction), and energy used by industry (93.7% reduction) compared to a

business as usual scenario (Chiodi et al. 2013). Within the transportation sector, emission reductions were found to be a result of increased efficiency, the electrification of passenger vehicles, and the use of biomethane and imported biofuels in freight transportation and in the public transport sector (Chiodi et al. 2013). Renewable energy sources, namely biomass and biomethane were also found to play a major role in the provision of thermal energy to the industrial and residential sectors, in addition to increased electrification of thermal energy production in these sectors. The use of renewable energy sources (predominantly non-dispatchable on-shore and off-shore wind turbines) in power generation was found to increase to 70% of total electricity production in 2050, along with dispatchable electricity production from biomass and biogas (Chiodi et al. 2013).
Owing to the potentially large role of bioenergy in the future energy system in Ireland additional work by Chiodi et al. assessed the implications of applying EU wide sustainability criteria on liquid biofuels and the implications of limiting the use of imported sources of bioenergy on the future energy system when required to reduce GHG emissions by 80% relatives to 1990 levels in 2050 (Chiodi et al. 2015). In a case of unconstrained bioenergy use renewable energy consumption in transport accounted for 81% of total energy use and was found to consist of biomethane (28%), bioethanol (34%), biodiesel (28%), and bio-DME (10%). Renewable energy consumption in thermal energy production accounted for 61% of energy consumption predominantly sourced from solid biomass and biogas (Chiodi et al. 2015).
Application of sustainability criteria to imported biodiesel used in transportation resulted in a lower total consumption of bioenergy in transportation in 2050, however, the actual consumption of bioethanol and biomethane increased. The use of bioenergy in thermal energy production also showed a reduction when sustainability criteria were implemented, however biogas was still found to play a significant role in the provision of renewable thermal energy (Chiodi et al. 2015). Limiting the import of bioenergy to Ireland resulted in a significant reduction in total bioenergy use in transportation compared to the unconstrained scenario, however, the remaining bioenergy used in transportation was almost entirely

comprised of biomethane. Solid biomass supplied the bulk of bioenergy used in thermal energy production however biogas remained a significant contributor. Further work assessing the implications of sustainability criteria on the role of bioenergy in Ireland's future energy system was conducted by Czyrnek-Delêtre et al. in which the impact of including or not including both direct and indirect land use change emissions on the role of bioenergy was assessed (Czyrnek-Delêtre et al. 2016). The results of the work indicated that the role of bioenergy in Ireland's future energy system varies dramatically depending on whether direct or indirect land use change emissions are included, and in the case of indirect land use change, the level of indirect land use change emissions. Results indicated that the main source of renewable energy used in transportation and thermal energy production was bioenergy. Within freight transportation sector liquid biofuels and biomethane represented the major source of renewable energy used while the main sources of renewable thermal energy were solid biomass and biomethane (Czyrnek-Delêtre et al. 2016). Inclusion of direct land use change emissions did not impede the development of bioenergy as a renewable energy resource in 2050 which increased to 40% of primary energy requirement in Ireland in 2050, predominantly in the form of imported land based feedstocks. When optimistic indirect land use emissions were considered the total consumption of bioenergy reduced compared to when only direct land use change emissions were considered, predominantly a result of the reduction in solid biomass use. The use of biomethane derived from grass silage however increased markedly in this scenario and contributed 31% of total bioenergy consumption (Czyrnek-Delêtre et al. 2016).

A key conclusion of the above works is that although the optimal future energy system is highly dependent on the constraints and assumptions applied in each study a number of common trends are present within each analysis;

i. The use of certain fossil fuels persists into the future, predominantly in the form of natural gas combined with carbon capture and storage for power generation (Capros et al. 2012b; Capros et al. 2012a; Chiodi et al. 2013).
ii. The use of renewable energy sources was found to increase significantly in all assessments conducted, the exact share of each renewable energy

used and where each source was used varied (Capros et al. 2012b; Capros et al. 2012a; Chiodi et al. 2013).

iii. Bioenergy plays a vital role in the transportation sector. A common conclusion in the transportation sector is the use of liquid biofuels and biomethane in the freight transportation sector owing to the difficulties in electrification of this sector (Capros et al. 2012b; Capros et al. 2012a; Chiodi et al. 2013; Chiodi et al. 2015). In the provision of thermal energy, the implementation of efficiency measures, electrification, and bioenergy use all occur. The use of bioenergy is found to be dominated by sold biomass, with a small but still significant role filled by biomethane in all assessments.

iv. The role of the natural gas network to act as a storage mechanism for excess renewable electricity via conversion to hydrogen and the subsequent injection to the gas network was highlighted at a pan European level (Capros et al. 2012b; Capros et al. 2012a).

Owing to the ubiquitous presence of renewable gaseous fuels in potential future energy systems in Ireland, the following section outlines the possible role of renewable gas in Ireland in greater detail in relation to current fossil fuel and renewable energy demand.

1.5 The potential role of renewable gas

1.5.1 Use as a transport fuel

As outlined in prior sections the single largest share of final energy demand in Ireland is transport, it is also the second largest overall emitter of GHGs in Ireland, and is the largest source of energy related GHG emissions in Ireland. Currently Ireland is utilising renewable biofuels in transport to meet the 10% RES-T goal, and the overall 16% RES goal. As these biofuels are sustainable this aids in reducing overall GHG emissions in transport a main source of non-ETS sector emissions. At present Ireland imports 83.6% of all biofuels on an energy basis, as such, Ireland is dependent on non-domestic sources of renewable transport fuel.

The use of electricity in transportation is encouraged through a weighting of 2.5 applied to the share of electricity used in transport that comes from renewable sources. Ireland initially aimed to convert 10% of the light commercial vehicles and private cars to electric vehicles (230,000 vehicles) by 2020 (Dineen et al. 2014), owing to slow uptake (a total of ca. 1,000 electric vehicles in 2015 (Scheer et al. 2016)) the goal was reduced to 50,000 electric vehicles by 2020 (Dineen et al. 2014).

Average annual mileage of a private car in Ireland is 17,396km (Dineen et al. 2014), specific energy consumption of a Nissan Leaf (electric vehicle) is 150Wh.km^{-1} (Nissan 2017), thus a Nissan Leaf would consume 2,609.4kWh.year^{-1}. The target goal of 50,000 Nissan Leafs would consume 130,470MWh.year^{-1} (0.47PJ), the share of renewable electricity in 2015 was 25.3%, thus 33,009MWh.year^{-1} (0.12PJ) of renewable electricity would be used. On an energy basis, this would be 0.06% of energy used in road and rail transportation (in 2015), application of the weighting factor of 2.5 results in 0.15% RES-T (in 2015). Projected electric vehicle numbers will have a minor role in supplying renewable energy to transport.

Directive 2014/94/EU stipulates that EU member states should provide refuelling points to allow for the use of compressed natural gas (CNG) in motor vehicles, the maximum suggested distance between such refuelling points should be ca. 150 km (The European Parliament and the Council of the European Union 2014). In line with this requirement, Gas Networks Ireland (GNI) who own and operate the gas network in Ireland have launched the Causeway Project which aims to install 14 fast fill CNG refuelling stations in Ireland (Gas Networks Ireland 2017b). GNI have a target of supplying 5% of the transport energy demand in commercial fleets, and 10% of transport energy demand in bus fleets from CNG by 2025, with a long term goal of 70 refuelling stations also in place (Gas Networks Ireland 2016). This proposed development of a market for gaseous fuels in transportation would allow for the use of renewable gas (which can include biomethane sourced from anaerobic digestion) as a transport fuel.

The use of indigenously produced renewable gas in transport would; increase the share of renewable energy used in transport (RES-T), reduce the dependency on

imported sources of energy in the transport sector, and would reduce GHG emissions in the transport sector, thus contributing to the overall 20% GHG reduction target in non-ETS sectors.

From the perspective of a transport fuel supplier, the provision of renewable gas as a transport fuel is incentivised in the BOS. Gaseous biofuels with a net energy value greater than 35MJ.Nm^{-3} benefit from a gas to liquid conversion factor of 1.5, as decided by the National Oil Reserve Agency (NORA). Biofuel obligation certificates (BOCs) are issued to transport fuel suppliers and consumers for each litre of biofuel dispensed by the biofuel obligation account holder. Two BOCs are issued for each litre of biofuel produced from second or third generation substrates such as waste materials. Thus a cubic meter of gaseous biofuel produced from these feedstocks is eligible for 3 BOCs (The National Oil Reserve Agency 2015).

It is therefore necessary to assess the resource potential of renewable gaseous fuels within Ireland to determine the share of energy use in transport that can be supplied.

1.5.2 Use as a source of renewable heat

Prior sections have outlined the lack of development of a renewable heat industry in Ireland outside of the wood and wood products industry. The final consumption of thermal energy in Ireland in 2015 was alluded to in prior sections, a breakdown of final thermal energy use can be seen in Figure 1-8 (adapted from (Howley & Holland 2016)).

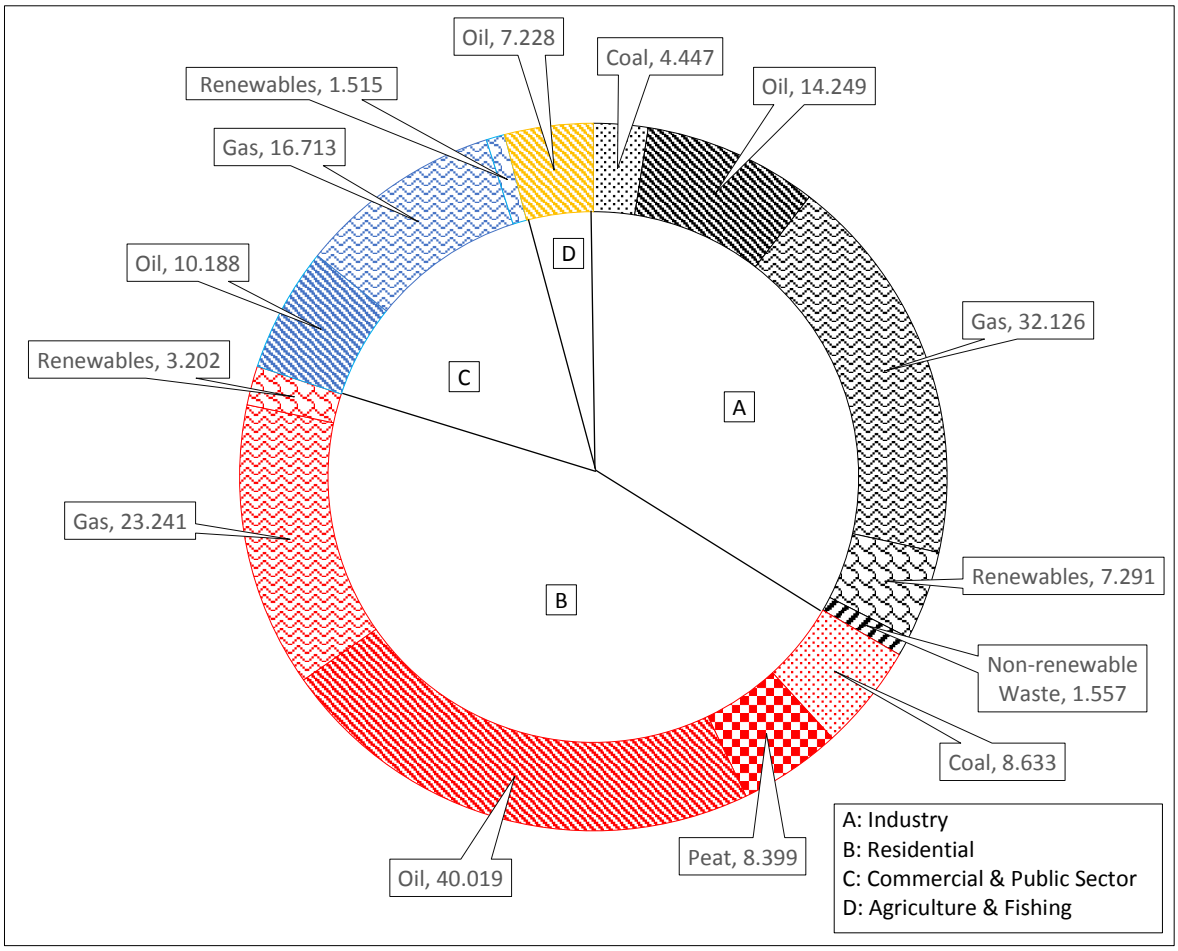


Figure 1-8: Final thermal energy demand, 2015 (Howley & Holland 2016). Units are in PJ.

The largest sources of thermal energy in 2015 were natural gas (40%) and oil (40%). Natural gas is transported to end user via the natural gas network in Ireland which is 13,772km in length and can be seen in Figure 1-9 (Gas Networks Ireland 2016), oil is transported to end users via the road network in oil tankers.



Figure 1-9: Natural gas network in Ireland (Gas Networks Ireland 2016)

The largest sector in terms of final thermal energy demand is the residential sector (47%), followed by the industrial sector (33%). Within the industrial sector, natural gas is the largest source of thermal energy, responsible for 54% of thermal energy.

The ubiquitous nature of natural gas in thermal energy production provides access to an existing market for renewable gaseous fuels in Ireland. An added benefit of supplying renewable gas as a source of thermal energy is the ability to use existing infrastructure and end user equipment. Renewable gas (when injected to the natural gas network and compliant with grid specifications) can be used in existing gas boilers. Providing renewable gas as a source of renewable heat would aid in meeting the 12% RES-H target in 2020 and would also contribute towards meeting the 16% RES goal in 2020.

Depending on the end user of the renewable gas it could also aid in reducing GHG emissions in the ETS or non-ETS sectors. If renewable gas is used to produce thermal energy in a facility under the remit of the ETS then GHG savings will aid the facility in meeting the required GHG reduction of 21% in 2020. If the renewable gas

is used in a non-ETS sector e.g. the residential sector, GHG savings will contribute to the national target of reducing non-ETS emissions by 20% in 2020. GNI aim to have 20% of gas in the network sourced from renewable sources by 2030 (Gas Networks Ireland 2016) and are cognisant of the suitability of renewable gas as a source of thermal energy for large consumers of heat in the food processing, brewing and distilling, and pharmaceutical sectors.

These large thermal energy consumers are typically part of the ETS , the emissions of GHGs from these large energy users in the ETS are calculated as the product of fuel consumption, emissions factor, and oxidation factor (European Parliament and the Council of the European Union 2014). Emissions associated with electricity imported from the electricity network are not included as these emissions are already counted in ETS facilities within the power generation sector. For a large thermal energy user in the ETS (e.g. a brewery) to reduce its GHG emissions it must either reduce the total quantity of fossil fuel burned, or, use renewable fuels. As the largest non-electrical source of energy in industry is natural gas, replacement of this natural gas with renewable gas is a potential method for these facilities to reduce their GHG emissions without altering their heat production equipment. Unilever recently announced plans to source 10,000MWh of biomethane to supply a number of their facilities in the UK and Ireland, including a manufacturing facility in Cork, Ireland (Unilever 2017). Demand for renewable gas in industry does currently exist.

Assessing the resource of renewable gas in Ireland is required to determine the potential contribution toward thermal energy demand that can be made.

1.5.3 Renewable gas as a method of reducing greenhouse gas emissions in agriculture

As highlighted previously the main source of GHG emissions in the non Emissions Trading System sector in Ireland is agriculture. Agriculture was responsible for the emission of 19,277ktCO2eq of GHGs in 2015 (United Nations Framework Convention on Climate Change 2017). As outlined in prior sections the largest source of GHG emissions in agriculture is methane arising from enteric

fermentation in ruminants (57%), followed by agricultural soils (34%) and manure management (9%).

The total emission of GHGs from the management of manures and slurries in Ireland was approximately 1,790ktCO_2eq in 2015. The majority of the emissions associated with manures and slurries were associated with the management of cattle slurry (1,210 ktCO_2eq in 2015), mainly as a result of the storage of cattle slurry in slurry pits on farms. Cattle slurry is a suitable feedstock for the production of renewable gaseous fuels via anaerobic digestion. Treatment of cattle slurry in anaerobic digesters would result in the avoidance of GHG emissions that would have occurred if the slurry was stored in a slurry pit, equivalent to 6.3% of total GHG emissions in agriculture.

As highlighted in prior sections, the options available to reduce GHG emissions in Irish agriculture are limited owing to the major role played by methane emissions arising from enteric fermentation. While there are methods available to reduce methane emissions from enteric fermentation (supplementation of diet with grains, lipids, distiller's grains, and microalgae) they all result in an increase in feed cost, the primary source of fodder in Ireland is grass and grass silage which is both low cost and high quality. Anaerobic digestion of cattle slurry offers a means of reducing GHG emissions in agriculture while also allowing for the production of renewable gaseous fuels.

In addition to avoided GHG emissions from manure and slurry storage, anaerobic digestion is also a recognised method of treating nitrogenous livestock slurries, the effluent or digestate remaining after anaerobic digestion is a viable fertiliser and can be utilised subject to hygienisation requirements where applicable. Use of digestate can aid in offsetting the requirements for industrially manufactured fertilisers which have a high GHG emission intensity associated with their production and supply (eg. 4,572gCO_2eq/kg N-fertiliser) (Edwards et al. 2017) .

The suitability of anaerobic digestion to treat nitrogenous livestock slurries has been realised in "Le Plan Énergie Méthanisation Autonomie Azote" in France which highlights the benefits of anaerobic digestion of livestock slurries as being; the production of renewable energy to promote farm-level energy autonomy, the substitution of fossil fuels and fertiliser to reduce on farm costs, an improvement

of the greenhouse gas balance of farms through the mitigation of methane emissions from livestock slurries and through the reduced use of fossil fuels and synthetic fertiliser (Ministère de l'Écologie du Developpement Durable et de L' Énergie 2013). As such, the production of renewable gaseous fuel via the anaerobic digestion of livestock slurries can have added benefits to the agricultural sector in addition to the production of renewable energy.

1.6 Production of renewable gas

1.6.1 Renewable gas in the form of biomethane from anaerobic digestion

Interest in the production of renewable gas is present in other European countries, 7 gas transmission operators have already signed a joint declaration to supply 100% CO_2 neutral gas by 2050 (De Buck et al. 2015). A key route to achieving this is the utilisation of biomethane from biogas produced through the anaerobic digestion (AD) of biodegradable materials including (but not limited to) wastes, energy crops, and algae. Anaerobic digestion is a biological process involving a range of microbial populations, in which biodegradable material is converted into biogas, a mixture of CH_4, CO_2, and trace gases such as H_2S. An overview of the anaerobic digestion process for biogas production can be found in the literature (Wellinger et al. 2013; Al Seadi et al. 2013; Gerardi 2003).

The biogas produced from AD must be processed before injection into the gas network. Wet, un-processed biogas leaving a digester is saturated with water vapour, this is removed via passive cooling of the biogas in buried biogas pipes, or through the use of gas coolers (Al Seadi et al. 2013; Petersson 2013). Removal of water from biogas also facilitates the removal of ammonia from the biogas as this dissolves in the water removed (Petersson 2013).

Dry raw biogas is then cleaned to remove H_2S. This is achieved via; controlled dosing of air or oxygen to the anaerobic digester to facilitate the growth of sulphur oxidising bacteria, passing the biogas through a biofilter in which sulphur oxidising bacteria are present, addition of iron containing compounds to the AD reactor ($FeCl_2$, $FeCl_3$, $FeCO_4$), passing the biogas through a aqueous solution (containing

NaOH, $FeCl_2$, or $Fe(OH)_3$), passing the biogas through activated carbon filters, or any combination of the above (Al Seadi et al. 2013; Petersson 2013).

Dry de-sulphurised biogas is then upgraded to increase the volumetric energy content of the gas, this is achieved through the removal of CO_2 from the biogas and can be carried out in a number of ways including; pressure swing adsorption, water scrubbing, chemical scrubbing, cryogenic separation, and membrane separation (Petersson 2013; Beil & Beyrich 2013; Bauer et al. 2013). Following the removal of CO_2, biogas is then classified as biomethane (renewable gas) and can be compressed and injected into the gas network if it meets the relevant gas quality specifications. The quality specifications for natural gas entering the Irish natural gas network are shown in Table 1-4 (Gas Networks Ireland 2017a).

Table 1-4: Natural gas specifications for network injection (Gas Networks Ireland 2017a).

Parameter	**Unit**	**Value**	**Comment**
Total sulphur (including hydrogen sulphide)	$mg.m^{-3}$	<50	
Oxygen	mol %	<0.2	
Carbon dioxide	mol %	<2.5	
Hydrogen sulphide	$mg.m^{-3}$	<5	
Water	$mg.m^{-3}$	<50	
Gross calorific value	$MJ.m^{-3}$	36.9-42.3	
Wobbe index	$MJ.m^{-3}$	47.2-51.41	
Incomplete combustion factor	Na	<0.48	
Temperature	°C	1-38	
Hydrogen	mol %	<0.1	
Soot index	Na	<0.6	
Organo halides	$mg.m^{-3}$	<1.5	
Radioactivity	$Becquerels.g^{-1}$	<5	
Ethane	mol %	<12	
Nitrogen	mol %	<5	
Hydrocarbon dewpoint	°C	<-2	Up to $85Bar_{gauge}$

An added benefit of anaerobic digestion for biogas production is the ability to alter the feeding regime or to store the produced biogas and use it as a source of renewable electricity during times of high electricity demand (such as during the morning or evening). These so-called demand driven biogas systems can provide a

controllable source of renewable electricity, as opposed to wind turbines (the main source of renewable electricity in Ireland), which cannot be deployed on demand. Outside of periods with a high electricity demand the biogas can be sent to an upgrading process to produce biomethane.

The production of renewable gas in the form of biomethane from anaerobic digestion is a mature technology, as of 2016 there were ca. 17,376 biogas plant in Europe and 459 biomethane plants (European Biogas Association 2016). The United Kingdom, Ireland's closet neighbour in Europe, had 81 biomethane projects injecting 3.75TWh.year^{-1} (13.5PJ.year^{-1}) of biomethane to the gas network as of 2016 (Baldwin 2017). Production of renewable gas in the form of biomethane is technically mature and feasible. Therefore, the majority of this thesis will deal with the production of biomethane from anaerobic digestion.

1.6.2 Renewable gas in the form of substitute or synthetic natural gas (SNG) from thermal gasification

In addition to the production of renewable gas from anaerobic digestion (biomethane), renewable gas can also be generated in the production of synthetic natural gas (SNG) via thermal gasification of woody biomass. Synthetic natural gas production involves the thermal gasification of woody biomass to produce synthesis gas in a gasifier using an externally supplied oxidising agent and a sub-stoichiometric oxygen supply. The main components of synthesis gas include CO, H_2, CO_2 H_2O, and CH_4, the synthesis gas is cleaned to remove dust and other particulate matter, tars, and acid gases. The cleaned synthesis gas can then undergo a catalytic methanation process in which the methane concentration is increased and the gas quality achieved is close to that of natural gas, the resulting gas is termed SNG and can be injected to a natural gas network (provided that it meets gas quality specifications) (Hrbek 2016).

Thermal gasification for SNG production is less technically developed than anaerobic digestion and the number of functional plants producing SNG is far lower than the number of plants producing biomethane in Europe. BioSNG Guessing in

Austria (on hold), CHP Agnion Biomasse Heizkraftwerk Pfaffenhofen in Germany (pilot project), Bio2G in Sweden (idle), and GoBiGas (operational) are the only Bio SNG projects in Europe as of 2016, with the GoBiGas plant the only fully operational plant of significant scale (20MW of SNG production) (Hrbek 2016). It was found that the net energy balance of SNG derived from willow in Ireland was similar to that of grass biomethane from anaerobic digestion, however the large cost associated with a SNG plant would likely lead to biomethane production from anaerobic digestion being prioritised in Ireland (Gallagher & Murphy 2013). Owing to the immature state of development of SNG plants in Europe the role of SNG as a source of renewable gas will not be discussed in this thesis.

1.6.3 Renewable gas production from excess renewable electricity

The potential role of the natural gas network to act as a storage mechanism for surplus renewable electricity was also highlighted on a pan European level by Capros et al. who showed that the least cost method of storing surplus renewable electricity was via conversion to H_2 and subsequent injection to the natural gas network in concentrations up to 30% (Capros et al. 2012a). As outlined in Table 1-4 the maximum allowable concentration of H_2 in the Irish gas network is 0.1% on a molar basis, therefore large-scale injection of H_2 derived from surplus renewable electricity is currently infeasible in Ireland. The anaerobic digestion process can allow for the conversion of H_2 and CO_2 (sourced from either the anaerobic digestion process itself or from another highly concentrated source of CO_2) into CH_4 which can then be injected into the existing natural gas infrastructure.

Within the process of anaerobic digestion, a sub group of methanogenc archaea (hydrogenotrophic methanogens of the orders *Metahnobacteriales, Methanococcales, Methanomicrobials,* and *Methaosarcinaceae*) are able to convert CO_2 and H_2 into CH_4. The conversion of H_2 and CO_2 is also possible via the Sabatier process through the use of nickel based catalysts or ruthenium based catalysts (De Saint Jean et al. 2015; Benjaminsson et al. 2013). The ability to convert H_2 and CO_2 to CH_4 has led to the development of power to gas systems in which surplus electricity (often surplus to demand owing to a mismatch between production from

fluctuating sources of renewable electricity such as wind turbines and demand) is converted to H_2 via electrolysis. This H_2 is then combined with CO_2 to produce CH_4 which can then be injected to the natural gas network and used in place of natural gas (Audi 2017; Benjaminsson et al. 2013). The number of power to gas systems in Europe is limited, however, owing to their ability to link the electricity and gas networks, and the ability of power to gas systems to convert excess renewable electricity into an easily stored energy vector (CH_4) a minor portion of this thesis will address the potential role of power to gas systems in Ireland.

1.7 Aims and Objectives

The aims of this thesis were to determine the potential resource of renewable gas in Ireland from a range of sources. The thought process was that initially waste streams would be utilised, after this the use of land based energy crops (grass silage) would be developed, these feedstocks would initially be processed in large centralised facilities. A comparison of two resource utilisation methods, centralised vs. decentralised was conducted to assess potential benefits of decentralised biogas production. Once the conventional sources of renewable gas are developed more advanced feedstock need to be used, a fundamental analysis (the first of its kind for Ireland) of the potential resource of one such feedstock, microalgae, is assessed in this work. The use of non-biological feedstocks such as H_2 and CO_2 for the production of renewable gas via power to gas systems is also addressed in this work. The resource of renewable gas identified in this work can be used as a renewable transport fuel and as a source of renewable heat, however, it could also be used as a source of dispatchable controllable renewable electricity. A potential regime for the operation of such a system was assessed.

To achieve the aims outlined above the following objectives were decided upon:

1. Quantify the spatially explicit resource of biomethane that can be generated from waste streams available in Ireland via anaerobic digestion.
2. Develop a utilisation plan for the conversion of waste streams to biomethane which allows for the identification of optimal locations for

plants processing waste streams with the injection of biomethane to the natural gas network.

3. Assess the impact of gate fees, incentive values, and plant scale on the resource of biomethane derived from waste streams that can be produced in a financially viable manner.
4. Investigate the spatially explicit resource of biomethane that can be generated from the anaerobic digestion of grass silage in excess of livestock requirements in Ireland and compare this to the location and resource of cattle slurry.
5. Develop a utilisation plan to produce biomethane from grass silage and cattle slurry, which enables optimal locations for plants producing biomethane from grass silage and cattle slurry, with injection to the natural gas network, to be identified.
6. Assess the impact of silage price, plant size, feedstock mixture, and incentive value on the production of biomethane from grass silage and cattle slurry.
7. Compare centralised and decentralised biogas production with respect to the greenhouse gas balance of biogas production and delivery in a rural townland.
8. Provide and initial assessment of the potential resource of biomethane from microalgae that could be cultivated using exhaust gases from fossil fuel fired power stations in Ireland.
9. Estimate the current resource of renewable gas that could be generated using existing sources of CO_2 in Ireland in power to gas systems.
10. Evaluate a potential feeding regime for use in a demand driven biogas system for the production of renewable electricity at times of high electricity demand, and to produce biomethane outside of these periods.

1.8 Outline of thesis and link between chapters

This thesis is comprised of 10 chapters and 4 appendices**.** The overall theme of the chapters is an assessment of the resource of renewable gas and its use. Chapter 2 provides an overview of prior assessments of the resource of renewable gas (in the form of biogas and biomethane) available in Ireland and in other countries. Chapter 3 assesses the total theoretical resource of biomethane derived from waste streams in Ireland. Chapter 4 examines the utilisation of these waste streams and the optimal location for plants processing them with the injection of biomethane to the natural gas network. Chapter 5 determines the biomethane resource associated with a land based energy crop (grass silage) and examines the utilisation of this resource in conjunction with cattle slurry. Chapter 6 evaluates the impact of alternative biogas production pathways (decentralised or centralised) on the GHG balance of biogas production and delivery. Chapter 7 assesses the resource of biomethane associated with an advanced feedstock (microalgae) cultivated using exhaust gases from power stations in Ireland, this is the first such work conducted in an Irish context and as such is a first principles assessment intended to lay the ground work for subsequent studies. Chapter 8 provides an initial estimation of the potential resource of renewable gas that could be available using existing sources of CO_2 in Ireland and excess renewable electricity, using power to gas systems, again this is the first work to assess the current potential of such power to gas systems in Ireland and is intended to be the starting point for subsequent studies. Chapter 9 deals with experimental trials that were conducted to evaluate a potential feeding regime for demand drive biogas production. A summary of chapters 2 to 9 is outlined below.

1.8.1 Chapter 2: Literature of renewable gas resource assessments

This chapter provides an overview of the production of renewable gas (biomethane) through the process of anaerobic digestion from feedstock suitable for biomethane production. Renewable energy targets in Ireland and the sustainability criteria applied to biofuels and thermal energy derived from biomass are introduced. The potential role of renewable gas, specifically biomethane, in supplying renewable energy and meeting sustainability criteria is introduced. Prior assessments of the resource of renewable gas conducted internationally are critiqued.

International studies were conducted on a range of levels, some reported overall national resource potential, others presented results on a finer spatial scale. Several studies also proposed plans to utilise the identified resource, considerations made in these utilisation plans included feedstock location, potential facility location, and access to energy infrastructure.

A critique of prior resource assessment conducted in Ireland is also presented, studies conducted in Ireland are compared to those conducted internationally. No prior study in Ireland specified the spatially explicit resource of biomethane at a local level; the majority of studies determined the overall national resource potential. Utilisation plans for Ireland did not consider the location of feedstock, potential plant locations, or access to energy infrastructure.

Comparison of existing studies conducted in Ireland to those conducted internationally highlighted potential knowledge gaps in Ireland. These knowledge gaps include the lack of a spatially explicit resource assessment and the absence of proposed utilisation plans that consider feedstock location, facility location, and access to energy infrastructure. The need for resource assessments of more advanced feedstocks such as microalgae and gaseous feedstock of non-biological origin (also known as Power to Gas) is also highlighted.

1.8.2 Chapter 3: Quantification and location of a renewable gas industry based on digestion of wastes in Ireland

Chapter 3 outlines the resource of biomethane available from waste streams in Ireland. The waste streams assessed were; cattle slurry, sheep manure, pig slurry, chicken manure, slaughterhouse waste, milk processing waste, and source separated household organic food waste. The resource assessment was conducted using the most up to date data and was spatially explicit. This allowed the identification of the regions with the highest potential resource of biomethane. The total theoretical resource of biomethane was found to be 12.47PJ, equivalent to 6.23% of energy consumed in transportation in Ireland in 2015 or 6.88% of total natural gas consumption in 2015.

The majority of the potential biomethane resource is associated with cattle slurry (9.59 PJ) which is concentrated in the southern and north-eastern parts of Ireland in regions with the highest dairy cow population. Source separated household organic food waste represents the second largest potential biomethane resource (1.5 PJ) and is mainly found in urban and city locations. This feedstock could be processed in 6 large centralised anaerobic digestion facilities processing ca. 120,000t_{wwt} per year. Sheep manure was found to contribute 0.61 PJ of potential resource and was located mainly located on the western seaboard.

The biomethane resources of; pig slurry, chicken manure, slaughterhouse waste, and milk processing waste were for individual facilities and represent point sources of waste for use in biomethane production. Pig slurry (0.27 PJ) was found mainly in two regions within Ireland and was not distributed throughout the country. Chicken manure (0.12 PJ) was located almost entirely in one region within Ireland highlighting its potential use as a feedstock in this region. Milk processing waste (0.17 PJ) was located in regions with the highest dairy cow population and could represent a possible feedstock for co-digestion with cow slurries. Slaughterhouse waste (0.21 PJ) was more distributed throughout the country than milk processing waste however there is no discernible resource in the west or north-west of the country.

1.8.3 Chapter 4: Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise

This chapter outlines the development of, and results from, an optimisation model to determine the best locations on the natural gas network at which to construct plants producing biomethane from waste feedstocks. The inputs to the optimisation model included; the spatially explicit resource of waste streams identified in Chapter 3, potential locations on the gas network suitable for biomethane injection, and the biomethane yields of each potential feedstock. Additionally, the maximum allowable plant size, incentive value per unit of biomethane produced, and the gate fee accepted for certain feedstocks were varied in the optimisation model to assess their impact on feedstock utilisation.

The optimisation model determined which possible biomethane plants should be developed in order of descending net present value (profitability). The model also identified which feedstock which plants would use, and where this feedstock was sourced from. The levelized cost of energy of the biomethane produced by each plant was also calculated to give an indication of the value that the biomethane needed to be sold at to ensure financial viability. At a maximum plant size of 50GWh.a^{-1} the first 5 plants to be built process source separated household food waste almost exclusively. These first 5 plants are located near regions where this resource is the highest. Subsequent to this, plants co-digested multiple feedstocks in order to maximise net present value. In general, initial plants had the highest net present value and the lowest levelized cost of energy, subsequent plants had a lower net present value and a higher levelized cost of energy.

In the most optimistic scenario (plant size of 50GWh.a^{-1}, incentive value of 106€.MWh^{-1}, gate fee of 75€.t_{wwt}^{-1}) 22 potential biomethane plants were found to have a positive net present value, the total production of biomethane was ca. 3.4 PJ, equivalent to 1.7% of the energy used in transportation in 2015. It was found that over 95% of the theoretical resource of slaughterhouse waste, milk processing waste, and source separated household organic waste were utilised. Only 28% of potential resource from cattle slurry was utilised, and 27% of the potential resource of pig slurry was utilised.

1.8.4 Chapter 5: Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region

The total theoretical resource of biomethane associated with grass silage in excess of livestock use was found in Chapter 5, the location of this potential resource was also determined. The resource assessment calculated the gross grass and grass silage production in each region in Ireland and the total consumption of grass and grass silage by livestock within each region. This allowed for the spatially explicit resource of biomethane from grass silage to be assessed.

The total theoretical resource of biomethane from grass silage was found to be 128 PJ, this is equivalent to 64% of the total energy consumption of the transportation sector in 2015. The potential resource of grass silage was mainly located in western regions of Ireland. The co-digestion of this grass silage with cattle slurry was proposed, the location and scale of the cattle slurry resource from Chapter 3 was also considered.

An updated optimisation model was developed to determine the optimal locations of plants processing grass silage and cattle slurry for the production of biomethane and injection to the gas network. The inputs to the optimisation model included plant size, feedstock price, the value of the incentive per unit of biomethane produced, and the feedstock mixture accepted by the plants. The optimisation model outputted a potential build order (in order of descending net present value) of plants, along with the location from which they sourced feedstock.

A total of 81 scenarios were assessed. The production of biomethane from plants with a positive net present value ranged from 3.5PJ to 12.2 PJ, approximately 2.5-8.8% of the combined theoretical resource of grass silage and cattle slurry. The largest quantity of biomethane produced by plants with a positive net present value was equivalent to 6% of the energy used in transportation in 2015. Marginal cost curves of the levelized cost of energy (LCOE) from biomethane plants processing grass silage and cattle slurry showed that the levelized cost of energy decreased with reduced silage price, increased plant size, and with an increase in the portion of grass silage in the feedstock mixture.

1.8.5 Chapter 6: An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network.

A comparison between large centralised anaerobic digestion for biogas production and decentralised anaerobic digestion with biogas transportation via low pressure biogas pipelines was performed in Chapter 6. The analysis was conducted for a rural townland in Ireland, the feedstock assessed was pig slurry from 5 large pig farms, the biogas end user was a large milk processing plant which burned the biogas in a boiler for heat production.

Four scenarios were assessed; centralised anaerobic digestion of pig slurry at the biogas user, centralised digestion of pig slurry remote from the biogas user (biogas was transported in a low pressure biogas pipeline), decentralised anaerobic digestion of pig slurry at each pig farm with biogas transport to the biogas user from each pig farm in low pressure pipelines, and decentralised anaerobic digestion of pig slurry at each pig farm with biogas transport to the biogas user in a pipe network of minimum length. The scenarios were assessed in terms of energy consumption and the associated greenhouse gas emissions in the production and delivery of biogas to the biogas user.

The centralised anaerobic digestion of pig slurry remote from the biogas user reduced total greenhouse gas emissions in the production and delivery of biogas by 7% compared to centralised anaerobic digestion at the biogas user. Decentralised anaerobic digestion of pig slurry at each pig farm with biogas transport from each pig farm directly to the biogas user reduced greenhouse gas emissions by 19% compared to centralised anaerobic digestion of pig slurry at the biogas user. Decentralised anaerobic digestion at each pig farm with biogas transport to the biogas end user in a pipe network of minimum length reduced the greenhouse gas emissions by 18% relative to centralised anaerobic digestion at the biogas user, and reduced the overall length of pipeline required by 34% compared to decentralised anaerobic digestion at each pig farm with transport of biogas from each pig farm to the biogas user in a pipe.

1.8.6 Chapter 7: Assessing the biomethane resource of microalgae cultivated using carbon dioxide from thermal power stations in a temperate oceanic climate

Microalgae are seen as an advanced source of bioenergy which could potentially have high energy yields per hectare of cultivation system, to date no assessment of the potential resource of microalgae has been conducted in Ireland. Assessment of the cost effectiveness and net energy ratios of microalgae cultivation systems are an important aspect of deciding whether microalgae are a viable source of renewable energy in a region. Cost effectiveness and net energy ratio assessments are inherently based upon an initial assessment of the potential resource of microalgae in a region. To this end an overview of the potential resource of microalgae (a potential feedstock for use in biomethane production via anaerobic digestion) that could be grown using CO_2 from the exhaust gases of large fossil fuel fired power stations in Ireland was carried out. A rudimentary resource assessment was developed in which the impact of weather on the growth rate of microalgae was not considered, and in which the variation in the availability of CO_2 from power stations was not considered. The potential biomethane resource from microalgae according to the rudimentary assessment was 9.8 PJ, equivalent to 4.95% of energy consumption in transportation in 2015.

An in-depth resource assessment was then carried out in which the impact of weather conditions and CO_2 availability on the potential resource of microalgae were considered. The in-depth assessment consisted of a basic thermal model of a microalgae cultivation system (a raceway pond) which estimated the temperature of the culture in the pond for each hour in a year. This culture temperature was combined with data on solar radiation to provide a more realistic estimate of the microalgae resource that could be grown at a power station, assuming that CO_2 would always be available to the microalgae cultivation system. A further consideration of the in-depth assessment was the actual availability of CO_2 (influenced by the operational schedule of each power station) from the power stations assessed and the influence of this on the potential resource of microalgae that could be grown at each power station. The results of the in-depth assessment

indicated a potential resource of 1.75 PJ from microalgae if converted to biomethane (0.9% of energy consumption in transportation). This is a significant reduction compared to the rudimentary assessment and highlights the need to consider the impact of both weather and CO_2 availability on the potential resource of microalgae grown using CO_2 from power stations in a region. Further works assessing the net energy ratio and cost effectiveness of microalgae cultivation as a source of bioenergy are required in the future, future assessments should build upon the resource assessment conducted in this thesis.

1.8.7 Chapter 8: The potential of power to gas to provide green gas utilising existing CO_2 sources from industries, distilleries and wastewater treatment facilities

The role of the gas network as a potential storage mechanism for surplus renewable electricity was emphasised at a pan European scale in work by Capros et al. as highlighted in prior sections (Capros et al. 2012b). The role of power to gas systems in bridging the gap between the electricity and gas networks through the conversion of H_2 to CH_4 was also outlined in prior sections. As a starting point for Ireland an investigation of the potential resource of methane that could be produced via power to gas systems using existing sources of CO_2 was carried out in chapter 8. The assessment identified the main sources of CO_2 in Ireland namely; power stations, industries, and CO_2 from distilleries and anaerobic digesters at waste water treatment plants. The suitability of each of the identified sources of CO_2 was determined using Multi Criteria Decision Analysis, the analysis criteria assessed were; quantity of CO_2 available, concentration of CO_2 in the gas stream, the source of the CO_2 (biological or non-biological), the distance to the electricity network, and the distance to the gas network. The most suitable sources of CO_2 were found to be distilleries and waste water treatment plants with anaerobic digesters. A total of 12 sources of CO_2 were identified as being highly suitable for use in power to gas systems for the production of CH_4 from renewable electricity that would otherwise have been dispatched down. The total resource of CH_4 that

could be produced from the most suitable CO_2 sources was 396GWh, equivalent to 1.42 PJ.

The CO_2 source with the highest suitability for use in a power to gas system was a large distillery. The total quantity of electricity required in a power to gas system at this single distillery was found to be ca. 461GWh.a^{-1}, this is larger than the total quantity of electricity from variable renewable generators (wind turbines) that was dispatched down in 2015 (248GWh.a^{-1}). The most suitable source of CO_2 represents a significant mechanism for the conversion of excess renewable electricity into methane gas that could then be used as a source of renewable heat, or as a renewable transport fuel. The resource of methane that could be produced by a power to gas system at the large distillery is equivalent to 46% of the fuel consumption by the two main bus fleets in Ireland in 2015. Possible methods of integrating power to gas facilities at a distillery and at a waste water treatment plant were also introduced. Future works in which the optimal operation of power to gas systems (linked to distilleries and waste water treatment plants) within the single electricity market should be based upon this work which highlighted the current resource potential of power to gas in Ireland.

1.8.8 Chapter 9: Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times

A potential feeding regime for use in a demand driven biogas system for on demand generation of renewable electricity was assessed for 4 feedstocks; grass silage, source separated food waste, *Laminaria digitata* (common kelp), and dairy cow slurry. Biochemical methane potentials of the four feedstocks were determined using an Automated Methane Potential Test system (AMPTS). Continuous trials were conducted using 5L continuously stirred tank reactors (CSTR) at an organic loading rate of 2kg of volatile solids per cubic meter of reactor per day, to ascertain the profile of biogas production and biomethane production following pulse feeding of each digester. Kinetic models of gas production were compared to the actual production of biogas and methane during the continuous trials.

These kinetic models of gas production were used to calculate the time at which a digester using one of the substrates assessed should be fed to ensure sufficient biogas is produced to fuel a combined heat and power (CHP) unit for on demand electricity production. The time at which an upgrading plant processing biogas to biomethane was to be turned on subsequent to this was also determined. In the case of grass silage, if a 2MWe CHP unit is to be run for one hour (e.g. at times of peak electricity demand) the anaerobic digester should be fed 187 minutes prior to CHP dispatch. Following this, the upgrading plant should be turned on 221 minutes after CHP shutdown to maximise the use of the biogas storage volume on site. In the proposed system 21% of the total energy produced by the anaerobic digester was sent to the CHP unit, the remaining 79% was sent to the upgrading system for the production of biomethane.

1.8.9 Chapter 10: Conclusion and recommendations

The conclusions of the thesis are presented in Chapter 10 along with several recommendations. A section on potential future work as a result of this thesis is also included.

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2 Chapter 2: Literature of renewable gas resource assessments

2.1 Chapter overview

The purpose of this chapter is to give an overview of potential feedstocks suitable for use in anaerobic digestion and their status with regard to EU legislation surrounding the production of renewable energy. Prior resource assessments of various feedstocks for use in anaerobic digestion conducted internationally will be critiqued. Comparison to prior resource assessments conducted in Ireland will be conducted. An outline of the methodologies to be used in this thesis is provided.

2.2 A review of the anaerobic digestion of feedstock for renewable gas production

2.2.1 Basics of anaerobic digestion process

As mentioned in Chapter 1 the process of anaerobic digestion (AD) for the production of biogas involves a multitude of microbial populations which convert biodegradable materials into biogas (CH_4 and CO_2 along with trace gases) and digestate (the remaining biodegradable material after digestion), an overview of the anaerobic digestion process can be found in the literature (Wellinger et al. 2013; Al Seadi, Rutz, Prassl, et al. 2013; Gerardi 2003).

The process of anaerobic digestion can be can be batch or continuous, additionally it can be “wet” or “dry”. Anaerobic digesters can also be categorised depending on whether the entire process takes place in a single reactor, in which all the microbial populations involved in the digestion process are present, or whether these microbial populations are present in two conjoined reactors with acidogenic microbes present in the first reactor and methanogenic archaea present in the second reactor. In the context of the anaerobic digestion process, “wet” implies the processing of a feedstock mixture with a moisture content above 88%, while “dry” implies the processing of feedstock with a moisture content between 50-80% (Nizami & Murphy 2010). The process of anaerobic digestion can also be classified according to the temperature at which it occurs; psychrophilic digestion at temperatures below 25°C, mesophilic at temperatures between 25-45°C, and thermophilic at temperatures between 45-70°C (Al Seadi, Rutz, Prassl, et al. 2013; Murphy & Thamsiriroj 2013). The temperature at which anaerobic digestion occurs can impact; the rate of degradation of feedstock (increased temperature increases degradation rate thus reducing retention time), the ability of the digester to kill pathogens, and the stability of the process (increased temperature can result in higher concentrations of free ammonia (NH_3) which is toxic to the digestion process) (Murphy & Thamsiriroj 2013; Bochmann & Montgomery 2013).

Current research into the field of advanced anaerobic digestion includes the use of two phase high pressure anaerobic digestion (Lemmer et al. 2015; Chen et al. 2014). In this advanced system the first acidogenic stage operates as a dry

sequencing leach bed reactor, the resulting volatile fatty acids produced are then fed to a methanogenic second stage (a high rate anaerobic filter with retained microbial biomass). The second methanogenic phase is pressurised by the production of biogas within it, this elevated pressure causes increased solubility of CO_2 within the process fluid in the reactor, the resulting biogas thus has an increased CH_4 concentration, in excess of 75%. This advanced anaerobic digestion system could reduce the down stream cost of processing biogas to meet the standards for injection into natural gas networks, however testing of the system has been limited to laboratory scale settings.

While each type of anaerobic digestion system has its benefits and flaws, in this study it will be assumed that anaerobic digestion occurs as a mesophilic, wet, and continuous process. This choice was made owing to the wealth of knowledge associated with biogas and biomethane yields associated with various feedstocks at mesophilic conditions, and owing to the reduced risk of process instability at mesophilic temperatures. While more advanced anaerobic digestion systems do exist, the mesophilic, wet, and continuous process would allow for the current resource associated with wastes and land based energy crops to be estimated in a pragmatic manner.

2.2.2 Feedstock suitable for use in anaerobic digestion

Anaerobic digestion in comparison to biomass combustion is a “wet” process, the moisture content of feedstock used in anaerobic digestion can range from 60-90% (Al Seadi, Rutz, Janssen, et al. 2013; Al Seadi, Rutz, Prassl, et al. 2013) and as such the anaerobic digestion process can treat feedstocks unsuitable for combustion. This allows anaerobic digestion to utilise feedstocks that can also be classified as wet wastes, and that would otherwise require disposal in a landfill, or treatment via compositing.

Feedstocks suitable for use in anaerobic digestion can be disaggregated into a number of categories, this is typically done with respect to the source of the feedstock, and whether the feedstock is a residue (a low value waste stream) or

whether the feedstock must be specifically produced for use in anaerobic digestion. An example of the classifications of biomass feedstock for use in anaerobic digestion (along with examples of each feedstock type) can be seen in Table 2-1 adapted from (Al Seadi, Rutz, Janssen, et al. 2013).

Several feedstocks which can be used to produce renewable gas via anaerobic digestion are residues or waste streams, this is an added benefit of anaerobic digestion as it can be used for the production of renewable gas, and for the treatment of wastes. Agricultural waste streams suitable for anaerobic digestion include animal manures and slurries, and crops residues.

Table 2-1 Feedstock classification and examples of feedstock, adapted from (Al Seadi, Rutz, Janssen, et al. 2013)*. This is a non-exhaustive list.*

Feedstock classification	**Examples**	**Residue or specifically produced**
Agricultural	Animal manures and slurries	Residue
	Plant or crop residues	Residue
	Energy crops	Specifically produced
Industrial	Slaughterhouse waste	Residue
	Milk processing waste	Residue
	Other food processing waste	Residue
Municipal	Source separated food and garden waste	Residue
Aquatic	Microalgae	Depends on source of feedstock
	Macroalgae	Depends on source of feedstock
Non-biological[3]	Gaseous feedstocks	
	H_2	Specifically produced
	CO_2	Depends on source of feedstock

As outlined in Chapter 1 greenhouse gas (GHG) emissions from agriculture are responsible for 33% of Irish GHG emissions, manure management is responsible for ca. 9% of GHG emissions (1,790ktCO_2eq) in agriculture, this is equivalent to 92% the total GHG emissions from heavy duty trucks and buses (1,939ktCO_2eq). Use of animal slurries and manures in anaerobic digestion for renewable gas production would help to mitigate the GHG emissions associated with manure management. In relation to waste streams arising from large scale food and drink industries, and from municipal sources, the benefit of anaerobic digestion is recognised within EU

[3] Non-biological feedstocks (CO_2 and H_2) are not technically used in the entire anaerobic digestion process, they can be utilised by a sub population of methanogenic archaea present in anaerobic digesters (hydrogenotrophic methanogens) for the production of CH_4.

reference material on Best Available Techniques in; the waste treatment industry (European Commission 2006), slaughterhouses and animal by-products industries (European Commission 2005), the intensive rearing of poultry and pigs (European Commission 2003), and the food drink and milk industries (European Comission 2006). Treatment of wastes within these sectors using anaerobic digestion would avoid the need for landfilling of a portion of these biodegradable wastes streams and the associated GHG emissions.

In addition to waste streams, anaerobic digestion can also process dedicated land based energy crops to produce renewable gas. Examples of such energy crops are maize silage, grass silage, whole crop wheat, sugar beet, oats, and sunflower, and sorghum (Murphy et al. 2011; Al Seadi, Rutz, Janssen, et al. 2013). In the case of some energy crops, anaerobic digestion can be seen as a direct competitor for the use of crops suitable for human consumption (oats, wheat), other energy crops could use tillage land that could otherwise have been used for food production (maize), while some compete with land that could be used for fodder production (maize and sugar beet). The implications of using energy crops in anaerobic digestion within the food vs. fuel debate has been keenly followed by the EU, the impact of legislation on the use of energy crops for renewable gas production will be discussed in section 2.2.3.

Moving away from land based sources of feedstock for use in anaerobic digestion, aquatic biomass can also be utilised as feedstock in the anaerobic digestion process. Macroalgae (seaweed) (Al Seadi, Rutz, Janssen, et al. 2013; Allen et al. 2015; Vivekanand et al. 2012) and microalgae (Golueke & Oswald 1959; Converti et al. 2009; Mussgnug et al. 2010) have been assessed in terms of their potential to produce biogas in anaerobic digesters. The benefit of these feedstocks is that they have high biomass yields per hectare, may not compete with land that could be used for food or fodder production, and are thus outside of the food vs. fuel debate to a certain degree. Macroalgae and microalgae can be classified as either a residue (a waste stream) or as a specifically produced feedstock depending on the source of the biomass.

A final source of potential feedstock for the production of renewable gas is non-biological gaseous feedstocks. These typically consist of H_2 and CO_2 which can be utilised by a group of archaea present in anaerobic digesters (hydrogenotrophic methanogens) to produce CH_4 (Benjaminsson et al. 2013). These gaseous feedstocks do not require any land or sea area for their production (beyond the foot print of the facility producing them) and have a limited impact on land use and the food chain. The source of each gaseous feedstock can vary, H_2 is typically produced via the electrolysis of water using electricity surplus to demand, as such this is a specifically produced feedstock. On the other hand, CO_2 can be sourced from existing gas streams with a high volumetric percentage of CO_2. Sectors in which such gas streams can be found are the brewing and distilling industry, and in the production of biogas.

2.2.3 Potential feedstocks for use in anaerobic digestion (Applicability to EU targets)

EU Directive 2009/28/EC recognised energy from renewable sources to include energy from biogases, it additionally recognised a biofuel as a liquid or gaseous fuel used for transportation purposes (The European Parliament and the Council of the European Union 2009). Directive 2009/28/EC outlined the requirement for member states to ensure a minimum share of renewable energy by 2020 (16% in the case of Ireland) and a minimum share of 10% renewable energy in transport (RES-T) by 2020 (The European Parliament and the Council of the European Union 2009).

The sustainability criteria to which biofuels were required to adhere to in order to be counted as a source of renewable energy were also stipulated. Initially a minimum GHG saving of 35% when compared to a standardised fossil fuel was applicable to biofuels, as of January 1st 2017 the minimum required GHG saving increased to 50%, and from January 1st 2018 it will rise to 60%. The directive also outlined that in the calculation of meeting the 10% RES-T target, the contribution from biofuels produced from wastes, residues, non-food cellulosic material, and ligno-cellulosic material shall be twice that of other biofuels to promote their use.

Based on the default GHG savings for renewable gas from the anaerobic digestion of municipal organic waste, wet animal manure, and dry animal manure (73%, 81%, and 82% respectively) when used as a transport fuel, and the ability to count their energy content twice in relation to the RES-T target, the use of municipal waste streams and animal manures in the production of renewable gas for use as a transport fuel is favourable. The use of such waste streams in anaerobic digestion for the production of renewable gas should therefore be prioritised.

Subsequent to Directive 2009/28/EC, Directive 2015/1513 emphasised the need to encourage the development of advanced biofuels derived from feedstocks that are not in competition with food and fodder crops for agricultural land (The European Parliament and the Council of the European Union 2015). A limit of 7% on the share of RES-T that can be contributed by biofuels produced from "cereal and other starch rich crops, sugars and oil crops and from crops gown as main crops primarily for energy purposes on agricultural land" was implemented by Directive 2015/1513 (The European Parliament and the Council of the European Union 2015). Feedstock which are not bound by this limit include (but are not limited to); animal manure, biomass fraction of mixed municipal waste, biomass fraction of industrial waste, non-food cellulosic material (including grassy energy crops such as ryegrass which can be used to produce grass silage), algae, and renewable liquid and gaseous transport fuels of non-biological origin. These feedstocks are used in the production of so called "advanced biofuels", a proposed minimum share of such biofuels in each member state by 2020 is 0.5% RES-T (The European Parliament and the Council of the European Union 2015). In order to promote the use of advanced biofuels Directive 2005/1513 also stipulates that their energy contribution toward the 10% RES-T target be doubled (The European Parliament and the Council of the European Union 2015). The feedstocks listed in Part A of Annex IX of Directive 2015/1513 (Table 2-2) are suitable feedstocks for the production of renewable gas as a transport fuel via anaerobic digestion. As such, under the current legislative framework within the EU, production of renewable gas as a transport fuel (via anaerobic digestion) for the purpose of meeting the 10% RES-T target in Ireland should be assessed.

Table 2-2 Feedstock in Part A Annex IX of (European Commission 2017). ** Feedstock suitable for anaerobic digestion to produce renewable gas. [a]Non-food cellulosic materials include gassy energy crops such as ryegrass.*

Annex IX of COM (2016) 767 (European Commission 2017)
Part A
Algae (cultivated on land in ponds or photobioreactors) *
Biomass fraction of mixed municipal waste*
Bio-waste from private households*
Biomass fraction of industrial waste not fit for use in the food or feed chain*
Straw
Animal manure and sewage sludge*
Palm oil mill effluent and empty palm fruit bunches
Tall oil and tall oil pitch
Crude glycerine
Bagasse
Grape marcs and wine lees
Nut shells
Husks
Corn cobs cleaned of kernels of corn
Biomass fraction of wastes and residues from forestry and forestry based industries
Non-food cellulosic material*[a]
Other lignocellulosic material
Part B
Used cooking oil
Animal fats
Molasses that are a by-product from refining of sugar cane or sugar beet

The proposed directive for the promotion of the use of energy from renewable sources beyond 2020 highlights the importanceof the heating and cooling sectors in terms of energy consumption in the EU, and the importance of transportation energy consumption (European Commission 2017). The proposal does not specify a specific goal for RES in member states, nor does it specify a continuation or increase of the 10% RES-T target in member states. It does however propose that the contribution of renewable energy as a portion of gross energy consumption in each member state in 2020 be the baseline contribution for that member state out to 2030, with an overall goal of 27% of energy from renewable sources in 2030 across the EU. The proposed directive suggests that a gradual reduction in the quantity of food and feed based biofuels and their replacement with advanced biofuels be implemented, the maximum limit of food based biofuels for 2021 is proposed as 7%, reducing to 3.8% in 2030. In conjunction, the proposed directive aims to promote the use of “advanced” biofuels produced from feedstock listed in Annex IX (Table 2-2) by ensuring a minimum share of 1.5% of energy used is transport in 2021, increasing to 6.8% in 2030.

Additionally, the minimum required GHG saving for energy sources used in transport to be considered renewable will increase to 70% from 2021. Renewable gas produced from the anaerobic digestion of feedstock listen in Part A of Annex IX is an eligible production route to meet these renewable transport targets.

The proposed directive recognises the need to promote the use of energy from renewable sources for the provision of heat and suggests that member states increase their share of renewable energy in heat by 1 percentage point per year from 2021. The proposed directive outlines that the minimum required GHG saving for energy used in the provision of heat to be considered renewable will be 80% from 2021 rising to 86% from 2026. Suggested routes for the increasing the share of renewable energy used in the provision of heat within the directive include the "physical incorporation of renewable energy and energy fuel supplied for heating and cooling". The use of renewable gas to achieve increased renewable energy use in heat production is recognised by the proposed directive.

In order to facilitate the use of renewable heat it is suggested within the proposal for a directive on the promotion and the use of energy from renewable sources beyond 2020 (European Commission 2017) that member states conduct an assessment of the national potential of renewable energy sources. It is also suggested that in order to contribute to the decarbonisation of the EU economy, member states should promote greater sustainable mobilisation of existing agricultural resources (European Commission 2017). As renewable gas can play a significant role in achieving the use of renewable energy in transportation and in the production of renewable heat, there is a need to assess the potential of renewable gas associated with feedstock available in Ireland.

2.3 Prior assessments of the resource of renewable gas

Assessments of the resource of renewable gas associated with biomass within a country or a region can be conducted on several levels ranging from national to local. The data required within each level is broadly similar, and may include; waste production statistics, livestock numbers, land areas under specific crops (along with

associated yields), and climate conditions. The assessments may or may not be spatially explicit i.e. they may or may not consider the location of potential resources and their location with respect to end users of energy or the electricity and gas networks.

When assessing the resource of renewable gas from biomass in a region, proposals for the utilisation of the identified resource can be developed depending on the level of resource assessment conducted. A resource assessment at national level, utilising data on a national scale, can only be used to draw up broad national plans for resource utilisation. In contrast to this, resource assessments at a local level can be used to inform the development of a plan to utilise the resource in much finer detail. Utilisation plans may contain much of the same data as the initial resource assessments, along with added consideration to the cost of resource utilisation and the cost of the final product.

A sample of biogas resource assessments conducted internationally can be seen in Table 2-3. These resource assessments generally identified the resource of biogas which could be derived from waste streams and energy crops. The studies listed are critiqued with respect to; the level of the resource assessment (National, regional, local), whether or not the study was spatially explicit, and whether or not a plan for the utilisation of the resource identified was proposed.

*Table 2-3 International resource assessments. *Denotes assessments in which the location of facilities utilising feedstock was assessed*

Feedstock	Level	Spatially Explicit	Utilisation plan	Country	Summary	Year	Reference
Livestock manure (Cattle, pigs, poultry)	National	No	Yes	UK	National resource of biogas produced from anaerobic digestion of livestock manures. Based on national livestock population. Outlines the need for resource mapping. Proposed utilisation via centralised anaerobic digestion of livestock manure. No sites identified.	1995	(Dagnall 1995b)
Livestock manure (Cattle, pigs, poultry)	Local	Yes	Yes*	UK	National biogas resource based on data at a local level (Local livestock populations). Proposed utilisation via centralised anaerobic digestion of livestock manure. Method to find suitable sites developed, 130 sites found.	1995	(Dagnall 1995a)
Livestock manure (Cattle, pigs, poultry)	Local	Yes	Yes*	UK	National biogas resource based on data at a local level (Local livestock populations). Proposed utilisation via centralised anaerobic digestion of livestock manure. Accounted for road network, distance to electricity grid, and land use restrictions.	2000	(Dagnall et al. 2000)
Livestock manure	Local	Yes	Yes	Greece	Spatially explicit biogas resource associated with livestock manures in Greece based on livestock census data for Greek sub-regions. Proposed utilisation via grid injection of biomethane.	2005	(Batzias et al. 2005)
Livestock manure, landfills, wastewater treatment	Regional	Yes	No	USA	Methane resource associated with livestock manures, landfills, and wastewater treatment.	2005	(Milbrandt 2005)
Livestock Manure	Local	Yes	Yes*	USA	Assessed the suitability of sites for anaerobic of animal manures in a county in New York using land suitability maps to identify which large farms were in suitable areas.	2005	(Ma et al. 2005)
Livestock manure	National	No	No	Taiwan	National resource associated with livestock manures in Taiwan. Based on national livestock population.	2009	(Tsai & Lin 2009)
Livestock manures	National	No	No	Italy	National resource associated with livestock manures and slurries based on national livestock population.	2009	(Tricase & Lombardi 2009)

Feedstock	Level	Spatially Explicit	Utilisation plan	Country	Summary	Year	Reference
Numerous feedstocks	Regional	Yes	Yes	Chile	National resource assessment of biomethane resource on a regional level (Provinces). Proposed use of biomethane was injection to the natural gas network.	2009	(Seiffert et al. 2009)
Pig slurry	Local	Yes	Yes*	USA	Assessment of the resource of biogas associated with the anaerobic digestion of pig slurry from large scale pig farms. Proposed utilisation plan was injection to the natural gas grid, location of the gas grid was considered.	2013	(Prasodjo et al. 2013)
Urban waste, industrial residues, agricultural residues, energy crops	National	No	Yes	Sweden	National resource assessment of multiple feedstock types. Potential utilisation via co-digestion of some feedstock at existing biogas plants.	2013	(Lönnqvist et al. 2013)
Multiple feedstocks	Local	Yes	Yes*	Finland	Spatially explicit resource associated with the anaerobic digestion of multiple feedstock in the south of Finland. Centralised anaerobic digestion of feedstock was proposed.	2014	(Höhn et al. 2014)
Maize silage and livestock manure	Local	Yes	Yes*	Italy	Spatially explicit resource of biogas available in an Italian region. Utilisation of feedstock via centralised anaerobic digestion.	2014	(Chinese et al. 2014)
Livestock manures	Local	Yes	Yes*	Denmark	Calculation of the spatially explicit biogas resource from livestock manures. Utilisation via centralised anaerobic digestion.	2014	(Bojesen et al. 2014)
Livestock manure and the organic fraction of municipal solid waste	Regional	No	Yes	Spain	Calculation of biogas resource associated with pig slurries in the environs of Madrid and Barcelona. No information on the location of feedstock was provided. Centralised anaerobic digestion was proposed as a utilisation method.	2014	(Fierro et al. 2014)
Livestock manures and agricultural crops residues	Local	Yes	Yes	Chile	Calculation of the resource of biogas, and biomethane available in Chile from animal manures and crop residues. Utilisation of feedstock in centralised anaerobic digestion facilities.	2014	(Bidart et al. 2014)
Landfill gas, livestock manures, biogas from waste water treatment plants,	National	No	No	USA	National resource biogas resource potential based on livestock population, landfill gas production, and wastewater treatment plant biogas production. No utilisation pathway was proposed.	2014	(Murray et al. 2014)

Feedstock	Level	Spatially Explicit	Utilisation plan	Country	Summary	Year	Reference
Wastewater treatment plant biogas production, landfill gas, livestock manure, industrial waste streams.	National	Yes	No	USA	Resource of biogas arising from anaerobic digestion at waste water treatment plants, use of livestock manures, and use of organic industrial wastes. No utilisation pathway was proposed.	2014	(Saur & Milbrandt 2014)
Food waste, sewage sludge, industrial residues, agricultural residues, and energy crops	Local	No	Yes	Sweden	Resource associated with biogas in a Swedish sub region. Utilisation of household food waste at existing anaerobic digesters located at sewage treatment plants.	2015	(Lönnqvist et al. 2015)
Livestock manure	Regional	Yes	No	Iran	Resource of biogas from the anaerobic digestion of cattle slurry in Iran. Data presented on a regional level. No utilisation pathway was proposed.	2015	(Noorollahi et al. 2015)
Municipal waste, sewage sludge, livestock manure, maize, grass	Regional	Yes	No	Poland	Biogas resource at a regional level within Poland from anaerobic digestion of various feedstock. No utilisation pathway was proposed.	2015	(Igliński et al. 2015)
Industrial biodegradable wastes, domestic sewage, municipal solid waste, energy crops	National	No	No	Uruguay	Biogas resource associated with multiple waste streams based on national level data. No spatial data was provided. No utilisation pathway was proposed.	2016	(Moreda 2016)
Livestock manure, slaughterhouse waste	Regional	No	No	Malaysia	National resource on a regional level associated with wastes from livestock and from slaughterhouses. No utilisation pathway proposed.	2016	(Abdeshahian et al. 2016)

The resource assessments summarised in Table 2-3 were conducted on a range of differing levels ranging from national assessments based on national statistics with no consideration for feedstock location, to assessments conducted on a local scale with consideration given to the location of feedstock. Of the 23 studies, 14 provided spatially explicit results at a range of scales within the country of interest (1 national level, 4 regional level, and 9 local level assessments). A total of 13 assessments proposed utilisation plans in which the feedstock assessed could be processed in anaerobic digestion plants for the production of renewable gas (1 national, 2 regional, 10 local). The utilisation pathways typically consisted of large centralised anaerobic digestion facilities at which feedstock was to be accepted and processed (Dagnall et al. 2000; Höhn et al. 2014).

The location of facilities which would utilise the feedstock was analysed in 7 of the studies. Within these studies varying consideration was paid to the proximity or ease of connection to energy grids, some considered the location of natural gas and electricity grids (Ma et al. 2005), while others assumed that grid access would be of no issue (Bojesen et al. 2014). The studies were conducted in 14 different countries, highlighting the international interest in determining the potential resource of renewable gas across the world.

Assessments of the total theoretical resource of biomass and wastes streams available in numerous countries for use in other energy production systems including (but not limited to) biomass combustion, gasification, and liquid biofuel production share several similarities with the resource assessments for renewable gas outlined above. Prior works which aimed to assess the available biomass and waste streams in a region or country were conducted either on a national scale (Steetskamp et al. 1995; Faaij et al. 1997; A. Faaij et al. 1998; André Faaij et al. 1998; de Wit & Faaij 2010) or on a regional and local scale (van der Hilst & Faaij 2012; van der Hilst et al. 2014; Lewandowski et al. 2006). These prior studies used national statistics on waste stream production (along with projections) to assess waste availability for use as a source of energy. In relation to energy crops, data on land use, crop production, and demand, along with projections of each into the

future was used to assess the potential availability of land that could be used to produced bioenergy crops.

2.3.1 Prior national resource assessments of renewable gas potential

Several studies have been conducted in Ireland to determine the potential resource of renewable gas. These studies can be seen in Table 2-4. The studies are again critiqued in terms of the level at which the study was conducted (National, regional, local, site specific), whether or not the study was spatially explicit, and whether or not a utilisation plan for the identified resource was proposed. The main feedstock types assessed in prior studies of renewable gas potential in Ireland were waste streams from the agricultural and food processing sectors, and grass silage for use as an energy crop in anaerobic digestion.

Table 2-4 Resource assessments in Ireland

Feedstock	Level	Spatially explicit	Utilisation plan	Year	Comment	Reference
Biodegradable fraction of municipal solid waste	National	No	Yes	2003	National production of biodegradable fraction of municipal solid waste. Utilisation of feedstock in centralised anaerobic digestion plants.	(Murphy & McKeogh 2004)
Landfill gas	National resource	No	Yes	2004	National resource of landfill gas available in Ireland.	(Sustainable Energy Ireland 2004)
Biodegradable fraction of municipal solid waste	Site specific	No	Yes	2004	Biogas resource associated with a plant treating biodegradable municipal solid waste from 1 million persons.	(Murphy et al. 2004)
Biodegradable fraction of municipal solid waste, pig slurry	Site specific	No	Yes	2005	Biogas production of pig slurry co-digested with biodegradable municipal solid waste at large centralised anaerobic digestion plants. The pig slurry arose from 37,800 pigs, municipal waste arose from 69,000 or 125,000 persons (depending on the scenario)	(Murphy & McCarthy 2005)
Newspaper waste and biodegradable fraction of municipal solid waste	Regional	No	Yes	2007	Biogas resource from the anaerobic digestion of newspaper waste and biodegradable municipal solids waste arising from 400,000 persons. Waste processed in large centralised anaerobic digestion facilities.	(Murphy & Power 2007)
Wheat, barley, sugar beet	National	No	Yes	2009	Resource associated with crop production on 48,000ha of land previously used for sugar beet production. Processing of feedstock in large centralised anaerobic digestion facilities accepting 100,000t.a^{-1} or 200,000t.a^{-1}.	(J.D. Murphy & Power 2009)
Grass silage	Site specific	No	Yes	2009	Biogas resource associated with an anaerobic digestion plant processing 39,440t/a of grass silage.	(Jerry D. Murphy & Power 2009)
Grass silage	Site specific	No	Yes	2009	Energy balance of anaerobic digestion of grass silage at a facility processing 7,500t of grass silage per year. Energy production from this single plant was scaled up to determine the biogas resource from 10%of grassland in Ireland	(Smyth et al. 2009)
Livestock manures, slaughterhouse waste, grass silage,	National	No	Yes	2010	Biogas resource from the anaerobic digestion of multiple feedstocks. Locations of feedstock or potential anaerobic digesters were not considered in detail. Large centralised anaerobic digesters processing 50,000t.a^{-1} of cattle slurry and grass silage were proposed for rural locations,4-5 similar sized facilities were proposed around the main population centres in Ireland to process biodegradable municipal solid waste.	(Singh et al. 2010)
Slaughterhouse waste, paunch	National	No	No	2010	Estimated potential of biogas from the anaerobic digestion of paunch arising in slaughterhouses. No utilisation pathway was proposed.	(Thamsiriroj & Murphy 2010)

Feedstock	Level	Spatially explicit	Utilisation plan	Year	Comment	Reference
Grass silage	National	No	No	2010	Potential biogas production from silage grown on 163,000ha of land in excess of livestock requirement assuming 60% utilisation of the available resource. No utilisation pathway was proposed.	(Smyth et al. 2010)
Grass silage	National	Yes	Yes	2011	Ranking of regions in Ireland in terms of suitability for biomethane production from grass silage. Determined resource in 20km radium of slaughter facilities for co-digestion plants processing ca. 30,000t feedstock.	(Smyth et al. 2011)
Livestock slurries, household and commercial food wastes.	National	No	No	2012	National resource of biogas associated with cattle slurry and pig slurries. Estimates of the available resource were based on 10% of dairy cattle slurry utilisation, 5% of beef cattle slurry utilisation, and 75% of pig slurry utilisation. Food waste resources were based on source separated collection.	(Clancy et al. 2012)
Pig slurry and grass silage	Site specific	No	Yes	2012	Biogas resource associated with co-digestion of pig slurry and grass silage at pig farms.	(Xie 2012)
Dairy cow slurry and grass silage	National	No	Yes	2013	Resource of biogas associated with the anaerobic co-digestion of grass silage and dairy cow slurry. A range of resource levels was given depending on the share of grass silage and cow slurry. Utilisation pathway proposed was digestion of feedstock in centralised anaerobic digesters processing 50,000t of feedstock per year.	(Wall et al. 2013)
Slaughterhouse waste, milk processing waste, food waste, pig slurry, waste water treatment plant sludge	Site specific	No	Yes	2013	Calculation of the biogas yield arising from the anaerobic digestion of multiple feedstock streams amounting to 33,000t per year in a rural townland.	(Browne et al. 2013)
Source separated household organic waste	National	No	No	2013	Biogas resource associated with the portion of food waste in Ireland which cannot be landfilled. No utilisation pathway was proposed.	(Browne & Murphy 2013)
Cattle slurry (Dairy cows and beef cattle), food waste, grass silage	National	No	No	2016	Biogas resource from the anaerobic digestion of waste available wastes based on national waste data. The land area of grass silage required to provide 10% RES-T was estimated to be 68,000ha.	(Allen et al. 2016)
Potential carbon dioxide from anaerobic digestion of number feedstocks	National	No	No	2015	Resource of CH_4 that could be produced from power to gas systems using the potential resource of CO_2 associated with biogas in Ireland.	(Ahern et al. 2015)

Of the 18 prior studies assessing the resource of renewable gas production from anaerobic digestion in Ireland only one spatially explicit study was conducted (Smyth et al. 2011). This was on a regional scale within Ireland and did not offer more detail at a finer scale. Of interest is the fact that 15 studies did propose a utilisation plan, typically the processing of feedstock at centralised anaerobic digestion facilities. However, these studies did not consider feedstock or facility location. Prior studies suggested that anaerobic digestion facilities processing the biodegradable fraction of municipal solid waste be located in close proximity to high population urban regions, while large centralised anaerobic digestion facilities processing grass silage and cattle slurry were to locate in rural regions (Singh et al. 2010). Prior works used national or regional statistics on waste stream production or national statistics on grass silage availability for use in anaerobic digestion, spatially explicit studies were rare.

The lack of major spatially explicit studies inhibits the ability to compare regions or local areas to one another and does not allow for the distribution in the availability of resources to be ascertained as outlined by (Batidzirai et al. 2012).

One of the main proposed uses of the biogas produced in the anaerobic digestion process was upgrading to biomethane and injection into the natural gas network for use as a source of renewable transport fuel or renewable heat. However, only one study considered the location of the natural gas network in Ireland when assessing the grid injection of biomethane produced from anaerobic digestion (Smyth et al. 2011). A total of 6 studies assessed the performance of a single anaerobic digestion facility processing either waste feedstock or grass silage. Studies were typically technoeconomic and did not consider or develop a detailed plan for the implementation of a renewable gas industry in Ireland.

In addition to the production of biomethane, prior work has assessed the possibility of using anaerobic digestion as a method of interlinking the electricity and gas networks (Ahern et al. 2015). The proposed system used renewable electricity which would otherwise be curtailed to generate hydrogen, this hydrogen would then be combined with CO_2 from anaerobic digestion plants to produce additional CH_4 in a power to gas system. The CH_4 could be injected to the gas network. Prior

work assessed the potential resource of CH_4 associated with power to gas systems that would use CO_2 from the potential biogas resource in Ireland. The resource of CH_4 that could be produced using an existing source of CO_2 was not determined (Ahern et al. 2015) and the location of such facilities was not considered. The proposed system would also be able to generate renewable electricity at times of high demand and would act as a controllable source of renewable electricity (Ahern et al. 2015). The use of a variable feeding rate to control biogas production was proposed but no laboratory trials were conducted to assess a potential feeding regime that could be used at an anaerobic digester for such a system.

2.4 Comparison of international to national studies

Comparing the methodologies utilised in resource assessments conducted outside of Ireland and within Ireland highlights several differences.

1. No spatially explicit assessment of the resource of renewable gas in Ireland has been conducted for multiple waste streams, these have been conducted internationally and could provide greater insight into the location of potential feedstock available for use in renewable gas production in Ireland. As highlighted in literature, of main relevance for a commercially viable biogas plant is the local potential and availability of suitable feedstock within a certain area around the plant (Al Seadi, Rutz, Janssen, et al. 2013). This depends on spatial distribution and is influenced by feedstock type. Plant location is determined by feedstock logistics and availability (Al Seadi, Rutz, Janssen, et al. 2013). The importance of spatial distribution of feedstock was also highlighted for bioenergy systems as it gives insight into the distribution of biomass resources within a region or a country (Batidzirai et al. 2012).
2. While studies conducted within Ireland have proposed utilisation plans for harnessing the potential renewable gas resource in Ireland, no major assessment of the implementation of these plans was conducted. Internationally, assessments have considered the location of gas and electricity networks, potential locations for anaerobic digestion facilities,

and their location with respect to potential feedstock. Estimates of the practically available resource that could be utilised by anaerobic digestion facilities in Ireland were made in prior studies. However these were based on the authors' experience and on expert opinion (Singh et al. 2010; Clancy et al. 2012). A more detailed utilisation plan for feedstock suitable for the production of renewable gas in Ireland which considers the potential location of anaerobic digestion facilities in relation to energy transportation infrastructure and the locations of feedstock types would be beneficial.

3. Feedstock price, sale price of energy produced, and plant size (while considered for individual plants in prior studies conducted in Ireland) were not assessed in terms of their impact on the overall utilisation of the theoretical potential resource in Ireland. Assessing the impacts of potential incentives for the production of renewable gas on the financial viability of such facilities, and thus on the utilisation of the potential renewable gas resource in Ireland is pertinent to informing the design of such incentives.
4. Studies conducted in Ireland mainly proposed processing of feedstock in centralised anaerobic digestion facilities as the main utilisation plan (Murphy & McCarthy 2005; Murphy & Power 2007; Singh et al. 2010). Internationally, alternative utilisation plans have been proposed, specifically decentralised or small scale anaerobic digestion, with biogas transportation to a central user via biogas pipelines (Hengeveld et al. 2014; Hengeveld et al. 2016; Prasodjo et al. 2013; IEA Bioenergy Task 37 2017). An assessment of the implications of such a system in Ireland should be conducted as an alternative case to the road haulage of feedstock to a large centralised facility, to ascertain whether decentralised systems can offer benefits in terms of increased greenhouse gas savings. This could be of benefit in regions of Ireland in which there is limited access to either the electricity or gas networks.
5. Existing studies have assessed the theoretical potential biogas resource from waste streams and grass silage in Ireland. No single body of work has assessed the potential resource of these feedstocks, in addition to more advanced feedstocks, namely microalgae and gaseous feedstocks of non-

biological origin (H_2 for the production of CH_4 in power to gas systems). Assessing the potential resource of these more advanced feedstocks at a fundamental level within Ireland is required to determine whether they are of significance and can provide the basis for further works such as net energy ratio analyses and production cost estimates.

6. Prior works conducted in Ireland introduced the potential for renewable gas to act as a source of on demand renewable electricity. No assessment of the operation of such a demand driven process in Ireland, using indigenous feedstock was conducted. Assessing a potential operational regime for such a system in Ireland could be beneficial in terms of informing plant operators.

The goal of this work is to address the gaps in knowledge as highlighted above.

2.5 Methodology employed in this work

2.5.1 Resource assessments

In order to address the gaps in knowledge identified, this work comprises of a number of resource assessments to estimate the spatially explicit theoretical resource of renewable gas in Ireland. The resource assessments were conducted for waste streams suitable for biomethane production and the potential resource of grass silage in excess of livestock requirements for use in biomethane production. Additionally, the possible resource of microalgae that could be grown using CO_2 from fossil fuel fired power stations for use in biomethane production and the possible resource of CH_4 that could be produced in power to gas system using existing sources of CO_2 were assessed.

The data used in these resource assessments were the most up to date spatially explicit data available and were sourced for individual regions or facilities, this was done to highlight areas of high resource potential. These assessments outlined the theoretical resource of renewable gas that could be available in Ireland.

The in depth methodology used for each resource assessment can be found in; Chapter 3 for waste streams, Chapter 5 for grass silage, Chapter 7 for microalgae using CO_2 from fossil fuel fired power stations, and Chapter 8 for CH_4 derived from

CO_2 in power to gas systems. A simplified graphical overview of the methodologies used for each resource assessment can be seen in Figure 2-1.

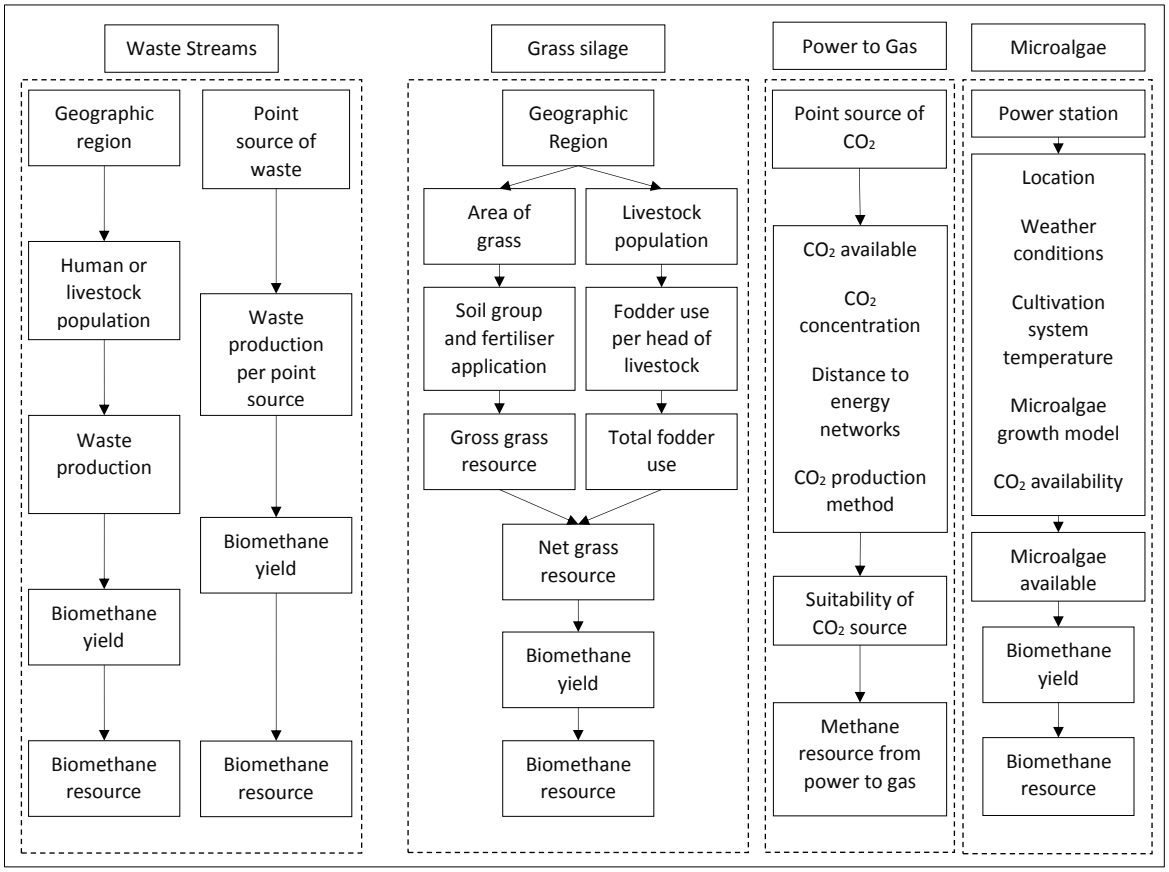


Figure 2-1 Overview of resource assessment methodology

2.5.2 Waste stream utilisation plan

Based on the resource assessment of waste streams suitable for biomethane production, a utilisation plan was developed. This waste utilisation plan factored in the location of waste streams and the location of potential sites on the gas network suitable for biomethane injection. The methodology determined the optimal locations on the gas network (from a list of potential sites) for biomethane injection in a sequential manner under several scenarios of plant size, feedstock cost, and potential incentive per unit of biomethane produced. Optimal plants were those with the highest net present value. The locations of feedstock supplying each biomethane production facility were also determined, along with a build order of

biomethane plants i.e. which plants should be built first and where they source their feedstock from.

In addition to identifying the optimal locations for biomethane production facilities processing waste streams, this work also allowed for an assessment of the impact of plant scale, feedstock price, and incentive per unit of biomethane produced on the total production of biomethane in Ireland. A detailed description of the methodology used can be found in Chapter 4. A simplified graphical overview of the waste stream utilisation plan methodology is shown in Figure 2-2.

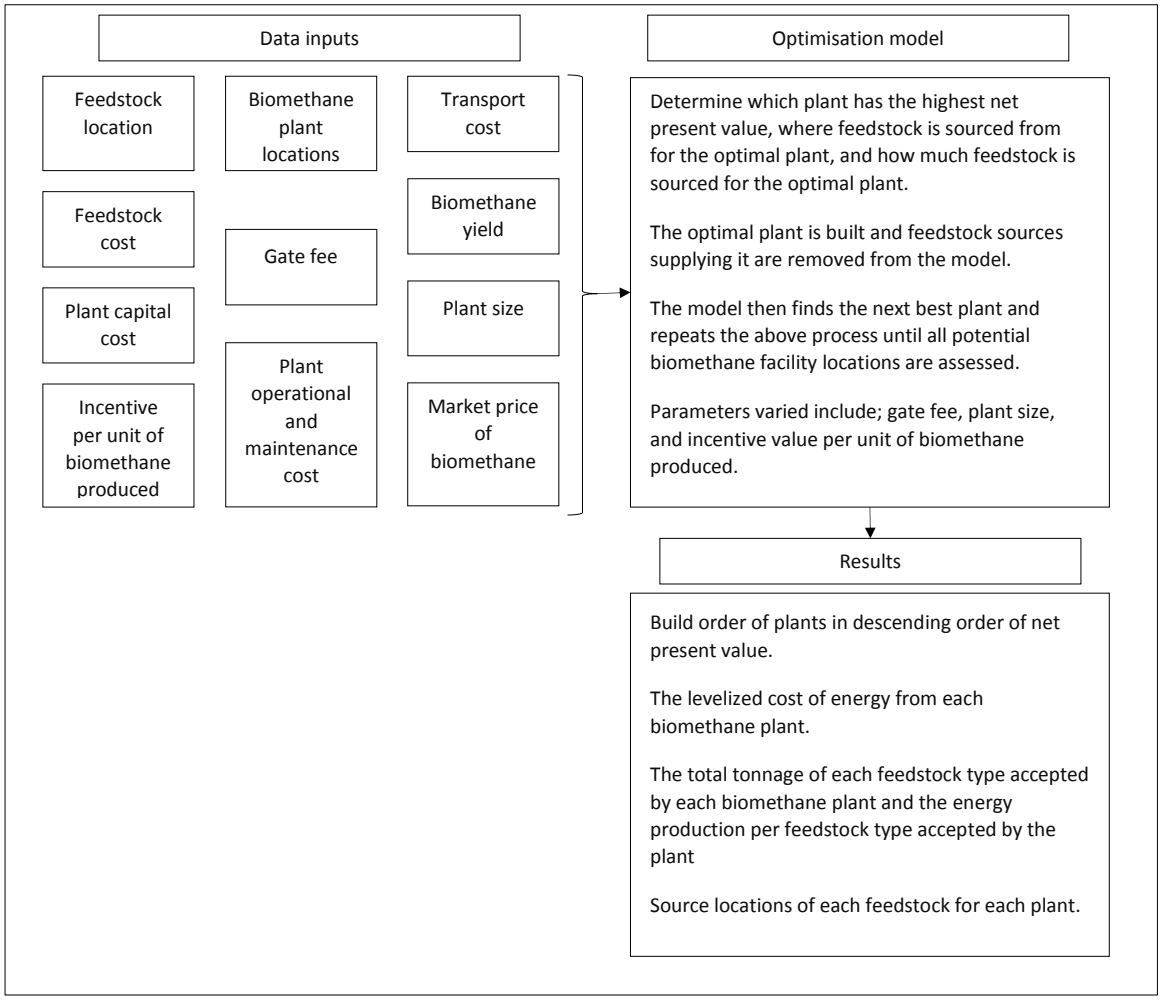


Figure 2-2 Graphical overview of waste stream utilisation plan

2.5.3 Grass silage utilisation plan

A utilisation plan for grass silage and cattle slurry was also developed. This methodology, while similar to the utilisation plan for wastes, was more detailed in that it considered the impact of feedstock mixture on plant performance. The grass silage utilisation plan also determined where the optimal biomethane production facilities were and where they sourced feedstock from. The number of scenarios assessed was greater than in the waste stream utilisation plan. The impact of plant scale, feedstock mixture, feedstock price, and potential incentive per unit of biomethane produced were also determined in this assessment. An in-depth description of the methodology can be found in Chapter 5. A simplified graphical overview of the grass silage utilisation plan methodology is shown in Figure 2-3.

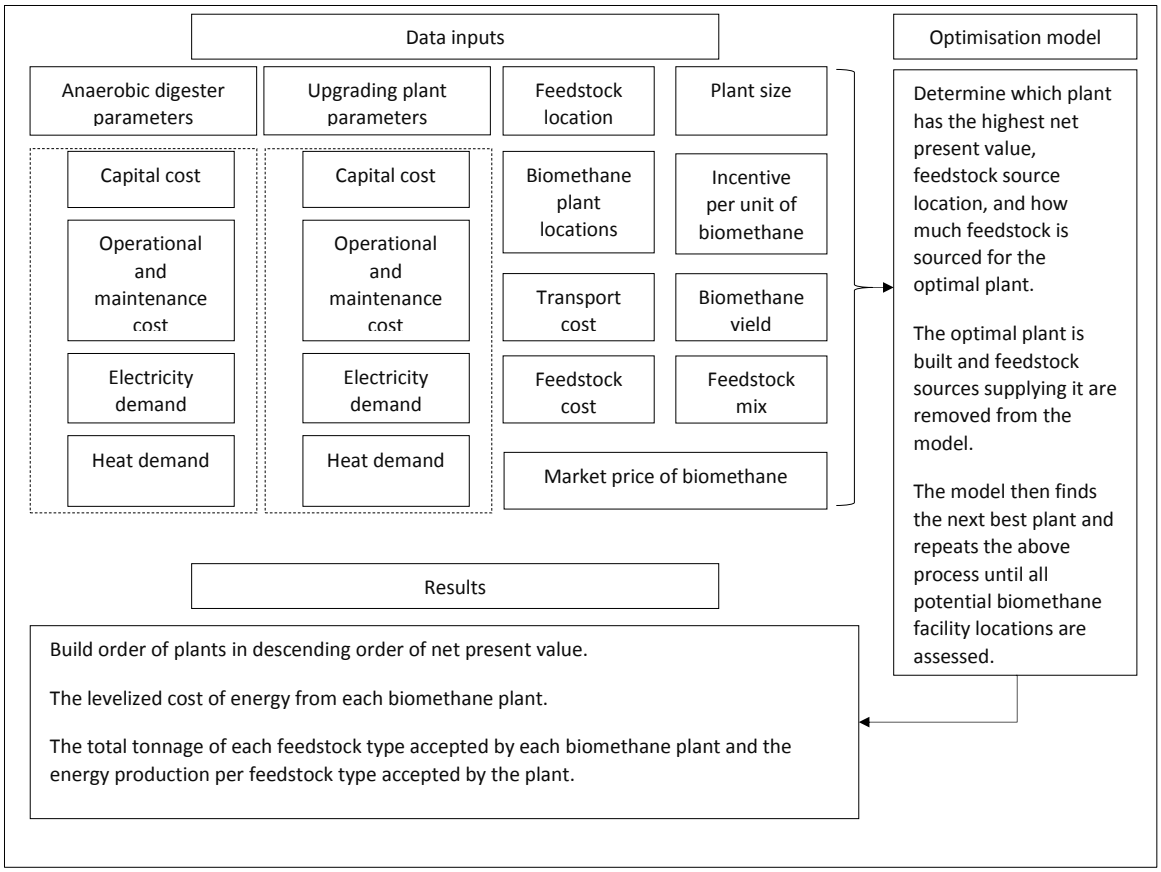


Figure 2-3 Graphical overview of grass silage utilisation plan

2.5.4 Alternative utilisation plan: decentralised anaerobic digestion

The prior utilisation plans for waste streams and grass silage consisted of biomethane production at large centralised anaerobic digestion facilities. As an alternative, a utilisation plan consisting of decentralised anaerobic digestion with biogas transportation to an energy end user via low pressure biogas pipelines was assessed in terms of energy consumption and the emission of GHGs during the biogas production and transportation process. This alternative utilisation plan could be implemented in regions, which are remote from the natural gas network and allow for the production of renewable gas in the form of biogas in a distributed manner. The detailed methodology can be found in Chapter 6. In summary, a number of differing biogas production configurations were compared with respect to energy consumption and GHG emissions at each process in the configuration. The main processes were feedstock haulage, digestion of feedstock, digestate haulage, and biogas transportation. A graphical overview of the methodology can be seen in Figure 2-4.

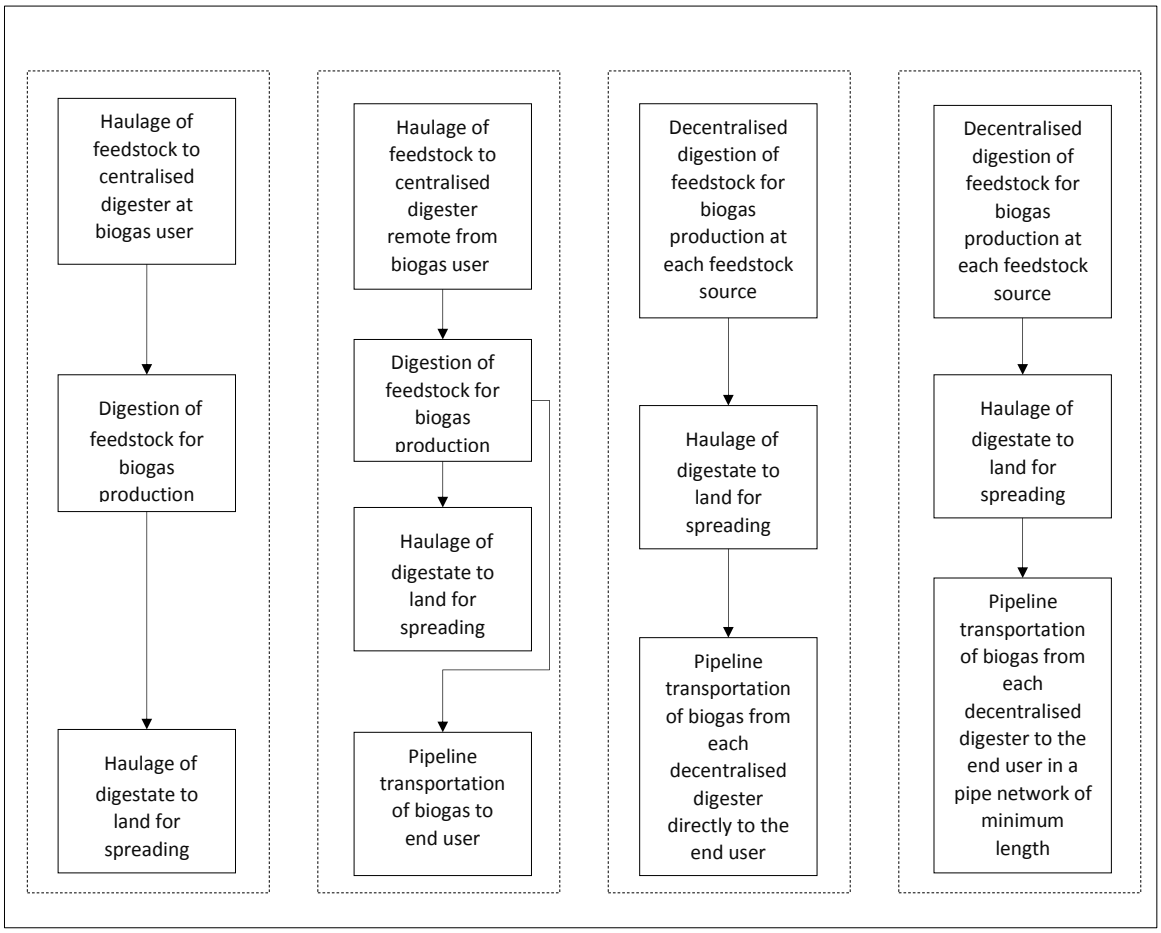


Figure 2-4 Graphical overview of decentralised anaerobic digestion comparison methodology

2.5.5 Demand driven biogas for use as a controllable source of renewable electricity

With regard to the ability of anaerobic digestion to link the electricity and gas networks, the resource assessment conducted to determine the potential resource of CH_4 that could be realised through the use of power to gas systems using existing sources of CO_2 represents one aspect of this system. The potential of anaerobic digestion to act as a controllable source of renewable electricity to supplement variable sources of renewable electricity is the other aspect of this system. In order to use anaerobic digestion as a source of renewable electricity in a demand driven process, sufficient biogas must be available to fuel a combined heat and power unit when electricity is required. Outside of this time period biogas can be upgraded to biomethane and injected to the gas network. A potential feeding regime for anaerobic digestion plants operating in this demand driven manner was developed

based on laboratory trials using four anaerobic digesters, each fed with a different feedstock. The production of biogas and methane were monitored in order to allow for a simplified model, which would minimise the storage volume between the digester, the CHP unit, and the upgrading plant to be developed. A detailed description of the methodology can be found in Chapter 9, a graphical overview of the methodology can be seen in Figure 2-5.

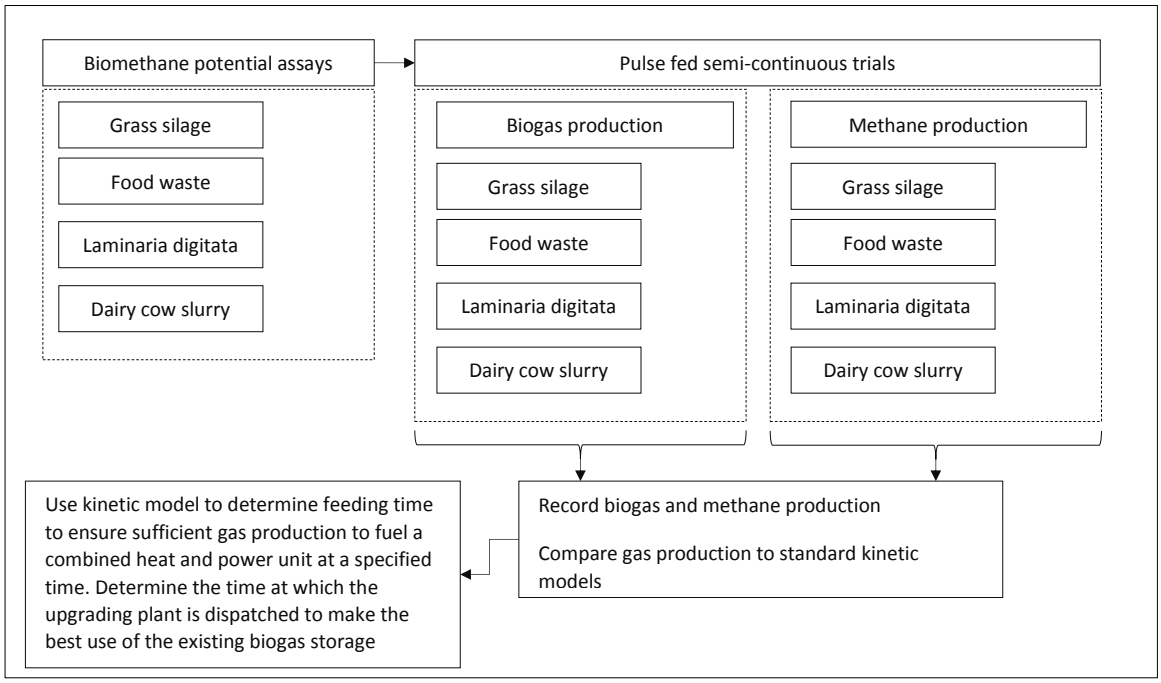


Figure 2-5 Graphical overview of demand driven assessment of feedstock

2.5.6 Overall biomethane resource potential

Based on the resource assessments conducted according to the above methodologies the total theoretical resource of renewable gas in the form of biomethane that can be produced from the anaerobic digestion of waste streams and grass silage can be determined. These feedstocks can be seen as readily available sources of biomethane, and have a high technology readiness level. Moving onto more advanced feedstocks, the total theoretical resource of biomethane that could be produced from microalgae, and the total theoretical resource of renewable gas that could be produced from H_2 and CO_2 in power to gas systems can also be found. These methods of renewable gas production are more

advanced and as such have a lower technology readiness level. Assessing the total theoretical resource potential will give an insight into the potential scale of the renewable gas resource in Ireland and the relative importance of each possible source.

The total theoretical resource of renewable gas identified in the resource assessments do not provide a true reflection of the quantity of renewable gas that could actually be produced. The waste stream utilisation plan and the grass silage utilisation plan allow for a more realistic estimate of the quantity of renewable gas that could be produced from these feedstocks. Utilisation plans were developed for these feedstocks as they are seen to be the most technologically ready sources of renewable gas (in this case biomethane). The total production of renewable gas from these feedstocks can be expressed in terms of the volume of renewable gas (biomethane) that could be produced at a given levelized cost of energy, or at a given combination of plant size, feedstock price, gate fee, feedstock mixture, and incentive level per unit of biomethane produced. Inspection of these results will yield a more realistic conclusion as to the potential quantity of renewable gas available from these high technology readiness level feedstocks.

The utilisation pathways developed (which consist of large centralised anaerobic digestion systems for biomethane production) may not capture a portion of the available theoretical resource owing to issues with feedstock location and transportation cost. Assessment of an alternative utilisation plan, decentralised anaerobic digestion, will yield valuable results in relation to the potential impact on CO_2 savings of the produced biogas and could allow for the utilisation of feedstock surplus to the requirements of large centralised plants.

The concept of demand driven biogas production for use as a source of renewable electricity allows for the role of renewable gas to be expanded beyond the production of transportation fuel and the provision of heat. Currently, the electricity and gas networks are linked, fossil natural gas is used to generate electricity for both based load and peak load requirements. Transitioning to a fully renewable electricity system will require the ability to produce renewable electricity on demand, variable renewable electricity sources cannot provide this

service. The ability of renewable gas to provide on demand renewable electricity, and renewable transport fuel or renewable heat outside of these demand periods exemplifies the interaction between energy sectors that will be required in the future.

2.6 References

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3 Chapter 3: Quantification and location of a renewable gas industry based on digestion of wastes in Ireland

Quantification and location of a renewable gas industry based on digestion of wastes in Ireland

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Abstract

Six EU Gas grids have a target of 100% substitution of natural gas with renewable gas by 2050. This industry will start with biogas upgraded to biomethane. The biomethane resource and location of waste substrates (such as agricultural slurries, slaughterhouse waste, milk processing waste, and source separated household organic waste) were determined using the most recent spatially explicit data for Ireland. The total biomethane resource estimated was equivalent to: 6.9% of natural gas usage, 6.2% of energy in transport; 47.6% of the fuel usage in heavy goods vehicles in 2015. In terms of natural gas use it corresponded to 22.0% of industrial gas use, and 48.3% of residential natural gas use. Biomethane as a source of thermal energy is equivalent to wood chips sourced from 16.5% of arable land under short rotation coppice willow. Thematic maps illustrating the location of each resource were developed to highlight regions of significant biomethane production potential. The regions with the greatest resource of cattle slurry are located in the south and east of the country; sheep manure resources are concentrated on the western seaboard, while the largest biomethane resource from household organic waste is found in urban and city areas (63% of household organic waste biomethane resource).

Keywords: Biogas; biomethane; resource assessment; renewable gas; biofuel; renewable heat.

3.1 Introduction

3.1.1 Energy consumption

Total primary energy requirement (TPER) is the total amount of energy used in a given year including energy used in the conversion of primary energy sources such as oil and gas into forms used by end customers, such as electricity. In 2015, the TPER for the Ireland (with a population of ca. 4.4 million) was 581.463PJ with oil and natural gas the main contributors (48% and 27%, respectively) (Howley & Holland 2016). Total Final Consumption is defined as TPER minus losses in the conversion of primary energy sources (oil, gas and coal) into useable energy sources. In 2015, TFC amounted to 469.2PJ with the largest shares attributed to oil (266.4PJ), electricity (90.3PJ), and natural gas (72.1PJ) (Howley & Holland 2016). In 2015 transportation TFC was 200.2PJ, the largest share of TFC (43%), 97.2% of energy used in transport was sourced from imported oil (Howley & Holland 2016).

3.1.2 Renewable energy in transport

EU Directive 2008/28/EC mandates that 20% of the energy consumed by the EU in 2020 is sourced from renewables. In Ireland that target is 16% of the gross final consumption of energy by 2020. Additionally, 10% of the energy used in transportation must be renewable by 2020. Renewable energy supply in transport (RES-T) can be achieved through the use of biofuels, or renewable electricity used in electric vehicles (EVs). Limits have been set on the contribution of first generation biofuels (cereals, starch rich crops, sugar and oil crops) to 7% of TFC in transport by 2020 (The European Parliament and the Council of the European Union 2015). To promote the use of second generation biofuels, non-food related feedstocks are allocated double their energy content towards RES-T calculation for 2020.
Within Ireland the Biofuels Obligation Scheme (BOS) requires that 6 out of every 100 litres of road transport fuel is a biofuel. In 2015, a total of 195,987m^3 of liquid biofuel was used, of which only 27,905m^3 (14% on a volume basis) was sourced indigenously, all of which was biodiesel (Byrne Ó'Cléirigh & LMH Casey McGrath 2016). As of 2010, two certificates are issued for each litre of transport biofuel produced from: biodegradable waste, residues, non-food cellulosic material, lingo-

cellulosic material, or algae. A cubic meter of gaseous biofuel derived from wastes or residues, with a net calorific value in excess of 35MJ.Nm^{-3} is eligible for 3 certificates (The National Oil Reserve Agency 2015). As these certificates can be traded between parties a market for biomethane use as fuel in transport now exists.

3.1.3 Natural gas and renewable gas

Ireland has a substantial natural gas infrastructure. The natural gas network in the Ireland is 13,772km in length and covers over 60% of the country (Gas Networks Ireland 2016) . The total gas system demand was 181 PJ from October 2015 to October 2016, comprising of 99 PJ by power generation, 57 PJ by industrial and commercial users, and 26PJ by residential customers (Gas Networks Ireland 2016). The use of natural gas as a vehicle fuel in Ireland is limited, however Gas Networks Ireland (GNI), the operator of the gas network, aim to provide 5% of the energy used in commercial transport, and 10% of the energy used in buses from compressed natural gas (CNG) or biomethane by 2025 (Gas Networks Ireland 2016). This ranges from 6.5-13PJ of gaseous fuels in transport by 2025 depending on demand forecasts (Gas Networks Ireland 2016). The total consumption of energy by heavy goods vehicles (HGVs) for freight transportation amounted to approximately 26PJ in 2015 (Howley & Holland 2016).

EU member states are required to provide CNG refuelling stations to enable public access to CNG and biomethane for use in transport, with a recommended average distance between refuelling points of 150km(The European Parliament and the Council of the European Union 2014). A minimum of 5 refuelling stations are required in Ireland. CNG as a transport fuel has a low excise duty (0.11€.$L_{Diesel\ Equivalent}^{-1}$) as compared to that of petrol (0.59€.L^{-1}) and diesel (0.48€.L^{-1}) which could promote the uptake of CNG as a transport fuel (Comisison for Energy Regulation 2015).

Within Europe, 7 gas transmission operators from 6 natural gas grids have already signed a joint declaration to supply 100% CO_2 neutral gas by 2050 (De Buck et al. 2015). GNI have announced a target of 20% renewable gas in the Irish gas network

by 2030 with an interim goal of 5.2PJ by 2024 (Gas Networks Ireland 2016). A key route to achieving this is the utilisation of biomethane produced through anaerobic digestion (AD) of biodegradable materials including wastes, energy crops, and algae. Renewable gas can also be generated in the production of synthetic natural gas via thermal gasification of biomass, and through the conversion of excess renewable electricity from intermittent sources (wind turbines) to methane in power to gas systems.

3.1.4 AD for the production of renewable gas

Renewable gas can be sourced from biogas. Following removal of carbon dioxide and other impurities, biogas with a methane concentration >97% (termed biomethane) can be compressed, injected into gas cylinders or the natural gas network. Renewable methane from biodegradable waste streams can be utilised in heat production, electricity generation, and transportation. The biodegradable materials assessed in this work are; cattle slurry, sheep manure, chicken manure, pig slurry, slaughterhouse waste, milk processing waste, and source separated household organic waste. These waste streams are thought of as the “low hanging fruit”, feedstock with no major sources of competition, and which are double counted in the contribution to RES-T.

3.1.5 Overview of biomethane resource assessments

The overall national resource of biomethane from various feedstocks has been assessed for a number of countries worldwide (Abdeshahian et al. 2016; Seiffert et al. 2009; Moreda 2016; Noorollahi et al. 2015; Singh et al. 2010; Browne & Murphy 2013; Gallagher & Murphy 2013; Lönnqvist et al. 2013; Dagnall et al. 2000; Dagnall 1995). These works typically use high level national figures for livestock population and waste generation and result in an overall national or high level regional resource. Data on the biomethane resource of a country on a refined regional level, detailed enough to inform the development of a biomethane industry, is limited. The biomethane potential of three regions in southern Finland was assessed using GIS developed by Hohn et al.(Höhn et al. 2014), quantities of wastes generated

were determined from a combination of reports, studies, and interviews. The overall national resource was not assessed. A similar GIS based methodology to estimate the biogas resource of two regions in Italy was carried out by Chinese et al.(Chinese et al. 2014). The study assessed the resource of livestock manure and maize silage with data on livestock numbers and land use areas obtained from census results in the two regions. Again, the overall national resource was not determined. The regional potential biomethane resource of grass silage and cattle slurry in Ireland was assessed using a GIS (Smyth et al. 2011) incorporating information on land use, crop yields, livestock populations, and the presence of natural gas infrastructure in sub-regions. The work did not assess the biomethane resource on a finer geographical scale than these sub-regions. Within Ireland, significant work has been carried out assessing the potential biomethane resource of numerous waste streams, these are summarised below.

3.1.6 Prior assessments of the biomethane potential of wastes in Ireland

3.1.6.1 Cattle slurry

Use of cattle slurry as a feedstock for biogas production is permitted following treatment at 70°C for 60 minutes, or 60°C for 48 hours, twice, if quantities in excess of 5,000$t_{wwt}.a^{-1}$ are used (Department of Agriculture Fisheries and Food 2009). Singh et al. estimated that 30 Mt_{wwt} of cattle slurry was produced in 2010 in Ireland, with an energy resource of 13.7 PJ (Singh et al. 2010). Wall et al. calculated the production of slurry from dairy cows to be 7 Mt_{wwt} (Wall et al. 2013). Using a dry solids (DS) content of 87.5$g.kg_{wwt}^{-1}$, a volatile solids content (VS) of 66.9$g.kg_{wwt}^{-1}$ and a methane yield of 239$LCH_4.kgVS^{-1}$ for dairy slurry (Wall et al. 2013), 7Mt_{wwt} of dairy slurry equates to 4.06 PJ of energy (35.9$MJ.Nm^{-3}CH_4$). The resource of cattle slurry available out to 2020 was estimated by Clancy et al. as 0.356 PJ in 2011 (Clancy et al. 2012) assuming only 10% of dairy cow slurry and 5% of “non-dairy cattle” slurry could be used.

3.1.6.2 Sheep manure, pig slurry and chicken manure

Sheep manure and pig slurry can be used with prior treatment conditions as specified for cattle slurry. Singh et al. estimated the quantity of sheep manure available in 2010 to be 170,000 t_{wwt}, with a potential energy resource of 0.19 PJ (Singh et al. 2010).

Singh et al. estimated a pig slurry resource of 2.32 Mt_{wwt} in 2010, with an associated energy potential of 1.06PJ (Singh et al. 2010). Xie estimated a total annual pig slurry generation of 3.2 Mt_{wwt} in 2011. Applying a VS content of 9.3%$_{wwt}$, and a methane yield of 280 $LCH_4.kgVS^{-1}$ (Xie 2012) yields an energy resource of 3.15 PJ (37.78 $MJ.Nm^{-3}CH_4$) assuming that all pig slurry can be utilised. Clancy et al. estimated an energy potential of 1.64 PJ in 2010, assuming 75% of available pig slurry was accessible (Clancy et al. 2012). The use of pig slurry in large AD facilities was modelled by Murphy & McCarthy in which 73,000$t_{wwt}.a^{-1}$ of pig slurry was co-digested with 14,000 $t_{wwt}.a^{-1}$ of the organic fraction of municipal solid waste (OFSMW) for the production of 1.1-1.5 $x10^6$ $m^3CH_4.a^1$ (55.5 $GJ.a^{-1}$) (Murphy & McCarthy 2005).

The resource of chicken manure was estimated by Singh et al. to be 1.7Mt_{wwt} of manure (from 12,000,000 head of poultry) and 1.58 $PJ.a^{-1}$ in 2010 (Singh et al. 2010). Chicken production in Ireland is typically intensive (Central Statistics Office 2012), enabling the collection of chicken manure from chicken production facilities.

3.1.6.3 Slaughterhouse waste

Animal slaughter produces solid waste from the digestive tract of slaughtered livestock (paunch) which can be used in AD, and large quantities of wastewater which requires treatment prior to discharge (European Comission 2005). Treatment of wastewater can result in two additional waste streams; dissolved air floatation sludge, and excess activated sludge(Environmental Protection Agency 2008). The potential resource associated with slaughterhouse waste (SHW) in Ireland was estimated by Singh et al. to be 1.43 PJ arising from 440,000t_{wwt} of SHW in 2010 (Singh et al. 2010). Biochemical methane potential assays of wastes originating from an Irish slaughterhouse were conducted by Browne et al. generating yields of

238$LCH_4.kgVS^{-1}$ for paunch, 403$LCH_4.kgVS^{-1}$ for "green sludge", and 165$LCH_4.kgVS^{-1}$ for dewatered activated sludge (Browne et al. 2013). The use of digestive tract content (paunch) is permitted following: a reduction to 12mm particle size and exposure to 70°C for 60 minutes uninterrupted (The European Parliament and the Council of the European Union 2002), or, reduction to 400m particle size and exposure to 60°C for 48 hours uninterrupted, twice (Department of Agriculture Fisheries and Food 2009).

3.1.6.4 Milk processing waste

Milk processing for the production of "white products" (milk, yoghurt, and cream), "yellow products" (cheeses and butter), or "specialty products" (concentrates, powders) generates significant volumes of wastewater (European Comission 2006). AD can treat high strength wastewater, directly prior to aerobic treatment, or treat excess waste activated sludge generated in the aerobic treatment of wastewater (European Comission 2006). Browne et al. analysed the methane production of milk processing wastes (MPW) comprising of dissolved air floatation (DAF) sludge and "biologically treated effluent", arising from a milk processing plant, which produced 6,000$t_{wwt}.a^{-1}$ of waste (Browne et al. 2013). The study found that DAF sludge generated a methane yield of 787$LCH_4.kgVS^{-1}$, and 461$LCH_4.kgVS^{-1}$ for "biologically treated effluent". The total resource of biomethane from that one facility was 228,600$m^3CH_4.a^{-1}$, equivalent to 8.6$TJ.a^{-1}$ (Browne et al. 2013). Milk processing is an intensive industry in Ireland with approximately 5.6 billion litres of milk processed in 2014 (CSO 2015b). The abolishment of EU milk quotas in 2015 and a set target of increasing milk production by 50% (Food Harvest 2020) will increase the quantities of waste streams available.

3.1.6.5 Source separated household organic waste

The maximum allowable quantity of biodegradable waste that could be landfilled in 2016 in Ireland was 420,000t_{wwt} (Council of the European Union 1999). Thus alternative waste treatment methods are required for the remaining biodegradable waste (Browne & Murphy 2013), AD is classified as a potential authorised

treatment process. Furthermore, all waste collectors are required to have separate collection of household food and bio-waste, and each household is required to segregate their food waste prior to its collection in all population agglomerations greater than 500 persons by July 1st 2016 (Department for the Environment Community and Local Government 2013). The use of household food waste and bio-waste in AD is permitted following appropriate treatment under EU standards (12mm particle size, 70°C for a minimum of 60minutes) or national standards (400mm particle size, 60°C for 48 hours, twice) (Department of Agriculture Fisheries and Food 2009).

Singh et al. estimated the total resource of Irish household food waste and bio-waste to be 810,000t_{wwt} in 2010**,** with an energy potential of 2.1 PJ (125$nm^3 Biogas.t_{wwt}^{-1}$, 65% CH_4, 37.78 $MJ.Nm^{-3}CH_4$) (Singh et al. 2010). Browne et al. estimated the resource of the organic fraction of municipal solid waste to be 950,000t_{wwt} in 2016 (530,000t_{wwt} requiring treatment such as AD)**,** yielding a biomethane potential of 2.65PJ (131$Nm^3CH_4.t_{wwt}^{-1}$, 37.78 $MJ.Nm^{-3}$) (Browne & Murphy 2013). Clancy et al. estimated that the potential energy resource of biological municipal solid waste (BMSW) in 2010 was 0.262 PJ, based on the portion suitable for processing in AD plants (Clancy et al. 2012).

3.1.7 Objectives

Six EU gas grids have a target of 100% substitution of natural gas by renewable gas in the gas grid by 2050; Ireland has a target of 5.2PJ of renewable gas by 2025. The route to this substitution has not been quantified in detail before in scientific press. This work aims to determine how much natural gas can be substituted by biomethane produced by anaerobic digestion of residues and wastes.

The transition towards a renewable gas supply in any region requires an in-depth knowledge of the quantity of substrates, their conversion potential to renewable gas and their location. It is clear that there is considerable information available on the potential biogas resource on a national scale (Abdeshahian et al. 2016; Seiffert et al. 2009; Moreda 2016; Noorollahi et al. 2015; Singh et al. 2010; Browne & Murphy 2013; Gallagher & Murphy 2013; Lönnqvist et al. 2013). However, in order

to promote the informed development of a biomethane industry within a country or a region, information regarding the geographic specific location as well as the quantity of the biomethane resource at that location is required. Currently there is a lack of such data in the literature.

An objective of this work is to provide a comprehensive and up to date assessment of the available resource of biomethane from wastes in a region (exemplified by Ireland) and highlight the specific regions where these resources are found using the most up to date spatially explicit data on each resource.

This work is intended to inform the reader on both the location and scale of the biomethane resource within a country (exemplified by Ireland), in order to facilitate the development and use of this sustainable energy resource. The audience of this work is intended to be researchers, policy makers and engineers involved in energy conservation, energy conversion, and alternative renewable energy sources.

3.2 Methodology

3.2.1 Cattle slurry

The methodology used in this calculation is in line with the spatially explicit method (Vis & van den Berg 2010), similar to a spatially explicit resource focused assessment (Batidzirai et al. 2012), for the calculation of the biogas resource associated with animal manures and slurries. The smallest areas containing detailed livestock figures in Ireland are electoral divisions (EDs), of which there are 3,409 (CSO 2011a). Figures on the number of livestock for each ED from 2010 (June livestock numbers) were obtained from the Central Statistics Office (CSO) on 20th May 2015 (Agricultural Surveys, CSO). The data detailed the most up to date number of bulls, dairy cows, other cows, and other cattle. EDs with less than 10 farms were omitted owing to data protection. There were no livestock numbers for EDs in city areas.

Livestock numbers vary throughout the year as a result of slaughtering. In order to avoid over, or under, estimation of livestock numbers, the average of the June and December livestock number surveys were used (Mceniry et al. 2013). In determining the average figures for each ED (for which only June figures were

provided), a scaling factor was applied to each category of cattle within the EDs. The scaling factor was the average of the CSO figures for the number of each livestock type in June and December 2010 (CSO 2011b), divided by the total figure of each livestock type from all EDs sourced from the CSO. The number of each class of bovine animal in each ED (following disaggregation) was multiplied by the scaling factor to determine the average number of each bovine animal in each ED in 2010. The slurry production of dairy cows used was $5.84 t_{wwt}.a^{-1}$, an average of slurry production per head of dairy cow reported in literature (Singh et al. 2010; Wall et al. 2013). The weekly production of slurry per head of other cattle was sourced from literature (Hennessy et al. 2011) where categories of animal were grouped into; cattle>2 years, cattle 1-2, and cattle <1. Total annual slurry production for each category of bovine animal was calculated assuming animals are housed indoors for 20 weeks per year (Wall et al. 2013; Hennessy et al. 2011), during which time slurry collection is feasible.

It is expected that the methane yield of cattle slurry varies depending on the age and type of animal (beef or dairy production) as their diets vary, however, at the time of writing the authors were not been able to source this information. Therefore, the values presented are taken to represent all bovine slurries, irrespective of animal age or type. Table 3-1 summarises the dry solids content (DS), volatile solids content (VS), and specific methane yield (SMY) used in the calculation of the biomethane resource associated with cattle slurry.

Table 3-1 Cattle slurry properties

Parameter	Value	Source
Dry Solids Content ($\%_{wwt}$)	8.35	(Wall et al. 2013; Allen et al. 2014; Wall et al. 2014)
Volatile Solids Content ($\%_{wwt}$)	6.23	(Wall et al. 2013; Allen et al. 2014; Wall et al. 2014)
Specific Methane Yield ($LCH_4.kgVS^{-1}_{added}$)	143	(Wall et al. 2014)

3.2.2 Sheep manure

Quantities of sheep manure were also calculated on a per ED basis in the same manner as cattle slurry. In Ireland, sheep must be kept indoors for a minimum of 6 weeks in each year (Hennessy et al. 2011), only manure generated during this period can be collected. The figures for the production of manure per head of

sheep, as well as the dry solids fraction and volatile solids fraction of sheep manure were averages of values obtained from literature (Singh et al. 2010; Bidart et al. 2014; American Society of Agricultural Engineers 2003; Barker et al. 2002; Hennessy et al. 2011; Patil et al. 2014; Alvarez & Lidén 2009; Kafle & Chen 2016). Manure production per head was taken to be $0.088t_{wwt}.a^{-1}$, DS content was $35\%_{wwt}$, VS content was $22.6\%_{wwt}$, and SMY was $171LCH_4.kgVS^{-1}_{Added}$ (Singh et al. 2010; Bidart et al. 2014; Patil et al. 2014).

3.2.3 Pig slurry

In 2010 there was approximately 1.5 million pigs in Ireland from 1,029 farms, with 99% of all pig production taking place on 486 farms (Central Statistics Office 2012). To determine the resource associated with known locations of pig production, Annual Environmental Reports (AERs) for pig production facilities were sourced from the Environmental Protection Agency (EPA) (Environmental Protection Agency 2015). Within the AERs, the location of the facility and the quantity of pig slurry produced onsite in the report year must be recorded. The most recent (2013 or 2014) AERs for a total of 106 pig production facilities were sourced; 74 AERs yielded usable data. The number of pig production facilities used in this analysis is small in comparison to the total number of pig farms, however, the facilities identified are the largest facilities in Ireland and report the exact location and quantities of pig slurry available. The DS content used was $3.7\%_{wwt}$ (Xie 2012), VS content used was $2.6\%_{wwt}$ (Xie 2012), and methane yield used was $292LCH_4.kgVS^{-1}$ (Xie 2012; Thygesen et al. 2014; Asam et al. 2011) for pig slurry in this work.

3.2.4 Chicken manure

The methodology used to locate and estimate the quantity of chicken manure was identical to that used for pig slurry, a total of 79 AERs for the years 2013/2014 were sourced from the EPA, 67 yielded usable data. Values used for the DS content, VS content, and methane yield of chicken manure were average values sourced from literature (Tricase & Lombardi 2009; Nie et al. 2015; Liu et al. 2015; Environmental Protection Agency 1994; Kafle & Chen 2016; Angelidaki & Ellegaard 2003;

Braeutigam et al. 2014; Li et al. 2013). The DS content of chicken manure used in this work was 41.7%$_{wwt}$, VS content was 21.8%$_{wwt}$, and methane yield was 248LCH_4.kgVS^{-1}.

3.2.5 Slaughterhouse waste (SHW)

In Ireland, there are a total of 60 approved facilities involved in the slaughter of livestock (Department of Agriculture Food & the Marine 2015), however waste generation from all of these facilities is not published. AERs for 36 facilities were sourced from the EPA for the years 2011-2014. Within the AERs, paunch production and sludge from onsite wastewater treatment plants are reported separately in some instances, and combined in others. To disaggregate the combined waste reports, the average contribution of paunch and sludge to combined waste from facilities, which report waste streams separately was used. No distinction was made between “green sludge” and excess activated sludge in AERs. To disaggregate overall sludge figures into “green sludge” and excess activated sludge, the portion of each type was taken to be 32% “green sludge” and 68% excess activated sludge (Browne et al. 2013).

3.2.6 Milk processing waste (MPW)

AERs for a total of 21 milk processing facilities and dairy produce facilities were source from the EPA, of which 19 yielded useable data. Within the AERs, no distinction is made between sludge generated during DAF treatment and “bio-treatment effluent”. For this work, DAF was considered to be 16.7%$_{wwt}$ of total sludge while the bio-treatment effluent was 83.3%$_{wwt}$ of total sludge (Browne et al. 2013).

3.2.7 Source separated household organic waste

The analysis was carried out per ED, similar to cattle slurry and sheep manure. The population (as of 2011) of each ED was sourced from the Central Statistics Office (CSO 2015a) and the collectable quantity of source separated food and garden

waste per person was sourced from CRÉ (CRÉ 2010) for rural, urban, and city regions outlined in Table 3-2.

Table 3-2 Collectable source separated household organic waste

Area Type	Collectable Food Waste ($kg_{wwt}.person^{-1}.a^{-1}$)	Collectable Garden Waste ($kg_{wwt}.person^{-1}.a^{-1}$)	Source
City	42	33	(CRÉ 2010)
Urban	88	74	(CRÉ 2010)
Rural	81	60	(CRÉ 2010)

Urban areas are classified as areas with a population of 1,500 persons or greater (CRÉ 2010), rural areas are classed as EDs with less than 1,500 persons. City areas were identified as EDs within Dublin City, Cork City, Limerick City, Galway City, and Waterford City. The DS and VS portion, and the methane yield associated with household food and garden waste were sourced from literature in which the methane yield of a mixture of food and garden waste, from both urban and rural sources, was determined (Browne et al. 2014). The total collectable household food and garden waste within each ED was calculated by multiplying the population of the ED by the quantity waste generated per person per year. The quantity of biomethane available at each ED was then determined by applying the DS, VS, and methane yield of the waste stream to the total quantities of each waste stream. A summary of the parameters of feedstocks assessed in this work can be seen in Table 3-3.

Table 3-3 Waste stream properties

Waste stream	DS ($\%_{wwt}$)	VS ($\%_{wwt}$)	$LCH_4.kgVS^{-1}$
Cattle slurry	8.35	6.23	143
Sheep manure	35	22.6	171
Pig slurry	3.7	2.6	292
Chicken manure	41.7	21.8	248
SHW: Paunch		15.6	238
SHW: Green sludge		18.1	403
SHW: Excess activated sludge		10.7	165
MPW: DAF		6.8	787
MPW: bio-treatment effluent		7.6	461
Household organic waste: Urban & City	25.7	18.9	297
Household organic waste: Rural	33.4	27.5	274

SHW: Slaughterhouse waste, MPW: Milk processing waste

3.2.8 GIS: Thematic map development

A GIS was developed illustrating the biomethane resource of each waste stream per ED or per facility using QGIS (**www.qgis.org**). Each ED or facility was plotted on a thematic map of Ireland using ESRI shapefiles sourced from the CSO (CSO 2015a). The coordinate reference system utilised in the GIS was the IRENET95/Irish Transverse Mercator (EPSG 2157).

3.3 Results

3.3.1 Animal slurries and manures

The theoretical biomethane resource associated with cattle slurry, sheep manure, pig slurry, and chicken manure is shown in Table 3-4.

Table 3-4 Total biomethane resource of waste streams

Waste stream	**Substrate Production (kt_{wwt})**	**Biomethane Resource ($x10^6$ m^3CH_4)**	**Energy Resource (PJ)**
Cattle slurry	28,500	253.7	9.6
Sheep manure	400	16.1	0.6
Pig slurry	900	7.1	0.3
Chicken manure	100	3.1	0.1
Total manure and slurry	**29,900**	**280**	**10.6**
Slaughterhouse waste: Paunch	39.5	1.5	0.06
Slaughterhouse waste: Sludge	86.2	4.2	0.16
Slaughterhouse waste: Total	**125.7**	**5.6**	**0.2**
Milk processing waste	**115.2**	**4.4**	**0.2**
Source separated household organic waste: Rural	191.9	14.5	0.5
Source separated household organic waste: Urban	389.0	21.8	0.8
Source separated household organic waste: City	62.0	3.5	0.1
Source separated household organic waste: Total	**642.8**	**39.7**	**1.5**
Combined Total			**12.5**

A detailed breakdown of the biomethane resource associated with each livestock type is shown in Table 3-5.

Table 3-5 Detailed breakdown of biomethane resource associated with slurries and manures

Livestock Type	Head of Livestock	Slurry Production (kt_{wwt})	Methane Resource ($x10^6$ m^3)	Energy Resource (PJ)
Dairy Cows	1,067,793	6,235.911	55.592,264	2.1
Beef Cattle	1,155,358	6,701.076	59.739,146	2.3
Cattle >=2 years	927,717	4,824.131	43.006,446	1.6
Cattle 1-2 years	1,627,660	6,673.407	59.492,484	2.2
Cattle <=1 years	1,757,331	4,041.861	36.032,621	1.4
Total Cattle	6,535,860	28,476.387	253.862,963	9.6
Sheep	4,734,769	417.701	16.106,094	0.6
Pigs		938.508	7.116,209	0.3
Chickens		136.891	3.085,348	0.1

The largest theoretical biomethane resource arising from livestock slurries and manures is from cattle slurry, which represents 91% of the total theoretical resource, the next largest contributor is sheep manure (6%), followed by pig slurry (3%), and chicken manure (<1%). Figure 3-1 details the location and quantity of the biomethane resource associated with animal slurries and manures in Ireland, the scale used is logarithmic. From Figure 3-1, the regions with the highest biomethane resource associated with cattle slurry are in the central southern region and in the northeast. EDs with no shading correspond to areas with a low resource, typically associated with mountainous regions or urban areas.

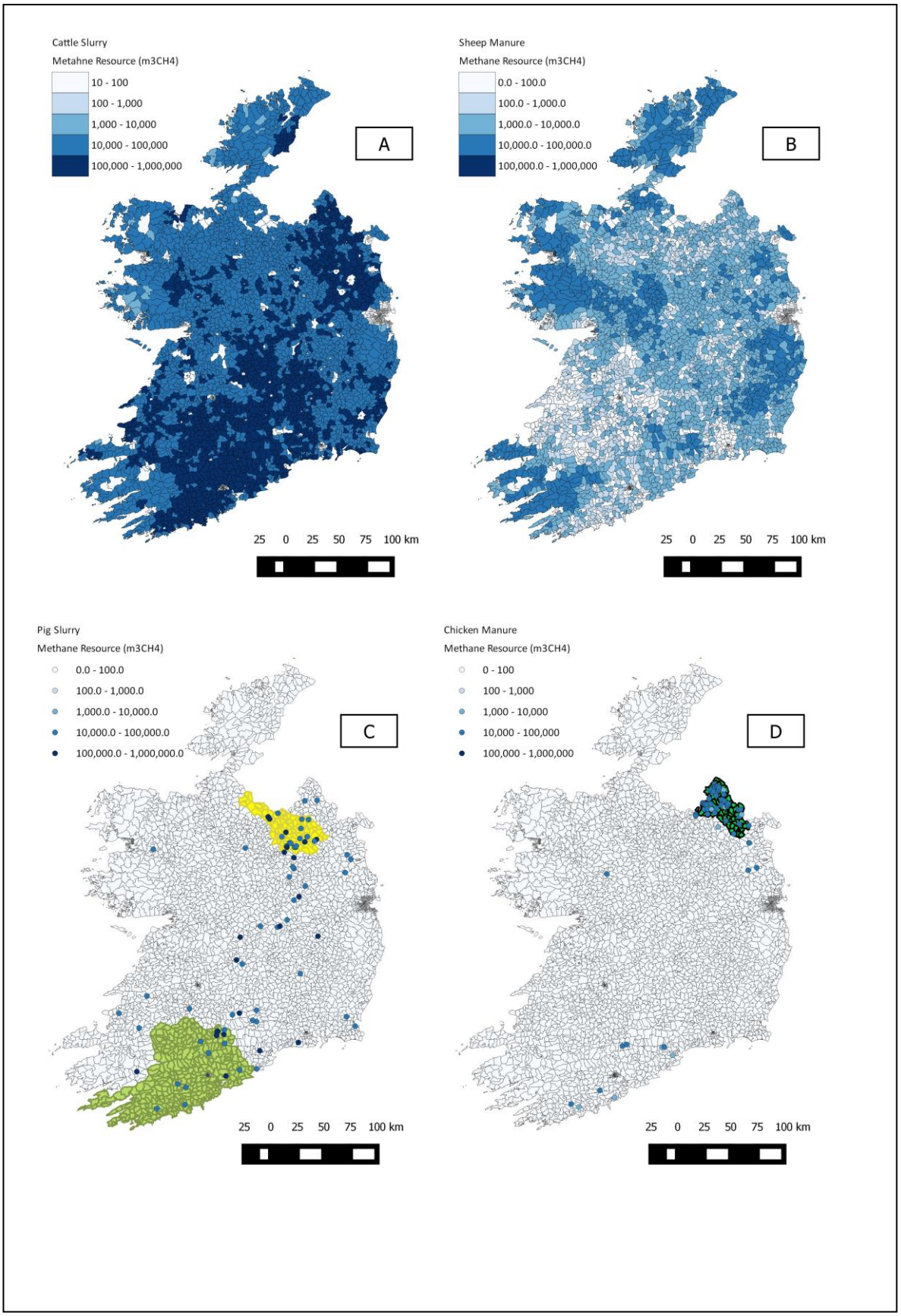


Figure 3-1 Thematic maps of biomethane resource, A: cattle slurry, B: sheep manure, C: pig slurry, D: chicken manure

3.3.2 Slaughterhouse waste

The total theoretical biomethane resource arising from slaughterhouse waste was found to be 0.2PJ, shown in Table 3-4. Figure 3-2A illustrates the location and quantity of the biomethane resource associated with SHW. Facilities are represented as point features, with their colour corresponding to the biomethane resource available at each facility.

3.3.3 Milk processing waste

The total theoretical biomethane resource associated with anaerobic digestion of wastes at the milk processing plants identified in this study is shown in Table 3-4. Figure 3-2B outlines the location and biomethane resource associated with sludge arising in milk processing plants identified in this study. A total of 11 facilities have a potential biomethane resource of 10,000-100,000 $m^3CH_4.a^{-1}$; 7 facilities have a resource of 100,000-1,500,000 $m^3CH_4.a^{-1}$. According to AERs sourced from the EPA, the majority of facilities identified (18 of the 19) currently land spread or compost the sludge produced onsite.

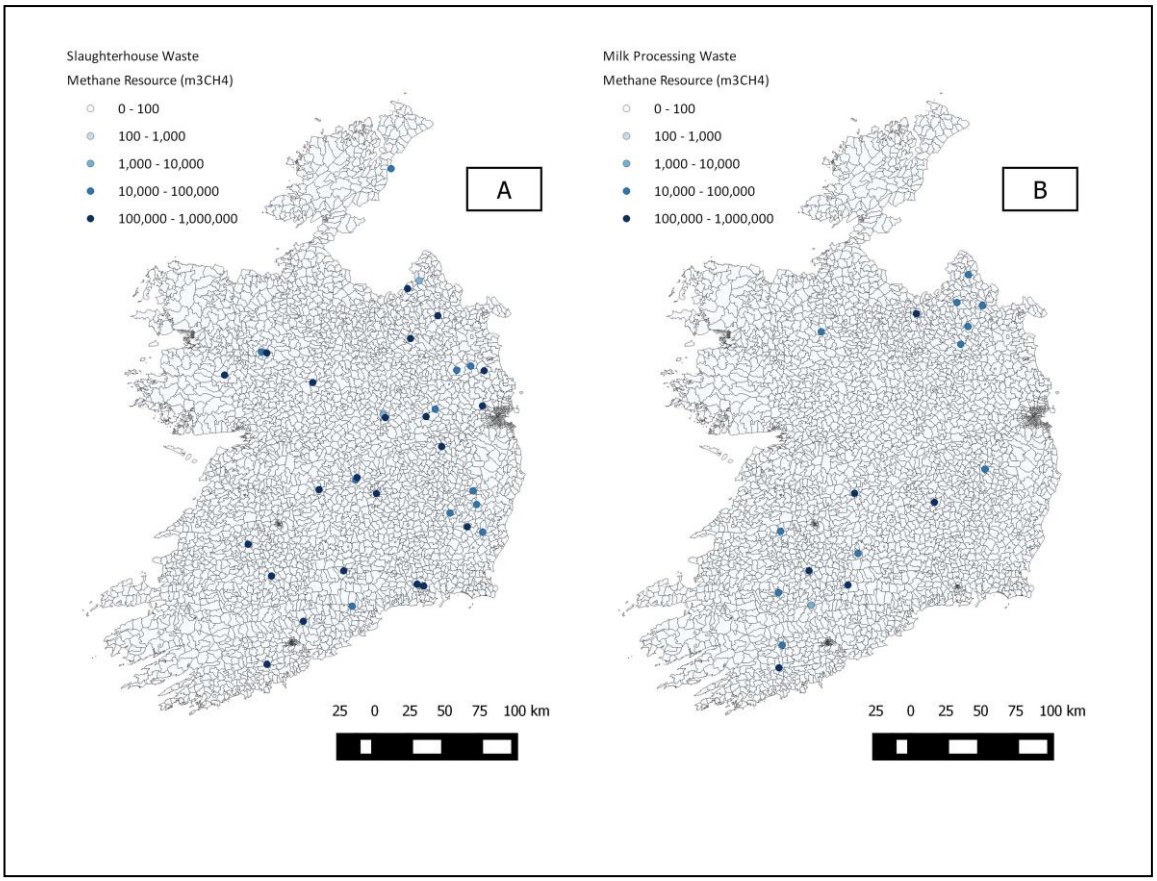


Figure 3-2 Thematic map of biomethane resource, A: Slaughter House Waste, B: Milk Processing Waste

3.3.4 Source separated household organic waste

The total biomethane resource associated with source separated household organic waste was found to be 1.5PJ, shown in Table 3-4. The total collectable resource of household organic wastes (combined food waste and garden waste) in rural, urban, and city areas, and their associated biomethane and energy resources are also presented. The total theoretical biomethane resource associated with source separated household organic waste arising in urban areas represents the largest share (approximately 55% of the total resource), followed by rural and city areas (36% and 9%), respectively. Figure 3-3 illustrates the location and quantity of biomethane available from source separated household organic waste. EDs with the largest biomethane resource are located around the major urban areas of the country, these have the highest population, and therefore the largest generation of waste.

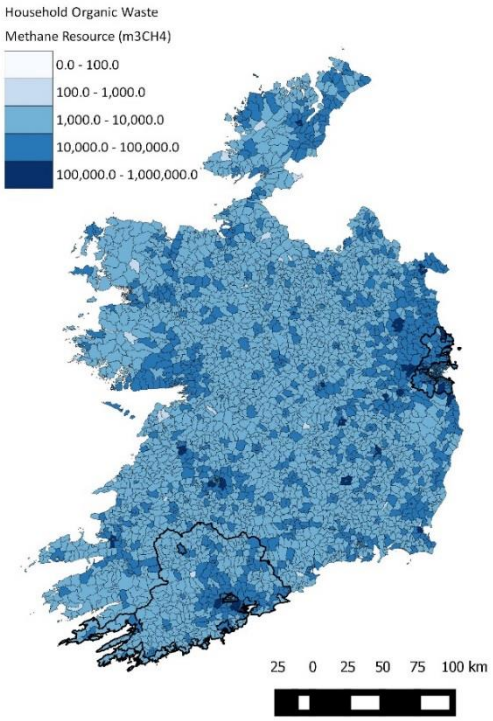


Figure 3-3 Thematic map of source separated household organic waste biomethane resource

3.3.5 Scale of biomethane resource

The contribution of biomethane derived from the above waste streams toward the 10% RES-T target, HGV total final consumption in 2015, and the 2025 GNI targets of 5.2PJ of renewable gas are documented in Table 3-6. As discussed in section 3.1.4 biogas derived from wastes is allowed a double credit for assessment of the 2020 target for renewable transport fuel. Thus the 2020, 10% RES-T, target can be readily surpassed using biomethane from residues.

Table 3-6 Overall theoretical resource of renewable gas from selected substrates

Waste Stream	Energy Resource ($PJ.a^{-1}$)	%Transport TFC	% Transport TFC Double Weighting	% HGV TFC	% Gas	%Commercial /Industry Gas	%Residential Gas	% GNI 2025 5.2PJ Goal
Cattle Slurry	9.59	4.79	9.58	36.64	5.29	16.93	37.17	185.01
Sheep Manure	0.61	0.30	0.61	2.32	0.34	1.07	2.36	11.74
Pig Slurry	0.27	0.13	0.27	1.03	0.15	0.47	1.04	5.19
Chicken Manure	0.12	0.06	0.12	0.45	0.06	0.21	0.45	2.25
SHW	0.21	0.11	0.21	0.82	0.12	0.38	0.83	4.12
MPW	0.17	0.08	0.17	0.63	0.09	0.29	0.64	3.20
Household	1.50	0.75	1.50	5.73	0.83	2.65	5.82	28.95
Total	12.47	6.23	12.45	47.62	6.88	22.01	48.31	240.45

TFC: Total Final Consumption; HGV: Heavy Goods Vehicles; GNI; Gas Networks Ireland; SHW: Slaughter House Waste; MPW: Milk Processing Waste.

3.4 Discussion of results

3.4.1 Animal slurries and manures

3.4.1.1 Scale of resource and comparison to other works

The total theoretical resource associated with cattle slurry identified in this work lies between the results of Singh et al. (29.95Mt_{wwt} resource, 13.69PJ energy potential) (Singh et al. 2010), and that reported by Wall et al. (7.07Mt_{wwt}, 4.06PJ from dairy cows only) (Wall et al. 2013). The energy potential is lower than that of Singh et al. as the methane potential of cattle slurry used in this work was 8.9$m^3CH_4.t_{wwt}^{-1}$ compared to 12.1$m^3CH_4.t_{wwt}^{-1}$ used by Singh et al. (Singh et al. 2010). The total mass of slurry available, 28.5Mt_{wwt}, could be processed in 62 facilities of a similar scale to the Maabjerg biogas plant in Denmark (IEA Task 37 2014) processing 460,000$t.a^{-1}$ of slurry.

The resource of sheep manure calculated in this work is larger than the resource identified by Singh et al. (Singh et al. 2010). The larger resource potential identified herein is a result of a larger sheep population (4.7 million vs. 3.5 million), along with greater annual quantities of manure (0.088$t_{wwt}.head^{-1}.a^{-1}$ vs. 0.05$t_{wwt}.head.^{-1}a.^{-1}$), and a higher methane yield (38.6$m^3CH_4.t_{wwt}^{-1}$ vs. 29.92$m^3CH_4.t_{wwt}^{-1}$).

For pig slurry, a total of 22 out of 74 facilities have a potential biomethane resource greater than 100,000$m^3CH_4.a^{-1}$ (0.0038$PJ.a^{-1}$). The pig slurry resource identified is less than the resource identified previously (Singh et al. 2010; Xie 2012). A lower resource level was calculated in this study because only slurry produced at large pig production farms reporting annual production of slurry to the EPA was considered. Additionally, the methane yield per fresh tonne of pig slurry used in this work was 7.6$m^3CH_4.t_{wwt}^{-1}$, less than the methane yield used in Singh et al. (Singh et al. 2010) (12.1$m^3CH_4.t_{wwt}^{-1}$) and Xie et al. (Xie 2012) (26$m^3CH_4.t_{wwt}^{-1}$).

A total of 55 out of 67 chicken production facilities had a biomethane resource between 10,000 to 100,000 $m^3CH_4.a^{-1}$. The biomethane resource associated with chicken manure identified in this work is lower than that identified by Singh et al. (Singh et al. 2010). Only data on chicken manure production from large producers of chickens sourced from their AERs was used in this work, therefore the associated biomethane resource was lower than in other analyses which used national flock numbers. The methane yield per tonne of chicken manure used in this study was 22.5$m^3CH_4.t_{wwt}^{-1}$, and was similar to the methane yield of chicken manure in Singh et al. (Singh et al. 2010) of 24.55$m^3CH_4.t_{wwt}^{-1}$.

3.4.1.2 Location of resource

The largest theoretical biomethane resource arising from cattle slurry can be found in the southern (45% of resource) and eastern regions (32% of resource) of Ireland. These regions should be targeted initially for development of cattle slurry AD systems.

The majority of the total theoretical biomethane resource associated with sheep manure is to be found in the western region of Ireland, which constitutes 44% of the resource. In comparing the thematic maps of cattle slurry and sheep manure (Figure 1A & B), it is evident that regions with large cattle slurry biomethane resource typically show low sheep manure resource, and vice a versa, as a result of land suitability for each livestock type.

The main resources of biomethane from pig slurry are located in counties Cavan (Figure 3-1C northern highlighted region) and Cork (Figure 3-1C southern

highlighted region), where 30% and 22% of the resource can be found, respectively. Transportation of pig slurry can be costly due to the high moisture content; therefore it is suggested that pig slurry be combined with other feedstock types in close proximity to pig production facilities.

It is evident from Figure 3-1D that the majority of the biomethane resource of chicken manure is found in a small region in the north of the country, contributing 2.69Mm^3CH_4. This represents 87% of the total biomethane resource of chicken manure (Figure 3-1D northern highlighted region). This is in agreement with comments in the 2010 census of agriculture which stated poultry rearing is primarily carried out by a small number of specialist producers (Central Statistics Office 2012).

3.4.2 Slaughterhouse waste (SHW)

3.4.2.1 Scale of resource and comparison to other works

SHW identified in this work yielded a biomethane resource of 0.22PJ from a total of 0.126Mt_{wwt} of waste. The SHW resource estimated by Singh et al. (Singh et al. 2010) was 1.43PJ arising from 0.44Mt_{wwt} of waste. The resource of biomethane identified in this study is associated with large scale slaughter facilities which are required to provide information on the quantity of waste generated in their facilities annually to the EPA. The methodology employed by Singh et al. (Singh et al. 2010) was based on the total number of animals slaughtered and the waste generated per head of livestock slaughtered. As such, the resource identified by Singh et al. (Singh et al. 2010) will be larger than the resource presented herein as it deals with all slaughterhouse waste generated nationally.

3.4.2.2 Location of resource

The thematic map of the biomethane potential of SHW (Figure 3-2A) shows that there is no discernible resource located in the northwest or south west of the country. The location of the slaughterhouses identified in this work also shows some degree of overlap with areas of high cattle slurry resource. This is possibly due to slaughterhouses locating in regions with the highest number of cattle to

reduce transportation costs and time in delivering livestock to facilities. Co-digestion of cattle slurry and SHW waste streams could be a viable way of utilising these resources more effectively. An example of this is the Sinding-Orre plant in Denmark which processes a combination of cattle slurry and food processing waste (Al Seadi et al. 2000). A total of 23 facilities out of 36 have a biomethane resource in excess of 100,000$m^3CH_4.a^{-1}$ with the theoretical biomethane resource associated with SHW being more distributed throughout the country than that of pig slurry and chicken manure.

3.4.3 Milk processing waste

3.4.3.1 Scale of resource

The total theoretical biomethane resource associated with MPW was 0.18PJ arising from 0.115Mt_{wwt} of waste. The resource was based on the anaerobic digestion of waste activated sludge and "bio-treatment effluent" arising in the large milk processing facilities which are obliged to report the quantity of waste generated on site. It does not include all milk processing facilities in Ireland. The figure reported in this work is lower than the total theoretical national resource, which would include all milk processing facilities if the data were available.

3.4.3.2 Location of resource

The theoretical resource associated with MPW is predominantly located in the southern half of the country responsible for 76% of the total resource, and in a relatively small region of the north of the country in which 12% of the total theoretical biomethane resource can be found. The location of milk processing plants identified in this report typically coincides with regions which have the highest population of dairy cows as can be seen in Figure 3-4.

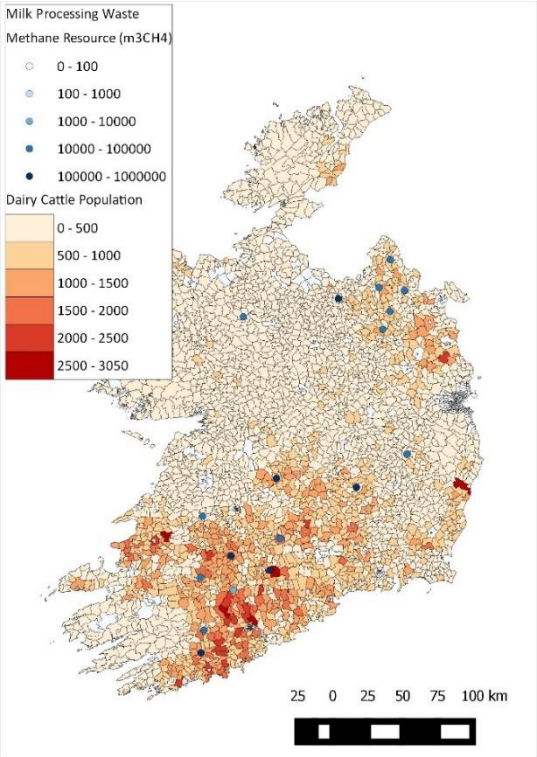


Figure 3-4 Location of milk processing facilities and dairy cow population

This may be due to the requirement to reduce transport time between dairy farms and milk processing plants in order to ensure that milk quality is maintained in transit. Once more, the co-digestion of MPW and cattle slurry may be an effective method for maximising the utilisation of both feedstocks owing to their co-location.

3.4.4 Source separated household organic waste

3.4.4.1 Scale of resource and comparison to other works

The biomethane resource of source separated household organic waste identified in this work is less than the resource identified by Singh et al. (Singh et al. 2010) in 2010 and Browne et al. (Browne & Murphy 2013) predicted for 2016. The difference in the energy potential originates from the total resource of waste, comprised of different quantities of both urban and rural waste, having different methane potentials. The methane yield of household organic waste used by Singh et al. (Singh et al. 2010) was 81.25$m^3CH_4.t_{wwt}^{-1}$, while that used by Browne et al. (Browne & Murphy 2013) for source segregated food waste was 131.7$m^3CH_4.t_{wwt}^{-1}$. The average methane yield of household organic waste used in this report (total

production of methane divided by the total production of all waste types) was 61.8$m^3CH_4.t_{wwt}^{-1}$. This figure is lower than prior values owing to the lower biomethane yield of rural waste streams; prior works assumed all waste streams had a similar biomethane yield. The total mass of organic waste available (642.8kt_{wwt}) could be processed in 6 AD facilities processing 120$kt_{wwt}.a^{-1}$ of waste, similar in scale to the ReFood Widnes plant in Cheshire UK (NNFCC 2015).

3.4.4.2 Location of resource

The biomethane resource associated with source separated household organic waste is highest in urban and city areas (contributing 64% of the overall biomethane resource) as can be seen from the darker areas on the thematic map (Figure 3-3), specifically in urban areas of the south and east. The most populous region in Ireland is county Dublin, located in the east of the county. Dublin county (Figure 3-3 eastern region, black border), excluding EDs in Dublin city, is responsible for the largest biomethane resource (17% of total theoretical potential) highlighting the resource from urban regions, which are not actually defined as cities. Electoral divisions within Dublin City, the capital of the Ireland, located on the eastern seaboard account for 6% of the total theoretical biomethane potential, a large biomethane resource from household organic waste is present in this small geographical area.

Cork county, which is the second most populous region in Ireland (Figure 3-3 southern region, black border) is responsible for 10% of the total theoretical potential; this is a combination of rural, urban, and city regions.

3.4.5 Contribution to targets and implications

From a transportation perspective, the biomethane resource identified could alleviate the consumption of approximately 347ML of diesel fuel (36$MJ.L^{-1}$ (The European Parliament and the Council of the European Union 2009)) equivalent to 11% of diesel consumption in 2015, and could offset approximately 7.8% of the total CO_2 emissions in transport in 2015 (Howley & Holland 2016). The resources' significance to Ireland's current biofuel production practices must also be noted.

The total theoretical energy resource of biomethane identified herein is 2.2 times greater than the total consumption of all liquid biofuels in Ireland in 2015, and 14 times greater than the total consumption of indigenously produced biofuel in 2015 (Byrne Ó'Cléirigh & LMH Casey McGrath 2016). This resource could aid Ireland in developing an indigenous, secure, and renewable source of energy for use in transportation. The largest biomethane resource in this work is from cattle slurry, contributing 77% of the total biomethane resource identified owing to the large population of cattle in Ireland. Source separated household organic waste represents 12% of the total biomethane resource identified in this work, the second largest resource after cattle slurry. This energy resource could meet a significant portion of energy consumption in HGVs (5.7%) or 26% of the fuel consumption of public transport in Ireland in 2015 (Howley & Holland 2016).

In terms of providing renewable heat, the resource of biomethane identified herein is equivalent to 7% of final thermal demand in Ireland in 2015. If this renewable heat were to be sourced from wood chips, 663,481 tonnes of dry matter (tDM) of wood chips from short rotation coppice willow (18.84GJ.tDM^{-1}(Clancy et al. 2012)) which would need 66,348 ha.a^{-1} of land (10tDM.ha^{-1}.a^{-1} (Clancy et al. 2012)). This is equivalent to 16.5% of the total arable land area in Ireland. Utilising the identified waste streams for biomethane production would not only address issues of waste disposal but also generate a source of renewable energy that would not impact upon current arable land usage. Another potential benefit is that customers already using natural gas would avoid the need and therefore cost of installing solid biomass boilers.

The total theoretical energy resource arising from the anaerobic digestion of waste streams can potentially contribute more than 12.5% of renewable energy supply in transport (RES-T) when allowing for the double weighting associated with biofuel from residues (Table 3-6). The biomethane resource is equivalent to 22% of natural gas use by industry/commercial users and 48.3% of natural gas use by residential consumers; as such it could also play a significant role in providing an indigenous source of renewable heat to these sectors with no change of equipment necessary as they already use natural gas boilers.

The resource of biomethane is twice the target for CNG use in commercial transport by 2025 and approximately 2.4 times the renewable gas target for 2025, provided all waste streams identified herein are utilised. To supply 20% of gas from renewable sources by 2030 the renewable gas would need to be sourced from alternative feedstock types such as grass silage of which Ireland has an abundant resource. Advanced biofuels such as micro- and macro-algae may also contribute in the future.

Future work investigating the economic viability of biomethane production facilities, taking into account feedstock transportation, facility scale, and revenue from the sale of biomethane should be conducted in order to ascertain potential locations for biomethane plant development. Such future work requires initial knowledge of biomethane resource and location within the study region. This work addressed this knowledge gap, exemplified by Ireland. Similar work can, and should, be carried out in other countries aiming to promote the development of biomethane as a source of renewable and sustainable energy source.

3.5 Conclusions

This work has highlighted both the quantity and location of the biomethane resource associated with various waste streams in a region, exemplified by Ireland. There are clear and distinct variations in the geographical distribution of the biomethane resource associated with each waste stream assessed. Highlighting both the quantity and location of biomethane resources on a national scale is required in order to determine potential locations for the construction of biomethane facilities. Facilities should locate in areas with the highest resource in order to minimise transportation costs and improve profitability. Knowing the location of the biomethane resource can aid policy makers in determining which regions are of interest when developing a biomethane industry.

In this work, the total theoretical biomethane resource from waste streams in Ireland was assessed; for example, biogas from residues can substitute for 6.9% of natural gas use. Use as a transport fuel is a potential route to ensure the use of indigenously sourced renewable energy in transport in Ireland. The total theoretical resource of biomethane from wastes is approximately 14 times the current production of indigenous biofuels in Ireland. Biomethane from residues can substitute for 17% of arable land under woody energy crops for renewable heat.

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4 Chapter 4: Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise

Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise

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Abstract

This work determined the optimal locations for biomethane injection, from Centralised Anaerobic Digestion (CAD) facilities processing wastes, into a gas network. The effects of incentives and plant size on; the sites selected, biomethane production, and feedstock utilisation, were assessed while maximising plant profitability. The first facilities to be constructed process household organic waste and were located in regions where this resource was highest. The number of viable facilities was dependent on the available incentives and ranged from 6 plants producing 0.55% of final thermal energy use, to 22 plants producing 1.9% of final thermal energy use. The model proposed two facilities that processed household organic waste at a maximum size of 200GWh.a^{-1} or 6 at a maximum size of 50GWh.a^{-1}. Increasing maximum allowable plant size reduced the total number of viable plants from 22 to 18, increased the total production of biomethane by 11%, but also increased the levelized cost of energy. Approximately 1.9% of final thermal energy use could be met by 22 plants with a maximum size of 50GWh.a^{-1}, or 2.1% of final thermal energy use from 18 plants with a maximum size of 200GWh.a^{-1}. The biomethane from these plants is equivalent to 6%, and 7% of total industrial natural gas consumption in 2015/2016.

Keywords: Biomethane; gas grid; optimal; location; incentive.

4.1 Introduction

4.1.1 Thermal Energy and Green Gas

Total final consumption (TFC) of energy in Ireland in 2015 amounted to 469.2PJ of which thermal energy production accounted for 178PJ; of this 88% was imported (Howley & Holland 2016). The annual gas system demand in Ireland from October 2015 to October 2016 was 181 PJ, comprising of 99 PJ of power generation, 57 PJ of industrial and commercial use, and 26PJ of residential customer use (Gas Networks Ireland 2016). Use of natural gas as a vehicle fuel is limited in Ireland, GNI aim to supply 5% of energy used by commercial vehicles and 10% of the energy used by bus fleets in the form of compressed natural gas (CNG) by 2025 (Gas Networks Ireland 2016). Gas Networks Ireland (GNI), the owner and operator of the gas network, aim to facilitate 20% gas supply from sustainable gas sources (such as biomethane) by 2030. The interim goal for renewable gas supply is 5.2PJ by 2025 (Gas Networks Ireland 2016).

Ireland must ensure that 16% of the gross final consumption of energy in 2020 is sourced from renewables (The European Parliament and the Council of the European Union 2009) with an indigenous target of supplying 12% of thermal TFC from renewable sources (Department of Communications Marine and Natural Resources 2007). EU states must ensure that 10% of the energy used in transport be renewable by 2020. Biofuels sourced from cereal and starch rich crops, sugar and oil crops, are limited to 7% of transport energy in member states in 2020(The European Parliament and the Council of the European Union 2015). Second generation biofuels (originating from wastes and non-food sources) and third generation biofuels such as algae are allocated double their contribution in terms of energy content to promote their development and use for the purposes of the 2020 RES-T target, however these weightings are not applied in calculating progress toward the national RES target of 16%.

Within Ireland the Biofuels Obligation Scheme requires that 6 out of every 100 litres of road transport fuel be a biofuel in Ireland (Byrne Ó'Cléirigh & LMH Casey McGrath 2015). Gaseous biofuels with a net energy value greater than 35MJ.Nm^{-3} benefit from a gas to liquid conversion factor of 1.5, according to the National Oil

Reserve Agency (NORA). Biofuel obligation certificates (BOCs) are issued to transport fuel suppliers and consumers for each litre of biofuel dispensed by the biofuel obligation account holder. Two BOCs are issued for each litre of biofuel produced from second or third generation substrates. Thus a cubic meter of gaseous biofuel produced from these feedstocks is eligible for 3 BOCs (The National Oil Reserve Agency 2015).

Seven European gas network operators have committed to supplying 100% carbon neutral gas by 2050 (De Buck et al. 2015). As outlined previously, GNI aim to achieve 20% renewable gas in the gas network by 2030. The technology for producing renewable gas is mature, in particular anaerobic digestion (AD) of organic matter to produce biogas, which has been identified as a key pathway in achieving these goals. Biogas is comprised of primarily methane (CH_4) and carbon dioxide (CO_2). After upgrading (removal of CO_2 and other impurities), compression, and injection of biomethane into the natural gas network, it can be used in heating, power generation, or as a transport fuel. Over 8,000 AD facilities are currently operating in Germany as of 2014 (Persson & Baxter 2014). As of the first half of 2014, 151 German plants were injecting biomethane (renewable gas) into the grid.

4.1.2 Literature on logistics of green gas industry

The literature is sparse on investigation of the optimal locations for biomethane production plants. Smyth et al. using GIS and multi-criteria decision analysis, determined potential locations for biomethane production from grass silage and cattle slurry, although financial aspects were not considered (Smyth et al. 2011). Gallagher et al. analysed the potential of biomethane production from the gasification of willow woodchips in Ireland (Gallagher & Murphy 2013). The analysis considered differing plant sizes and suitable land areas around plant locations, amongst other aspects. The work did not assess sites in terms of their financial viability.

Internationally, few studies have accounted for the effect of plant size, feedstock availability and location, and policy support schemes on the optimal deployment of

biomethane to grid systems. Höhn et al. carried out work in which the spatial distribution and amount of biomass feedstock for biomethane production, the optimal location, number, and size of biomethane plants were investigated (Höhn et al. 2014). The optimal number and location of plants was found so as to minimise the total weighted transportation cost of biomass feedstock from source points to the selected plants using a P-median solution (Höhn et al. 2014). The analysis did not consider the financial viability of plants. Chinese et al. analysed the impact of changing support mechanisms on the optimal plant size, feedstock mix, and annual revenue by using a spatially explicit biogas supply chain model (Chinese et al. 2014). Different scenarios with cost minimisation and profit maximisation were assessed. The study was designed for electricity production from biogas, as opposed to biomethane production for use as transport fuel. Bojesen et al. assessed competition for feedstock between existing, planned, and proposed AD facilities using a location allocation model and a spatial interaction model (Bojesen et al. 2014). The study determined the optimal location of 10 new AD facilities digesting animal slurries whilst minimising the weighted transportation distance between sources of slurry and potential AD sites. Financial viability of plants was not assessed.

4.1.3 Objectives

The aim of this work was to determine the optimal locations for biomethane injection to a gas network for large centralised anaerobic digestion (CAD) facilities which process waste feedstocks and produce biomethane, under a number of scenarios of plant size and incentive. The intention was to highlight the impact of varying incentive levels and maximum allowable plant sizes on the total production of biomethane and the utilisation of the total theoretical resource of each waste stream. A detailed analysis was carried out in which the build order of plants, the utilisation of feedstock, the collection radius of feedstock, and the impact of plant size were assessed.

This work is intended to inform policy makers, planners, and researchers in the field of biomethane production of a methodology to determine suitable locations for

biomethane to grid facilities. The methodology developed herein was applied to a study region, Ireland, to showcase its implementation and provide some assessment of the results. The methodology developed in this work is intended to be applicable internationally.

4.2 Methodology

4.2.1 Potential locations of large scale AD facilities with grid injection of biomethane

Analysis of the gas grid in Ireland undertaken with GNI identified 42 locations for the construction of potential CAD facilities with biomethane injection to the gas network. These locations were digitized into a GIS using QGIS (see Figure 4-1) to determine the distance between the potential plant locations and the sources of waste to be used by the plants. Table 4-1 details the names and plant I.D. numbers for potential injection points.

Table 4-1 Potential injection points, identification number (ID) and name

ID	Plant Name	ID	Plant Name	ID	Plant Name
1	Tullamore Split	15	Tuam Split	29	Great Island
2	Virginia Split	16	Loughrea Split	30	Chair Split
3	Mullingar Split	17	Ballinrobe Split	31	Limerick Split
4	Kingscourt	18	Castlebar	32	Waterford
5	Athlone	19	Carlow	33	Ardfinnan
6	Enfield Split	20	Gort Split	34	Tipperary Branch
7	Drogheda Split	21	Wicklow	35	Askeaton Split
8	Dundalk Split	22	Ballina	36	Aughinish Split
9	Ballinasloe	23	Cross Molina	37	Mitchelstown
10	SW Dublin	24	Kilkenny	38	Charleville
11	Athy Split	25	Ballyragget Split	39	Fermoy
12	Blessington Split	26	Ennis	40	Mallow
13	Galway Split	27	Shannon Split	41	Whitegate
14	Athy Split 2	28	Cashel Split	42	Bandon

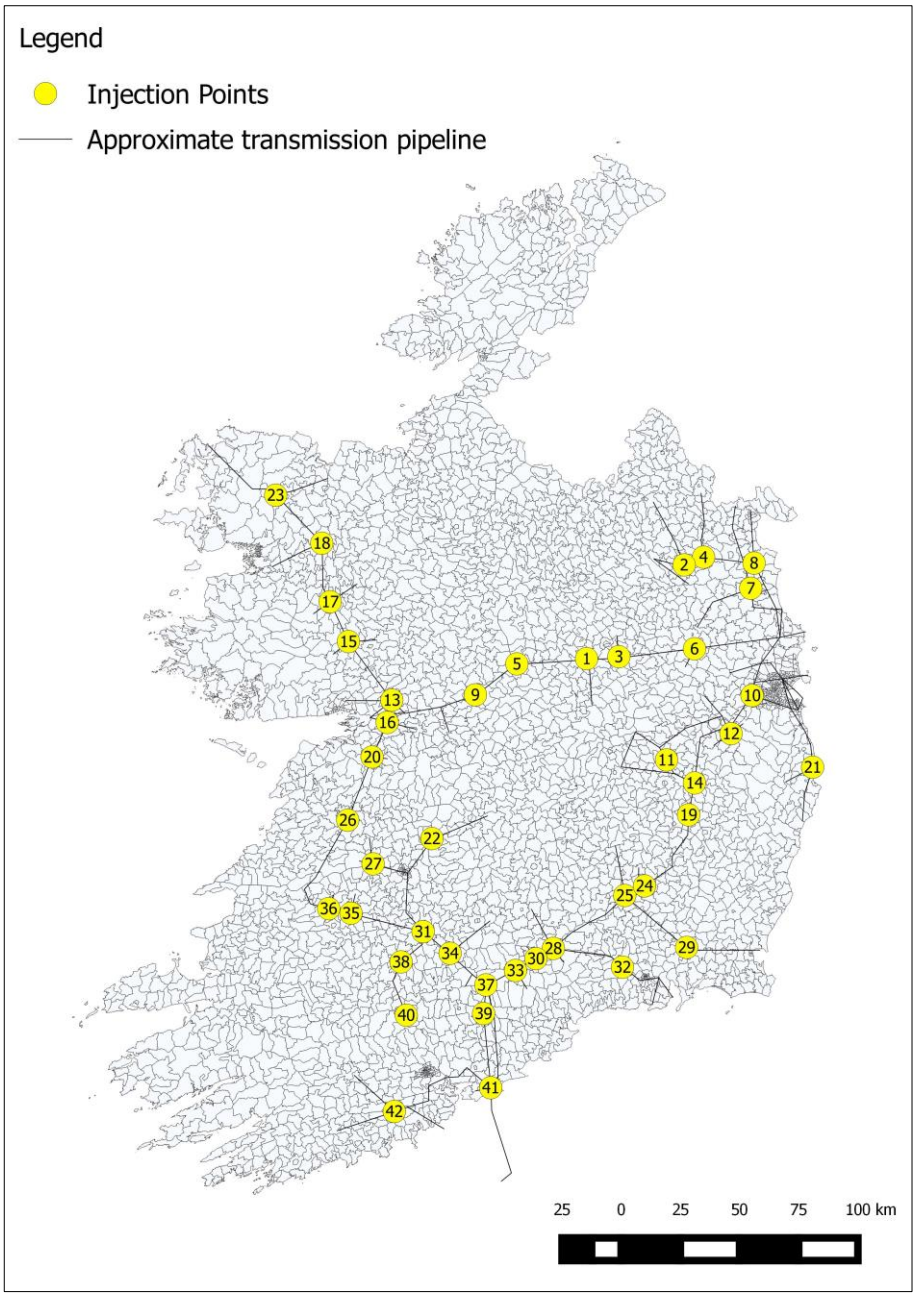


Figure 4-1 Locations of potential biomethane injection points to the gas transmission network

4.2.2 Feedstock locations and quantities

The wastes analysed in this work were; cattle slurry, sheep manure, chicken manure, pig slurry, slaughterhouse waste, milk processing waste, and source separated household organic waste. Data on the location of waste streams, their associated tonnage, and biomethane potential were sourced from prior work by the author (O'Shea et al. 2016). The total theoretical resource of biomethane from waste streams was determined in prior work by the author, this represented the theoretical maximum resource. No assessment of the portion of this resource which could be utilised was made previously. A summary of the properties of feedstocks and the total theoretical resource of biomethane from each waste stream can be seen in Table 4-2.

The methane yield per wet tonne (t_{wwt}) of combined slaughterhouse wastes, and milk processing wastes respectively, was the average of the methane yield per wet tonne of combined waste at each individual facility. The methane yield per wet tonne of waste at each facility was the total methane potential of wastes at the facility, divided by the total mass of waste generated at the facility.

Table 4-2 Waste stream properties and theoretical biomethane resource

Feedstock	Dry Solids (DS)	Volatile Solids (VS)	Methane yield	Methane per wet tonne	Total Theoretical Resource
	$\%_{wwt}$	$\%_{wwt}$	$LCH_4.kgVS^{-1}$	$m^3CH_4.t_{wwt}^{-1}$	PJ (GWh)
Cattle slurry	8.35	6.234	143	8.915	9.6 (2,667)
Sheep manure	35.23	22.568	171	38.559	0.6 (167)
Pig slurry	3.7	2.6	292	7.582	0.3 (83)
Chicken manure	41.66	21.787	248	22.539	0.1 (28)
Slaughterhouse waste: Paunch	Na	15.6	238	37.128	0.06 (17)
Slaughterhouse waste: "Green sludge"	Na	18.1	403	72.943	0.16 (44)
Slaughterhouse waste: Waste activated sludge	Na	10.7	165	17.655	
Milk processing waste: DAF sludge	Na	6.8	787	53.516	0.2 (56)
Milk processing waste: Bio-treatment effluent	Na	7.6	461	35.036	
Source separated household organic waste: Urban	25.66	18.886	297	75.345	0.8 (222)
Source separated household organic waste: City	25.66	18.886	297	75.345	0.1 (28)
Source separated household organic waste: Rural	33.4	27.488	274	56.034	0.5 (139)
Total					12.46 (3,463)

wwt: wet weight, VS: volatile solids

4.2.3 Transportation costs

Transportation of feedstock to AD facilities can incur a significant cost, up to 30% of the total production cost of biogas (Bojesen et al. 2014). Transportation costs were calculated using the specific energy consumption of moving 1t a distance of 1km by heavy good vehicle (HGV) in Ireland in 2013. The total HGV tonne kilometres (tkm) in 2013 were 9,138 Mtkm, total energy consumption of HGVs was 24.3 PJ (Howley et al. 2014), yielding a specific energy consumption of $2.66MJ.tkm^{-1}$. This was similar to values specified in Berglund et al. of $1.5\text{-}2.3MJ.tkm^{-1}$ (Berglund & Börjesson 2006). Thus, 0.74L diesel was required to move 1t a distance of 1km (energy content of $36MJ.L_{diesel}^{-1}$), at $1.51€.L_{diesel}^{-1}$ (average cost of diesel in 2013 (Dineen et al. 2014)), giving a cost of $0.112€.tkm^{-1}$. The Euclidian distance between waste sources and potential facility locations was determined using QGIS, this was

multiplied by a tortuosity factor of √2 in order to take into account the winding nature of rural roads (Smyth et al. 2011). The cost of transportation of the feedstock from its source to the AD facility was assumed to be covered by the AD facility owners.

The transportation costs for cattle slurries and sheep manure included the cost of digestate return to the areas from which the feedstocks were originally sourced. The mass of digestate returned was equal to the mass of feedstock sourced from each area (Berglund & Börjesson 2006) ensuring farmers did not lose the fertiliser value of the slurry or manure they supplied to the AD facility. The same assumption regarding digestate return was applied to chicken manure, pig slurry, slaughterhouse waste, and milk processing waste. The energy consumption of land spreading was not accounted for as it was assumed that was the farmer's responsibility and would be carried out whether or not the facility was in place.

For source separated household organic waste, the cost of feedstock transportation only covered the cost associated with waste transport to the AD facility from the centroid of each source location area. Waste collection operators would be responsible for collection and transportation of waste to the central collection point within the area. The collection of household organic waste requires an "empty return", sending an empty collection vehicle to the source of household organic waste(Berglund & Börjesson 2006). The specific energy consumption of household organic waste collection increased by 62%, the average increase in order to take into account empty return as per Berglund et al.(Berglund & Börjesson 2006) . The specific energy consumption of transportation of household organic waste to an AD facility was 4.39MJ.tkm^{-1}, equating to a specific transportation cost of 0.184€.tkm^{-1}.

4.2.4 Feedstock cost and gate fees

It was assumed that there was no cost associated with the feedstocks, they were essentially free (Clancy et al. 2012; Browne et al. 2011). Gate fees can be charged on the acceptance of source separated household organic waste. Disposal of source separated household organic waste in a landfill incurs a charge of 75€.t_{wwt}^{-1}

(McCoole et al. 2012). CAD facilities could charge a gate fee less than or equal to 75€.t_{wwt}^{-1} to ensure household organic waste is provided to the facility. Three gate fee levels were investigated; 20€.t_{wwt}^{-1}, 47.5€t_{wwt}^{-1}, and 75€.t_{wwt}^{-1}.

Gate fees may also apply to the disposal of paunch from slaughterhouses, and waste sludge from onsite wastewater treatment plants at slaughterhouses and milk processing facilities (Browne et al. 2011). The land application of the digestate resulting from the processing of these feedstock requires a nutrient management plan (NMP). In this analysis it was assumed that the costs of the NMP were met by the gate fee associated with wastes from slaughterhouses and milk processing facilities, as such these feedstocks were cost neutral.

4.2.5 Plant capital expenses (CAPEX) and operating expenses (OPEX)

The CAPEX and OPEX of CAD plants with grid injection of biomethane were sourced from The Department of Energy and Climate Change (DECC) in the United Kingdom (in the absence of such data in Ireland) for plants processing wastes (Department of Energy and Climate Change 2014). Costs were converted to Euros from sterling using an exchange rate of 1.3€.£$^{-1}$. The combined capital costs were plotted against the net GWh of biomethane injected into the gas network to derive a cost curve and an equation of CAPEX as a function of net GWh injected to the gas grid (Figure 4-2).

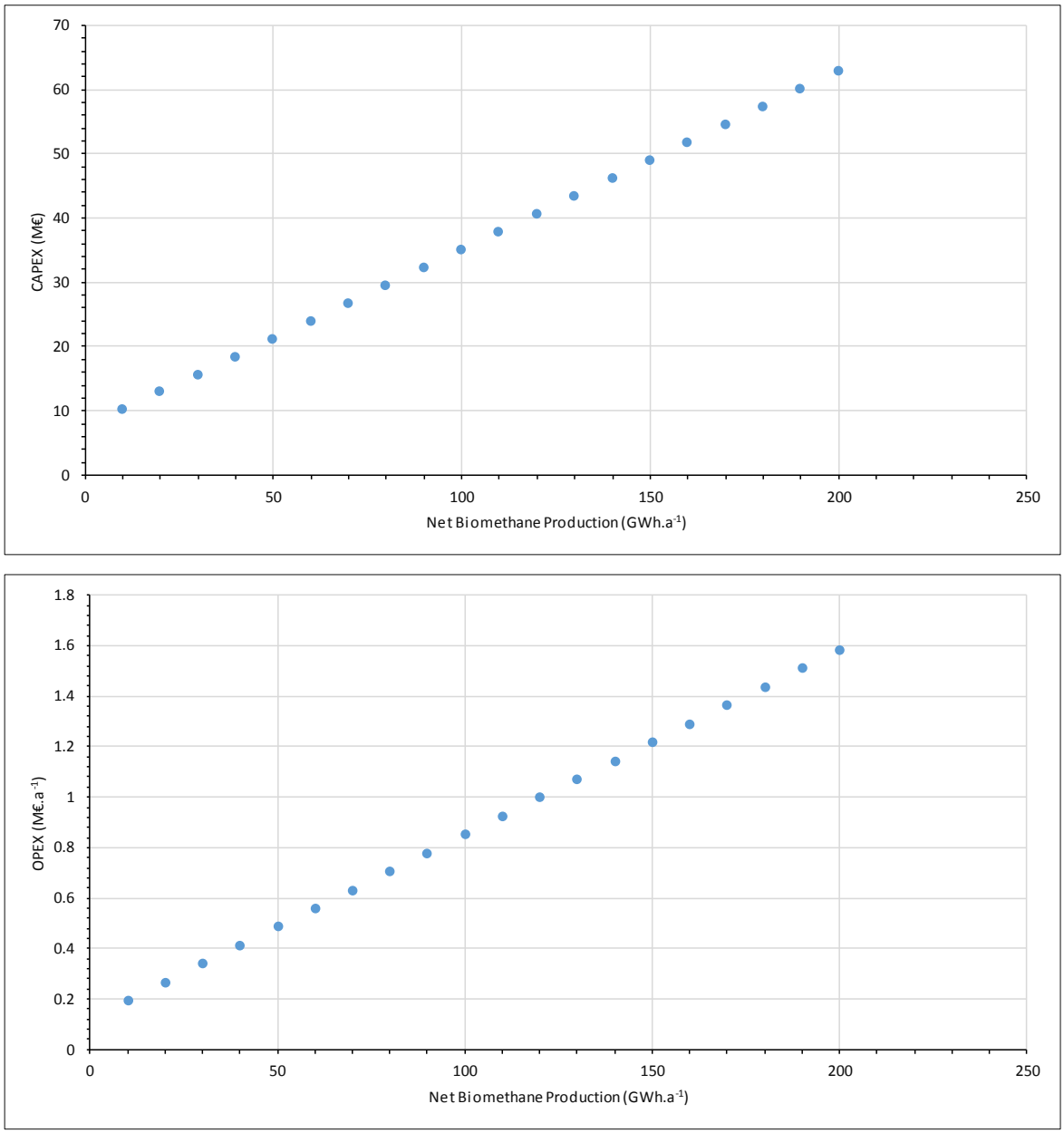


Figure 4-2 CAPEX and OPEX cost curves of AD plants processing waste with biomethane to grid injection in the UK

The annual net energy output (GWh.a^{-1}) of each facility was calculated according to Equation 4-1.

Equation 4-1 Annual net energy production of biomethane plants

$$E_j = \sum_m \left(tonnage_m * x_m * Y_m * \frac{36.65}{3.6 * 10^6} \right) * \eta_{digest} * LoadFact$$

In Equation 4-1 E_j is the annual net energy (GWh) from biomethane injected to the gas network from plant *j*, $tonnage_m$ and Y_m are the total tonnage (t_{wwt}) and associated methane yield ($Nm^3CH_4.t_{wwt}^{-1}$) of each feedstock type *m* accepted at the facility. x_m is the binary decision whether or not to source feedstock from a given source. η_{digest} and *LoadFact* are the digestion efficiency taken to be 80% of the biochemical methane potential, and the load factor (taking into account parasitic thermal and electrical demand, and methane losses in upgrading) taken to be the 84%.

4.2.6 Sources of revenue

Revenue was generated from the sale of biomethane at a market value of $28€.MWh^{-1}$ (Bruton et al. 2009), held constant for the lifetime of the project. Biomethane produced from CAD plants in this work was envisaged to be used in CNG vehicles. The Biofuel Obligation Scheme allows for the sale of BOCs between parties generating additional revenue. BOC prices fluctuate based on market forces and trade within the range of $€0.13-€0.36.L^{-1}$ of liquid biofuel (Ahern et al. 2015), hence, biomethane sourced from waste feedstock is potentially worth €38-€106 per MWh. Three different levels of BOC value were used in this work, $38€.MWh^{-1}$, $78€.MWh^{-1}$, and $106€.MWh^{-1}$.

4.2.7 Defining optimal

Net present value (NPV) was used to determine the optimal plant size, feedstock used, and feedstock source locations, at each potential injection point. NPV is the sum of the total discounted lifetime cash flows, both incoming and outgoing. NPV can be calculated according to Equation 4-2.

Equation 4-2 Net present value calculation

$$NPV = \left(\sum_{t=1}^{n}\left(Cash_t^{in} - Cash_t^{out}\right) * \left(\frac{1}{(1+dr)^t}\right)\right) - C_0$$

$Cash^{in}{}_t$ and $Cash^{out}{}_t$ are the incoming and outgoing cash flows in year *t* respectively, *dr* is the discount rate, *n* is the total number of years (20 in this work), and C_0 is the initial capital expenditure in year 0. Financing, depreciation repayments, and taxes were not included in the calculation of NPV, as per Zamalloa et al. (Zamalloa et al. 2011). The discount rate used in the calculation of NPV was 8% as specified in Zamalloa et al. (Zamalloa et al. 2011) and by Sustainable Energy Ireland(Sustainable Energy Ireland 2004).

4.2.8 Model Structure

At the start of the optimisation process all potential plant locations and feedstock sources were available. The model determined the optimal facility size, feedstock quantity, and source, at each injection point individually to maximise the NPV of each facility. The model selected the plant with the highest NPV and removed that plant location and the sources of feedstock supplying that plant from the problem space. The model then ran again for the remaining possible plant locations and the remaining feedstock sources, and built the next most profitable plant from the potential plant sites and feedstock sources remaining. The process was repeated until all the potential plant locations were assessed.

When building CAD facilities, ideally the most profitable site will be developed first, the next best site will then be developed from the remaining sites and feedstock sources. This process is repeated until no more viable sites remain. The model attempts to mimic this behaviour in its structure. The decision to source feedstock from a given location is binary, the plant can accept either all, or none, of the feedstock available at a given source. The flow cart in Figure 4-3 outlines the calculation steps in the optimisation model.

The model was implemented in MATLAB as a mixed integer linear optimisation model and was solved using the Gurobi solver engine. The MATLAB code developed for this model can be seen Appendix A.

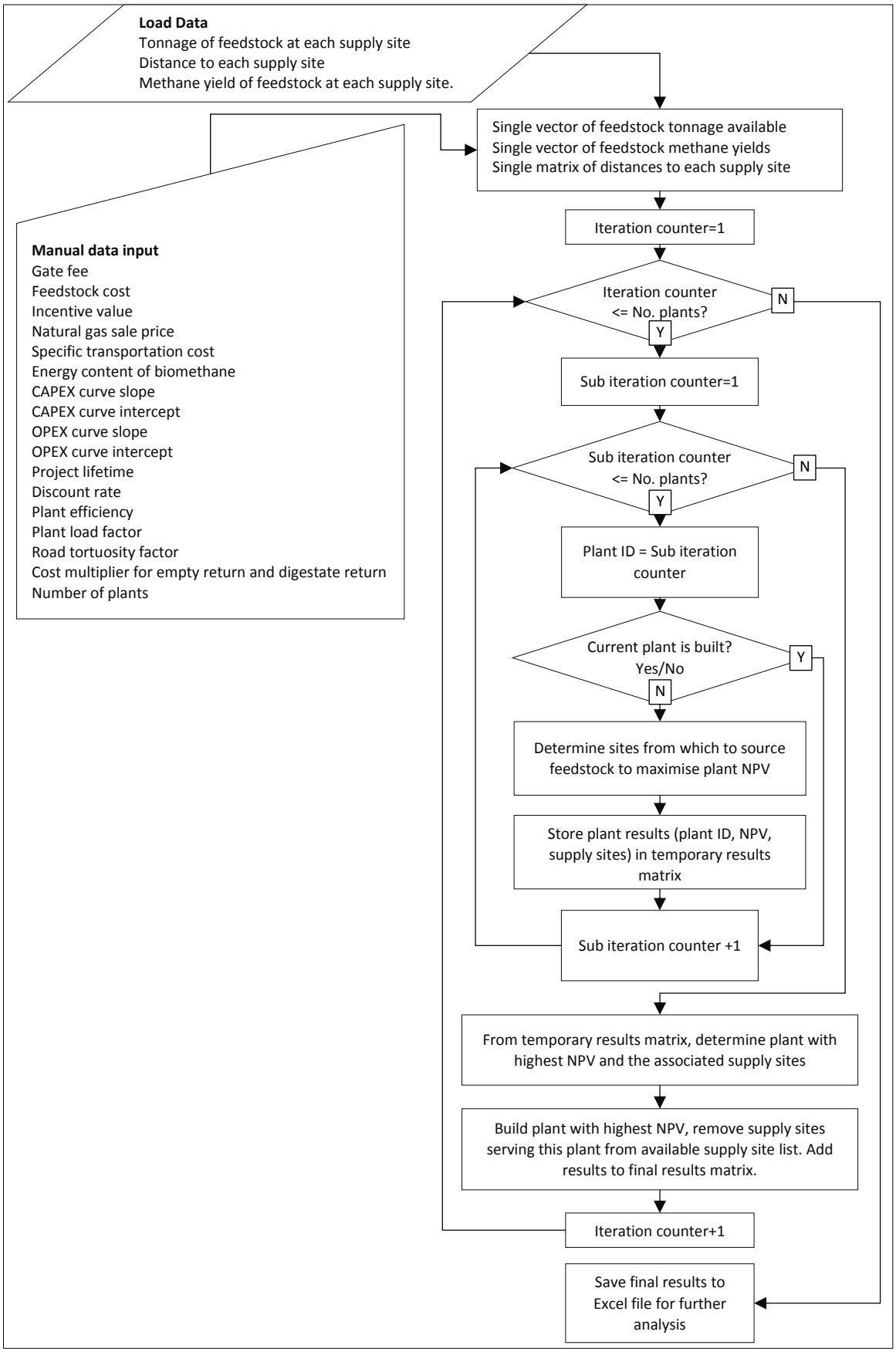


Figure 4-3 Flow chart of optimisation model

4.2.9 Detailed mathematical description of the optimisation model

A detailed description of the model developed follows. Table 4-3 outlines the parameters and variables used in the model description.

Table 4-3 Variables used in model

Parameter	Unit	Variable
Feedstock tonnage at supply site	t_{wwt}	m_i
Feedstock CH_4 yield at supply site	$m^3CH_4.t_{wwt}^{-1}$	SMY_i
Distance to feedstock supply site	km	D_i
Tortuosity	-	T
Specific transportation cost	$€.t_{wwt}^{-1}.km^{-1}$	STC
Cost multiplier to account for empty return and digestate return	-	CM_i
Feedstock cost	$€.t_{wwt}^{-1}$	FC_i
Natural gas price	$€.MWh^{-1}$	NGP
Gate fee	$€.t_{wwt}^{-1}$	FC_i
Incentive	$€.MWh^{-1}$	I
Energy content of biomethane	$MWh.m^{-3}$	E
CAPEX cost curve slope	$€.MWh^{-1}$	Sc
CAPEX cost curve intersection	€	Cc
OPEX cost curve slope	$€.MWh^{-1}$	So
OPEX cost curve intersection	€	Co
Plant lifetime	Years	Y
Discount rate	-	dr
Discount factor	-	DF
Plant efficiency	-	η
Plant load factor	-	LF
Max plant size	MWh	P_{Max}
Annual transport cost	$€.a^{-1}$	TC_t
Annual feedstock cost	$€.a^{-1}$	FC_t
Annual energy output	$GWh.a^{-1}$	P_t
Annual OPEX	$€.a^{-1}$	$OPEX_t$
Annual revenue	$€.a^{-1}$	R_t
Annual gate fee	$€.a^{-1}$	G_t
CAPEX	€	$CAPEX$
Decision variable	-	x_i
Number of supply sites	-	n

Annual transportation cost of feedstock to the plant was calculated according to Equation 4-3:

Equation 4-3 Annual transport cost

$$TC_t = \sum_{i=1}^{n} x_i * m_i * D_i * CM_i * STC$$

Annual feedstock cost was calculated using Equation 4-4:

Equation 4-4 Annual feedstock cost

$$FC_t = \sum_{i=1}^{n} x_i * \ m_i * FC_i$$

Annual net biomethane production was found using Equation 4-5:

Equation 4-5 Annual energy output

$$P_t = \sum_{i=1}^{n} x_i * \ m_i * SMY_i * \eta * CF * E$$

Annual OPEX was calculated using Equation 4-6:

Equation 4-6 Annual OPEX

$$OPEX_t = C_o + \sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E * So$$

Annual revenue from the sale of biomethane and incentives per unit of biomethane were calculated using Equation 4-7:

Equation 4-7 Annual revenue

$$R_t = (NGP + I) * \sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E$$

The gate fee from accepting feedstock at the plant was found using Equation 4-8:

Equation 4-8 Annual gate fee

$$G_t = \sum_{i=1}^{n} x_i * m_i * GF_i$$

Plant CAPEX was found according to Equation 4-9:

Equation 4-9 Initial CAPEX

$$CAPEX = Cc + \sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E * Sc$$

Conversion of future cash flows to their present-day value was found using Equation 4-10 (Short et al. 1995):

Equation 4-10 Discount factor

$$Discount\ factor\ (DF) = \frac{((1+r)^L - 1)}{(r * (1+r)^L)}$$

Net present value was then calculated according to Equation 4-11:

Equation 4-11 Net present value calculation

$$NPV = DF * (R_t - OPEX_t - FC_t - TC_t) - CAPEX$$

Expansion of the terms in Equation 4-11 yields Equation 4-12 in which the NPV is a function of the decision variable x_i for each potential feedstock source *i*:

Equation 4-12 Net present value (Objective function)

$$NPV = DF * \left\{ (NGP + I) * \sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E + \sum_{i=1}^{n} x_i * m_i * GF_i - C_o \right.$$
$$- \left(\sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E \right) * S_o - \sum_{i=1}^{n} x_i * m_i * FC_i$$
$$\left. - \sum_{i=1}^{n} x_i * m_i * D_i * CM_i * STC \right\} - Cc - \left(\sum_{i=1}^{n} x_i * m_i * SMY_i * \eta * CF * E \right)$$
$$* S_c$$

The decision variables in the optimisation model are binary, all or none of the feedstock available at a potential feedstock source *i* will be assigned to the biomethane plant as per Equation 4-13:

Equation 4-13 Binary constraint on decision variable

$$x_i \in \{0,1)$$

The maximum allowable plant size is also a constraint in the optimisation model as shown in Equation 4-14:

Equation 4-14 Constraint on maximum plant size

$$P_t \leq P_{Max}$$

The goal of the optimisation model was to maximise Equation 4-12 i.e. net present value, by selecting which feedstock sites to supply the plant (x_i) subject to the constraints that the decision variables x_i were binary (Equation 4-13), and subject to a limitation on maximum plant output or size (Equation 4-14).

4.2.10 Model outputs

In addition to the NPV, the levelized cost of energy (LCOE) of biomethane injected into the gas network was calculated. LCOE is used to compare the cost of energy production of different energy technologies over the economic lifetime of the project (International Energy Agency 2010; Short et al. 1995). LCOE is the sum of the total present value of the outgoing cash flows from the project, divided by the sum of the total net energy output of the facility over its lifetime (adjusted for its economic value). It is the price per unit of energy, which a developer or investor needs to charge to achieve an NPV of zero.

The model also outputted the annual net energy production, the energy contributed by each different feedstock, the mass of each different feedstock supplied to the facility, and the sites from which each feedstock was sourced for each plant. Knowing the location from where feedstock was sourced allowed for the production of a GIS to visualise the collection radius of each facility, for each feedstock type.

4.2.11 Scenarios

Two plant sizes were investigated, one constraining the energy output of the plant to a maximum of 50GWh.a^{-1} (equivalent to 2.28MW_e with an electrical efficiency of 38%), the second constraining the energy output of the plant to a maximum of 200GWh.a^{-1} (8.74MW_e). This was done in order to investigate the effect of allowable plant scale on economic viability, feedstock use, and collection radius. At each plant size a total of three gate fees (20€.t^{-1}, 47.5€.t^{-1}, and 75€.t^{-1}) and three BOC values (38€.MWh^{-1}, 78€.MWh^{-1}, and 106€.MWh^{-1}) were assessed, resulting in a total of nine scenarios at each plant size or a total of eighteen scenarios (Table 4-4).

Table 4-4 List of scenarios based on gate fee, biofuel obligation certificate (BOC) value and plant size

Gate Fee (€.t^{-1})	BOC (€.MWh^{-1})		Max plant size 50GWh.a^{-1}	Max plant size 200GWh.a^{-1}
20	38	Scenario	1a	1b
20	78	Scenario	2a	2b
20	106	Scenario	3a	3b
47.5	38	Scenario	4a	4b
47.5	78	Scenario	5a	5b
47.5	106	Scenario	6a	6b
75	38	Scenario	7a	7b
75	78	Scenario	8a	8b
75	106	Scenario	9a	9b

4.3 Results

4.3.1 Results for scenarios sized at 50GWh.a^{-1} (1a-9a)

The NPV of the optimal plants built at each injection point in scenarios 1a-9a are shown in Figure 4-4. Results highlighted in yellow are plants with a positive NPV for all scenarios.

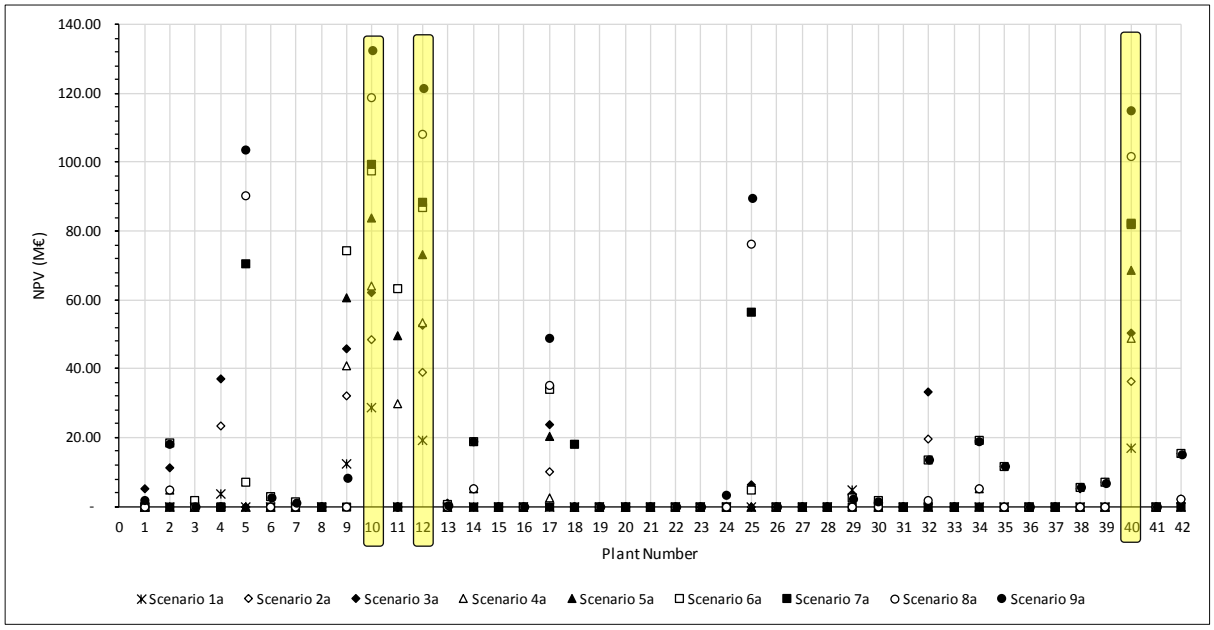


Figure 4-4 Net present value (NPV) of potential plants in scenarios 1a-9a, yellow boxes highlight plants with a positive NPV in all scenarios

Figure 4-5 illustrates the total annual injection of biomethane to the gas network in terms of GWh.a^{-1} on the positive portion of the primary y-axis (solid columns) and

the total mass of feedstocks utilised by injection plants are shown on the negative portion of the secondary y-axis (shaded columns). Only plants with an NPV greater than zero in each scenario are plotted. The data corresponding to Figure 4-5 is shown in Table 4-5 and Table 4-6.

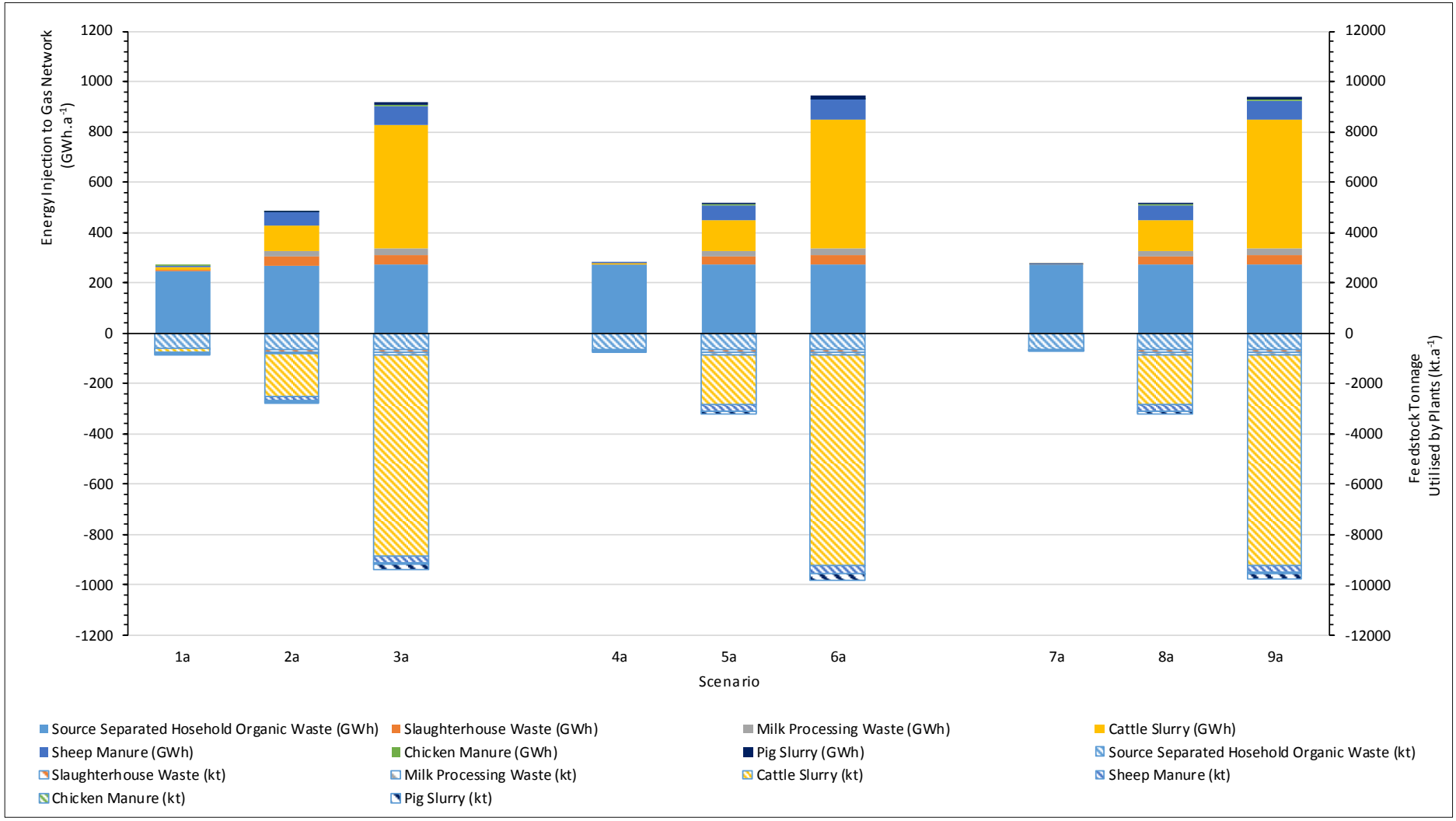


Figure 4-5 Total production of biomethane from waste feedstocks, and mass of feedstock utilised scenarios 1a-9a

Table 4-5 Energy contribution of feedstock type scenarios 1a-9a

Scenario	Gate Fee (€.t^{-1})	BOC Value (€.MWh^{-1})	Source Separated Household Organic Waste (GWh)	Slaughterhouse Waste (GWh)	Milk Processing Waste (GWh)	Cattle Slurry (GWh)	Sheep Manure (GWh)	Chicken Manure (GWh)	Pig Slurry (GWh)
1a	20	38	244.9	7.7	1.6	9.3	5.7	1.3	0.0
2a	20	78	269.8	35.9	19.2	101.3	55.2	1.8	4.7
3a	20	106	271.8	38.1	30.0	486.0	78.4	5.8	10.8
4a	47.5	38	271.6	4.0	0.0	3.1	5.6	0.0	0.0
5a	47.5	78	271.8	35.6	21.3	122.9	58.2	3.3	7.1
6a	47.5	106	271.8	38.1	30.0	509.6	77.2	3.7	13.8
7a	75	38	271.8	0.5	0.0	1.4	2.7	0.0	0.0
8a	75	78	271.8	35.6	21.3	122.9	58.2	3.3	7.1
9a	75	106	271.8	38.1	30.0	507.8	77.5	3.7	12.1

Table 4-6 Tonnage of feedstock type used, scenarios 1a-9a

Scenario	Gate Fee (€.t^{-1})	Additional Revenue (€.MWh^{-1})	Source Separated Household Organic Waste (kt_{wwt})	Slaughterhouse Waste (kt_{wwt})	Milk Processing Waste (kt_{wwt})	Cattle Slurry (kt_{wwt})	Sheep Manure (kt_{wwt})	Chicken Manure (kt_{wwt})	Pig Slurry (kt_{wwt})
1a	20	38	582.4	24.1	6.1	151.9	21.5	8.1	0.0
2a	20	78	638.2	116.4	73.5	1,661.8	209.1	11.8	90.4
3a	20	106	642.8	123.6	115.2	7,969.3	297.4	37.5	207.3
4a	47.5	38	642.5	13.3	0.0	50.7	21.1	0.0	0.0
5a	47.5	78	642.8	115.4	81.9	2,014.9	220.5	21.6	136.0
6a	47.5	106	642.8	123.6	115.2	8,356.1	292.8	23.8	266.7
7a	75	38	642.8	1.5	0.0	22.9	10.1	0.0	0.0
8a	75	78	642.8	115.4	81.9	2,014.9	220.5	21.6	136.0
9a	75	106	642.8	123.6	115.2	8,326.0	293.7	23.8	232.3

wwt: wet weight

The portion of the total theoretical energy potential of each feedstock type used in scenarios 1a-9a is highlighted in Figure 4-6, with corresponding data in Table 4-7.

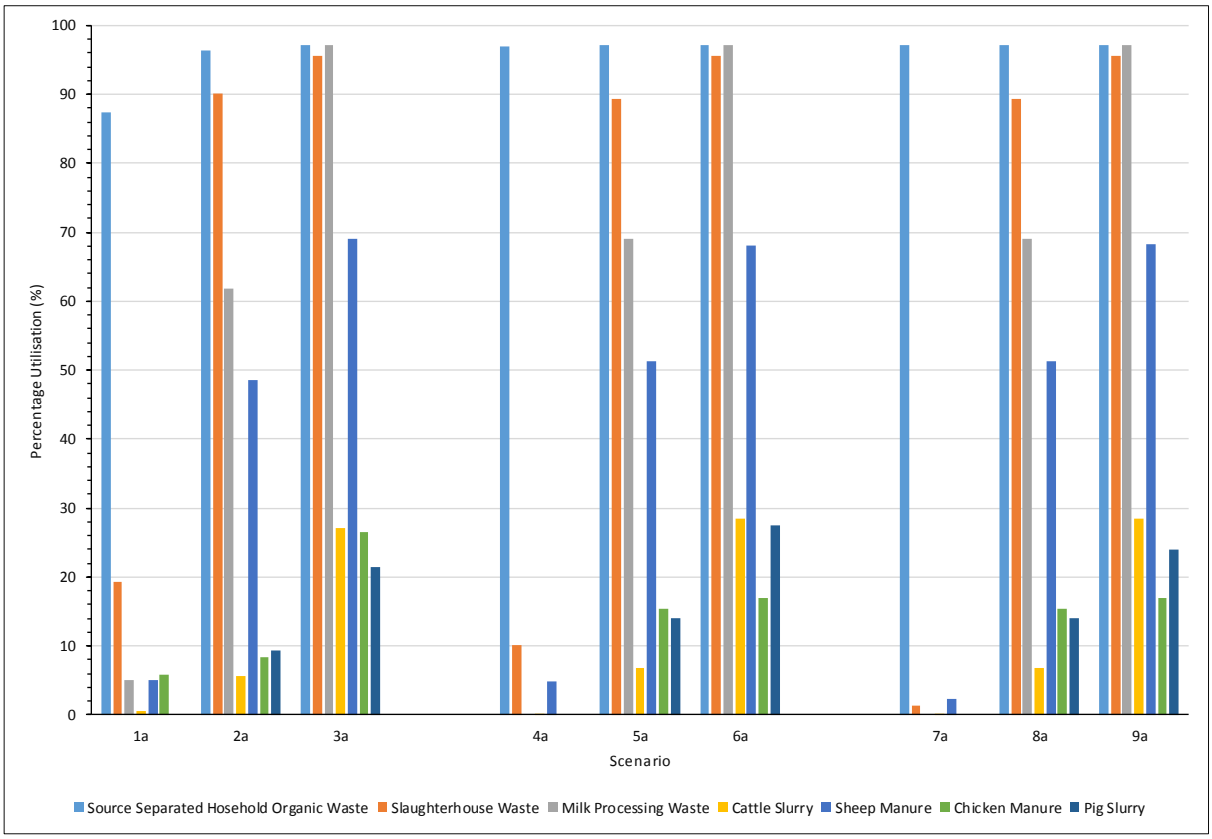


Figure 4-6 Utilisation of total theoretical waste resources for scenarios 1a-9a

Table 4-7 Percentage Utilisation of feedstock types, scenarios 1a-9a

Scenario	Gate Fee (€.t^{-1})	Additional Revenue (€.MWh^{-1})	Source Separated Household Organic Waste (%)	Slaughterhouse Waste (%)	Milk Processing Waste (%)	Cattle Slurry (%)	Sheep Manure (%)	Chicken Manure (%)	Pig Slurry (%)
1a	20	38	87.5	19.2	5.1	0.5	5.0	5.8	0.0
2a	20	78	96.4	90.1	61.9	5.7	48.6	8.4	9.4
3a	20	106	97.1	95.6	97.1	27.2	69.1	26.6	21.4
4a	47.5	38	97.0	10.1	0.0	0.2	4.9	0.0	0.0
5a	47.5	78	97.1	89.4	69.0	6.9	51.2	15.3	14.1
6a	47.5	106	97.1	95.6	97.1	28.5	68.1	16.9	27.6
7a	75	38	97.1	1.3	0.0	0.1	2.3	0.0	0.0
8a	75	78	97.1	89.4	69.0	6.9	51.3	15.3	14.1
9a	75	106	97.1	95.6	97.1	28.4	68.3	16.9	24.0

Figure 4-7 gives a detailed breakdown of plants with a positive NPV in scenario 9a, the scenario with the greatest biomethane injection, in terms of energy production and feedstock utilisation of the plants (disaggregated according to feedstock type). Figure 4-7 also displays the NPV and LCOE of each plant. The energy production of

each feedstock can be seen on the positive portion of the primary y-axis (solid columns), the mass of feedstock utilised in each plant can be seen on the negative portion of the secondary y-axis (shaded columns). The NPV (M€) of each plant and the LCOE (€.MWh^{-1}) are displayed on the positive portion of the primary y-axis. The data used in the Figure 4-7 can be seen in Table 4-8.

Figure 4-8 illustrates a number of examples of plant locations and feedstock utilisation for scenario 9a. Panel A illustrates the feedstock sources allocated to plant 10, which utilises primarily household organic waste. Panels B1-B4 relate to plant 17, which uses a mixture of household organic waste and other feedstock. Panels C1-C3 relate to plant 42 in which the primary source of biomethane was cattle slurry. All of the above plants had a net production of 50GWh.a^{-1}. Panel D relates to plant 24, whose primary source of biomethane was cattle slurry, with an annual energy production less than 50GWh (approximately 38GWh).

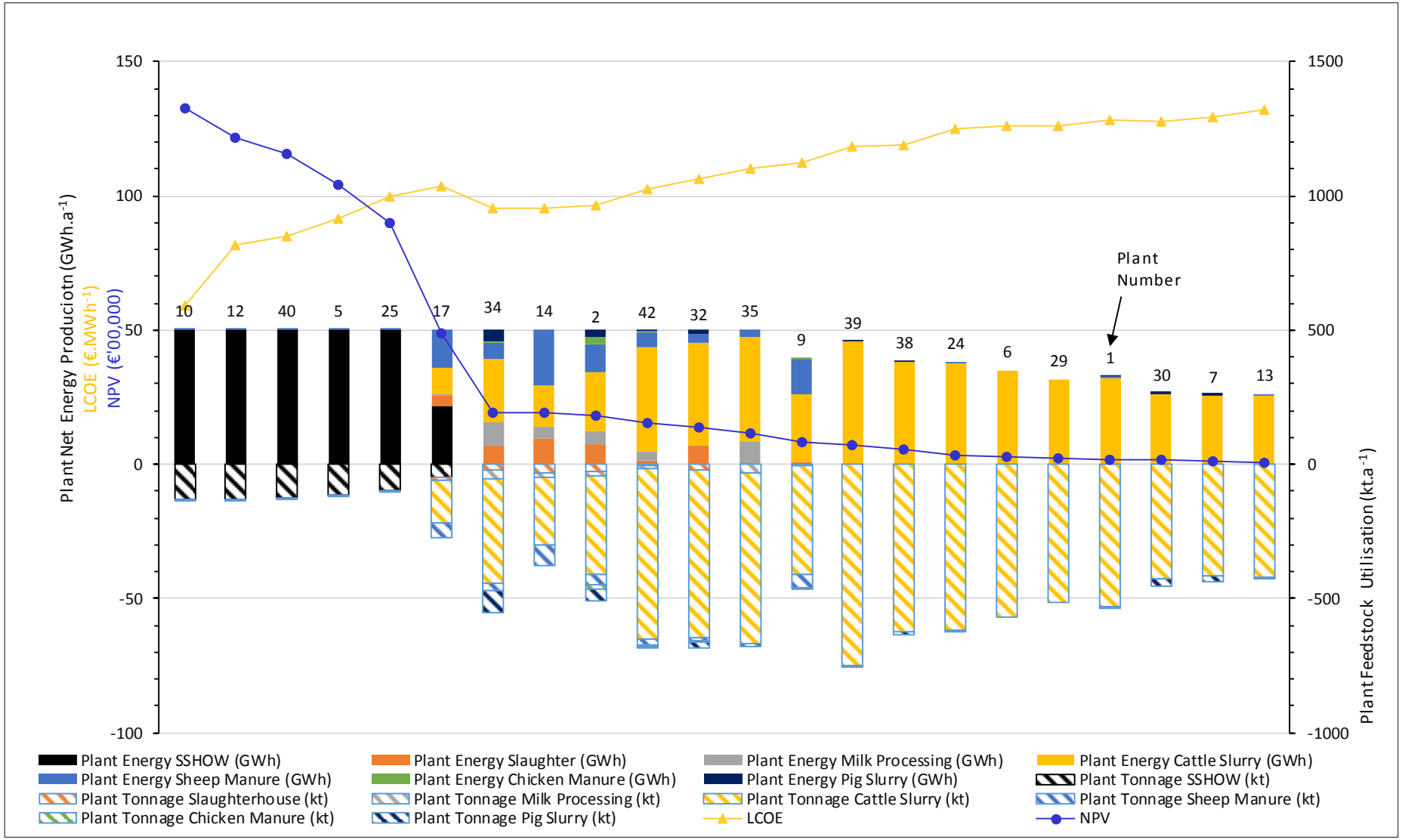


Figure 4-7 Plant energy production, net present value (NPV), levelized cost of energy (LCOE), and feedstock utilisation for scenario 9a. SSHOW: Source Separated Household Organic Waste.

Table 4-8 Feedstock energy production, tonnage used, net present value (NPV), and levelized cost of energy (LCOE) for Scenario 9a.

Plant Number	10	12	40	5	25	17	34	14	2	42	32	35	9	39	38	24	6	29	1	30	7	13
NPV (M€)	132.7	121.8	115.4	103.9	89.8	48.9	19.1	19.0	18.4	15.4	13.7	11.7	8.3	6.9	5.6	3.4	2.7	2.4	1.9	1.7	1.2	0.49
LCOE (€.MWh^{-1})	59.4	81.5	85.0	91.5	99.9	103.3	95.2	95.3	96.5	102.6	106.1	110.1	112.5	118.5	119.1	124.8	126.0	126.1	128.1	127.9	129.3	132.1
Source Separated Household Organic Waste (kt)	130.4	130.4	124.0	112.7	99.2	46.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slaughterhouse (kt)	0.0	0.0	0.0	0.0	0.0	13.3	21.8	32.0	25.4	5.3	22.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Milk Processing (kt)	0.0	0.0	0.0	0.0	0.0	1.9	33.6	16.2	17.7	12.5	0.0	33.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cattle Slurry (kt)	0.0	0.0	0.0	0.0	0.0	158.3	389.8	252.6	365.5	635.4	623.6	631.7	404.7	746.9	624.2	618.4	570.0	516.4	528.7	426.2	415.1	418.4
Sheep Manure (kt)	0.0	0.0	0.0	0.0	0.0	53.3	23.6	77.9	39.1	21.2	13.4	10.5	50.8	0.0	0.0	0.5	0.0	0.0	1.0	0.0	0.0	2.3
Chicken Manure (kt)	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	17.9	2.0	0.8	0.0	1.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pig Slurry (kt)	0.0	0.0	0.0	0.0	0.0	0.0	81.7	0.0	45.5	8.8	25.0	0.0	0.0	4.4	8.6	0.0	0.0	0.0	6.6	26.9	24.9	0.0
Household Organic Waste (GWh)	50.0	50.0	50.0	50.0	50.0	21.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slaughterhouse (GWh)	0.0	0.0	0.0	0.0	0.0	4.0	6.7	9.8	7.7	1.6	7.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Milk Processing (GWh)	0.0	0.0	0.0	0.0	0.0	0.5	8.8	4.2	4.6	3.3	0.0	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cattle Slurry (GWh)	0.0	0.0	0.0	0.0	0.0	9.7	23.8	15.4	22.3	38.7	38.0	38.5	24.7	45.6	38.1	37.7	34.8	31.5	32.2	26.0	25.3	25.5
Sheep Manure (GWh)	0.0	0.0	0.0	0.0	0.0	14.0	6.2	20.6	10.3	5.6	3.5	2.8	13.4	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.6
Chicken Manure (GWh)	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	2.8	0.3	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pig Slurry (GWh)	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.0	2.4	0.5	1.3	0.0	0.0	0.2	0.4	0.0	0.0	0.0	0.3	1.4	1.3	0.0
Plant Size (GWh)	50	50	50	50	50	50	50	50	50	50	50	50	39.4	47.8	38.5	37.9	34.8	31.5	32.8	27.4	26.6	26.1

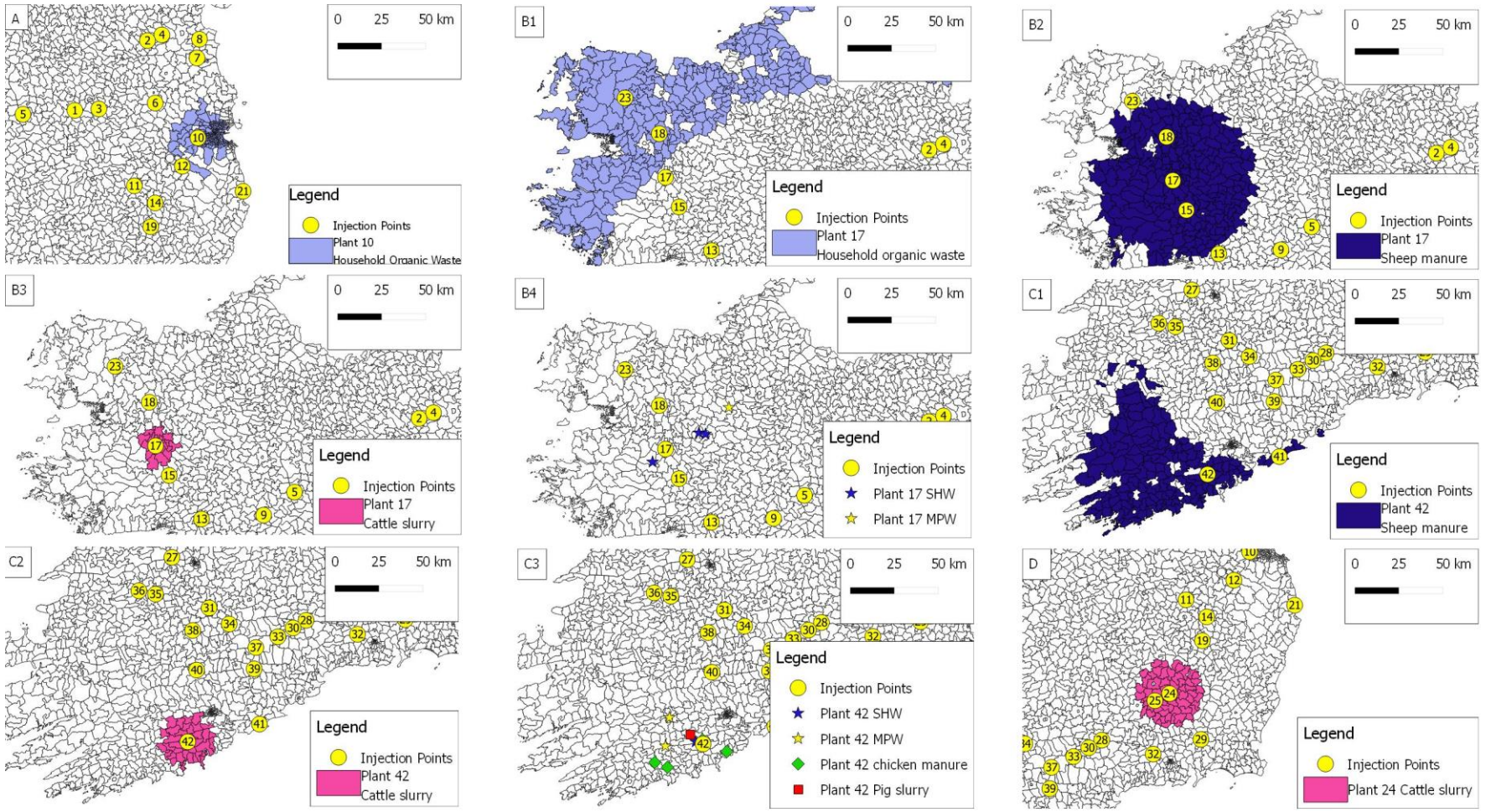


Figure 4-8 feedstock sources, scenario 9a. A: Plant 10, household organic waste. B1: Plant 17, household organic waste. B2: Plant 17, sheep manure. B3: Plant 17, cattle slurry. B4: Plant 17, slaughterhouse waste (SHW), milk processing waste (MPW). C1: Plant 42, sheep manure. C2: Plant 42, cattle slurry. C3: Plant 42, slaughterhouse waste (SHW), milk processing waste (MPW), chicken manure, pig slurry. D: Plant 24, cattle slurry

4.3.2 Results for scenarios sized at 200 GWh.a^{-1} (1b-9b)

Figure 4-9 illustrates the NPV of the optimal plants built at each injection point for scenarios 1b-9b.

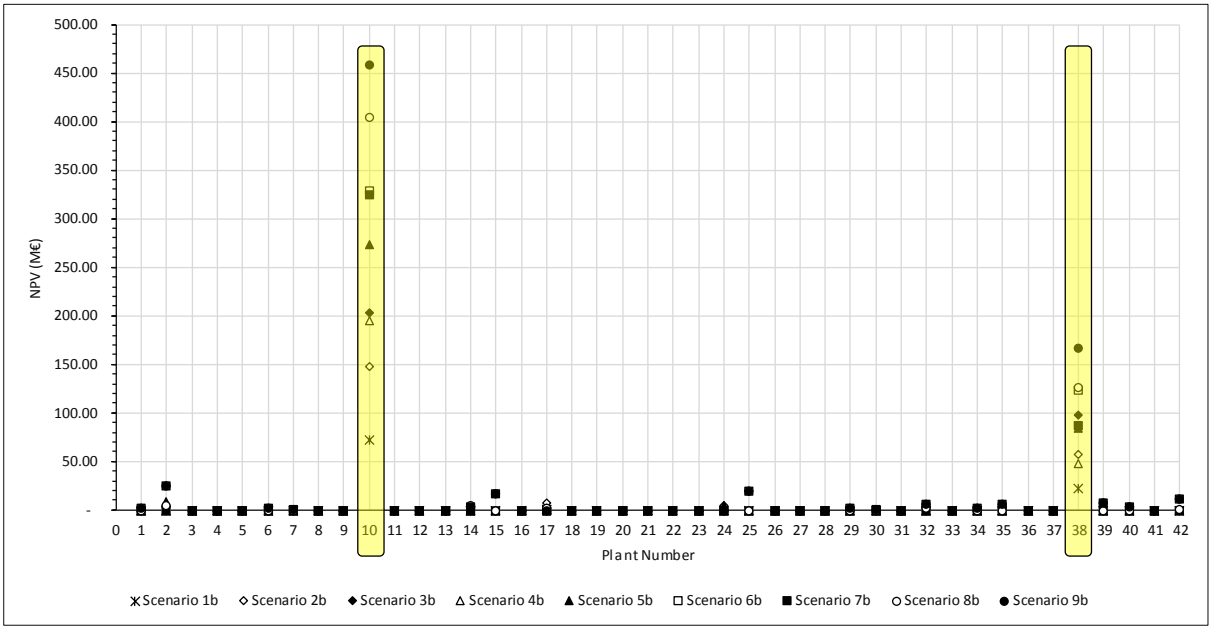


Figure 4-9 Net present value (NPV) of potential plants in scenarios 1b-9b, yellow boxes highlight plants with a positive NPV in all scenarios

The total biomethane injection and feedstock use can be seen in Figure 4-10. The data used in the Figure 4-10 can be found in Table 4-9 and Table 4-10.

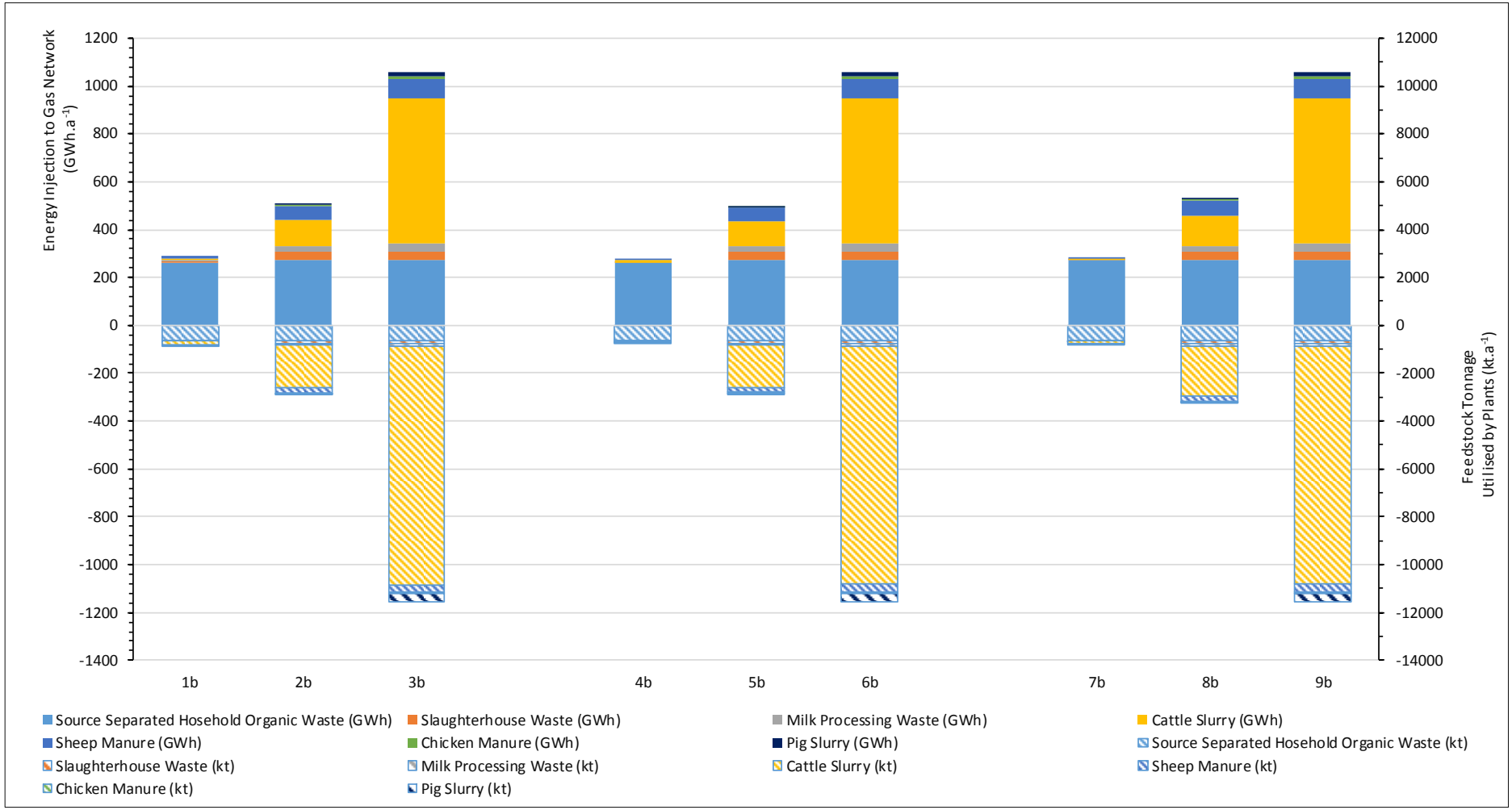


Figure 4-10 Total production of biomethane from waste feedstocks, and mass of feedstock utilised for scenarios 1b-9b

Table 4-9 Energy contribution of feedstock types. Scenarios 1b-9b

Scenario	Gate Fee (€.t^{-1})	BOC Value (€.MWh^{-1})	Source Separated Household Organic Waste (GWh)	Slaughterhouse Waste (GWh)	Milk Processing Waste (GWh)	Cattle Slurry (GWh)	Sheep Manure (GWh)	Chicken Manure (GWh)	Pig Slurry (GWh)
1b	20	38	262.6	6.1	1.7	9.5	9.6	0.0	0.0
2b	20	78	271.8	37.3	21.3	107.5	60.9	3.3	2.8
3b	20	106	271.8	38.1	30.0	608.5	83.2	9.4	17.5
4b	47.5	38	261.2	1.4	1.7	6.0	0.5	0.0	0.0
5b	47.5	78	271.8	37.3	21.3	105.8	55.5	3.3	2.8
6b	47.5	106	271.8	38.1	30.0	606.8	83.2	9.4	17.5
7b	75	38	271.6	1.4	1.7	6.0	0.5	0.0	0.0
8b	75	78	271.8	38.1	21.3	126.9	63.8	3.3	2.8
9a	75	106	271.8	38.1	30.0	606.8	83.2	9.4	17.5

Table 4-10 Tonnage of feedstock type used. Scenarios 1b-9b

Scenario	Gate Fee (€.t^{-1})	Additional Revenue (€.MWh^{-1})	Source Separated Household Organic Waste (kt_{wwt})	Slaughterhouse Waste (kt_{wwt})	Milk Processing Waste (kt_{wwt})	Cattle Slurry (kt_{wwt})	Sheep Manure (kt_{wwt})	Chicken Manure (kt_{wwt})	Pig Slurry (kt_{wwt})
1b	20	38	621.8	20.3	6.6	155.7	36.3	0.0	0.0
2b	20	78	642.8	121.0	81.9	1,762.8	230.7	21.6	54.3
3b	20	106	642.8	123.6	115.2	9,977.4	315.6	61.2	337.4
4b	47.5	38	618.9	4.5	6.6	99.0	1.8	0.0	0.0
5b	47.5	78	642.8	121.0	81.9	1,735.6	210.4	21.6	54.3
6b	47.5	106	642.8	123.6	115.2	9,950.1	315.6	61.2	337.4
7b	75	38	642.5	4.5	6.6	99.0	1.8	0.0	0.0
8b	75	78	642.8	123.6	81.9	2,081.0	242.0	21.6	54.3
9a	75	106	642.8	123.6	115.2	9,950.1	315.6	61.2	337.4

Figure 4-11 documents the share of total theoretical energy potential of each feedstock type, which is utilised in scenarios 1b-9b. The data used in Figure 4-11 can be found in Table 4-11.

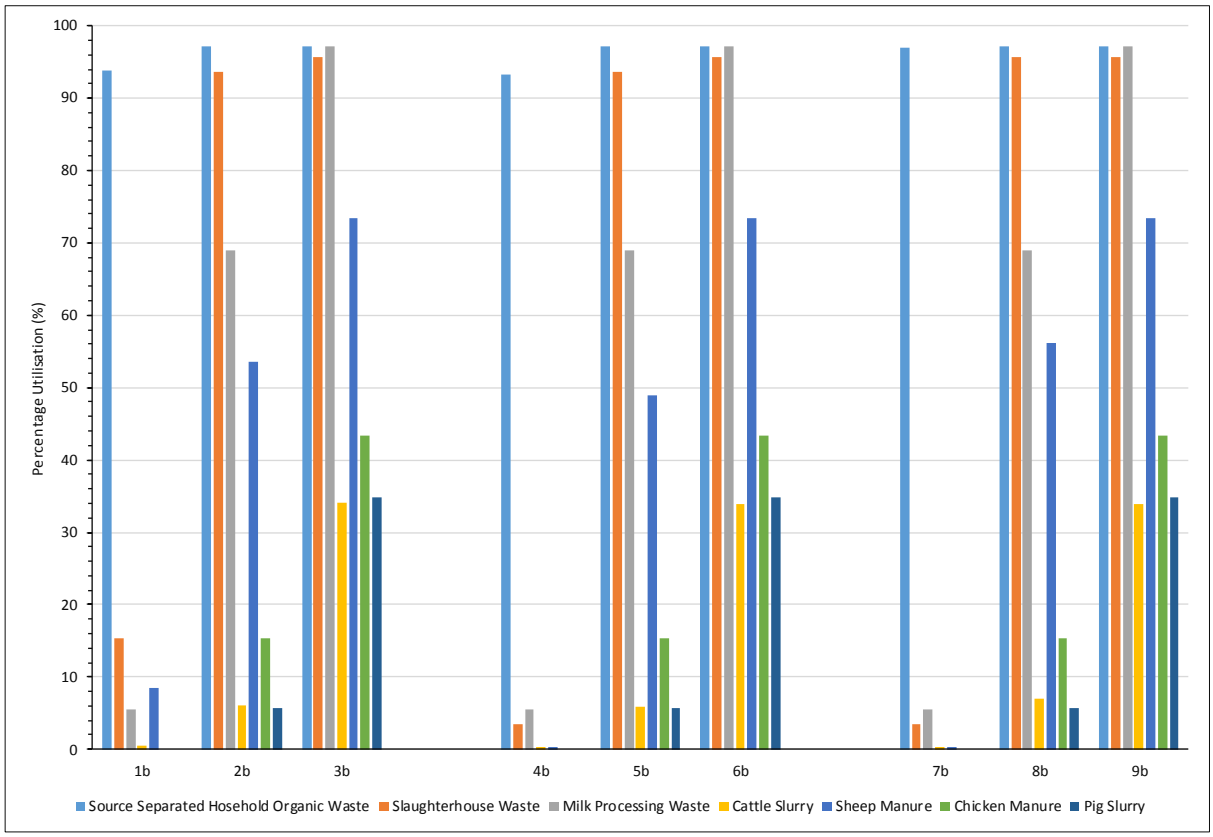


Figure 4-11 Utilisation of total theoretical waste resources for scenarios 1b-9b

Table 4-11 Percentage Utilisation of feedstock types. Scenarios 1b-9b

Scenario	Gate Fee (€.t^{-1})	Additional Revenue (€.MWh^{-1})	Source Separated Household Organic Waste (%)	Slaughterhouse Waste (%)	Milk Processing Waste (%)	Cattle Slurry (%)	Sheep Manure (%)	Chicken Manure (%)	Pig Slurry (%)
1b	20	38	93.8	15.3	5.6	0.5	8.4	0.0	0
2b	20	78	97.1	93.7	69.0	6.0	53.6	15.3	5.6
3b	20	106	97.1	95.6	97.1	34.0	73.3	43.4	34.9
4b	47.5	38	93.3	3.4	5.6	0.3	0.4	0.0	0
5b	47.5	78	97.1	93.7	69.0	5.9	48.9	15.3	5.6
6b	47.5	106	97.1	95.6	97.1	33.9	73.3	43.4	34.9
7b	75	38	97.0	3.4	5.6	0.3	0.4	0.0	0
8b	75	78	97.1	95.6	69.0	7.1	56.2	15.3	5.6
9a	75	106	97.1	95.6	97.1	33.9	73.3	43.4	34.9

Figure 4-12 gives a detailed breakdown of the feedstock use and energy production at plants with a positive NPV in scenario 9b, the scenario resulting in the highest quantity of biomethane injection into the gas network. The data used in Figure 4-12 can be found in Table 4-12.

Figure 4-13 illustrates the feedstock source locations for a number of plants in scenario 9b. Panel A illustrates the feedstock source locations for plant 10, panels B1-B4 illustrate the feedstock source locations for plant 38, and panel C illustrates the feedstock sources for plant 42 and plant 16.

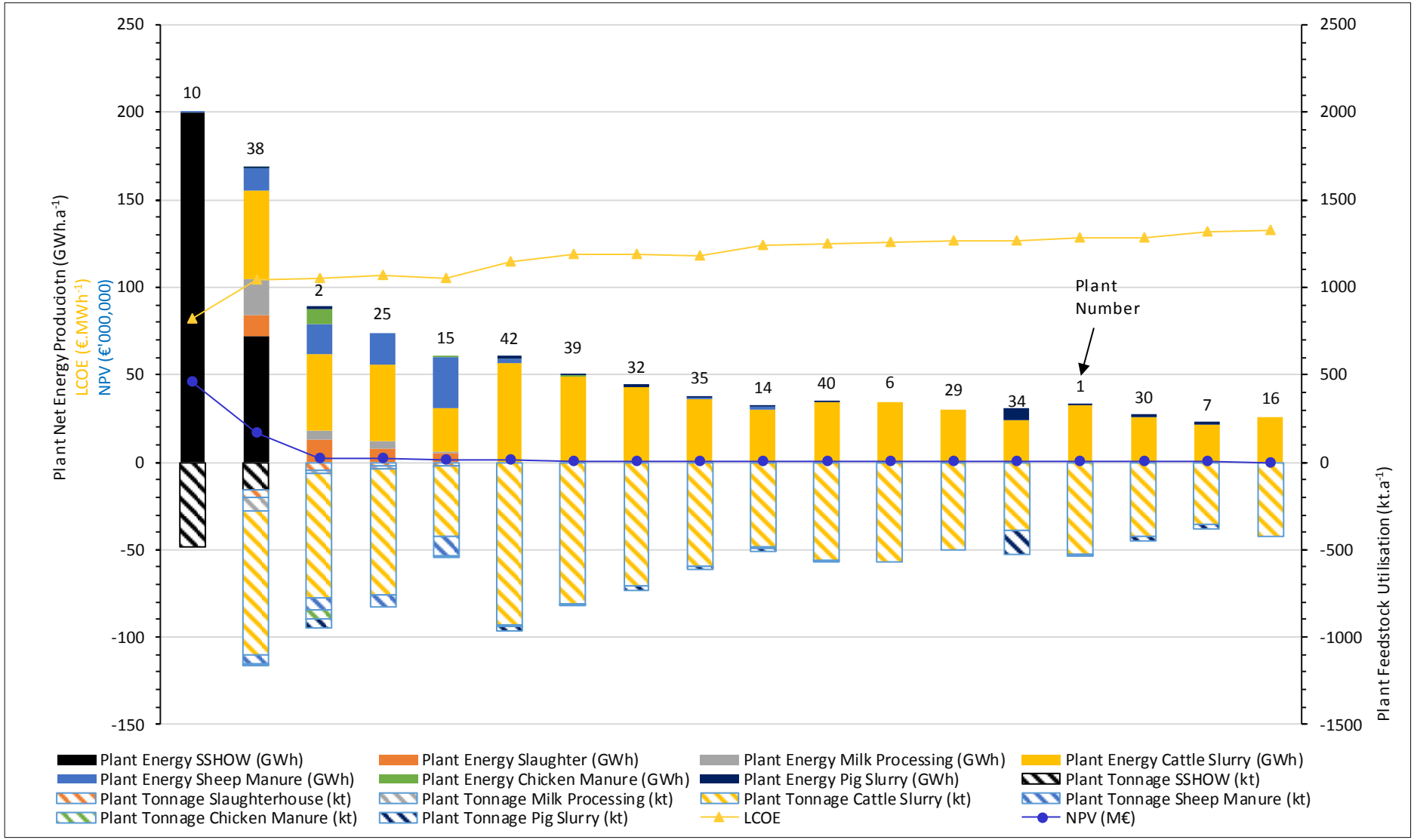


Figure 4-12 Plant energy production, net present value (NPV), levelized cost of energy (LCOE), and feedstock utilisation for scenario 9b. SSHOW: Source Separated Household Organic Waste.

Table 4-12 Feedstock energy production, tonnage used, net present value (NPV), and levelized cost of energy (LCOE) for scenario 9b

Plant Number	10	38	2	25	15	42	39	32	35	14	40	6	29	34	1	30	7	16
NPV (M€)	459.4	166.7	25.1	19.7	17.0	11.7	7.4	6.5	5.8	3.3	3.1	2.7	2.2	2.2	1.9	1.6	0.5	0.3
LCOE (€.MWh^{-1})	81.54	103.99	105.43	106.9291	105.22	114.28	118.85	119.02	118.32	123.77	124.99	125.99	126.47	126.59	128.16	127.88	131.72	132.74
Household Organic Waste (kt)	483.9	158.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slaughterhouse (kt)	0.0	38.7	43.5	24.3	17.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Milk Processing (kt)	0.0	79.5	17.7	16.2	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cattle Slurry (kt)	0.0	827.0	717.8	721.6	408.8	928.7	807.1	708.2	593.9	488.0	559.1	570.0	497.4	389.2	528.7	426.2	358.2	420.3
Sheep Manure (kt)	0.0	49.3	65.0	68.9	111.2	9.8	0.0	0.0	3.6	7.5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
Chicken Manure (kt)	0.0	1.7	55.4	0.0	1.3	2.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pig Slurry (kt)	0.0	8.6	45.5	0.0	0.0	21.3	4.4	25.0	12.1	16.0	10.9	0.0	0.0	135.1	6.6	26.9	24.9	0.0
Household Organic Waste (GWh)	200.0	71.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slaughterhouse (GWh)	0.0	12.1	13.2	7.6	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Milk Processing (GWh)	0.0	20.7	4.6	4.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cattle Slurry (GWh)	0.0	50.4	43.8	44.0	24.9	56.6	49.2	43.2	36.2	29.8	34.1	34.8	30.3	23.7	32.2	26.0	21.8	25.6
Sheep Manure (GWh)	0.0	13.0	17.2	18.2	29.3	2.6	0.0	0.0	0.9	2.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Chicken Manure (GWh)	0.0	0.3	8.5	0.0	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pig Slurry (GWh)	0.0	0.4	2.4	0.0	0.0	1.1	0.2	1.3	0.6	0.8	0.6	0.0	0.0	7.0	0.3	1.4	1.3	0.0
Plant Size (GWh)	200	169	90	74	60	61	50	44	38	33	35	35	30	31	33	27	23	26

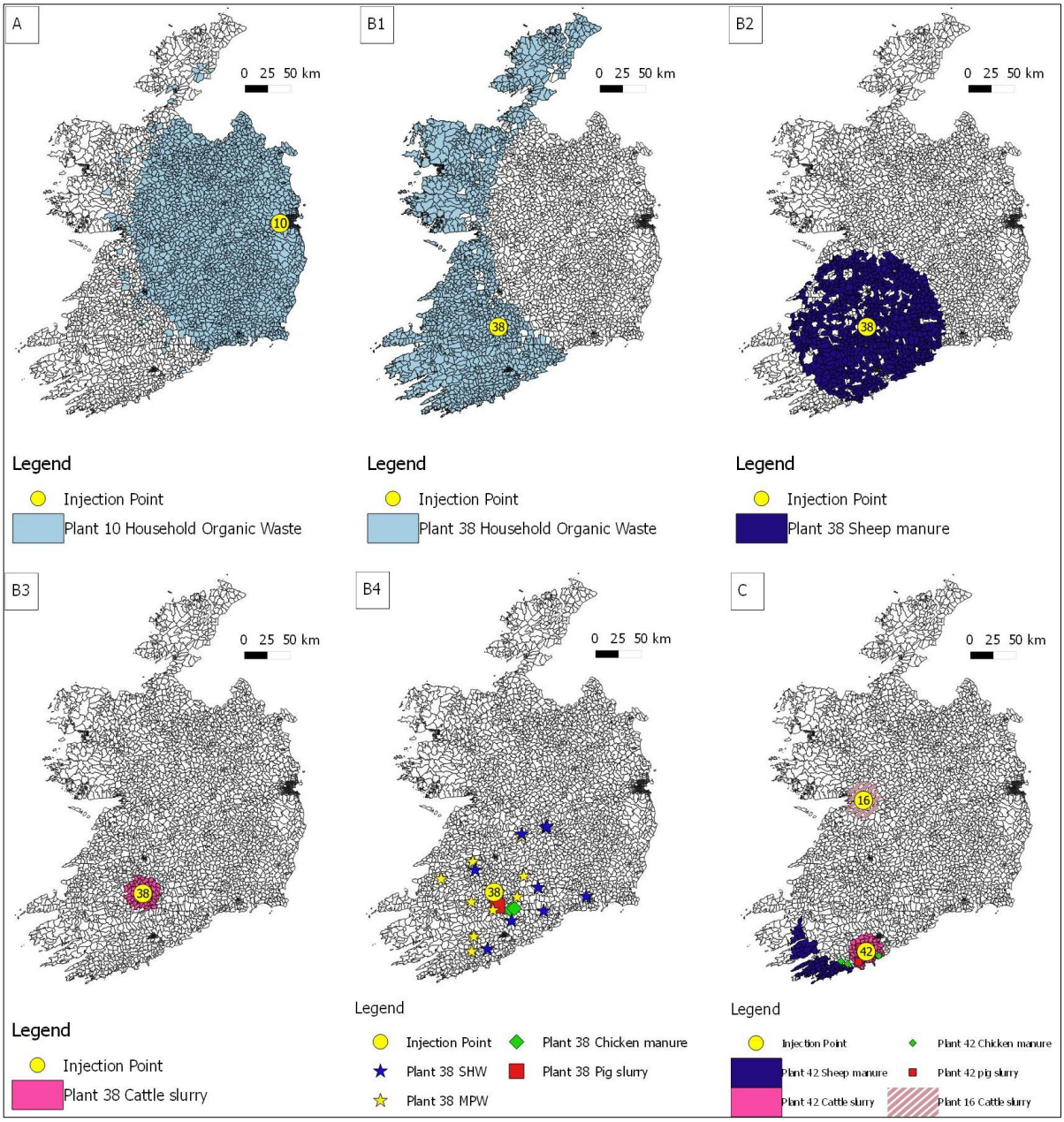


Figure 4-13 Feedstock sources, scenario 9b. A: Plant 10, household organic waste. B1: Plant 38 household organic waste. B2: Plant 38, sheep manure. B3: Plant 38, cattle slurry. B4: Plant 38, slaughterhouse waste (SHW), milk processing waste (MPW), chicken manure, pig slurry. C: Plant 42, sheep manure, cattle slurry, chicken manure, pig slurry, Plant 16, cattle slurry

4.4 Discussion of results

4.4.1 Scenarios at 50 GWh.a^{-1} (1a-9a)

4.4.1.1 Injection sites, biomethane production, and resource utilisation

Injection points 10, 12, and 40 had a positive NPVs in scenarios 1a-9a (Figure 4-4). As modelled these plants would be the first to be constructed. The sites had a positive NPV as they processed almost exclusively household organic waste, which enabled them to receive a gate fee, the market value of biomethane, and the additional revenue from BOCs. The potential sites were located close to the regions with the largest household organic waste resource. The development of these facilities was favourable both in terms of NPV and diverting biodegradable wastes from landfills as required under the Landfill Directive (Council of the European Union 1999). The use of source separated household organic waste by the initial plants according to the model is in agreement with the findings of (Junginger et al. 2006) which found that organic waste suitable for anaerobic digestion was contractually claimed by the first centralised anaerobic digestion plants in Denmark.

The number of potential sites with a positive NPV increased as the incentives available increased. In scenario 1a (lowest Gate Fee €20.t^{-1} and lowest BOC 38€.MWh^{-1}), a total of 6 sites had a positive NPV, while in scenario 9a (highest Gate Fee €75.t^{-1} and highest BOC 75€.MWh^{-1}), 22 sites had a positive NPV. The main factor influencing the number of NPV positive sites was the BOC value. As the BOC value increased (greater revenue per MWh of produced biomethane), additional sites used feedstock not eligible for a gate fee (such as cattle slurry) whilst achieving a positive NPV.

Variation of gate fee had no major impact on the total energy production of biomethane or feedstock utilised by plants (Figure 4-5). A minor increase in the total energy production from household organic waste occurred with an increase in gate fee from 20€.t^{-1} to 47.5€.t^{-1} at a BOC value of 38€.MWh^{-1}. Varying the gate fee did not alter the energy production from other waste streams significantly.

The impact of the BOC value was significant in determining the total biomethane injected to the gas network. At a BOC value of 38€.MWh^{-1} and a gate fee of 75€.t^{-1}

(Scenario 7a), approximately 276GWh.a^{-1} (1PJ) of biomethane was produced. This represents 0.55% of thermal TFC in 2015 and 19% of the GNI renewable gas goal in 2025. At a BOC value of 106€.MWh^{-1} and a gate fee of 75€.t^{-1} (scenario 9a), the energy generated was 941GWh.a^{-1} (3.4PJ). This represents 1.9% of thermal TFC in 2015 and 65% of the GNI renewable gas goal in 2025. Biomethane production in scenario 9a was equivalent to 6% of industrial gas consumption in 2015-2016 (Gas Networks Ireland 2016) and could play a role in supplying renewable energy to industrial gas users. Biomethane production from scenario 9a is equivalent to 13% of the energy consumption of HGVs in 2015 and 1.7% RES-T in 2015, double counting raises this contribution to 3.4% RES-T.

The largest increase in energy production and feedstock use, occurred for cattle slurry when the BOC value was increased. At a gate fee of 75€.t^{-1} and a BOC value of 38€.MWh$_{-1}$ (Scenario 7a) the total biomethane production from cattle slurry was 0.005PJ, however, when the BOC value was increased to 106€.MWh^{-1} (Scenario 9a), biomethane production was at 1.83PJ. This is equivalent to an energy consumption of 34,212 average households (14,858kWh of direct fossil fuel consumption per household (Dennehy & Howley 2013) or 7% of energy consumption by HGVs in 2015.

Utilisation of the total theoretical resource of household organic waste reached a maximum of 97% for most of the combinations of gate fee and BOC value; utilisation of the remaining 3% would have been financially unfavourable. The maximum utilisation of milk processing waste was 97%, sheep manure was 69%, slaughterhouse waste was 95%, cattle slurry was 28%, pig slurry was 27%, and chicken manure was 28%. The higher utilisation of household organic waste, slaughterhouse waste, and milk processing waste was a direct result of the higher methane yield per wet tonne for these feedstocks, and as a result they were preferentially utilised by the model. To utilise feedstock with lower methane yields, additional gas revenue per MWh must be increased to offset the increase in transportation costs.

Cattle slurry offered the largest theoretical resource of energy of all wastes streams identified (9.6PJ). However, the maximum utilisation of cattle slurry was 28%,

leaving an unused resource of 6.9PJ. This resource could potentially be utilised if the BOC value was increased, or if the slurry was co-digested with grass silage as proposed by Wall et al. (Wall et al. 2013). Alternatively, a different model could be developed for farm scale biogas systems coupled with mobile biomethane upgrading and compression (Vienne University of technology (Austria) 2012) or through the linking of smaller farm scale digesters to centralised upgrading facilities (Hengeveld et al. 2014; IEA Bioenergy Task 37 2015).

4.4.1.2 Detailed analysis of scenario 9a

Figure 4-7 indicates that the most financially viable plant in scenario 9a (thus the first built) was at location 10. The plant used almost 100% household organic waste, 130.4kt.a^{-1}, approximately 20% of the national total theoretical tonnage resource identified by the authors. The radius of collection was approximately 24km for household organic waste (Figure 4-8). The small collection radius for location 10 was due to the large quantities of household organic waste in its vicinity (this region had the highest resource of household organic waste in the Ireland) and thus reduced the total transportation cost of feedstock for plant 10, increasing the NPV. Plant 10 produced 50GWh.a^{-1} (180TJ.a^{-1}) of biomethane, sufficient to meet the heat demand of 3,365 average households, or 3% of energy consumption in public transport in 2015 (5.73PJ (Howley & Holland 2016)).

The next most profitable plants (Figure 4-7) again processed predominantly household organic waste with plants 12, 40, 5, and 25 accepting approximately 130kt.a^{-1}, 124kt.a^{-1}, 113kt.a^{-1}, and 99kt.a^{-1}, respectively. This result again agreed with the findings of (Junginger et al. 2006) which found that initial biogas plants in Denmark contractually claimed the most suitable organic wastes for anaerobic digestion purposes. The resource of household organic waste allocated to plants 10, 12, 40, 5, and 25 was approximately 250GWh, 89% of the total theoretical energy resource available. The scale of these facilities was on par with that of the five largest CAD plants in Denmark; Ribe: 151kt.a^{-1}, Lintrup: 197kt.a^{-1}, Lemvig: 157kt.a^{-1}, Arhus Nord: 141k.a^{-1}, and Blabjerg: 111kt.a^{-1} (Al Seadi et al. 2000). The proposed facilities were also similar to the ReFood Widnes biomethane to grid injection plant

in Cheshire in the UK (processing 120kt.a^{-1} of food waste) and the Poplars Landfill AD facility in Staffordshire in the UK (processing 120kt.a^{-1} of food waste) (NNFCC 2015). The first 5 plants to be built provided 250GWh.a^{-1}of biomethane at a maximum LCOE of 99.9€.MWh^{-1}, this would be sufficient to meet the heat demand of 16,825 average households, 3% of HGV energy use in 2015, or 13% of public transport use in 2015.

Following plant 25, the next plant to be constructed in the model was plant 17 which could not reach the required energy output to maximise its NPV using only household organic waste, thus the model allocated alternative feedstock types to this plant. The NPV of plant 17 (Figure 4-7) was significantly lower than that of the 5 initial facilities (48.9M€ vs. an average of 112M€ for the first 5 plants). Lower NPV was a result of a reduced revenue stream (less household organic waste accepted at the facility) and an increase in the transportation costs for alternative feedstocks and return of digestate. The model provided plant 17 with household organic waste, slaughterhouse waste, milk processing waste, cattle slurry, and sheep manure, giving a total of 273kt.a^{-1} of waste accepted at plant 17 (Figure 4-7). The large allocation of cattle slurry was a result of the considerable resource in close proximity to the proposed facility. This facility was smaller than Maabjerg biogas plant, which is one of the world's largest biogas pants (processing approximately 725kt.a^{-1} of feedstock, primarily animal slurry) (IEA Task 37 2014)and was on par with Girvan Distillery biomethane to grid plant in the UK (processing 300kt.a^{-1} of brewery wastes) (NNFCC 2015).

Box 4-1 outlines the maximum theoretical distance over which cattle slurry and household organic waste could be transported in a viable manner, considering only the transportation cost of the feedstock and the potential revenue from the feedstock. Distances for all feedstocks are reported in Table 4-13.

Calculation of maximum transportation distance

Volatile solids Destruction: 80%
Plant Efficiency (taking into account methane slippage and in-house consumption): 84%
Source Separated Household Organic Waste
Methane yield per wet tonne transported: 61.8m^3CH_4
Net Methane Yield per wet tonne transported: 41.5 m^3CH_4
Energy content of methane: 37.78$MJ.Nm^{-3}$
Energy content of methane: 0.01$MWh.Nm^{-3}$
Energy yield per wet tonne transported: 0.415$MWh.t_{wwt}^{-1}$
Cost of transportation per wet tonne (including empty return): 0.184$€.km^{-1}$
Tortuosity factor: √2
Cost of transportation per wet tonne: 0.260$€.km^{-1}$ (in terms of Euclidian distance between source and users)
Gate fee: 75$€.t_{wwt}^{-1}$
Market value of energy: 28$€.MWh^{-1}$
BOS certificate value: 106$€.MWh^{-1}$
Monetary value of one tonne of household organic waste: 75*1 + (106+28)*0.415 = €130.61
Maximum feasible transportation distance of one tonne of household organic waste: 130.61/0.26=502km
Cattle Slurry

Methane yield per wet tonne transported: 8.9m^3CH_4
Net Methane Yield per wet tonne transported: 5.98 m^3CH_4
Energy content of methane: 37.78$MJ.Nm^{-3}$
Energy content of methane: 0.01$MWh.Nm^{-3}$
Energy yield per wet tonne transported: 0.0598$MWh.t_{wwt}^{-1}$
Cost of transportation per wet tonne (including digestate return): 0.223$€.km^{-1}$
Tortuosity factor: √2
Cost of transportation per wet tonne: 0.315$€.km^{-1}$ (in terms of Euclidian distance between source and users)
Gate fee: 0$€.t_{wwt}^{-1}$
Market value of energy: 28$€.MWh^{-1}$
BOS certificate value: 106$€.MWh^{-1}$
Monetary value of one tonne of cattle slurry: (106+28)*0.0598 = €8.0132
Maximum feasible transportation distance of one tonne of cattle slurry: 8.0132/0.315=25.4km

Box 4-1 Calculation of theoretical transportation distance of waste streams

Table 4-13 Theoretical transport distance of wastes

Feedstock	Methane Yield ($Nm^3CH_4.t_{wwt}^{-1}$)	Net Methane Yield ($Nm^3CH_4.t_{wwt}^{-1}$)	Energy Yield ($MWh.t_{wwt}^{-1}$)	Energy Value ($€.t_{wwt}^{-1}$)	Gate Fee Value ($€.t_{wwt}^{-1}$)	Total Value ($€.t_{wwt}^{-1}$)	Transport Cost ($€.tkm^{-1}$)	Max Feasible Transport Distance (km)
Cattle Slurry	8.9	6.0	0.1	8.0	0.0	8.0	0.3	25.4
Sheep Manure	38.6	25.9	0.3	34.8	0.0	34.8	0.3	110.3
Chicken Manure	22.5	15.1	0.2	20.3	0.0	20.3	0.3	64.3
Pig Slurry	7.6	5.1	0.1	6.8	0.0	6.8	0.3	21.7
Slaughterhouse Waste*	44.9	30.2	0.3	40.4	0.0	40.4	0.3	128.4
Milk Processing Waste*	38.1	25.6	0.3	34.3	0.0	34.3	0.3	108.9
Source Separated Household Organic Waste*	61.8	41.5	0.4	55.6	75.0	130.6	0.3	502.5

*Total methane production of all sub-streams divided by total tonnage of all sub-streams

The radius of collection for plant 17 for household organic waste was approximately 220km (Figure 4-8), which seems unfeasible. However, the monetary value of $1t_{wwt}$ of household organic waste is €130.61 (see Box 4-1). Transportation including the empty return, incurs a cost of $0.26€.km^{-1}$ (in terms of Euclidean distance from feedstock source to AD facility). Thus, it is theoretically viable to transport one tonne of household organic waste up to 502km. The radius of collection of cattle slurry for plant 17 was 10-15km, less than the theoretical distance of 25.4km and in the range of values used by Bojesen et al of 10-40km (Bojesen et al. 2014) for animal slurries. The collection radius of sheep manure was approximately 45km. The distances within which slaughterhouse waste and milk processing wastes were collected was approximately 25km and 40km respectively.

Following the construction of the first 6 plants, which utilised household organic waste, the total annual tonnage of feedstock accepted at subsequent facilities increased considerably. Cattle slurry was the main feedstock in terms of energy production and mass (Figure 4-7). The largest facility (mass basis), plant 42, had an NPV of approximately 15.4M€ owing to the absence of household organic waste and lack of gate fee. Plant 42 accepted $685kt.a^{-1}$ of feedstock, predominantly cattle slurry ($635kt.a^{-1}$), approximately 2% of the total mass of cattle slurry available nationally. The scale of this plant was large and approached the scale of the aforementioned Maabjerg facility in Denmark. The collection radius of cattle slurry for plant 42 was approximately 15km, sheep manure was sourced within a radius of 78km, with the remaining feedstocks (slaughterhouse waste, milk processing waste, chicken manure, and pig slurry) sourced within 30km of the facility.

Following the construction of plant 35, the scale of each facility's energy output reduced below the $50GWh.a^{-1}$ maximum plant size due to reduced availability of feedstock with high methane yield in the areas of the remaining facilities (Figure 4-7). At this point additional gains in annual revenue associated with increased energy production were outweighed by the increase in cost associated with sourcing additional feedstock. The NPV of plant 24 (3.4M€) was significantly less than that of plant 42, with an annual net energy production of 37.9GWh. The only feedstock processed at plant 24 was cattle slurry (618.4kt) with the entire mass

sourced within approximately 20km (Figure 4-8). The greater collection radius of cattle slurry for plant 24 as opposed to plants 17 and 42 was a result of a lower resource of cattle slurry available in the vicinity of plant 24, thus feedstock must be sourced from further afield.

4.4.2 Scenarios at 200 GWh.a^{-1} (1b-9b)

4.4.2.1 4.2.1 Injection sites, biomethane production, and resource utilisation

In scenarios 1b-9b, the first plant to be constructed (the plant with the highest NPV) was plant 10, similar to scenarios 1a-9a, due to the large resource of source separated household organic waste in the vicinity of this plant. The second plant constructed in all scenarios (1b - 9b) was plant 38, which used the remainder of the source-separated household organic waste available (Figure 4-9). The number of NPV positive plants in scenarios 1b-9b varied from a minimum of 2, to a maximum of 18. The lower number of plants constructed in comparison to scenarios 1a-9a was a result of the larger plant size. This resulted in more of the available feedstock being used by plants that were initially built. In scenarios 1b-9b there was a large difference in NPV between plants 10, 38, and the remaining facilities (Figure 4-12). The high NPV of plants 10 and 38 was due to their use of significant quantities of household organic waste. The order in which plants were built in scenario 9b was much different to that in scenario 9a highlighting the impact of maximum allowable plant size on build order.

Maximum allowable plant size had a marginal effect on the total amount of energy injected to the gas network. In scenario 9a the total energy injected to the gas network was 941GWh.a^{-1} (3.4PJ.a^{-1}). The biomethane injection in scenario 9b was 1,056GWh.a^{-1} (3.8PJ.a^{-1}) (Figure 4-10), an increase of 11%. Biomethane injection in scenario 9b was equivalent to 2.12% of thermal TFC in 2015 and 73**%** of the GNI renewable gas goal in 2025. Total biomethane production in scenario 9b was 6.7% of industrial gas consumption in 2015/2016.

Varying the maximum allowable plant size did not alter the percentage utilization of the total theoretical resource of household organic waste, this reached a maximum

of 97% in both scenarios (Figure 4-11). The maximum utilisation of milk processing waste was 97%, sheep manure was 73%, slaughterhouse waste was 95%, cattle slurry was 34%, pig slurry was 35%, and chicken manure was 43% in scenarios 1b-9b. The increase in the utilisation of the total theoretical energy resource of each waste in scenarios 1b-9b (as compared to scenarios 1a-9a) may be a result of larger plants requiring more feedstock in order to maximise NPV. There was a significant resource of cattle slurry not utilised in scenarios 1b-9b (64% of the total theoretical resource). Alternative methods for the economic utilisation of cattle slurry in biomethane to grid facilities must be further investigated.

4.4.2.2 4.2.2 Detailed analysis of scenario 9b

Feedstock allocations and transport distance to plants in scenario 9b were considerably different to that of scenario 9a. In scenario 9b the most financially viable plant and the first to be constructed was plant 10, with a NPV of 495M€ and annual energy injection of 200GWh.a^{-1}, treating primarily household organic waste (484kt.a^{-1}) (Figure 4-12). The total quantity of household organic waste processed at plant 10 in scenario 9b represented 71% of the total theoretical national resource. Plant 10 in this scenario would be an extremely large biomethane to grid facility, sourcing household waste from the majority of Ireland (Figure 4-13A). The LCOE of plant 10 in scenario 9b was 81.54€.MWh^{-1}, which was higher than the LCOE of plant 10 in scenario 9a (59.39€.MWh^{-1}) as a result of the increased transport costs associated with the larger collection radius for household organic waste.

The total tonnage of household organic waste processed at plant 10 in scenario 9b (484kt.a^{-1}) was approximately 4 times larger than the largest AD facilities processing food waste in the UK, ReFood and Poplars Landfill AD (NNFCC 2015). However, it was smaller than the Maabjerg biogas plant in Denmark. For comparison, the Indaver waste to energy facility (an incinerator processing residual non-recyclable waste) in Duleek Co. Meath accepted 232kt of primarily municipal waste and residue waste from mechanical treatment(Envrionmental Protection Agency 2014). The proposed Poolbeg waste to energy plant to be located in Dublin is designed to process 600kt.a^{-1} of residual non-hazardous wastes of residential and commercial

origin (Environmental Protection Agency 2015). Thus, plant 10 in scenario 9b is not beyond the realms of possibility in terms of scale, but is still very large.

The collection radius of source separated household organic waste for plant 10 was approximately 160km in scenario 9b (Figure 4-13 A); transportation over such a distance requires further investigation. The total energy production of plant 10 (200GWh.a^{-1}) was sufficient to meet the thermal demand of 13,460 households, 2.8% of HGV energy consumption in 2015, or 12.6% of public transport energy consumption in 2015.

Following plant 10, the next most profitable plant in scenario 9b was plant 38 (Figure 4-12). This was in stark contrast to scenario 9a in which plant 38 was the 15th plant to be constructed and used cattle slurry almost exclusively. The NPV of plant 38 in scenario 9b was approximately 166€ million, with an annual energy input to the gas network of approximately 169GWh.a^{-1}, and a LCOE of approximately 104€.MWh^{-1}. The primary feedstock for plant 38 was household organic waste, which contributed 71GWh.a^{-1} (43%), followed by cattle slurry which contributed 50GWh.a^{-1} (30%). The remaining feedstock consisted of milk processing waste, sheep manure, slaughterhouse waste, pig slurry, and chicken manure (Figure 4-12). Combined, plants 10 and 38 could provide renewable heat to 24,835 households, 5% of HGV energy use in 2015, or 23% of public transportation energy use in 2015.

The total tonnage of feedstock accepted at plant 38 was large, approximately 1.2Mt of feedstock, this is far greater than any AD facilities located in the UK. The proposed facility is 65% larger than the Maabjerg AD facility in Denmark and thus results should be treated with caution. Household waste was sourced from the very north of the country, a distance of ca. 350km (Figure 4-13 B1). While this is within the maximum theoretical transportation distance for household organic waste, it requires further investigation regarding real world practicality. The collection radius was approximately 80km for sheep manure, 20km for cattle slurry, and 70km and 90km for slaughterhouse wastes and milk processing wastes, respectively. All collection radii were within their maximum theoretical distances. Pig slurry was only

collected from one location at a distance of approximately 16km owing to its low energy yield per wet tonne transported.

No plants built subsequent to the first plant constructed (plant 10) in scenario 9b reached an annual energy injection of 200GWh.a^{-1}. This was due to plant 10 utilising the majority of household organic waste in the country. Subsequent plants had to utilise alternative waste streams, which did not have a gate fee, and often had a higher transportation cost per unit of energy available in the raw waste. The model determined that the optimal scale of the remaining facilities which maximised NPV was less than 200GWh.a^{-1}. The scale of the least financially viable plant built in scenario 9b was approximately 26GWh.a^{-1}. This plant processed cattle slurry alone and was in the same size range as the minimum scale of plant built in scenario 9a, which also processed cattle slurry.

The primary feedstock in terms of tonnage and energy contribution for all plants built after plants 10 and 38 was cattle slurry which accounted for over 75% of the total tonnage of waste accepted and over 48% of the energy output of all remaining plants.

The feedstock utilised at plant 42 comprised of cattle slurry, sheep manure, chicken manure, and pig slurry. Plant 42 had an energy output of 61GWh.a^{-1}, primarily sourced from cattle slurry. The radii of collection of each of these feedstock types were; 20km, 80km, 30km, and 14km respectively (Figure 4-13 C). The absence of household organic waste, slaughterhouse waste, or milk processing was a result of all these feedstocks being allocated to prior facilities. Injection plant 16 utilised only cattle slurry as a feedstock with the total energy production at 26GWh.a^{-1}. The radius of collection for cattle slurry in this instance was approximately 20km (Figure 4-13 C). No other feedstock types were utilised in this plant owing to their allocation to prior plants by the optimisation model.

4.4.3 Overall discussion

The location of NPV positive facilities varied depending on the maximum allowable plant size. In scenarios 1a-9a, initial plants processed exclusively source separated household organic waste, they were located in regions with the largest resource of household organic waste. Following this, plants became more dispersed in order to source multiple feedstock streams while maximising NPV. In scenarios 1b-9b, the increase in maximum allowable plant size resulted in only two AD facilities processing source separated household organic waste. These facilities were large, with radii of collection correspondingly large, as such, the result of scenarios 1b-9b should be treated with caution.

The value of the BOCs, an additional revenue per unit energy of biomethane produced, was identified as the most important parameter in influencing the quantity of biomethane injected into the gas network. If waste streams (which do not accrue a gate fee) are to be utilised a BOC or some form of additional gas revenue should be available. The results of the optimisation model showed vastly different results for total biomethane production, depending on the gate fee charged for incoming household organic waste and depending on the BOC value. Increased BOC value resulted in increased biomethane production from wastes not eligible for gate fees, especially agricultural slurries.

The results of scenario 9a gave a total annual biomethane production of 3.4PJ.a^{-1}, arising from a total of 22 plants. The results of the scenarios 9b gave a biomethane production of 3.8PJ.a^{-1} from 18 plants. The plant locations identified in this work, and the waste streams utilised therein represent a significant renewable energy resource for renewable transportation. Total biomethane production in scenario 9a could supply 13% of HGV energy consumption, 59% of public transport energy consumption, and 3.4% RES-T (when double counted). Total biomethane production in scenario 9b could supply 15% of HGV energy consumption, 66% of public transport energy consumption, and 3.8% RES-T (when double counted). Incentives such as the BOC are vital for the development of an industry utilising waste feedstock in AD.

The optimisation model maximised the utilisation of household organic waste, slaughterhouse waste, and milk processing waste in order to maximise the NPV of potential biomethane plants. The utilisation of slurries and manures were lower due to the lower methane yield per tonne of feedstock transported. The first plants to be constructed should be those processing household organic waste for which a gate fee is available, subsequent plants will be required to co-digest a range of waste streams in order to maximise NPV.

The remaining resource associated with slurries and manures could potentially be used in different biomethane production pathways such as co-digestion with grass silage, or small scale anaerobic digestion (possibly on farm or by a co-operative of farms) coupled with mobile biogas upgrading and road haulage to a gas grid injection point, or biogas transportation in low pressure biogas networks. It is recommended that further work be carried out in determining the alternative uses of slurries and manures that are not utilised by facilities herein as these represent a significant energy resource.

4.5 Conclusion

The model suggests that the first injection points to be built process source separated household organic waste owing to the available gate fee. Maximum allowable plant size had a significant impact on the build order of plants and the allocation of feedstock to them. At a maximum plant size of 50GWh.a^{-1} the model suggested 6 plants as opposed to 2 plants at a maximum size of 200GWh.a^{-1}. The impact of incentives on the total production of biomethane was significant. The model suggested 6 plants producing 276GWh.a^{-1} (1 PJ.a^{-1}) of biomethane at an incentive of 35€.MWh^{-1} as opposed to 22 plants producing 941GWh.a^{-1} (3.4PJ.a^{-1}) at an incentive of 106€.MWh^{-1} (for a maximum plant size of 50GWh.a^{-1}). As incentive levels increased the production of biomethane from agricultural slurries and manures showed the largest increase in resource utilisation; 1.4GWh.a^{-1} (0.005PJ.a^{-1}) from cattle slurry at an incentive of 38€.MWh^{-1} as compared to 508GWh.a^{1} (1.8PJ.a^{-1}) at 106€.MWh^{-1}. LCOE is generally lowest for initial plants and increases for subsequent plants.

Five 50GWh.a^{-1} plants processing household organic waste could meet the thermal demand of 16,825 households at a maximum LCOE of 99.9€.MWh^{-1}. At a maximum plant size of 200GWh.a^{-1} the initial 2 plants could provide heat to 24,835 households at a maximum LCOE of 104€.MWh^{-1}. A total of 1.9% of thermal TFC and 3.44% of transport TFC in 2015 could be achieved using 22 CAD plants with a maximum size of 50GWh.a^{-1}. For a maximum plant size of 200GWh.a^{-1}, 2.1% of thermal TFC in 2015 and 3.8% of transport TFC could be achieved in 18 facilities. These plants could provide 6% and 7% respectively of total industrial gas consumption in 2015. The biomethane production of NPV positive plants in the most optimistic scenarios (9a and 9b) were capable of meeting 66% and 73% of the GNI renewable gas goal for 2025.

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5 Chapter 5: Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region

"Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region"

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Abstract

The total theoretical biomethane resource of cattle slurry and grass silage in Ireland was estimated using the most up to date spatially explicit data available. The cattle slurry resource (9.6PJ) was predominantly found in southern and north-eastern regions while the grass silage resource (128.4PJ) was more concentrated in western regions. The total biomethane resource of cattle slurry and grass silage was equivalent to 5% and 71% of total natural gas consumption in Ireland in 2015/16, respectively. A sequential optimisation model was run to determine where to source cattle slurry and grass silage from, for 42 potential biomethane plant locations in Ireland. The goal was to maximise plant net present value (NPV) and to identify potential plant locations in order of plant profitability, starting with the most profitable. The impact of plant size, grass silage price, volatile solids ratio (VSR) of grass silage to cattle slurry, and incentive per unit energy of biomethane was assessed in 81 separate scenarios. The results indicated that total biomethane production from plants with a positive NPV ranged from 3.51PJ.a^{-1} to 12.19PJ.a^{-1}, considerably less than the total theoretical resource. The levelized cost of energy (LCOE) of plants was also calculated and ranged from 50.2€.MWh^{-1} to 109€.MWh^{-1} depending on the various plant parameters. LCOE decreased with increased plant size and ratio of grass silage to cattle slurry. The relationship between grass silage price and LCOE was assessed. In the median scenario (33€.t_{wwt}^{-1} grass silage, VSR of 4, 75,000t_{wwt}.a^{-1} plant size, 60€.MWh^{-1} incentive) cattle slurry was sourced within 6.4km of the facility while grass silage was sourced within 10.5km of the facility. A high-level assessment of the carbon dioxide intensity of biomethane from the median scenario was conducted and showed a potential greenhouse gas reduction of 74-79% when compared to natural gas.

Keywords: Biomethane; optimisation; grass silage; slurry; gas grid; resource assessment.

5.1 Introduction

The total final consumption (TFC) of energy in transport in Ireland in 2015 was approximately 200.2PJ, of which 97.2% was imported petroleum fossil fuels (Howley & Holland 2016). Thermal energy consumption was 178PJ (Howley & Holland 2016). Ireland has an obligation to ensure that 10% of energy in transport and 12% of thermal energy is sourced from renewable sources by 2020(The European Parliament and the Council of the European Union 2009; Department of Communications Marine and Natural Resources 2007).

Biomethane production through the anaerobic digestion of biodegradable matter is a potential pathway to meeting such renewable energy targets using indigenous feedstock. Use of biomethane can also mitigate greenhouse gas emissions from agriculture through improved manure and slurry management, and contribute to the 20% national reduction target in the non-emissions trading sector (n-ETS) relative to 2005. The use of biomethane as an energy source can also contribute toward meeting the 20% reduction in total greenhouse gas emissions relative to 1990 levels, by offsetting the use of fossil fuels. Within the EU, seven natural gas grid operators have agreed to supply 100% carbon neutral gas by 2050, with anaerobic digestion (AD) being a key component in achieving this (De Buck et al. 2015). Gas Networks Ireland (GNI), the owner and operator of the natural gas network in Ireland has targeted 20% renewable gas in the network by 2030, with an interim goal of 5.184PJ of renewable gas by 2025 (Gas Networks Ireland 2016). Feedstock suitable for use in AD includes biodegradable materials with high moisture content such as household organic waste, agricultural residues and slurries, grass silage, energy crops, and macro algae (seaweed).

5.1.1 Prior assessments of grass silage as a source of biomethane

The scientific literature suggests a potentially significant resource of biomethane associated with grass silage and cattle slurry in Ireland (Wall et al. 2013; Singh et al. 2010; Allen et al. 2016), which could contribute more than 26% of the projected energy consumption in transportation in 2020 (Wall et al. 2013). Studies to date

have only provided an overall national resource; no spatially explicit studies have been undertaken, no potential build order of biomethane facilities whilst considering financial viability has been developed. An assessment of sub-regions within Ireland for development of a biomethane industry has been conducted (Smyth et al. 2011) however the financial viability of the plants was not assessed.

Internationally the development of a biomethane industry, whilst taking into consideration the location of potential feedstocks, has been assessed by Bojesen for the case of Denmark; the feedstock assessed were slurries from animal husbandry (Bojesen et al. 2015; Bojesen et al. 2014). The work by Bojesen utilised a p-median solution to determine the allocation of feedstock sources to potential biogas facilities, plant profitability was not considered, and the impact of feedstock mix was not assessed. Work by Hohn et al. assessed the resource potential of biogas in southern Finland and also determined potential locations for biogas facilities, again by solving a p-median problem which minimised the total transportation cost of feedstock to the proposed biogas facilities (Höhn et al. 2014). The impact of feedstock mixture on the energy production of facilities was not assessed. The most profitable plant, in terms of NPV, was not determined by either Bojesen et al. or Hohn et al.; a potential build order of plants ranked in terms of profitability was not developed by either. Chinese et al. investigated the impact of changing bioenergy promotion schemes in Italy on the agricultural biogas industry, by considering plant size, feedstock supply, feedstock mix, and digestate disposal (Chinese et al. 2014). The work by Chinese et al. did not consider the impact of varying ratios of feedstock, and it did not develop a potential build order of biogas facilities.

5.1.2 Innovation and objectives

The profitable operation of a potential biomethane facility may require a sufficient financial incentive; determining this required incentive is crucial.

The innovation in this work is that it provides a method to assess, and undertakes an exemplar analysis of, potential locations for anaerobic digesters for biomethane production and grid injection and ranks them in terms of financial viability. The

method considers plant size, feedstock price, feedstock source, transportation cost, potential incentive value, and feedstock mix. No such work has been reported previously in scientific literature to the authors best knowledge at the time this work was carried out. The region chosen for this analysis was Ireland, in which there is currently no large scale biomethane industry. Grass silage and cattle slurry were selected for this assessment owing to their large resource in Ireland. This work is aimed at policy makers, engineers, planners, and developers involved in the establishment of biomethane industries.

The methodology developed herein could be applied to any region in order to determine the total theoretical biomethane resource, and develop a potential build order to biomethane facilities ranked in terms of profitability.

The objectives of this work are to:

1) Determine the total theoretical biomethane potential of cattle slurry and grass silage on a regional level and highlight the regions of greatest resource;
2) Calculate the total biomethane production from potential plants for a range of silage prices, premium or incentive levels, volatile solids ratios (VSRs) of grass silage to cattle slurry, and plant sizes using an optimisation model which maximises plant profitability;
3) Develop cost curves outlining the quantity of biomethane which can be produced at a given levelized cost of energy;
4) Outline a potential build order of plants for a given scenario and assess the source locations of grass silage and cattle slurry used in the constructed plants.
5) Assess the relationship between resource and financially viable resource.

5.2 Methodology

5.2.1 Calculation of cattle slurry resource

The total resource of cattle slurry in terms of wet tonnes (t_{wwt}) was calculated at each ED (electoral division, the smallest regions for which such data was available) according to Equation 5-1 based on prior work by the author (O'Shea et al. 2016). The most up to date data (June 2010) on bovine livestock for each ED was sourced from the Central Statistics Office (CSO) on May 20th 2015.

Equation 5-1 Cattle slurry resource per electoral division (m_j^{CS}):

$$m_j^{CS} = N_{cows,dairy}Y_{cows,dairy} + N_{cows,other}Y_{cows,other} + N_{cattle\geq 2}Y_{cattle\geq 2} + N_{cattle1-2}Y_{cattle1-2} + N_{cattle\leq 1}Y_{cattle\leq 1}$$

In Equation 5-1 N_ϑ is the number of livestock type ϑ in an ED, Y_ϑ is the annual slurry production per head of livestock of type ϑ. The annual slurry yield per head of bovine livestock was taken from Hennessy et al. (Hennessy et al. 2011). The dry solids (DS_{CS}) content and volatile solids (VS_{CS}) content of cattle slurry was taken to be 8.35%$_{wwt}$ and 6.23%$_{wwt}$, respectively, an average of values obtained for Irish dairy cattle slurry in literature (Wall et al. 2013; Wall et al. 2014; Allen et al. 2014). The total methane yield per ED was found using a specific methane yield (SMY) of 143LCH_4.kgVS^{-1} (Wall et al. 2014), while the total energy resource was determined using a calorific value of 37.78MJ.$Nm^{-3}CH_4$.

5.2.2 Calculation of grass silage resource

Prior assessments of the potential biomass resource that could be grown in other European and non-European countries were based on agricultural land that was found to be surplus to requirements under a number of scenarios of increased productivity, whilst considering non-agricultural land demand, food production, and fodder production (Steetskamp et al. 1995; Faaij et al. 1998; de Wit & Faaij 2010; van der Hilst & Faaij 2012; van der Hilst et al. 2014; Lewandowski et al. 2006). In

prior studies, surplus agricultural land was converted to bioenergy production either through the planting of willow, Miscanthus, wheat, or other bioenergy crops.

The conversion of pasture land to tillage for energy crop production can result in an increase in greenhouse gas emissions as a result of tillage operations (Soussana et al. 2004; de Wit & Faaij 2010; van der Hilst et al. 2014) which could negate a portion of the emissions reductions realised by using bioenergy. In addition to this, the slow uptake of the planting perennial energy crops such as willow and Miscanthus in Ireland owing to; high establishment costs, lower than expected crop yields, lack of a definite long-term market, and farmer concerns relating to the long-term nature of the crop resulting in a loss of alternative opportunities in the future (Sustainable Energy Authority of Ireland & Ricardo Energy and Environment 2016), resulted in a modified methodology being used in this work.

The total area of land in each ED allocated to grassland pasture and silage production was sourced from the CSO. The annual production of dry matter (DM) grass from pasture, grass silage from land dedicated to grass silage production, and grassland allocated to hay production was calculated using the methodology outlined in McEniry et al. (Mceniry et al. 2013) as shown in Equation 5-2. An assumption that maximum nitrogen fertiliser application (to the limit permitted by the EU Nitrates Directive) was used.

Equation 5-2 Grass dry matter resource per ED (m_i^{GS}):

$$m_i^{GS} = A_{grass} * \left(F_{SG1} * Y_{SG1}^{grass} + F_{SG2} * Y_{SG2}^{grass} + F_{SG3} * Y_{SG3}^{grass}\right) + \left[A_{silage} * F_{1cut} * \left(F_{SG1} * Y_{SG1,1cut}^{silage} + F_{SG2} * Y_{SG2,1cut}^{silage} + F_{SG3} * Y_{SG3,1cut}^{silage}\right) + A_{silage} * F_{2cut} * \left(F_{SG1} * Y_{SG1,2cut}^{silage} + F_{SG2} * Y_{SG2,2cut}^{silage} + F_{SG3} * Y_{SG3,2cut}^{silage}\right)\right] + A_{hay} * \left(F_{SG1} * Y_{SG1}^{hay} + F_{SG2} * Y_{SG2}^{hay} + F_{SG3} * Y_{SG3}^{hay}\right)$$

In Equation 5-2 A_k is the area of land under grass type *k*. Different soil groups yield different quantities of grass, grass for silage, and grass for hay (Mceniry et al. 2013). The fractions of land area in each soil group (F_{SG1}, F_{SG2}, F_{SG3}) for each ED were taken as the average fraction of land in each soil group, for the region in which each ED is

located, for the years 2011-2013, based on the results of Ireland's National Farm Survey (Teagasc 2016). Values used for F_{1cut} and F_{2cut} (fraction of land under 1 cut or 2 cut silage) are those specified in McEniry et al. (Mceniry et al. 2013). Y^k_{β} is the yield ($tDM.ha^{-1}$) of grass type k in soil group β as per (Mceniry et al. 2013).

The total consumption of grass in each ED was calculated using current grass and silage consumption rates per head of livestock, and current herbage utilisation rates (0.6kgDM of herbage ingested by livestock per kgDM of herbage grown for cattle) of each type of livestock in an ED (Mceniry et al. 2013). The resource of grass in excess of livestock requirements was found by subtracting the total grass requirement of livestock from the total potential production of grass.

It is assumed that all surplus grass could theoretically be converted to grass silage as per Wall et al. (Wall et al. 2013). The total wet tonnage of grass silage produced in each ED was found taking a DS content of $29.3\%_{wwt}$ (Wall et al. 2014). The methane resource of excess grass silage was determined using a VS content of $26.8\%_{wwt}$ (VS_{GS}) and a SMY of $405LCH_4.kgVS^{-1}$, an average of values obtained during continuous mesophilic digestion of grass silage at a range of organic loading rates ($2kgVS.m^{-3}.day^{-1}$ to $3.5kgVS.m^{-3}.day^{-1}$) (Wall et al. 2014). The use of surplus grass for the production of grass silage as a feedstock for anaerobic digestion does not alter land use and leverages the existing knowledge that farmers have in relation to the production of grass silage. Additionally, if farmers wish to stop supplying grass silage and increase dairy of beef production, the land previously used for silage production can be immediately used for beef or dairy production.

5.2.3 Thematic mapping of cattle slurry and grass methane resource

Thematic maps of the methane resource (m^3CH_4) associated with cattle slurry and excess grass were generated using QGIS in order to facilitate a visual inspection of regions with the highest resource. The resource density of EDs ($m^3CH_4.km^{-2}$) was also determined.

5.3 Optimisation model

5.3.1 Facility size

Prior work by Singh et al. assumed a biomethane facility accepting a minimum of 50,000$t_{wwt}.a^{-1}$ consisting of grass silage and slurry (Singh et al. 2010). Three facility sizes (T^{plant}) were assessed in this work; 50,000$t_{wwt}.a^{-1}$, 75,000$t_{wwt}.a^{-1}$, and 100,000$t_{wwt}.a^{-1}$ in order to assess the financial viability of biomethane plants using grass silage and cattle slurry. Whilst a facility of 100,000$t_{wwt}.a^{-1}$ is large, it is included to highlight the impact of facility scale on the model outputs. There are three biomethane to grid facilities in the UK which process greater than 100,000$t_{wwt}.a^{-1}$ of feedstock (NNFCC 2015), as well as the Maabjerg biogas plant in Denmark which process ca. 800,000$t_{wwt}.a^{-1}$ (IEA Task 37 2014). A tolerance (A) of 5% of the desired plant size was allowed in the model, as such, the minimum and maximum plant tonnage (T_{min}^{plant}, T_{max}^{plant}) can be found according to Equation 5-3 and Equation 5-4.

Equation 5-3 Minimum plant tonnage (T_{min}^{plant}):

$$T_{min}^{plant} = T^{plant} * (1 - A)$$

Equation 5-4 Equation 4; Maximum plant tonnage (T_{max}^{plant}):

$$T_{max}^{plant} = T^{plant} * (1 + A)$$

The minimum and maximum tonnage of cattle slurry and grass silage (T^{CS}_{min}, T^{GS}_{min}, T^{CS}_{max}, *and* T^{GS}_{max}), which could be accepted by facilities in the model were calculated according to Equation 5-5, Equation 5-6, Equation 5-7, and Equation 5-8.

Equation 5-5 Minimum tonnage of cattle slurry to be accepted at a plant (T^{CS}_{min}):

$$T_{\min}^{CS} = \frac{\left(T_{min}^{plant} * VS_{GS}\right)}{(VSR * VS_{CS} + VS_{GS})}$$

Equation 5-6 Minimum tonnage of grass silage to be accepted a plant (T^{GS}_{min}):

$$T^{GS}_{min} = T^{plant}_{min} - T^{CS}_{min}$$

Equation 5-7 Maximum tonnage of cattle slurry to be accepted at a plant (T^{CS}_{max}):

$$T^{CS}_{max} = \frac{\left(T^{plant}_{max} * VS_{GS}\right)}{(VSR * VS_{CS} + VS_{GS})}$$

Equation 5-8 Maximum tonnage of grass silage to be accepted at a plant (T^{GS}_{max}):

$$T^{GS}_{max} = T^{plant}_{max} - T^{CS}_{max}$$

5.3.2 Specific methane yields

A number of ratios of grass silage to cattle slurry on a VS basis (*VSR*) were assessed with the specific methane yield of each ratio (SMY_{VSR}) sourced from Wall et al. (Wall et al. 2014). The *VSR*s assessed were 2:1, 4:1, and 6:1 (grass silage: cattle slurry) to determine the impact of feedstock mix i.e. *VSR,* on plant viability, feedstock use, and plant location.

5.3.3 Biomethane facility cost

The CAPEX of the AD system (C_{AD}) was calculated according to Equation 5-9 and Equation 5-10 (Browne et al. 2011).

Equation 5-9 Specific CAPEX (c_{AD}) of the AD facility

$$c_{AD}\ (€.t_{wwt}.a^{-1}) = 554.89 * feedstock\ mass^{-0.159}$$

Equation 5-10 CAPEX (C_{AD}) of the AD facility:

$$C_{AD}(€) = 554.89 * feedstock\ mass^{0.841}$$

To use this cost function in the optimisation model it was approximated by a linear equation at the desired plant size (T^{plant}). Linearization of the AD CAPEX function

was conducted by the authors. The slope of the linearized AD CAPEX function (M_{AD}) was found according to Equation 5-11.

Equation 5-11 Slope of linearized AD CAPEX function (M_{AD}):

$$M_{AD} = \frac{\left(554.89 * {T_{max}^{plant}}^{0.841} - 554.89 * {T_{min}^{plant}}^{0.841}\right)}{T_{max}^{plant} - T_{min}^{plant}}$$

The constant term in the linearized AD CAPEX equation was found using Equation 5-12.

Equation 5-12 Constant term in linearized AD CAPEX equation (I_{AD}):

$$I_{AD} = \left(554.89 * {T_{max}^{plant}}^{0.841} - M_{AD} * T_{max}^{plant}\right)$$

The approximate AD CAPEX ($\hat{C}_{AD}$) according to the linearized AD CAPEX function can be found using Equation 13.

Equation 5-13 Approximated AD CAPEX ($\hat{C}_{AD}$) :

$$\hat{C}_{AD} = M_{AD} * T^{plant^*} + I_{AD}$$

The variable T^{Plant*} is the tonnage of grass silage (T^{GS*}) and the tonnage of cattle slurry (T^{CS*}) accepted by the plant in the optimisation model. Specific operational expense (SO_{AD}) of the AD system was taken to be 5€.t_{wwt}^{-1} for an AD plant processing grass silage and cattle slurry (Browne et al. 2011). Annual operating cost of the AD facility (O_{AD}) was calculated according to Equation 5-14.

Equation 5-14 Annual operating cost of AD facility (O_{AD}):

$$O_{AD} = SO_{AD} * T^{Plant^*}$$

Biogas upgrading technologies include amine scrubbing systems, membrane separation systems, water scrubbing systems, and organic physical scrubbing systems among others; an overview of these can be found in Bauer et al. (Bauer et al. 2013).

An amine upgrading system was selected owing to the higher biomethane purity achieved (>99.9%), low levels of methane slip, technology maturity, large operational range, and the availability of up to date cost data.

The specific CAPEX of the amine upgrading system (c_{UP}) was sourced from Bauer et al. (Bauer et al. 2013), and can be seen in Equation 5-15; this was adapted to yield the CAPEX of an amine upgrading system (C_{UP}) as per Equation 5-16**.**

Equation 5-15 Specific CAPEX (c_{UP}) of an amine upgrading system:

$$c_{UP}\left(€.Nm^3_{Biogas}.hour^{-1}\right) = 181613 * (\dot{V_{Biogas}})^{-0.627}$$

Equation 5-16 CAPEX of an amine upgrading (C_{UP}):

$$C_{UP}\ (€) = 181613 * (\dot{V_{Biogas}})^{0.373}$$

The hourly flow rate of biogas to the upgrading unit ($\dot{V}_{Biogas}^{*}$) in the optimisation model was calculated using Equation 5-17 with a CH_4 content ($\%CH_4$) between 53%$_{vol}$ and 55%$_{vol}$ depending on the *VSR* (Wall et al. 2014), and a total of 8,585 operational hours (*H*) per annum corresponding to an annual availability of 98%.

Equation 5-17 Hourly flow rate of biogas ($\dot{V}^{Biogas}$) to the upgrading system

$$\dot{V^{Biogas^*}} = \frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS}\right) * SMY_{VSR}\right)}{H * \%CH_4}$$

To use the upgrading CAPEX function in the optimisation process a linear approximation of the upgrading CAPEX function was found using the minimum and maximum allowable plant sizes (T^{plant}_{min}, T^{plant}_{max}). The corresponding minimum and

maximum biogas flow rate ($\dot{V}^{Bioga}{}_{min}$, $\dot{V}^{Biogas}{}_{max}$) can be calculated according to Equation 5-18 and Equation 5-19.

Equation 5-18 Minimum biogas flow ($\dot{V}^{Biogas}{}_{min}$):

$$V_{min}^{\dot{Biogas}} = \frac{\left(\left(T_{min}^{GS} * VS_{GS} + T_{min}^{CS} * VS_{CS}\right) * SMY_{VSR}\right)}{H * \%CH_4}$$

Equation 5-19 Maximum biogas flow ($\dot{V}^{Biogas}{}_{max}$):

$$V_{max}^{\dot{Biogas}} = \frac{\left((T_{max}^{GS} * VS_{GS} + T_{max}^{CS} * VS_{CS}) * SMY_{VSR}\right)}{H * \%CH_4}$$

The slope of the linear approximation of the upgrading system CAPEX was found using Equation 5-20.

Equation 5-20 Slope of linearized upgrading CAPEX function (M_{UP}):

$$M_{up} = \frac{181613 * \left(\left(V_{max}^{\dot{Biogas}}\right)^{0.373} - \left(V_{min}^{\dot{Biogas}}\right)^{0.373}\right)}{V_{max}^{\dot{Biogas}} - V_{min}^{\dot{Biogas}}}$$

The constant term in the linearized upgrading CAPEX equation was found using Equation 5-21;

Equation 5-21 Constant term in linearized upgrading CAPEX function (IUP):

$$I_{UP} = \left(181613 * \left(V_{max}^{\dot{Biogas}}\right)^{0.373} - M_{UP} * V_{max}^{\dot{Biogas}}\right)$$

The approximate upgrading CAPEX ($\hat{C}_{UP}$) according to the linearized upgrading CAPEX function can be seen in Equation 5-22

Equation 5-22 Approximate upgrading CAPEX ($\hat{C}UP$):

$$\hat{C}_{UP} = M_{UP} * \left(V^{\dot{Biogas}^*}\right) + I_{UP}$$

Methane slippage (*CH_4Slip*) in the amine upgrading system was taken to be 0.5%, higher than the 0.1% specified by Bauer et al. (Bauer et al. 2013) and Beil et al. (Beil & Beyrich 2013). Annual maintenance cost of the upgrading system (*$Maint_{Up}$*) was estimated to be 101,293€.a^{-1} as per a quotation received by GNI from an amine upgrading system provider.

The cost of connection to the natural gas network (*$C_{Connect}$*) was taken to be €1.892million, as per Urban et al (Urban 2013) including a contingency cost of 10%, this was similar to initial cost estimates for connection to the gas transmission network developed in house by GNI (ca. €1.9million).

5.3.4 Parasitic energy costs

Consumption of electrical energy by the AD plant (*SE_{AD}*) was taken to be 10$kWh_e.t_{wwt}^{-1}.a^{-1}$ (Murphy et al. 2004; Power & Murphy 2009; Smyth et al. 2009).The thermal demand of the plant (*H_{AD}*) in $kWh_{th}.a^{-1}$ was found using Equation 5-23 which determines the energy required to heat the cattle slurry from a temperature of 10°C (*t_{Low}*) to 70°C (*t_{Hi}*) (required to pasteurise cattle slurry for use in AD plants in Ireland (Department of Agriculture Fisheries and Food 2009)) using the moisture content of cattle slurry (*MC_{CS}*), the mass of cattle slurry accepted by each plant (*T^{CS^*}*) (depending on the plant size and VSR), and the specific heat capacity of water (*C_pH_2O*), as outlined by Browne et al. (Browne et al. 2011).

Equation 5-23 Thermal energy requirement to heat cattle slurry (HAD):

$$H_{AD} = \left(T^{CS^*} * 1{,}000 * MC_{CS} * \frac{C_pH_2O}{3.6} * (t_{Hi} - t_{Low})\right)$$

The thermal energy requirement of heating grass silage to the digester temperature was neglected as mixing of the heated slurry with grass silage resulted in a mixture temperature in excess of 37°C for all ratios of silage and slurry assessed.

The electricity consumption of the upgrading system (SE_{UP}) was taken to be 0.11$kWh_e.Nm^{-3}_{biogas}$ processed (Bauer et al. 2013; Beil & Beyrich 2013). The thermal demand of the amine upgrading system was assumed to be 0.55$kWh_{th}.Nm^{-3}_{biogas}$ (Bauer et al. 2013; Beil & Beyrich 2013). Approximately 80% of the thermal input energy can be recovered by heat exchangers leading to a net thermal demand (SH_{UP}) of approximately 0.1 $kWh_{th}.Nm^{-3}_{biogas}$. The electrical demand of compression (SE_{Comp}) to 16bar was estimated to be 0.12$kWh_e.Nm^{-3}_{biomethane}$ (Bauer et al. 2013).

The source of electricity for the plant was the electricity grid, while thermal energy was provided by the combustion of natural gas in boilers with a thermal efficiency (η_{Boiler}) of 90%. The electricity price (PE) used in this work was 0.16€.kWh_e^{-1} and the natural gas price (PG) was 0.04€.kWh_{th}^{-1} as the plant sizes modelled fell within consumption bands for which these prices apply in Ireland.

The annual electricity cost of the AD facility (CE_{AD}), and the annual natural gas cost of heating the AD facility (CH_{AD}) were found using Equation 5-24 and Equation 5-25.

Equation 5-24 Annual cost of electricity incurred by the AD plant (CE_{AD}):

$$CE_{AD} = T^{Plant^*} * SE_{AD} * PE$$

Equation 5-25 Annual cost of natural gas incurred by the AD plant (HAD):

$$CH_{AD} = \frac{H_{AD}}{\eta_{Boiler}} * PG$$

The annual electricity cost of the upgrading system (CE_{UP}), and the annual natural gas cost for supplying heat to the upgrading system (CH_{UP}) were calculated according to Equation 5-26 and Equation 5-27.

Equation 5-26 Annual electricity cost of upgrading system (CE_{UP}):

$$CE_{UP} = \left(\frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right)}{\%CH_4} \right) * SE_{UP} * PE$$

Equation 5-27 Annual natural gas cost for supplying heat to the upgrading system (CH_{UP}):

$$CH_{UP} = \left(\frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right)}{\%CH_4} \right) * \frac{SH_{UP}}{\eta_{Boiler}} * PG$$

The annual electricity cost of the compressor was found according to Equation 5-28.

Equation 5-28 Annual electricity cost for compression of biomethane (CE_{Comp}):

$$CE_{Comp} = \left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right) * (1 - CH_4 Slip) * SE_{Comp} * PE$$

5.3.5 Location of cattle slurry, grass silage, and potential biomethane injection points

The location of the resource associated with cattle slurry and grass silage was taken to be the centroid of EDs in which each resource is found. The locations of 42 potential injection points on the gas transmission system were identified following discussions with GNI; locations were digitised into a GIS using QGIS (Figure 5-1).

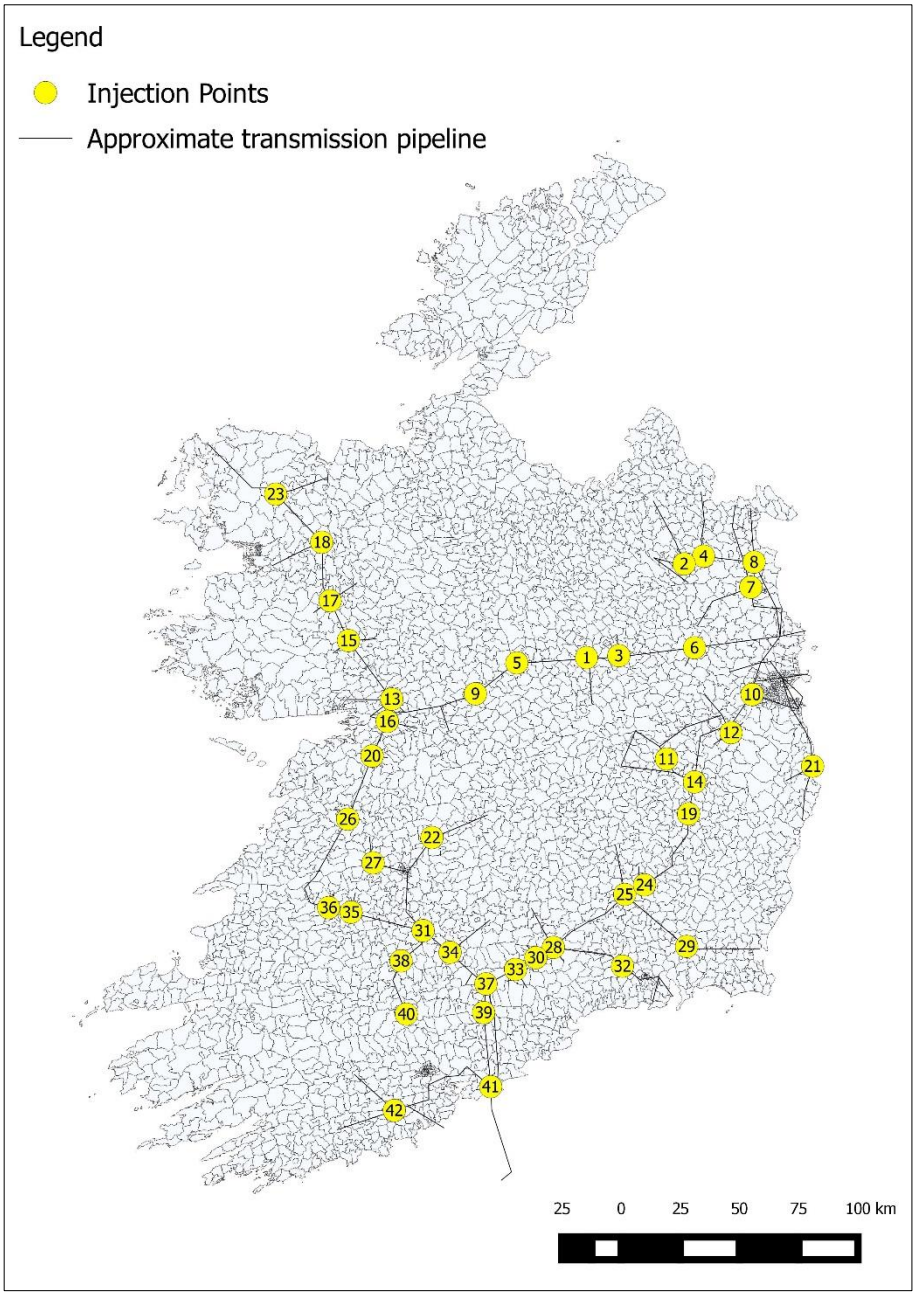


Figure 5-1 Map of gas network and potential biomethane injection points

The injection points correspond to above ground installations (AGIs) on the gas transmission network, as they are seen to be the least cost connection points on the transmission network (connection to an existing AGI is less costly than creating a new transmission pipeline connection) with the easiest access. These AGI locations are nodes on the gas network where gas pressure is reduced from transmission pressures of approximately 70 bar to below 16 bar for onward delivery to distribution networks which typically operate at 4 bar. The network at these

locations has sufficient capacity for additional gas flow so that there should be no availability constraints even in low summer time flow. A large number of potential biomethane injection facilities could be located on the distribution network. However, a more detailed analysis of gas flow and pressure profiles would be required for each potential site, which is beyond the scope of this study.

The Euclidian distance from the centroid of each ED to the potential injection points was calculated using QGIS, these distances were then multiplied by a tortuosity factor of √2 to account for the winding of roads in Ireland (Smyth et al. 2011), yielding d_i^{GS} and d_j^{CS}, the distance from each ED to each injection point for grass silage and cattle slurry respectively.

5.3.6 Transportation cost

The specific energy consumption of heavy goods vehicles (used to transport feedstock to potential biomethane facilities) was found to be 2.66MJ.tkm^{-1} (based on a total energy consumption of 24.3PJ and total tonne kilometres of 9,183Mtkm in 2013 (Dineen et al. 2014)). This specific energy consumption is equivalent to 0.074L_{diesel}.tkm^{-1} (36MJ.L_{diesel}^{-1}), which at an average diesel price of 1.51€.L^{-1} diesel for 2013 (Dineen et al. 2014) equated to a specific transportation cost (*STC*) of 0.11€.tkm^{-1}.

It was assumed that an equal mass of digestate was returned to each ED from which feedstock is sourced (Berglund & Börjesson 2006) to be used as a bio-fertiliser by farmers. This ensures that farmers are not deprived of the fertiliser value from the cattle slurry they supplied to the anaerobic digestion facility. The cost of sourcing feedstock and digestate return was solely borne by the operator of the biomethane production facility.

The maximum transportation distance of cattle slurry and grass silage was exogenously specified in this work as 40km to encapsulate the maximum collection radius of feedstock in the literature (Bojesen et al. 2014; Dagnall 1995). The total annual transportation cost (*TTC*) incurred by the biomethane facility in sourcing

grass silage from a number of EDs (N^{GS}) and cattle slurry from a number of EDs (N^{CS}) can be calculated according to Equation 5-29.

Equation 5-29 Annual feedstock transportation cost (TTC) of a biomethane facility:

$$TTC = \sum_{i=1}^{N^{GS}} m_i^{GS^*} * d_i^{GS^*} * STC * 2 + \sum_{j=1}^{N^{CS}} m_j^{CS^*} * d_j^{CS^*} * STC * 2$$

5.3.7 Feedstock cost

It was assumed that the cost of cattle slurry (FC_{CS}) was zero (Clancy et al. 2011; Browne et al. 2011). Currently cattle slurry is spread on agricultural land as a fertiliser; as digestate will be returned to farmers who provide cattle slurry for the biomethane plant they do not need to be reimbursed for supplying slurry. The cost of grass silage can have a significant impact on the final cost of biomethane (McEniry et al. 2011). The silage prices (FC_{GS}) assessed in this work were 19€.t_{wwt}^{-1}, 33€.t_{wwt}^{-1}, and 47€.t_{wwt}^{-1} (McEniry et al. 2011) to determine the impact of price on resource utilisation, plant profitability, optimal location, and feedstock sources. The annual feedstock cost of the plant (*TFC*) was found using Equation 5-30.

Equation 5-30 Annual feedstock cost (TFC):

$$TFC = T^{GS^*} * FC_{GS} + T^{CS^*} * FC_{CS}$$

5.3.8 Revenue from the sale of gas and monetisation of incentives

5.3.8.1 Revenue from the market price of natural gas

The biomethane produced is to be injected into the natural gas network, thus owners can receive a payment (P_{CH4}) equal to the market price of natural gas, taken to be 20€.MWh^{-1} held constant for the entire lifetime of the project (a real discount rate was used in this analysis, thus inflation was ignored). This was similar to the mean (21.2€.MWh^{-1}) and median (22.2€.MWh^{-1}) values of UK national balancing point market prices from January 2008 to December 2015 (data sourced from GNI).

The projected price of natural gas ranges from 34€.MWh^{-1} to 37€.MWh^{-1} in 2035 according to the International Energy Agency World Energy Outlook (International Energy Agency 2013). As such the price of gas assumed in this work is seen to be a conservative estimate.

5.3.8.2 Financial incentives for use as a transport fuel

Financial incentives for the produced biomethane depend on the end use. If biomethane is used as a transport fuel, a cubic meter is potentially eligible to receive three biofuel obligation certificates (BOCs) under the biofuel obligation scheme (BOS) (Byrne Ó'Cléirigh & LMH Casey McGrath 2015). These certificates can be traded between transport fuel suppliers and vary in price from 0.13-0.36 €.$L_{biofuel\ equivalent}^{-1}$ (Ahern et al. 2015), equivalent to 38-106€.MWh^{-1} of biomethane.

5.3.8.3 Potential incentive for use as a source of renewable heat

Biomethane could also be used as a source of renewable heat by natural gas users in the residential, commercial, or industrial sectors. In Ireland, there is currently no incentive available for the use of biomethane as a source of renewable heat. In the absence of such an incentive biomethane could be compared to an alternative source of renewable heat. In this work wood chips were used as a comparison.

The levelized cost of energy (LCOE) of sourcing heat from wood chips was calculated using data obtained from the Sustainable Energy Authority of Ireland (SEAI) which detailed the typical energy consumption of heat consumers, as well as the efficiency, capacity factor, CAPEX, OPEX and fuel costs of biomass boiler systems (Clancy 2015). The LCOE of providing the same thermal demand from natural gas was also calculated. The input data for the LCOE calculation are shown in Table 5-1. The calculations of LCOE for a biomass boiler, a new natural gas boiler, and an existing natural gas boiler are outlined in Box 5-1, Box 5-2, and Box 5-3 respectively.

Table 5-1 Input data for LCOE calculation of thermal energy from wood chips

Boiler type	Thermal Demand ($MWh.a^{-1}$)	Efficiency (%)	Capacity Factor (%)	CAPEX ($€.kW^{-1}$)	OPEX ($€.kW^{-1}$)	Fuel Cost ($c.kWh^{-1}$)	Discount Rate	Life	Contingency cost (€)
Industrial (wood chips)	14,919	81	68	425	35.00	3.97	0.12	15	12,743.00
Natural Gas (New)	14,919	90	68	65	0.50	4.33	0.12	15	1,840.00
Natural Gas (Existing)	14,919	90	68	0	0.50	4.33	0.12	15	1,840.00

Thermal demand: 14,918.92 $MWh_{th}.a^{-1}$
Capacity factor: 68%
Boiler capacity: (14,918.92/8760)/(0.68)= 2.5045MW
Efficiency: 81%
Primary energy input: (14,918.92)/(0.81)= 18,418.42$MWh.a^{-1}$
CAPEX: 2.5*425*1,000= €1,064,412.5
OPEX: 2.5*35*1000= €87,658.17.a^{-1}
Fuel cost: 18,418.42*1000*(3.97/100)= €730,981.03.a^{-1}
Discount rate: 12%
Discount Factor: = $1/(1+0.12)^t$
Contingency cost: €12,743

Year (t)	Cost (€)	Discount Factor	Present value of cost (€) (Cost in year *t* multiplied by discount factor for year *t*)	Energy production adjusted for economic value (MWh) (Energy in year *t* multiplied by discount factor for year *t*)
0	1,077,163.66 (CAPEX + contingency)	1	1,077,163.66	0
1	818,839.21 (OPEX + fuel cost)	0.892857143	730,927.86	13,320.46
2	818,839.21	0.797193878	652,614.16	11,893.27
3	818,839.21	0.711780248	582,691.22	10,618.99
4	818,839.21	0.635518078	520,260.02	9,481.24
5	818,839.21	0.567426856	464,517.87	8,465.40
6	818,839.21	0.506631121	414,748.10	7,558.39
7	818,839.21	0.452349215	370,310.80	6,748.56
8	818,839.21	0.403883228	330,634.65	6,025.50
9	818,839.21	0.360610025	295,209.50	5,379.91
10	818,839.21	0.321973237	263,579.91	4,803.49
11	818,839.21	0.287476104	235,339.21	4,288.83
12	818,839.21	0.256675093	210,124.29	3,829.32
13	818,839.21	0.22917419	187,610.98	3,419.03
14	818,839.21	0.204619813	167,509.80	3,052.71
15	818,839.21	0.182696261	149,562.32	2,725.63
SUM			6,652,804.36	101,610.74

LCOE: 6,652,804/101,611= 65.47 €.MWh_{th}^{-1}

Box 5-1 Calculation of LCOE for a biomass boiler system

Thermal demand: 14,918.92 $MWh_{th}.a^{-1}$
Capacity factor: 68%
Boiler capacity: (14,918.92/8760)/(0.68)= 2.5045MW
Efficiency: 90%
Primary energy input: (14,918.92)/(0.90)= 16,576.58$MWh.a^{-1}$
CAPEX: 2.5*65*1,000= €162,793
OPEX: 2.5*0.5*1000= €1,252.26.a^{-1}
Fuel cost: 16,576.58*1000*(4.33/100)= €717,765.a^{-1}
Discount rate: 12%
Discount Factor: = $1/(1+0.12)^t$
Contingency cost: €1,840

Year (t)	Cost (€)	Discount Factor	Present value of cost (€) (Cost in year *t* multiplied by discount factor for year *t*)	Energy production adjusted for economic value (MWh) (Energy in year *t* multiplied by discount factor for year *t*)
0	164,633 (CAPEX + contingency)	1	164,633.7483	0
1	719,018 (OPEX + fuel cost)	0.892857143	641,980.4262	13,320.46429
2	719,018	0.797193878	573,196.8091	11,893.27168
3	719,018	0.711780248	511,782.8653	10,618.99257
4	719,018	0.635518078	456,948.9869	9,481.24337
5	719,018	0.567426856	407,990.1669	8,465.395866
6	719,018	0.506631121	364,276.9347	7,558.389166
7	719,018	0.452349215	325,247.2631	6,748.561756
8	719,018	0.403883228	290,399.3421	6,025.501568
9	719,018	0.360610025	259,285.1268	5,379.912114
10	719,018	0.321973237	231,504.5775	4,803.492959
11	719,018	0.287476104	206,700.5157	4,288.832999
12	719,018	0.256675093	184,554.0318	3,829.315178
13	719,018	0.22917419	164,780.3856	3,419.031409
14	719,018	0.204619813	147,125.3443	3,052.706615
15	719,018	0.182696261	131,361.9145	2,725.630906
SUM			5,061,768.44	101,610.74

LCOE: 5,061,768/101,611= 49.82 €.MWh_{th}^{-1}

Box 5-2 Calculation of LCOE for a new natural gas boiler

Thermal demand: 14,918.92 $MWh_{th}.a^{-1}$
Capacity factor: 68%
Boiler capacity: (14,918.92/8760)/(0.68)= 2.5045MW
Efficiency: 90%
Primary energy input: (14,918.92)/(0.90)= 16,576.58$MWh.a^{-1}$
CAPEX: None as boiler is already in place
OPEX: 2.5*0.5*1000= €1,252.26.a^{-1}
Fuel cost: 16,576.58*1000*(4.33/100)= €717,765.a^{-1}
Discount rate: 12%
Discount Factor: = $1/(1+0.12)^t$
Contingency cost: €1,840

Year (t)	Cost (€)	Discount Factor	Present value of cost (€) (Cost in year *t* multiplied by discount factor for year *t*)	Energy production adjusted for economic value (MWh) (Energy in year *t* multiplied by discount factor for year *t*)
0	1,840 (CAPEX + contingency)	1	1840	0
1	719,018 (OPEX + fuel cost)	0.892857143	641,980.4262	13,320.46429
2	719,018	0.797193878	573,196.8091	11,893.27168
3	719,018	0.711780248	511,782.8653	10,618.99257
4	719,018	0.635518078	456,948.9869	9,481.24337
5	719,018	0.567426856	407,990.1669	8,465.395866
6	719,018	0.506631121	364,276.9347	7,558.389166
7	719,018	0.452349215	325,247.2631	6,748.561756
8	719,018	0.403883228	290,399.3421	6,025.501568
9	719,018	0.360610025	259,285.1268	5,379.912114
10	719,018	0.321973237	231,504.5775	4,803.492959
11	719,018	0.287476104	206,700.5157	4,288.832999
12	719,018	0.256675093	184,554.0318	3,829.315178
13	719,018	0.22917419	164,780.3856	3,419.031409
14	719,018	0.204619813	147,125.3443	3,052.706615
15	719,018	0.182696261	131,361.9145	2,725.630906
SUM			4,898,974.691	101,610.74

LCOE: 1898975/101,611= 48.21 €.MWh_{th}^{-1}

Box 5-3 Calculation of LCOE for an existing natural gas boiler

The price of gas (€.MWh^{-1}), which the customer would pay in order to achieve a LCOE equal to that of a biomass system, was calculated for the two natural gas boiler cases (a new boiler, and an existing boiler).

The difference between this new gas price and the market price of gas was the maximum potential premium, which could be charged per kWh of biomethane consumed by an end user (a higher premium would result in biomethane having a higher LCOE than biomass and thus result in customers choosing biomass from a purely financial perspective). For the above example the maximum potential premium which could be charged above the price of natural gas to the end user was 14.1€.MWh^{-1} for a new gas boiler, and 15.5€.MWh^{-1} for an existing natural gas

boiler. The calculations were repeated for biomass boilers at a commercial and domestic scale.

The results of the calculations showed that the maximum premium per MWh of biomethane ranged from ca. 14€.MWh^{-1} to ca. 106€.MWh^{-1} similar to the potential value of the BOCs associated with biomethane in transport. The additional values per MWh of biomethane (I_{CH4}) produced by biomethane plants assessed were; 20€.MWh^{-1}, 60€.MWh^{-1}, and 100€.MWh^{-1} on top of the market price of gas to determine their impact on total biomethane production, resource use, and facility location.

5.3.8.4 Net biomethane production and total annual revenue

Net biomethane production in terms of MWh.a^{-1} (E_{CH4}) from a facility was calculated using an energy content of (e_{CH4}) 37.78MJ.Nm^{-3} (Smyth et al. 2009) as per Equation 5-31.

Equation 5-31 Net biomethane production of a facility (E_{CH4}):

$$E_{CH_4} = \left(T^{GS^*} * VS_{GS} * SMY_{VSR} + T^{CS^*} * VS_{CS} * SMY_{VSR}\right) * (1 - CH_4Slip) * \frac{e_{CH_4}}{3{,}600}$$

The total revenue (*Rev*) generated from the sale of biomethane and the incentives received was found using Equation 5-32

Equation 5-32 Annual revenue from the sale of biomethane (Rev):

$$Rev = E_{CH_4} * \left(P_{CH_4} + I_{CH_4}\right)$$

5.3.9 Sequential optimisation model

5.3.9.1 Model overview

The goal of the model was to maximise the net present value (NPV) of a plant to be built at a potential location by selecting the optimal source locations of grass silage and cattle slurry. NPV is the present value of the sum of the total incoming and outgoing cash flows of the plant as per Equation 5-33, (Short et al. 1995). The cash flow of the plant in year *t* is C_t, the real discount rate (*r*) used in this work was 8%, while the lifetime of the facility (*L*) was taken to be 20 years. The impact of discount rate on NPV was not assessed in this work, a discount rate of 8% was used as it is a conservative estimate, compared to a discount rate of 6.88% used for landfill gas applications in Ireland (Sustainable Energy Ireland 2004). An increased discount rate would result in lower NPV and a higher LCOE.

Equation 5-33 Net present value (NPV)

$$NPV\ (€) = \sum_{t=0}^{L} \frac{C_t}{(1+r)^t}$$

Figure 5-2 illustrates the process of determining the NPV of an individual plant.

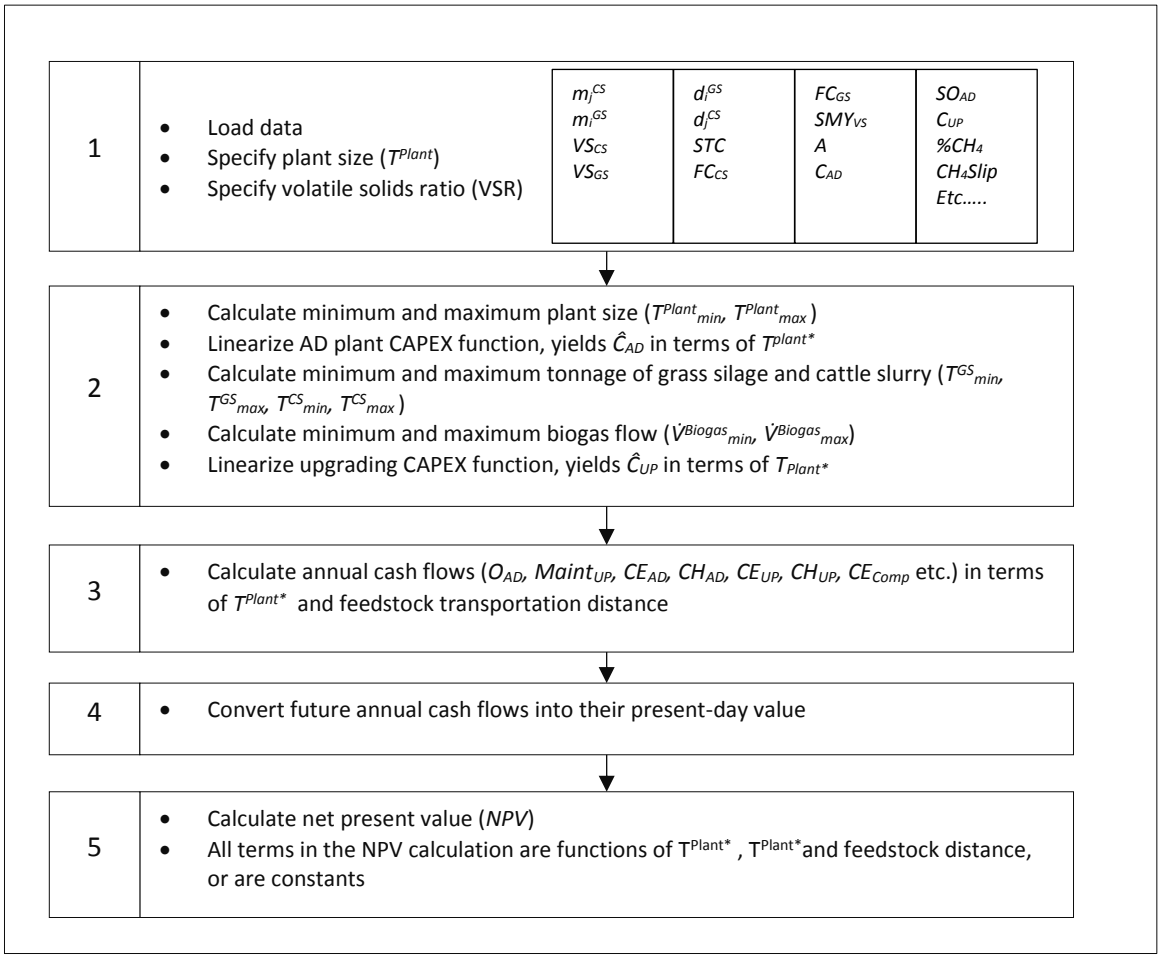


Figure 5-2 Flowchart of NPV calculation set up

5.3.9.2 Formulation of optimisation model for a single plant

A detailed example of the formulation of the optimisation model for a single plant follows.

Goal: Maximise the NPV of a plant by selecting the optimum sites from which to source grass silage and the optimum sites from which to source cattle slurry.

For a given plant size T^{plant} and accuracy (A), and for a given volatile solids ratio VSR find minimum and maximum allowable plant size;

Equation 5-34 Minimum allowable tonnage for example plant

$$Minimum\ plant\ tonnage\ \left(T_{min}^{plant}\right) = T^{plant} * (1 - A)$$

Equation 5-35 maximum allowable tonnage for an example plant

$$Maximum\ plant\ tonnage\ \left(T_{max}^{plant}\right) = T^{plant} * (1 + A)$$

Knowing the VS content of grass silage and cattle slurry (VS_{GS}, VS_{CS}) one can find minimum and maximum allowable mass of each feedstock to be accepted at the plant;

Equation 5-36 Minimum allowable tonnage of cattle slurry for an example plant

$$Minimum\ cattle\ slurry\ tonnage\ \left(T_{\min}^{CS}\right) = \frac{\left(T_{min}^{plant} * VS_{GS}\right)}{(VSR * VS_{CS} + VS_{GS})}$$

Equation 5-37 Minimum allowable tonnage of grass silage for an example plant

$$Minimum\ grass\ silage\ tonnage\ \left(T_{min}^{GS}\right) = T_{min}^{plant} - T_{min}^{CS}$$

Equation 5-38 Maximum allowable tonnage of cattle slurry for an example plant

$$Maximum\ cattle\ slurry\ tonnage\ (T_{max}^{CS}) = \frac{\left(T_{max}^{plant} * VS_{GS}\right)}{(VSR * VS_{CS} + VS_{GS})}$$

Equation 5-39 Maximum allowable tonnage of grass silage for an example plant

$$Maximum\ grass\ silage\ tonnage\ (T_{max}^{GS}) = T_{max}^{plant} - T_{max}^{CS}$$

CAPEX of the AD system (C_{AD}) as a function of feedstock mass accepted per year is calculated as follows;

Equation 5-40 Specific CAPEX of AD system for an example plant

$$c_{AD}\ (€.t_{wwt}.a^{-1}) = 554.89 * feedstock\ mass^{-0.159}$$

Equation 5-41 CAPEX of AD system for an example plant

$$C_{AD}(€) = 554.89 * feedstock\ mass^{0.841}$$

To use this cost function in the optimisation model it was approximated by a linear equation at the desired plant size (T^{plant}).

Using T_{min}^{plant} and T_{max}^{plant} one can linearize the AD CAPEX curve between these points.

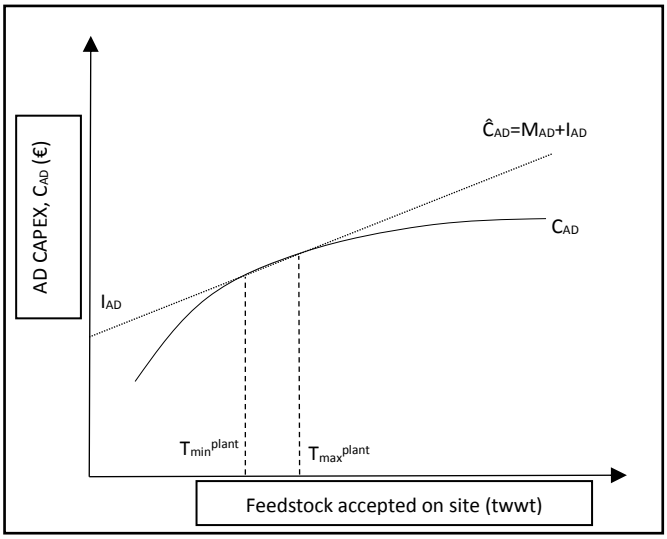


Figure 5-3 Linearization of AD CAPEX

Equation 5-42 Slope of linearized AD system CAPEX line for an example plant

$$Slope\ of\ AD\ CAPEX\ (M_{AD}) = \frac{\left(554.89 * {T_{max}^{plant}}^{0.841} - 554.89 * {T_{min}^{plant}}^{0.841}\right)}{T_{max}^{plant} - T_{min}^{plant}}$$

Equation 5-43 Intercept for linearized AD system CAPEX for an example plant

$$I_{AD} = \left(554.89 * {T_{max}^{plant}}^{0.841} - M_{AD} * T_{max}^{plant}\right)$$

Equation 5-44 Linearized (Approximated) AD system CAPEX equation for an example plant

$$Approximate\ AD\ CAPEX\ \left(\hat{C}_{AD}\right) = M_{AD} * T^{plant^*} + I_{AD}$$

Annual operating cost of the AD facility (O_{AD}) was calculated using a specific operating cost (SO_{AD}) (€.t_{wwt}^{-1}) as follows;

Equation 5-45 Annual AD system operating cost for an example plant

$$O_{AD} = SO_{AD} * T^{Plant^*}$$

T^{Plant*} being the total mass of feedstock accepted by a plant in the model

CAPEX of the amine upgrading system was calculated as follows;

Equation 5-46 Specific CAPEX for amine upgrading system for an example plant

$$c_{UP}\ \left(€.Nm_{Biogas}^{3}.hour^{-1}\right) = 181613 * (\dot{V}_{Biogas})^{-0.627}$$

Equation 5-47 CAPEX for an amine upgrading system for an example plant

$$C_{UP}\ (€) = 181613 * (\dot{V}_{Biogas})^{0.373}$$

The hourly flow rate of biogas to the upgrading unit ($\dot{V}_{Biogas}^{*}$) in the optimisation model was calculated using a CH_4 content ($\%CH_4$) between 53%$_{vol}$ and 55%$_{vol}$ depending on the *VSR*, the specific methane yield of the feedstock depending on the VSR (SMY_{VSR}) and a total *H* operational hours per annum corresponding to an annual availability of 98%.

Equation 5-48 Hourly flowrate of biogas for an example plant

$$\dot{V^{Biogas^*}} = \frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS}\right) * SMY_{VSR}\right)}{H * \%CH_4}$$

Calculation of the minimum and maximum flows of biogas is possible using T^{GS}_{min}, T^{GS}_{max}, T^{CS}_{min}, T^{CS}_{max};

Equation 5-49 Minimum biogas production for an example plant

$$Minimum\ produciton\ of\ biogas\ \left(V_{min}^{Biogas}\right) = \frac{\left(\left(T_{min}^{GS} * VS_{GS} + T_{min}^{CS} * VS_{CS}\right) * SMY_{VSR}\right)}{H * \%CH_4}$$

Equation 5-50 Maximum biogas production for an example plant

$$Maximum\ produciton\ of\ biogas\ \left(V_{max}^{Biogas}\right) = \frac{\left(\left(T_{msx}^{GS} * VS_{GS} + T_{max}^{CS} * VS_{CS}\right) * SMY_{VSR}\right)}{H * \%CH_4}$$

The minimum and maximum production of biogas can be used to linearize them upgrading CAPEX function.

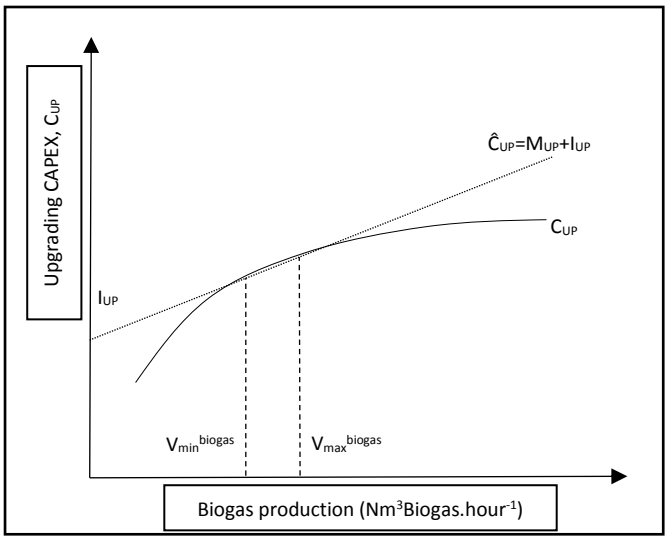


Figure 5-5 Linearization of upgrading system CAPEX

The slope of linearized upgrading CAPEX function (M_{UP}) was calculated;

Equation 5-51 Slope of linearized upgrading system CAPEX for an example plant

$$M_{up} = \frac{181613 * \left(\left(V_{max}^{Bi\dot{o}gas}\right)^{0.373} - \left(V_{min}^{Bi\dot{o}gas}\right)^{0.373}\right)}{V_{max}^{Bi\dot{o}gas} - V_{min}^{Bi\dot{o}gas}}$$

The intercept term in linearized upgrading CAPEX function (I_{UP}) was calculated;

Equation 5-52 Intercept for linearized upgrading system CAPEX for an example plant

$$I_{UP} = \left(181613 * \left(V_{max}^{Bi\dot{o}gas}\right)^{0.373} - M_{UP} * V_{max}^{Bi\dot{o}gas}\right)$$

The approximated upgrading system CAPEX can then be calculated accordingly;

Equation 5-53 Linearized (Approximated) upgrading system CAPEX for an example plant

$$Approximate\ Upgrading\ CAPEX\ \left(\hat{C}_{UP}\right) = M_{UP} * \left(V^{Bi\dot{o}gas^*}\right) + I_{UP}$$

The annual maintenance cost of upgrading system was also know ($Maint_{UP}$)

The cost of connection to the gas network was also know ($C_{connect}$)

Specific electrical energy consumption of the plant in terms of feedstock mass accepted was known (SE_{AD}).

Thermal energy consumption of the AD plant (H_{AD}) was taken to be the energy required to heat incoming cattle slurry from 10 degrees Celsius (t_{low}) to 70 degrees Celsius (t_{Hi}) based on the mass of cattle slurry accepted in the optimisation model (T^{CS*}), the specific heat capacity of water, and the moisture content of the cattle slurry (MC_{CS}).

Equation 5-54 Thermal energy consumption of the AS system for an example plant

$$H_{AD} = \left(T^{CS^*} * 1{,}000 * MC_{CS} * \frac{C_p H_2 O}{3.6} * (t_{Hi} - t_{Low}) \right)$$

Specific electrical consumption of the upgrading facility (SE_{UP}) was known per unit m^3 of biogas processed.
Specific thermal energy consumption of the upgrading facility (SH_{UP}) was also know per unit m^3 of biogas processed.

Electricity used in the AD facility and in the upgrading system was sourced from the electricity network at a known electricity price (PE).
The thermal demand of the AD system and the upgrading system was met using natural gas, at a known gas price (PG), and a gas boiler of efficiency η_{Boiler}.

Annual electricity expense (CE_{AD}) and natural gas expense (CH_{AD}) of the AD facility are found as follows;

Equation 5-55 Annual AD system electricity expense for an example plant

$$CE_{AD} = T^{Plant^*} * SE_{AD} * PE$$

Equation 5-56 Annual AD system natural gas expense for an example plant

$$CH_{AD} = \frac{H_{AD}}{\eta_{Boiler}} * PG$$

The annual electricity cost of the upgrading system (CE_{UP}), and the annual natural gas cost for supplying heat to the upgrading system (CH_{UP}) were calculated as follows;

Equation 5-57 Annual upgrading system electricity expense for an example plant

$$CE_{UP} = \left(\frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right)}{\%CH_4} \right) * SE_{UP} * PE$$

Equation 5-58 Annual upgrading system natural gas expense for an example plant

$$CH_{UP} = \left(\frac{\left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right)}{\%CH_4} \right) * \frac{SH_{UP}}{\eta_{Boiler}} * PG$$

In which T^{GS^*} is the mass of grass silage accepted by the plant in the optimisation model.

The annual electricity consumption required for biomethane compression was calculated knowing the net annual biomethane production (taking into account methane slip, CH_4Slip) and the specific electrical energy requirement of compression (SE_{Comp}).

Equation 5-59 Annual compressor electricity consumption

$$CE_{Comp} = \left(\left(T^{GS^*} * VS_{GS} + T^{CS^*} * VS_{CS} \right) * SMY_{VSR} \right) * (1 - CH_4Slip) * SE_{Comp} * PE$$

The specific transportation cost (*STC*) of moving feedstock (cost to move 1 tonne 1 kilometre) was known.

Total transportation cost of sourcing grass silage and/or cattle slurry from a number of EDs, and return digestate to those EDs was found as follows;

Equation 5-60 Annual transportation cost for an example plant

$$TTC = \sum_{i=1}^{N^{GS}} m_i^{GS^*} * d_i^{GS^*} * STC * 2 + \sum_{j=1}^{N^{CS}} m_j^{CS^*} * d_j^{CS^*} * STC * 2$$

In which m_i^{GS*} m_j^{CS*} are the mass of grass silage and cattle slurry at electoral divisions *i* and *j*.
The distance between the plant and the EDs from which grass silage and/or cattle slurry were sourced were d_i^{GS*} and d_j^{CS*} respectively.

Feedstock cost (FC) was calculated under the assumption that cattle slurry was free (FC_{CS}=0€.t_{wwt}^{-1}) of charge, while grass silage had a price (FC_{GS}≥0€.t_{wwt}^{-1}).
Total annual feedstock cost was found as follows;

Equation 5-61 Annual feedstock cost for an example plant

$$TFC = T^{GS^*} * FC_{GS} + T^{CS^*} * FC_{CS}$$

The price at which biomethane was sold by the plant operator was known (P_{CH4}), as was the incentive value available per unit of biomethane produced (I_{CH4}).

Total net energy production by the biomethane plant (E_{CH4}) was found knowing the net biomethane production, and the energy content of a cubic meter of methane (e_{CH4});

Equation 5-62 Total biomethane production of an example plant

$$E_{CH_4} = \left(T^{GS^*} * VS_{GS} * SMY_{VSR} + T^{CS^*} * VS_{CS} * SMY_{VSR}\right) * (1 - CH_4Slip) * \frac{e_{CH_4}}{3{,}600}$$

The total incoming annual revenue (*Rev*) generated from the sale of biomethane and the monetization of incentives was found as follows;

Equation 5-63 Annual revenue for an example plant

$$Rev = E_{CH_4} * \left(P_{CH_4} + I_{CH_4}\right)$$

Net present value (NPV) of the project is calculated according to the following equation;

Equation 5-64 Net present value for an example plant

$$NPV = \sum_{t=0}^{L} \frac{-\hat{C}_{AD_t} - \hat{C}_{UP_t} - C_{Connect_t} - O_{AD_t} - Maint_{UP_t} - CE_{AD_t} - CH_{AD_t} - CE_{UP_t} - CH_{UP_t} - CE_{Comp_t} - TTC_t - TFC_t + Rev_t}{(1+r)^t}$$

The CAPEX of the AD ($\hat{C}_{AD}$), the CAPEX of the upgrading system ($\hat{C}_{UP}$) and the connection cost ($C_{Connect}$) occur at the start of the projects lifetime. The future value of cashflows can be converted to their present value using an annuity factor, herein called a discount factor, *DF* (Short et al. 1995).

Equation 5-65 Discount factor

$$Discount\ factor\ (DF) = \frac{((1+r)^L - 1)}{(r * (1+r)^L)}$$

As such the NPV calculation then becomes;

Equation 5-66 Net present value using discount factor for an example plant

$$\begin{aligned} NPV = &-\hat{C}_{AD_t} - \hat{C}_{UP_t} - C_{Connect_t} \\ &+ \left(Rev_t - O_{AD_t} - Maint_{UP_t} - CE_{AD_t} - CH_{AD_t} - CE_{UP_t} - CH_{UP_t} \right. \\ &\left. - CE_{Comp_t} - TTC_t - TFC_t\right) * DF \end{aligned}$$

Substituting in for terms in the NPV equation and rearranging yields;

Equation 5-67 Expanded net present value calculation for an example plant

$$NPV =$$
$$\left[DF * \left(P_{CH_4} + I_{CH_4}\right) * (1 - CH_4Slip) * VS^{GS} * SMY_{VSR} * \frac{e_{CH_4}}{3600} - DF * \left(2 * STC * d_i + FC^{GS} + SO_{AD} + SE_{AD} * PE + \frac{SE_{UP} * PE * VS^{GS} * SMY_{VSR}}{\%CH_4} + \frac{SH_{UP} * PG * VS^{GS} * SMY_{VSR}}{\%CH_4 * \eta_{Boiler}} + CE_{Comp} * VS^{GS} * SMY_{VSR} * (1 - CH_4Slip) * PE\right) - \left(M_{AD} + \frac{VS^{GS} * SMY_{VSR} * M_{UP}}{H * \%CH_4}\right)\right] * \left(T^{GS^*}\right)$$
$$+ \left[DF * \left(P_{CH_4} + I_{CH_4}\right) * (1 - CH_4Slip) * VS^{CS} * SMY_{VSR} * \frac{e_{CH_4}}{3600} - DF * \left(2 * STC * d_j + FC^{CS} + SO_{AD} + SE_{AD} * PE + \frac{MC^{CS} * \frac{cpH_2O}{3.6} * (t_{Hi} - t_{Low}) * PG}{\eta_{Boiler}} + \frac{SE_{UP} * PE * VS^{CS} * SMY_{VSR}}{\%CH_4} + \frac{SH_{UP} * PG * VS^{CS} * SMY_{VSR}}{\%CH_4 * \eta_{Boiler}} + CE_{Comp} * VS^{CS} * SMY_{VSR} * (1 - CH_4Slip) * PE\right) - \left(M_{AD} + \frac{VS^{CS} * SMY_{VSR} * M_{UP}}{H * \%CH_4}\right)\right] * \left(T^{CS^*}\right) - (I_{AD} + I_{UP} + C_{Connect} + DF * Maint_{UP})$$

To maximise the NPV of a plant, a decision must be made as to whether or not to source feedstock from a given location. The decision variables x_i and y_j correspond to sourcing grass silage, and cattle slurry from EDs *i* and *j*.

The total tonnage of grass silage (T^{GS^*}) and cattle slurry (T^{CS^*}) accepted by a plant was found as follows

Equation 5-68 Tonnage of grass silage accepted at an example plant

$$T^{GS^*} = \sum_{i=1}^{N^{GS}} m_i^{GS^*} * x_i$$

Equation 5-69 Tonnage of cattle slurry accepted at an example plant

$$T^{CS^*} = \sum_{j=1}^{N^{CS}} m_j^{CS^*} * y_j$$

Substituting in for T^{GS*} and T^{CS*} yields;

Equation 5-70 Expanded net present value calculation considering feedstock sources for an example plant

$$NPV =$$
$$\left[DF * \left(P_{CH_4} + I_{CH_4}\right) * (1 - CH_4Slip) * VS^{GS} * SMY_{VSR} * \frac{e_{CH_4}}{3600} - DF * \left(2 * STC * d_i + \right.\right.$$
$$FC^{GS} + SO_{AD} + SE_{AD} * PE + \frac{SE_{UP} * PE * VS^{GS} * SMY_{VSR}}{\%CH_4} + \frac{SH_{UP} * PG * VS^{GS} * SMY_{VSR}}{\%CH_4 * \eta_{Boiler}} + CE_{Comp} *$$
$$\left.\left.VS^{GS} * SMY_{VSR} * (1 - CH_4Slip) * PE\right) - \left(M_{AD} + \frac{VS^{GS} * SMY_{VSR} * M_{UP}}{H * \%CH_4}\right)\right] * \left(\sum_{i=1}^{N^{GS}} x_i * m_i^{GS^*}\right)$$
$$+ \left[DF * \left(P_{CH_4} + I_{CH_4}\right) * (1 - CH_4Slip) * VS^{CS} * SMY_{VSR} * \frac{e_{CH_4}}{3600} - DF * \left(2 * STC * d_j + \right.\right.$$
$$FC^{CS} + SO_{AD} + SE_{AD} * PE + \frac{MC^{CS} * \frac{cpH_2O}{3.6} * (t_{Hi} - t_{Low}) * PG}{\eta_{Boiler}} + \frac{SE_{UP} * PE * VS^{CS} * SMY_{VSR}}{\%CH_4} +$$
$$\left.\frac{SH_{UP} * PG * VS^{CS} * SMY_{VSR}}{\%CH_4 * \eta_{Boiler}} + CE_{Comp} * VS^{CS} * SMY_{VSR} * (1 - CH_4Slip) * PE\right) -$$
$$\left.\left(M_{AD} + \frac{VS^{CS} * SMY_{VSR} * M_{UP}}{H * \%CH_4}\right)\right] * \left(\sum_{j=1}^{N^{CS}} y_j * m_j^{CS^*}\right) - (I_{AD} + I_{UP} + C_{Connect} + DF * Maint_{UP})$$

Subject to the constraints;

Equation 5-71 Total tonnage of feedstock accepted must be less than maximum allowable tonnage for an example plant

$$\sum_{i=1}^{N_{GS}} x_i * m_i + \sum_{j=1}^{N_{CS}} y_j * m_j \leq T_{max}^{plant}$$

Equation 5-72 Total tonnage of feedstock must be greater than the minimum feedstock allowed for an example plant

$$\sum_{i=1}^{N_{GS}} x_i * m_i + \sum_{j=1}^{N_{CS}} y_j * m_j \geq T_{min}^{plant}$$

Equation 5-73 Tonnage of grass silage accepted must be greater than minimum allowed tonnage of grass silage for an example plant

$$\sum_{i=1}^{N_{GS}} x_i * m_i \geq T_{min}^{GS}$$

Equation 5-74 Tonnage of grass silage accepted must be less than maximum allowed tonnage of grass silage for an example plant

$$\sum_{i=1}^{N_{GS}} x_i * m_i \leq T_{mmax}^{GS}$$

Equation 5-75 Tonnage of cattle slurry accepted must be greater than minimum allowed tonnage of cattle slurry for an example plant

$$\sum_{j=1}^{N_{CS}} y_j * m_j \geq T_{min}^{CS}$$

Equation 5-76 Tonnage of cattle slurry accepted must be less than maximum allowed tonnage of cattle slurry for an example plant

$$\sum_{j=1}^{N_{CS}} y_j * m_j \leq T_{max}^{CS}$$

With the decision variables x_i and y_j being binary;

Equation 5-77 Binary constraints on decision variables

$$x_i, y_j \in \{0,1\} \forall i, j$$

In this model an all or nothing allocation was used, as such the decision variables were binary. The optimisation model determines which EDs to source grass silage and cattle slurry from, to maximise NPV of a given plant.

5.3.9.3 Sequential optimisation

At the start of the process, all possible locations for biomethane injection points are available as well as all possible sources of cattle slurry and all possible sources of grass silage. The model determines the optimal locations from which to source feedstock for all of the possible biomethane injection points individually. The location with the highest NPV is selected and a plant is "built", this location is now no longer available as a possible site for future biomethane plants. The sources of

feedstock supplying this “built” plant are now unavailable for subsequent plants. The model then re-runs and determines the optimal sources of feedstock for the remaining possible biomethane injection points to maximise their NPV, it then selects the location with the highest NPV and builds this plant, the sources of feedstock supplying this plant are now unavailable for subsequent plants. The process is repeated until all possible biomethane injection points have been assessed.

Figure 4-3 illustrates the process in which the optimal sites for plants were identified sequentially, the overall structure of the model is similar to that of the optimisation model developed in Chapter 4, however the calculations conducted are considerably different. The model was implemented in MATLAB and used the Gurobi solver. The MATLAB code for the model can be found in Appendix B.

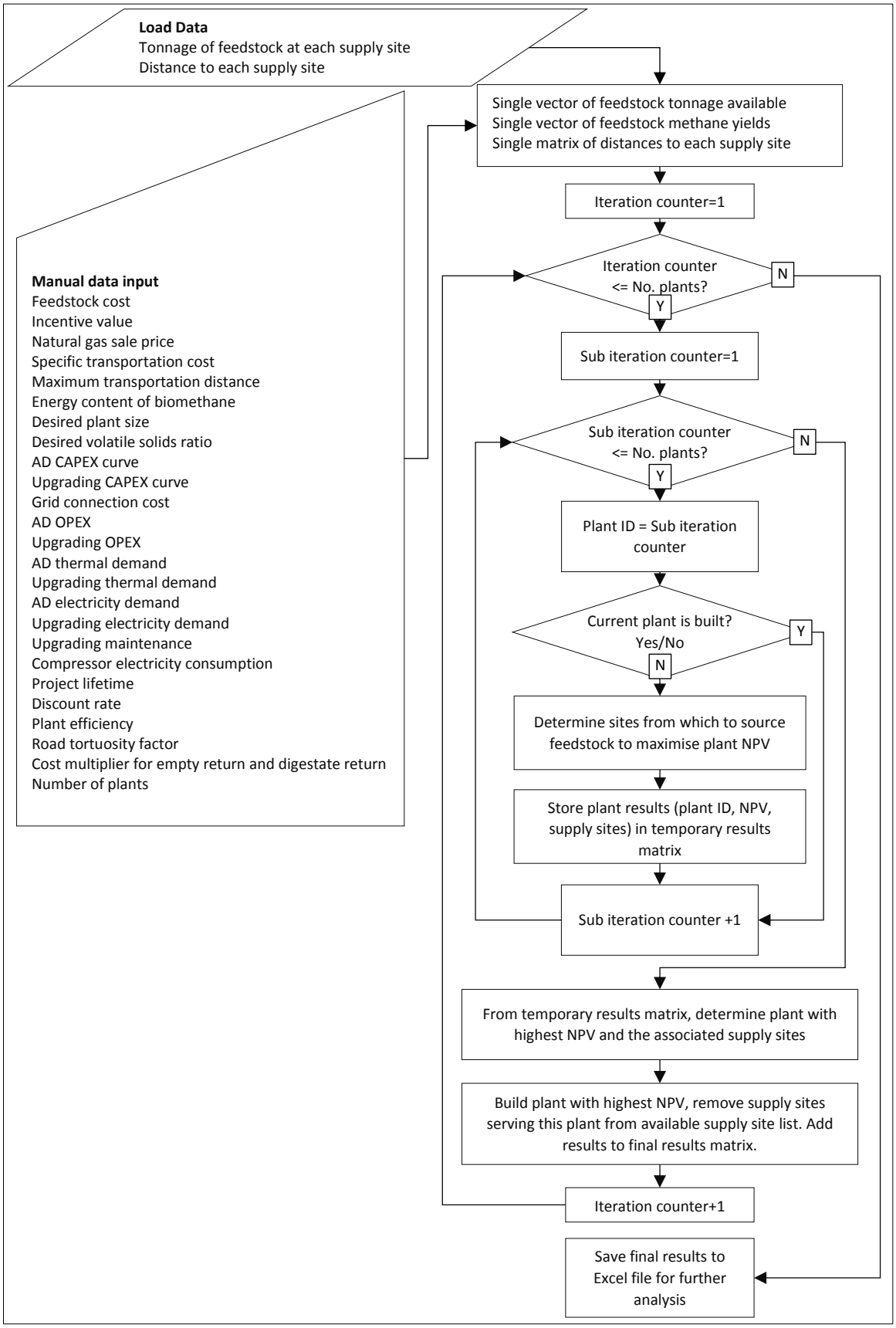


Figure 5-6 Flow chart of optimisation model

5.3.10 Model outputs

5.3.10.1 Main results

The results of the optimisation model were the potential plant locations ordered by decreasing NPV (the first plants have the highest NPV), and the source locations of feedstock to be supplied to these potential plants. Using this information, a GIS can be developed in which the regions which supply potential sites with feedstock, can be visualised. The model also outputted the total tonnage of grass silage and cattle slurry accepted by each plant, the net energy production of each plant, along with a full breakdown of capital costs and annual costs.

The model calculated the LCOE of each facility to be built. The LCOE is the present value of the sum of the outgoing cash flows of a plant (C_t^{out}), divided by the sum of the lifetime energy production of the plant (adjusted for its economic value). The LCOE represents the revenue per unit energy produced by the plant required for the plant to have an NPV of zero. The LCOE was calculated as per Equation 5-78 (Short et al. 1995).

Equation 5-78 Calculation of levelized cost of energy of a plant

$$LCOE = \frac{\left(\sum_{t=0}^{L} \frac{C_t^{out}}{(1+r)^t}\right)}{\sum_{t=0}^{L} \frac{E_t^{production}}{(1+r)^t}}$$

In Equation 5-78, $E_t^{production}$ is the net energy production of the plant in year *t.* Using the LCOE, marginal production cost curves were created in which the total cumulative biomethane production at a given cost of energy for a range of grass silage prices, plant sizes, and VSR could be visualised.

A total of 81 scenarios were investigated comprising of each combination of grass silage price (19 €.t_{wwt}^{-1}, 33€.t_{wwt}^{-1}, 57€.t_{wwt}^{-1}), facility size (50,000t_{wwt}.a^{-1}, 75,000t_{wwt}.a^{-1}, 100,000t_{wwt}.a^{-1}), VSR (2, 4, 6), and additional gas revenue (premium level) (20€.MWh^{-1}, 60€.MWh^{-1}, 100€.MWh^{-1}).

5.3.10.2 High Level CO_2 intensity of biomethane

A high level assessment of the carbon intensity of biomethane produced by each biomethane facility was carried out in a manner similar to that utilised by the Joint Research Centre (JRC) (Guintoli et al. 2014) and by Korres et al. (Korres et al. 2010) for the median scenario (75,000$t_{wwt}.a^{-1}$, VSR 4, incentive of 60€.MWh^{-1}, silage price of 33€.t_{wwt}^{-1}). The production of biomethane was divided into four main processes; cultivation of the grass silage (with land application of digestate), transportation of the grass silage and cattle slurry, the anaerobic digestion process, and upgrading of the produced biogas to biomethane. The functional unit used in this work was a kilowatt hour (kWh_{th}) of biomethane leaving the plant.

The CO_2eq emissions arising in the production of grass silage were taken from Korres et al. (Korres et al. 2010) on a $kgCO_2.ha^{-1}.a^{-1}$ basis and were converted to a $t_{wwt}.a^{-1}$ basis assuming a silage yield of 12tDM.$ha^{-1}.a^{-1}$ (Korres et al. 2010) and a dry solids content of 29.3%$_{wwt}$. The $gCO_2eq.kWh_{th}^{-1}$ of biomethane was found by multiplication of the grass silage production emissions ($gCO_2eq.t_{wwt}^{-1}$) by the total mass of silage accepted by each plant, and division by the net biomethane production of the plant in kWh_{th}. The CO_2 emissions in the production of cattle slurry are not counted, as it was a residue with no specific production step (Guintoli et al. 2014).

The CO_2eq emissions associated with the transportation of feedstock to the biomethane plants was found as the product of: the tonnage of feedstock sourced; the distance between each source ED and the biomethane plant; the specific energy consumption of transportation (2.66MJ.tkm^{-1}); and a CO_2 intensity of diesel of $93.95gCO_2eq.MJ^{-1}$ (Neeft & Ludwiczek 2016). The total CO_2eq emissions from the transportation of feedstock were divided by the net methane production of each plant.

The CO_2eq emissions in the anaerobic digestion process were found using the annual consumption of electricity and natural gas as per section 5.3.4 and multiplication by an emission factor of $456.6gCO_2eq.kWh_e^{-1}$ for electricity, and $204.7gCO_2eq.kWh_{th}^{-1}$ for natural gas (Howley et al. 2015). The annual emissions were then divided by the net biomethane production of each plant. The same

methodology was applied to the determine the CO_2eq emissions of energy used in the upgrading process.

The CO_2eq emissions due to fugitive methane emissions during the upgrading process were found by calculating the mass of methane lost (methane slip of 0.5% and a density of methane of 0.714kg.m^{-3}) and taking a global warming potential (GWP) of 25 for methane (Guintoli et al. 2014).

The digestate was assumed to be stored in a covered digestate storage system to facilitate the removal of residual biogas produced during the storage period (Guintoli et al. 2014).

Potential greenhouse gas savings due to the improved management of cattle slurry were calculated by determining the avoided emissions of methane that would have occurred if the cattle slurry sourced were to be left to decompose under anaerobic conditions in slurry pits. The methodology used assumed a methane yield of 0.24m^{3}CH$_4$.kgVS^{-1} (Dong et al. 2006; Duffy et al. 2016) and a methane conversion efficiency of 17% (Dong et al. 2006; Duffy et al. 2016) for cattle slurry treated in liquid systems in a cool climate. As such, 1kgVS of slurry, that is left to decompose in a slurry pit would yield 0.0408m^{3}CH$_4$, equivalent to 0.0273kgCH$_4$ (using a volume to mass ratio of 0.67kg.m^{-3} for methane (Dong et al. 2006)), which equated to 0.628kgCO_2eq when applying a GWP of 25 for methane. Applying a SMY of 143m^{3}CH$_4$.tVS^{-1} for cattle slurry in anaerobic digestion, the avoided emission of carbon dioxide from the digestion of cattle slurry was approximately 126gCO_2eq.MJ$_{biomethane}^{-1}$, this is similar to with work conducted by the JRC which estimated a CO_2 saving of ca. 100gCO_2eq.MJ$_{biomethane}^{-1}$ (Guintoli et al. 2014).

5.4 Results

5.4.1 Cattle slurry biomethane resource

The total theoretical biomethane resource of cattle slurry identified amounted to approximately 9.6PJ.a^{-1} (2.66TWh.a^{-1}) of biomethane sourced from c.a. 28.5Mt$_{wwt}$ of cattle slurry (Table 5-2). The cattle slurry biomethane resource (m^{3}CH$_4$ per ED) was concentrated in the southern half of the country and in the north-eastern region of the country (Figure 5-7 A). In terms of the resource density of the cattle slurry biomethane resource of each ED (m^{3}CH$_4$.km^{-2}), regions in the south of the country, north east, and an isolated region in the north exhibited the highest resource (Figure 5-7 B).

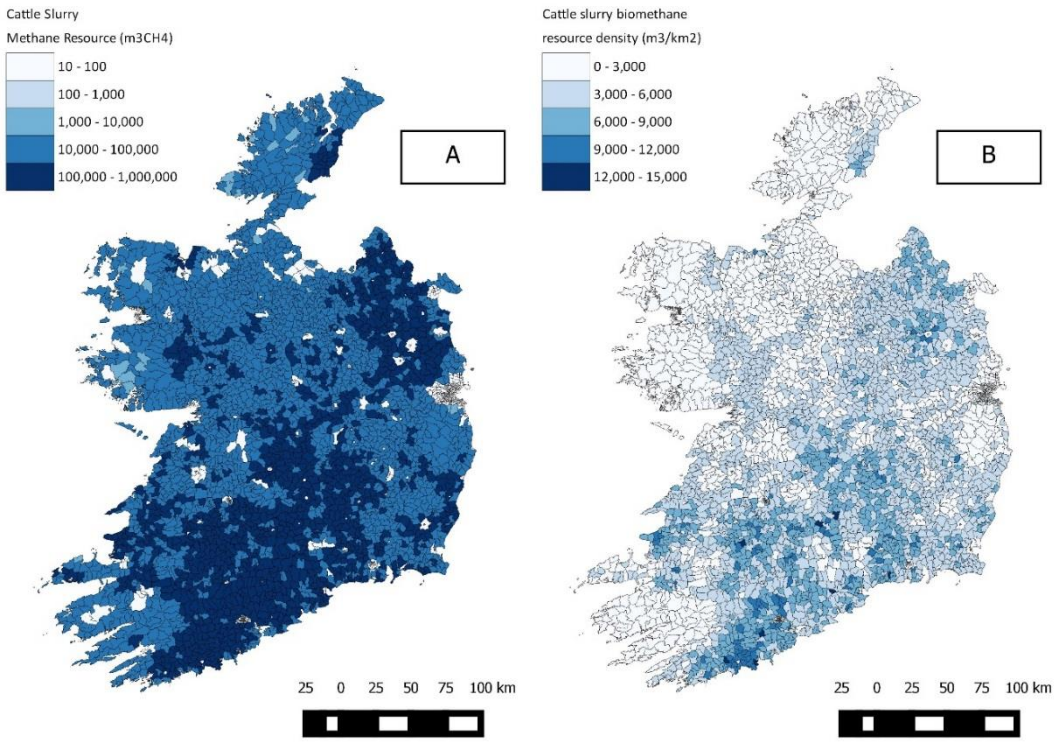


Figure 5-7 Cattle slurry biomethane resource (m^{3}CH$_4$) per electoral division, 4B: Cattle slurry biomethane resource density (m^{3}CH$_4$.km^{-2}) per electoral division

5.4.2 Grass silage biomethane resource

The total theoretical resource of biomethane arising from grass silage was approximately 128.4PJ.a^{-1} (35.67TWh.$^{-1}$a) (Table 5-2). This energy resource arose from ca. 31.3Mt$_{wwt}$ of grass silage that would be available in excess of livestock requirements. As per Figure 5-8 A areas of the country with the highest biomethane resource were predominantly located in the west of the country. Southern areas in which the biomethane resource was lowest (or absent) typically contained the highest cattle slurry resource owing to high cattle populations, this resulted in a reduction in silage available for AD.

Regions with the highest biomethane resource density (m^{3}CH$_4$.km^{-2}) were located in the west of the country and corresponded to regions with the lowest cattle slurry biomethane resource (Figure 5-8 B).

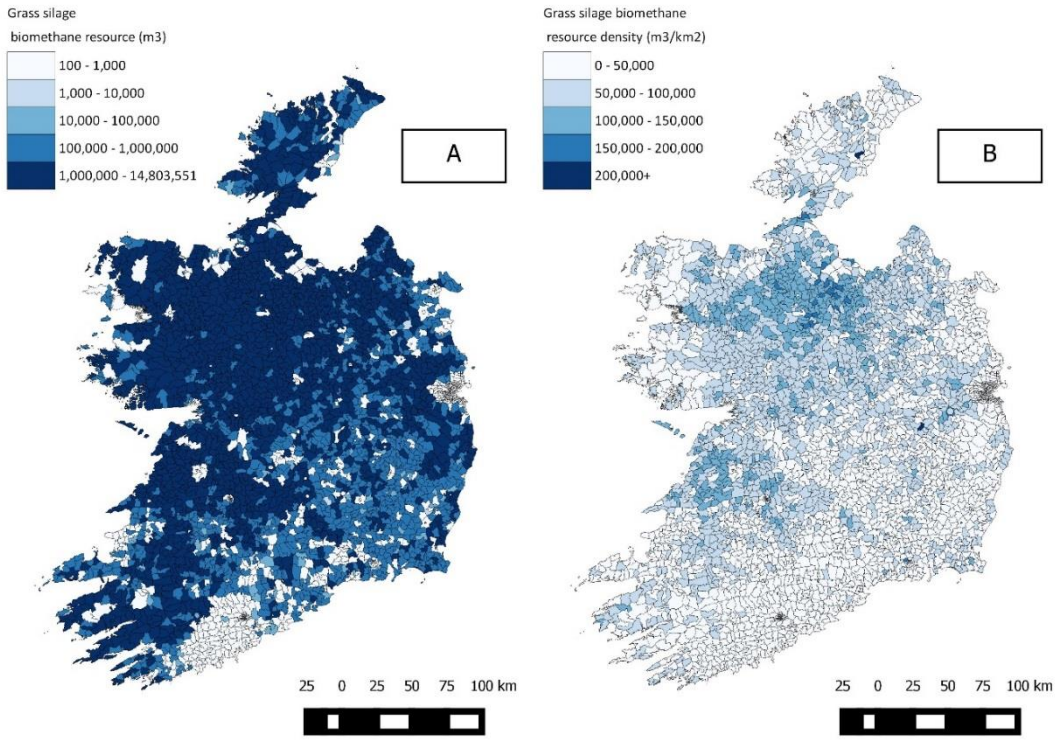


Figure 5-8 Grass silage biomethane resource (m^{3}CH$_4$) per electoral division, 5B: Grass silage biomethane resource density (m^{3}CH$_4$.km^{-2}) per electoral division

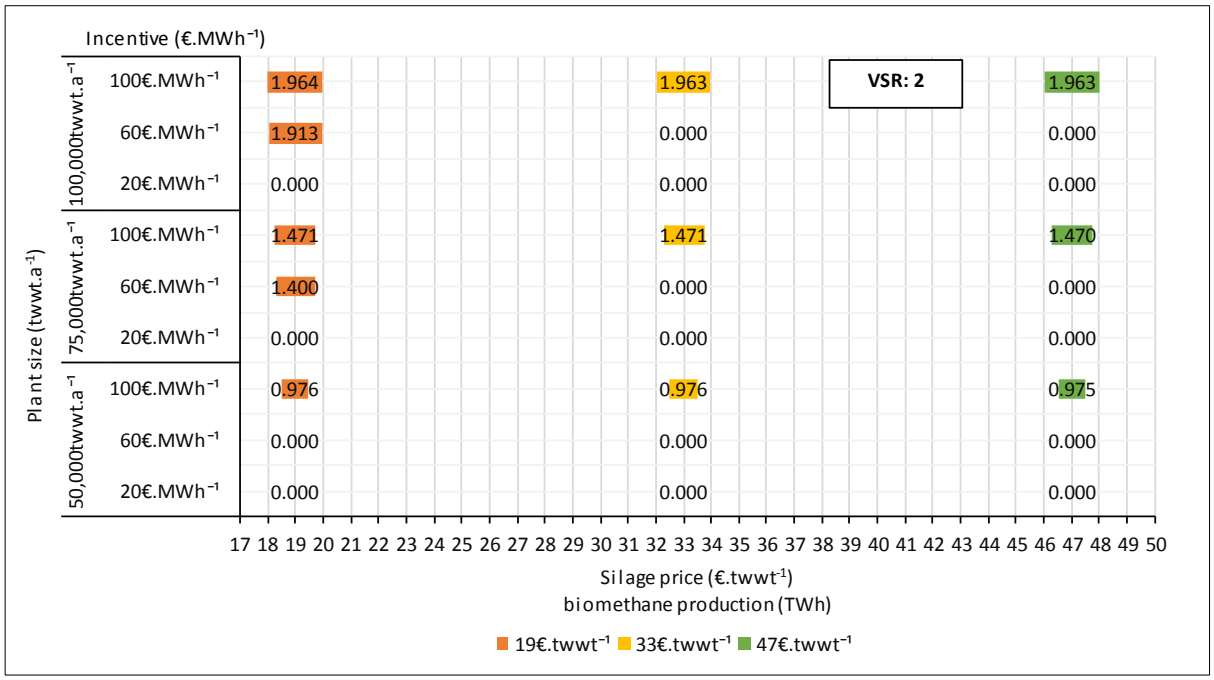
Table 5-2 Total theoretical biomethane resource. $_{wwt}$: wet weight

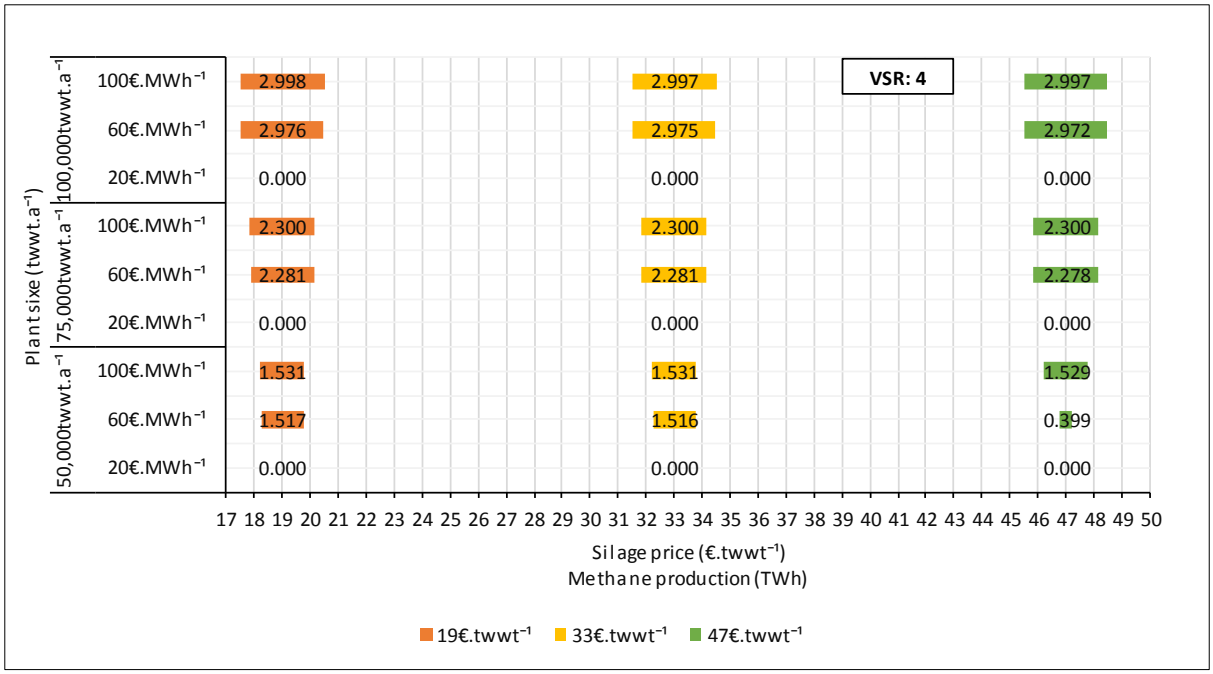
Feedstock	Total tonnage	Biomethane resource	Biomethane resource	Share of energy use in transport (2015)	Share of total natural gas consumption (2015)
	Mt_{wwt}	$PJ.a^{-1}$	$TWh.a^{-1}$	%	%
Cattle slurry	28.5	9.6	2.66	4.8	5.3
Grass silage	31.3	128.4	35.67	64.1	70.8

5.4.3 Total biomethane production from plants with a positive NPV

The total biomethane production by plants with a positive NPV can be seen in Figure 5-9 for all scenarios of plant size, silage price, incentive, and VSR. The width of the coloured columns corresponds to the quantity of biomethane (TWh) produced by plants with a positive NPV. Values of "0" indicate that no plants were able to achieve a positive NPV.

No plants were capable of producing biomethane while achieving a positive NPV when the incentive value was $20€.MWh^{-1}$. The total biomethane production of plants with a positive NPV ranged from $0.975TWh.a^{-1}$ ($47€.t_{wwt}^{-1}$ grass silage, $50{,}000t_{wwt}.a^{-1}$ plant size, $100€.MWh^{-1}$ incentive, VSR of 2) to $3.385TWh.a^{-1}$ ($19€t_{wwt}^{-1}$ grass silage, $100{,}000t_{wwt}.a^{-1}$ plant size, $100€.MWh^{-1}$, VSR of 6).





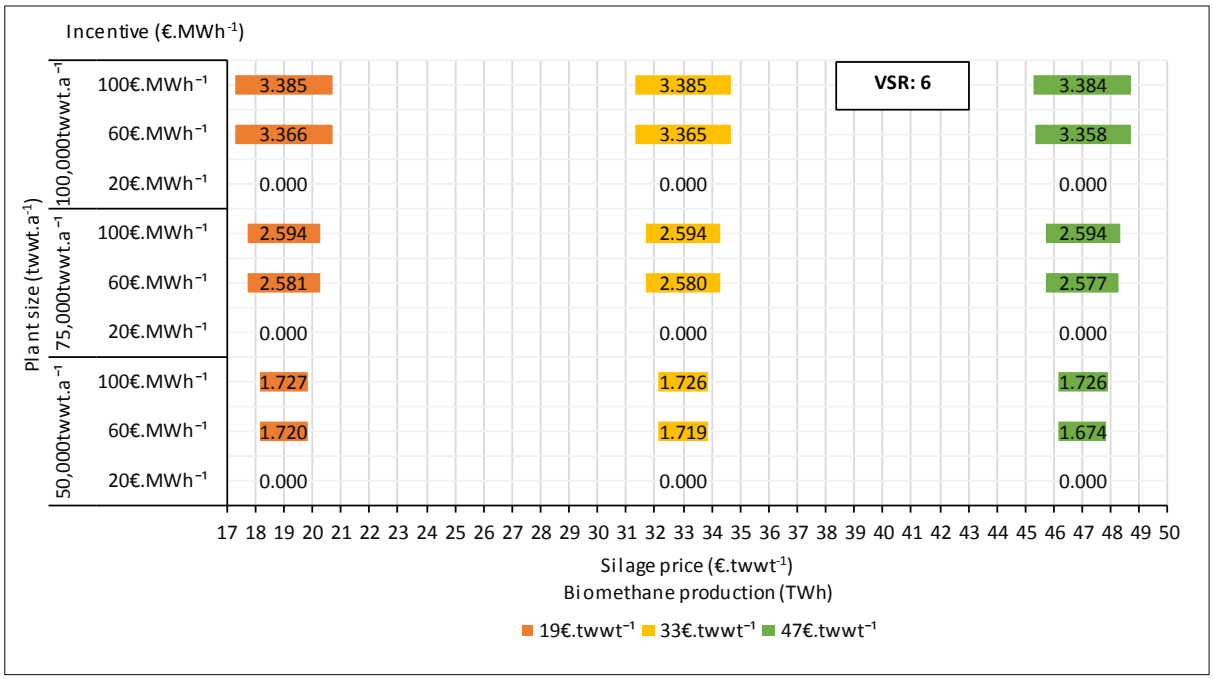
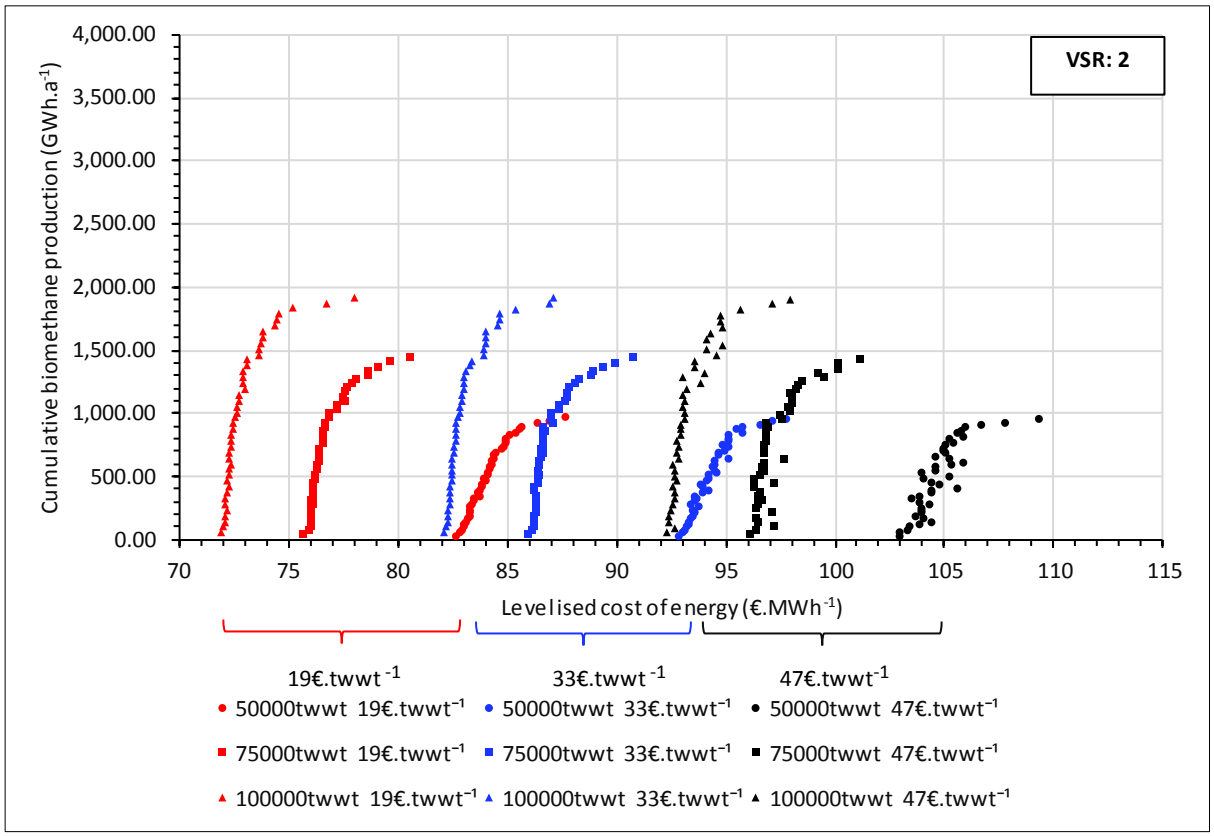
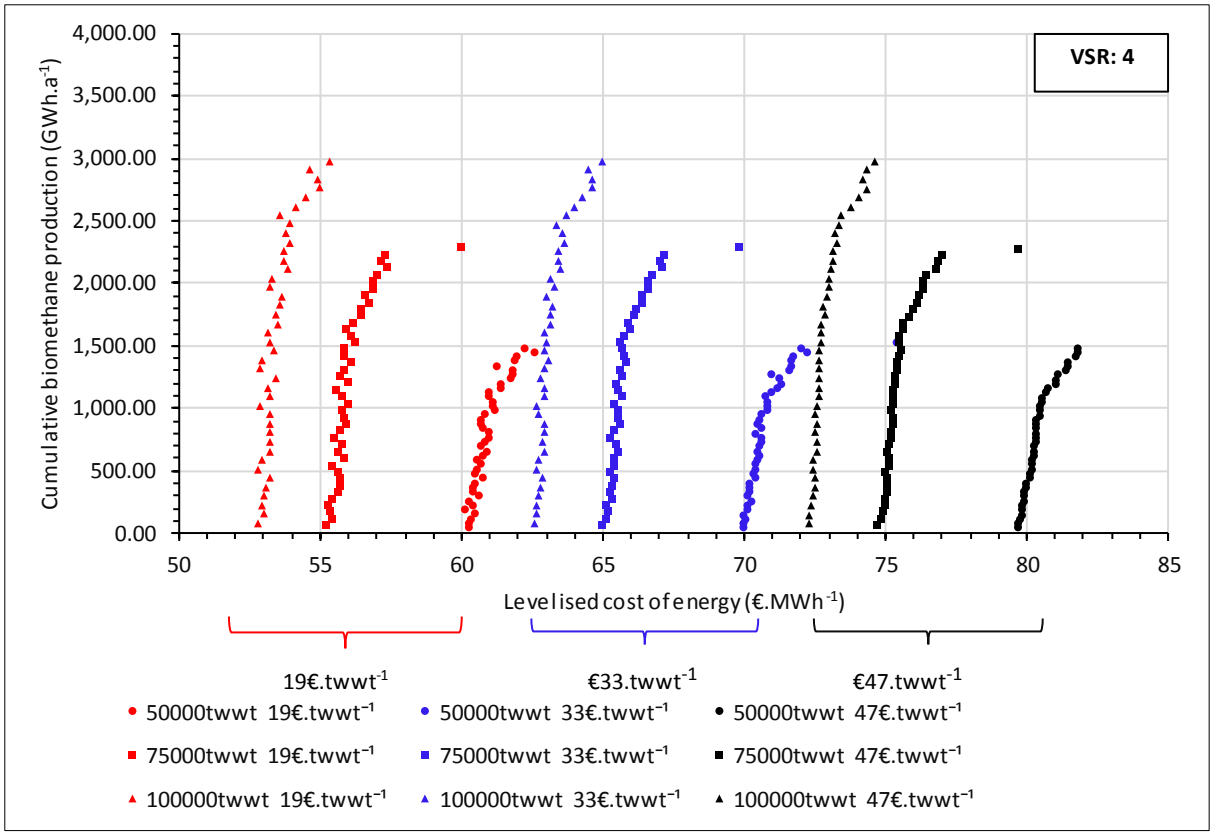


Figure 5-9 Biomethane production from plants co-digesting grass silage and cattle slurry. Only plants with a positive net present value are considered. Width of columns represents the biomethane production (TWh). VSR: volatile solids ratio.

5.4.4 Cost curves

Marginal cost curves of cumulative biomethane production can be seen in Figure 5-10 for three plant sizes, three silage prices, and the three VSRs assessed. An incentive of 60€.MWh^{-1} was applied to each combination (the median incentive assessed for each combination of plant size and silage price). The curve illustrates the cumulative biomethane production from plants at the marginal levelized cost of energy, that is, the LCOE of the most expensive plant. The curves show that the initial plants to be built, with the highest NPV (points lower on the curve) generally had the lowest LCOE, with some minor fluctuations. Results for cumulative biomethane production range from; 0.94TWh.a^{-1} at 109€.MWh^{-1} (50,000t$_{wwt}$.a^{-1}, silage price of 47€.t$_{wwt}^{-1}$, VSR of 2), to 3.37TWh.a^{-1} at 52€.MWh^{-1} (100,000t$_{wwt}$.a^{-1}, silage price of 19€.t$_{wwt}^{-1}$, VSR of 6).





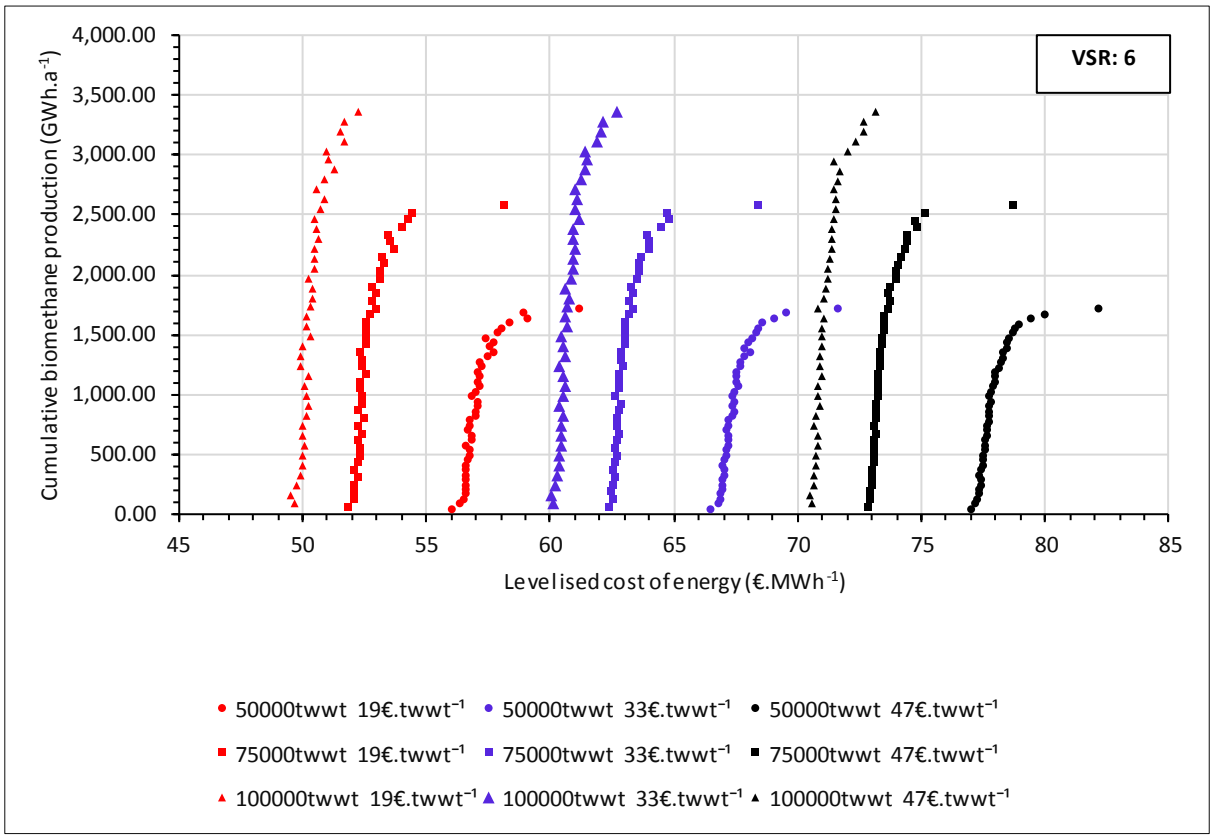


Figure 5-10 Cumulative production of biomethane at a given levelized cost of energy for differing plant sizes, and grass silage costs. Results are from the median scenario with an incentive of 60€.MWh^{-1}. VSR: Volatile solids ratio

5.4.5 Build order and source location of feedstock

The build order, NPV, LCOE, energy output, and tonnage of the median scenario can be seen in Figure 5-11 with data contained in Table 5-3.

*Table 5-3 Results of optimisation model for the median scenario (33€.twwt^{-1} grass silage, VSR (grass silage: cattle slurry) 4, plant size 75,000twwt.a^{-1}, incentive of 60€.MWh^{-1}). *VSR: Volatile Solids Ratio*

Build order	Plant No.	NPV (M€)	LCOE (€.MWh^{-1})	Biomethane (GWh.a^{-1})	Silage (kt$_{wwt}$.a^{-1})	Slurry (kt$_{wwt}$.a^{-1})	VSR*	Tonnage (kt$_{wwt}$.a^{-1})	Silage cost (k€.a^{-1})	Silage transport (k€.a^{-1})	Slurry transport (k€.a^{-1})
1	34	8.0	65.0	54.5	37.9	39.0	4.2	76.9	1251.5	40.1	33.7
2	16	7.9	65.1	54.2	37.9	38.4	4.2	76.3	1249.9	44.1	39.0
3	24	7.9	65.2	54.3	37.9	38.5	4.2	76.4	1252.2	48.6	38.0
4	20	7.9	65.1	54.0	37.8	37.7	4.3	75.5	1248.3	37.2	44.3
5	11	7.9	65.3	54.5	37.8	39.8	4.1	77.6	1247.7	42.0	46.4
6	36	7.9	65.2	54.2	37.9	38.0	4.3	75.9	1251.9	53.8	36.0
7	2	7.8	65.3	54.4	37.8	39.7	4.1	77.4	1246.0	47.2	41.0
8	9	7.8	65.4	54.5	37.9	39.5	4.1	77.4	1250.0	43.5	51.0
9	31	7.8	65.2	53.9	37.9	37.4	4.4	75.2	1249.8	45.1	45.1
10	14	7.8	65.4	54.4	37.9	38.7	4.2	76.7	1252.2	54.7	41.7
11	4	7.8	65.4	54.4	37.8	39.1	4.2	76.9	1248.8	54.5	39.2
12	29	7.8	65.5	54.8	37.9	40.3	4.1	78.2	1252.1	56.4	44.8
13	19	7.8	65.5	54.7	38.0	39.8	4.1	77.8	1252.4	49.2	52.1
14	1	7.8	65.3	53.9	37.9	37.0	4.4	74.9	1251.1	53.4	41.1
15	3	7.8	65.4	54.4	37.9	39.0	4.2	76.9	1250.7	49.8	48.4
16	37	7.8	65.6	54.8	37.9	40.5	4.0	78.4	1250.7	66.9	37.1
17	35	7.8	65.5	54.7	37.9	39.9	4.1	77.8	1250.7	63.6	39.5
18	22	7.7	65.5	54.3	37.9	38.6	4.2	76.5	1250.3	55.9	46.9
19	15	7.7	65.4	53.7	37.6	37.5	4.3	75.1	1240.4	36.8	54.7
20	25	7.7	65.7	54.7	37.9	40.2	4.1	78.1	1250.8	65.3	43.9
21	38	7.7	65.5	54.2	37.9	38.2	4.3	76.1	1251.4	71.7	35.1
22	13	7.7	65.4	53.8	37.6	38.0	4.2	75.6	1240.5	45.6	49.6
23	27	7.7	65.7	54.6	37.9	39.6	4.1	77.5	1250.4	59.4	52.6
24	6	7.7	65.6	54.1	37.8	38.2	4.2	76.1	1247.5	50.2	56.4
25	32	7.6	65.8	54.7	37.9	40.0	4.1	77.9	1252.1	77.0	41.3
26	17	7.6	65.8	54.4	37.7	40.0	4.0	77.7	1243.7	60.2	51.4
27	12	7.6	65.7	54.0	37.8	37.9	4.3	75.7	1248.0	54.6	57.4
28	18	7.6	65.6	53.8	37.5	38.5	4.2	76.0	1236.5	43.5	57.4
29	30	7.6	65.8	54.1	38.0	37.6	4.3	75.5	1252.4	77.2	43.2
30	39	7.5	66.0	54.7	37.9	40.1	4.1	78.0	1251.8	90.1	37.4
31	8	7.5	65.9	54.1	37.7	38.7	4.2	76.4	1244.7	71.7	47.9
32	33	7.5	66.1	54.7	37.9	39.9	4.1	77.9	1251.5	92.0	43.4
33	40	7.4	66.2	54.4	37.9	38.7	4.2	76.6	1252.2	80.2	61.9
34	21	7.3	66.4	54.7	37.9	40.2	4.1	78.1	1250.8	74.1	75.2
35	5	7.3	66.4	54.3	37.9	38.6	4.2	76.5	1250.7	75.3	74.9
36	28	7.2	66.6	54.6	37.9	39.3	4.2	77.2	1252.3	79.6	81.6
37	7	7.1	66.6	54.2	37.6	39.7	4.1	77.3	1240.4	91.6	63.0
38	26	7.1	66.8	54.3	37.6	39.5	4.1	77.2	1241.9	83.7	80.7
39	41	6.9	67.1	54.4	37.9	38.9	4.2	76.9	1251.4	149.9	40.3
40	10	6.8	67.0	53.6	37.5	37.6	4.3	75.0	1237.3	80.7	95.8
41	23	6.8	67.1	53.6	37.7	37.0	4.4	74.7	1243.9	92.3	97.9
42	42	5.4	69.8	54.0	37.9	37.1	4.4	75.1	1251.8	303.2	36.3

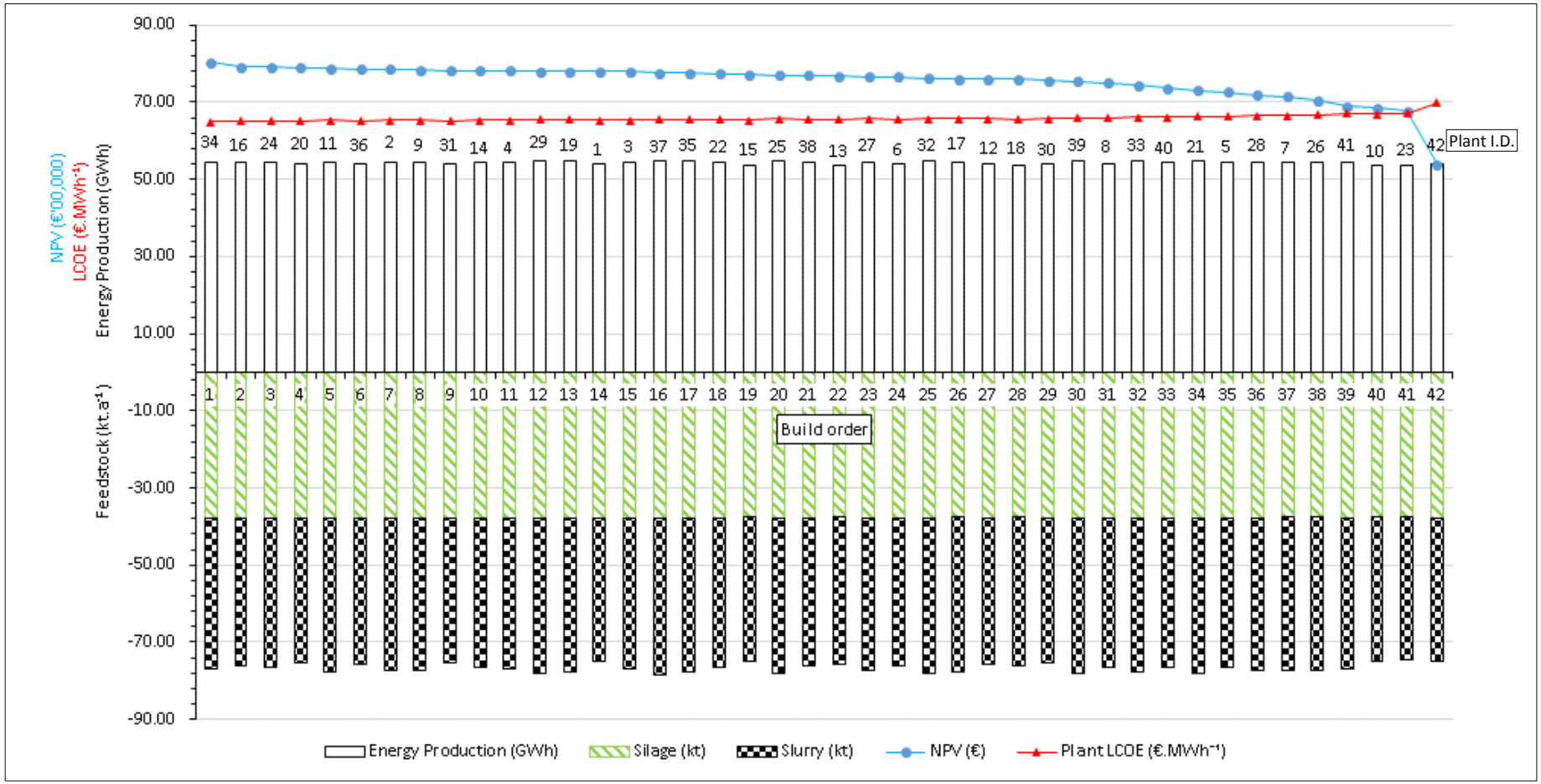


Figure 5-11 Plant energy production (GWh), NPV, and LCOE for the median scenario; (33€.twwt^{-1} grass silage, VSR (grass silage: cattle slurry) 4, plant size 75,000twwt.a^{-1}, incentive of 60€.MWh^{-1})

The average transportation distance of feedstock to each plant in the median scenario can be seen in Figure 5-12. Error bars represent the maximum and minimum transportation distance of feedstock to each individual plant. The source locations of grass silage and cattle slurry for the first four plants can be seen in Figure 5-13.

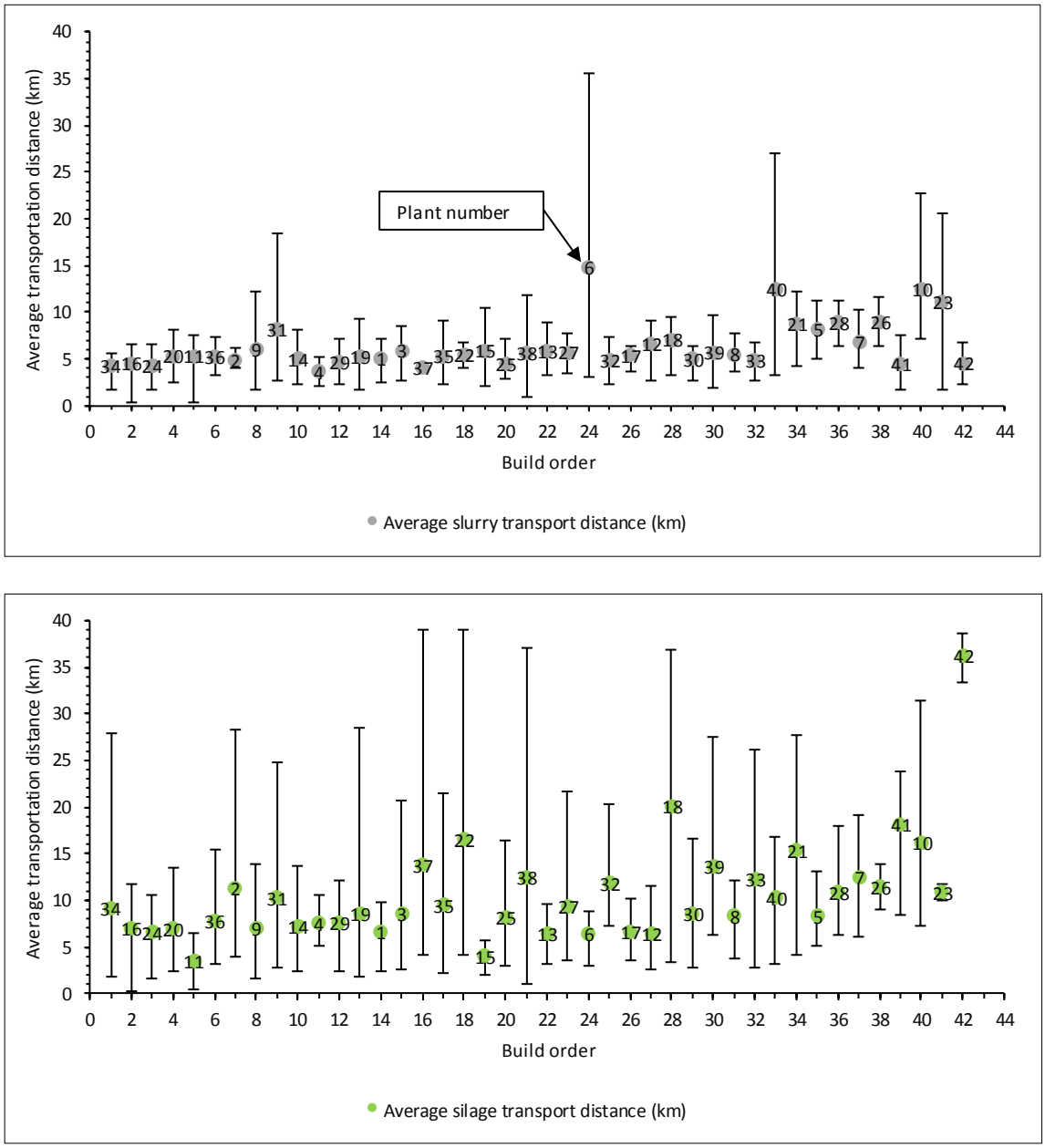


Figure 5-12 Average transportation distance of feedstock. Error bars represent minimum and maximum transportation distance of each plant.

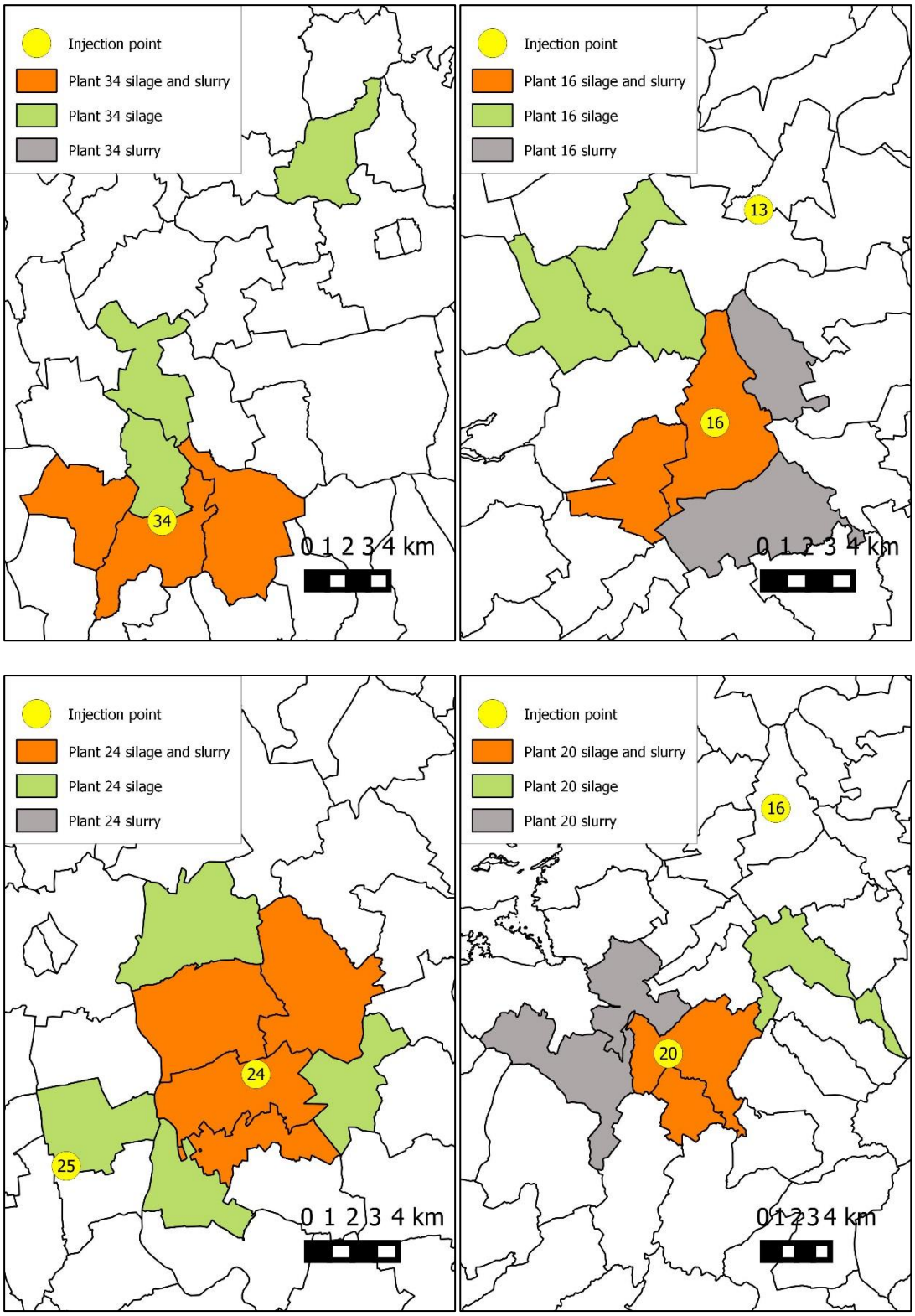


Figure 5-13 Source locations of grass silage and cattle slurry for injection points; 34, 16, 24, and 20

5.4.6 Carbon intensity of biomethane

The gross CO_2eq emission per kWh_{th} of biomethane produced by each plant in the median scenario (75,000$t_{wwt}.a^{-1}$, VSR 4, incentive of 60€.MWh^{-1}, silage price of 33€.t_{wwt}^{-1}), the CO_2 savings associated with improved slurry management, and the net CO_2 intensity of biomethane produced can be seen in Figure 5-14. Gross CO_2 intensity range from ca. 70.74gCO_2eq.kWh_{th}^{-1} to 81.36gCO_2eq.kWh_{th}^{-1}. Emissions avoided through improved slurry management range from 29-31gCO_2eq.kWh_{th}^{-1}; this emission saving is calculated as the total emissions savings as a result of improved slurry management, divided by the total biomethane production of the co-digestion plant (i.e. the biomethane production of grass silage and cattle slurry combined). The net CO_2eq emissions ranged from 40-52gCO_2eq.kWh_{th}^{-1} of biomethane produced.

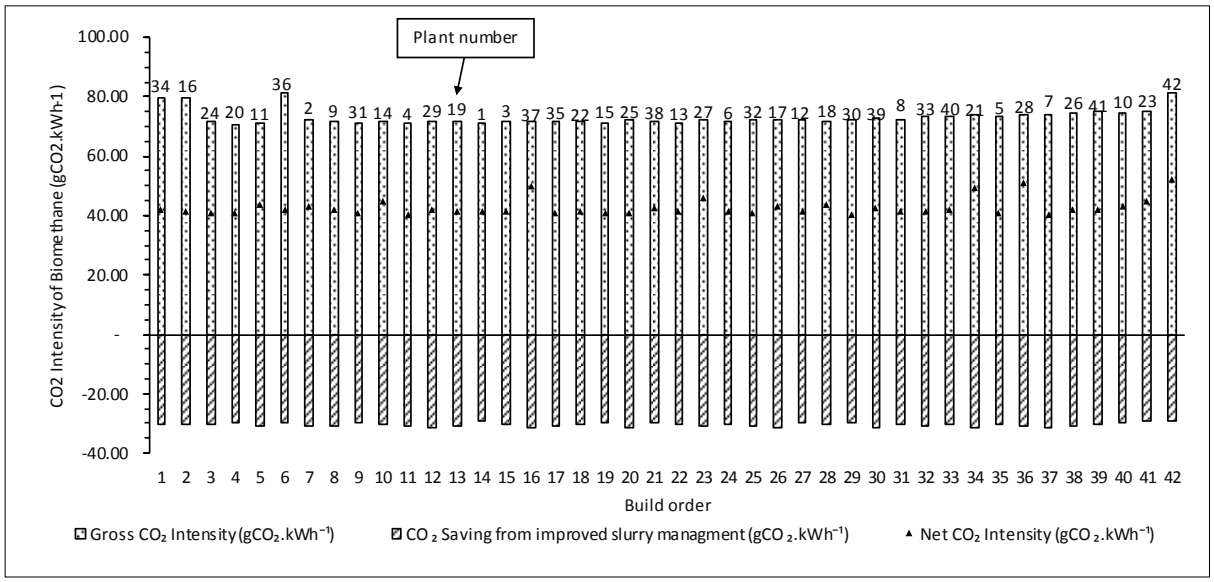


Figure 5-14 Carbon dioxide intensity of biomethane produced by plants. 75,000twwt.a^{-1}, VSR 4, silage price 33€.t_{wwt}^{-1}, Incentive 60€.MWh^{-1}

5.5 Discussion

5.5.1 Cattle slurry biomethane resource

The total theoretical biomethane resource arising from cattle slurry was found to be 9.6PJ (2,666GWh), approximately 70% of the 13.7PJ resource reported by Singh et al (Singh et al. 2010) owing to a lower slurry resource used in this work (28.48Mt_{wwt} vs. 29.95Mt_{wwt}) and a lower methane yield (8.91$m^3CH_4.t_{wwt}^{-1}$ vs 12.1$m^3CH_4.t_{wwt}^{-1}$). The resource was approximately 31% of the 30.55PJ identified by Allen et al. (Allen et al. 2016) arising from 46.575$Mt_{wwt}.a^{-1}$ of cattle slurry with an average methane yield of 17.4$m^3CH_4.t_{wwt}^{-1}$ and 2.24 times larger than that identified by Clancy et al. of 0.47$PJ.a^{-1}$ (Clancy et al. 2012) who considered 10% of the available dairy cow slurry, and 5% of slurry from other cattle. The regions with the largest cattle slurry resource were typically situated in the southern and north-eastern areas of Ireland as cattle populations were highest in these areas.

Biomethane from cattle slurry equated to ca. 5.3% of total natural gas consumption, 17% of industrial natural gas consumption in 2015/2016 and 1.85 times the GNI renewable gas target for 2025 (Gas Networks Ireland 2016). The total theoretical resource of cattle could provide heat to approximately 179,000 households (14,858kWh of direct fossil fuel consumption per household (Dennehy & Howley 2013)) equivalent to 37% of residential gas demand. The total theoretical resource of cattle slurry could meet the combined natural gas demand of the largest milk processor, brewery, and distillery in Ireland of 971$GWh.a^{-1}$ (Environmental Protection Agency 2014c; Environmental Protection Agency 2014a; Environmental Protection Agency 2014b) with no change of equipment required by the end user. In terms of energy use in transport, the total resource was ca. 4.8% of final energy consumption in 2015 (Howley & Holland 2016).

5.5.2 Grass silage biomethane resource

The total biomethane resource of grass silage was 128.4PJ.a^{-1} (35,666GWh) arising from 31.3Mt_{wwt} of grass silage. The total available tonnage of grass silage calculated in this work was 99% of the 31.7Mt_{wwt} (taking the DS fraction to be 29.3%) identified by McEniry et al. (Mceniry et al. 2013). The identified biomethane resource (128.4PJ) was larger than that identified by Singh et al. of 47.6PJ (Singh et al. 2010) arising from 15.9Mt_{wwt} of grass silage. Wall et al. estimated the biomethane resource of grass silage to be 2.2PJ (Wall et al. 2013) based on attaining 30% of current excess grass silage (1.7MtDS) (Mceniry et al. 2013). The larger total theoretical resource of grass silage calculated in this work is a result of assuming maximum application of N fertiliser as per McEniry et al. (Mceniry et al. 2013) which increases grass yields.

The resource is largest in western regions, corresponding to areas with a low cattle slurry biomethane resource. Regions with a high cattle slurry biomethane resource currently show little opportunity for excess grass silage availability owing to consumption of this grass silage by cattle. Development of biomethane facilities in these regions would directly compete with dairy or beef production for grass use, however, careful consideration as to whether biomethane production could provide an additional income stream for farmers should be made.

The biomethane resource of grass silage was equal to 70.8% of total natural gas consumption in 2015/16 and was 2.26 times the gas consumption of industry. The total theoretical resource of biomethane from grass silage was 24 times the GNI renewable gas goal in 2025 (Gas Networks Ireland 2016). If the equivalent energy resource were to be sourced from an alternative biomass, such as short rotation coppice (SRC) willow, approximately 682,000ha would be required (10t oven dry matter (ODM) per hectare, 18.84GJ.t_{ODM}^{-1}) (Clancy et al. 2012). This is higher than the maximum estimated area of land available for conversion to energy crops in Ireland of 250,000ha (Clancy et al. 2012).

In terms of transportation, the resource equated to approximately 65% of final energy use in 2015 (Howley & Holland 2016). The total theoretical biomethane resource of grass silage was approximately 4.9 times the energy consumption of

HGVs in 2015, and 1.1 times the final consumption of diesel in transportation in 2014. The potential biomethane resource from grass silage was over 22 times the consumption of all biofuels in 2015, and was 139 time the indigenous biofuels production in Ireland (Byrne Ó'Cléirigh & LMH Casey McGrath 2016).

5.5.3 Total biomethane production from plants with a positive NPV

5.5.3.1 Total biomethane production and resource utilisation

The total biomethane production by plants with a positive NPV ranged from 0.975TWh.a^{-1} (3.51PJ.a^{-1}) at a plant size of 50,000t_{wwt}, a silage price of 47€.t_{wwt}^{1}, an incentive of 100€.MWh^{-1}, and a VSR of 2, to 3.385TWh.a^{-1} (12.19PJ.a^{-1}) at a plant size of 100,000$t_{wwt}.a^{-1}$, a silage price of 19€.t_{wwt}^{-1}, an incentive of 100€.MWh^{-1}, and a VSR of 6 as seen in Figure 5-9. This represented approximately 2.5-8.8% of the combined total theoretical resource of cattle slurry and grass silage. The upper range of biomethane production from NPV positive plants would account for approximately 6.7% of primary natural gas consumption in 2015/16, equivalent to 22% of industrial natural gas consumption. It also represents approximately 2.35 times the 2025 goal for renewable gas injection to the natural gas network. The combined gas demand of the largest milk processor, brewery, and distillery in Ireland (971GWh.a^{-1}) could be met using biomethane from plants with a positive NPV. The total biomethane production was approximately 6% of energy use in transport in 2015, 12% when double counted. The biomethane production could potentially meet 47% of HGV energy consumption, 2.12 times the energy demand of public transportation, and could meet the energy demand of the two main bus fleets in Ireland six times over (annual diesel consumption of 0.556TWh of diesel fuel in 2013 (Central Statistics Office 2016)).

A significant portion of the biomethane resource of cattle slurry and grass silage was not utilised by the model (91.2-97.5%). Alternative pathways for the use of this remaining resource should be assessed. Alternatives may include for off grid biomethane production facilities combined with mobile biogas upgrading units and road haulage to a centralised injection point or a biomethane user, or

transportation of biogas from decentralised AD plant to centralised upgrading facilities in low pressure pipelines (Hengeveld et al. 2014). Additionally, the injection of biomethane into the gas distribution grid could also take place, this could increase the number of potential injection points, and result in greater utilisation of the available theoretical biomethane resource.

5.5.4 Impact of incentive, plant size, grass silage price, and VSR

5.5.4.1 Impact of incentive level

Total biomethane production from NPV positive plants showed a positive correlation with; incentive level, plant size, and VSR, and a negative correlation with grass silage price. At an incentive of 20€.MWh^{-1} no plants under any combination of silage price, plant size, or VSR achieved a positive NPV. The LCOE of biomethane plants under all scenarios investigated was in excess of 49€.MWh^{-1}, the market price of gas used in this analysis was 20€.MWh^{-1}, when combined with an incentive of 20.MWh^{-1}, this resulted in an incoming cash flow per MWh of 40€.MWh^{-1}, below the 49€.MWh^{-1} threshold to achieve a non-negative NPV.

At a VSR of 2 and a silage price of 19€.t_{wwt}^{-1}, only plants accepting 75,000$t_{wwt}.a^{-1}$ and 100,000$t_{wwt}.a^{-1}$ achieved positive NPVs when the incentive level was greater than or equal to 60€.MWh^{-1}.

Alteration of incentive value from 60€.MWh^{-1} to 100€.MWh^{-1} resulted in the greatest increase in total biomethane production ca. 1.963TWh.a^{-1} (plant size 100,000$t_{wwt}.a^{-1}$, silage price 47€.t_{wwt}^{-1}) at a VSR of 2. The increase in incentive from 60€.MWh^{-1} to 100€.MWh^{-1} did not greatly increase total biomethane production at a VSR of 4 or 6 as plants had reached their maximum size at an incentive level of 60€.MWh^{-1}, and almost all of the potential facility locations were profitable and were therefore developed. Increasing the incentive increased plant profitability, not the total production of biomethane as no more plants could be developed.

The total value of the incentive required in the median scenario (75,000$t_{wwt}.a^{-1}$, VSR 4, incentive of 60€.MWh^{-1}, silage price of 33€.t_{wwt}^{-1}) was found to be approximately 137M€ for ca. 2.28TWh_{th} of biomethane, equivalent to 4.5% of total natural gas

demand in 2015. The total incentive required in the median scenario is slightly less than the public service obligation (PSO) levy in Ireland for the period 2015-2016 which amounted to 180.9M€ (Commission for Energy Regulation 2015). The PSO levy provided to renewable electricity generators is paid in the form of a renewable energy feed in tariff, to ensure a minimum income per unit of electricity of 69.7-157.6€.MWh_e^{-1} generated. The incentive proposed in the median scenario (60€.MWh_{th}^{-1}) on top of a market price of gas of 20€.MWh_{th}^{-1}, is similar to existing incentives for renewable energy production. The introduction of an incentive to promote the production of biomethane could both increase energy security by developing indigenous renewable energy sources, and aid in greenhouse gas mitigation in agriculture through the improved management of cattle slurries (which accounted for approximately 9% of total greenhouse gas emissions in agriculture in Ireland in 2014 (Duffy et al. 2016)).

5.5.4.2 Influence of plant size

Increasing plant size alone increased biomethane production, as would be expected. The LCOE decreased as plant size increased; this can be seen in the marginal production cost curves in Figure 5-10(curves shift to the left as plant size increases). This was a result of economies of scale allowing for greater biomethane production whilst reducing the cost of biomethane production and increasing plant profitability.

5.5.4.3 Effect of grass silage price

Increased silage price reduced the total production of biomethane by NPV positive plants. This was most evident at a VSR of 2 and an incentive of 60€.MWh^{-1}, as when silage price increased from 19 to 33€.t_{wwt}^{-1}, no plants processing less than 100,000$t_{wwt}.a^{-1}$ were able to produce biomethane whilst achieving a positive NPV. For the remaining cases, increasing silage price did not result in a major change in biomethane production by NPV positive plants, with one exception; a 74% reduction occurred when silage price increased from 33€.t_{wwt}^{-1} to 47€.t_{wwt}^{-1}

(50,000$t_{wwt}.a^{-1}$, 60€.MWh^{-1} incentive, VSR 4). The impact of silage price on LCOE was more noticeable as can be seen in Figure 5-10. As silage price increased, the LCOE of biomethane increased under all combinations of plant size and VSR (curves shift to the right). Increasing silage price from 19€.t_{wwt}^{-1} to 47€.t_{wwt}^{-1} (50,000$t_{wwt}.a^{-1}$ plant, VSR of 2) resulted in the LCOE increasing by 20€.MWh^{-1}.

5.5.4.4 Impact of VSR

Changing VSR changed the total biomethane production of NPV positive plants. Increasing VSR from 2 to 4 increased biomethane production by 63% (75,000$t_{wwt}.a^{-1}$, 60€.MWh^{-1}, 19€.t_{wwt}^{-1}) while the average increase in biomethane production was 56% for all combinations of plant size, incentive level, and silage price. As VSR was increased from 4 to 6 the average increase in total biomethane production by NPV positive plants was 13%, with the exception of a threefold increase in biomethane production at a plant size of 50,000$t_{wwt}.a^{-1}$, an incentive of 60€.MWh^{-1}, and a silage price of 47€.t_{wwt}^{-1}. Increasing the VSR resulted in a greater mass of grass silage accepted by plants, this increased biomethane production as outlined by Wall et al. (Wall et al. 2014).

As VSR increased, plants used more grass silage. Thus, annual running costs increased (more silage was purchased); however, the increase in biomethane production outweighed the increase in cost. This can be seen in Figure 5-10, LCOE reduced as VSR increased for a given plant size and silage price. Increasing VSR increased biomethane production and reduced the LCOE of the produced biomethane.

5.5.5 Cost Curves

The goal of the optimisation model used was to maximise the NPV of each plant, not to minimise the LCOE of plants. Minimising LCOE would potentially result in a plant with a lower LCOE being preferentially selected, even if it had a lower NPV and was less profitable (Short et al. 1995). The general trend achieved was that initial plants to be built (those with the highest NPV) also had the lowest LCOE. Plotting

cumulative biomethane production vs. the LCOE of the marginal plant yielded marginal production cost curves, which can indicate the value of biomethane required to enable the production of a given quantity of biomethane whilst ensuring that all plants achieve a non-negative NPV. Marginal production cost curves for three plant sizes and three silage prices at each of the three VSR levels assessed, at the median incentive level of 60€.MWh^{-1} are shown in Figure 5-10. For a desired production of 1TWh.a^{-1}, the LCOE ranged from 50.2€.MWh^{-1} (VSR 6, 100,000t_{wwt}.a^{-1}, 19€.t_{wwt}^{-1}) to 109€.MWh^{-1} (VSR 2, 50,000t_{wwt}.a^{-1}, 47€.t_{wwt}^{-1}).

To ensure all plants achieve a non-negative NPV the total incoming cash flow per MWh of biomethane must be greater than or equal to these LCOE values. For an LCOE of 50.2€.MWh^{-1}, this could be achieved through the sale of biomethane as a transportation fuel at any price higher than 0.502€.L_{diesel}^{-1} equivalent (assuming 36MJ.L_{diesel}^{-1}), while for an LCOE of 109€.MWh^{-1} this could be achieved through the sale of biomethane as a transport fuel at a price higher than 1.09€.L_{diesel}^{-1} equivalent.

If the biomethane were to be used in the production of heat, the monetary value of the biomethane would need to be greater than or equal to 5.02c.kWh^{-1} or 10.9c.kWh^{-1} respectively.

The market price of biomethane used in this work was 20€.MWh^{-1}, as such a price gap exists that must be met. This could be met in the form of an incentive per unit energy of biomethane sold, a premium charge per unit energy of biomethane sold to a consumer, or a monetary value associated with the avoided CO_2 emissions of the biomethane consumer in contrast to using a fossil fuel source of heat.

5.5.6 Build order and source location of plants

The optimisation model determined the most profitable locations at which to construct facilities and the sources of feedstock for each facility.

All plants in the median scenario had a positive NPV ranging from 5.4M€ to 8.0M€, with LCOE ranging from 65.0€.MWh^{-1} to 69.8€.MWh^{-1} (Table 5-3). The total mass of feedstock accepted at all plants was between 74.7kt_{wwt}.a^{-1} and 78.4kt_{wwt}.a^{-1}. The

annual biomethane production ranged from 53.6 to 54.8GWh.a^{-1} (approximately equivalent to a 2.5 MW_e biogas facility if electricity is produced at 40% efficiency). This is equivalent to the energy consumption of 150-154 diesel buses (diesel consumption of one bus was ca. 355.5MWh.a^{-1} based on data from the CSO (Central Statistics Office 2016)). Each plant could provide renewable heat to 3,246-3,318 dwellings (non-electrical energy demand of 14.86MWh.a^{-1} (Dennehy & Howley 2013) with a 90% efficient gas boiler). If the renewable heat production of a plant were to be supplied by short rotation coppice willow wood chips approximately 1,024-1,047 ha (10t oven dry matter (ODM) per hectare, 18.84GJ.t_{ODM}^{-1} (Clancy et al. 2012)) would be required.

As scale, biomethane production and feedstock use were similar for all plants, only the cost of transportation of slurry and silage to the facilities varied significantly. The annual cost of feedstock and digestate transportation was lowest for the initial plants to be built (most profitable) and increased subsequently. Total transportation costs ranged from ca. €73,800.a^{-1} for the most profitable plant (plant 34) to €339,400.a^{-1} for the least profitable plant (plant 42) in the median scenario. Total annual transportation costs and NPV exhibited a linear relationship with a correlation coefficient of -0.99, reaffirming the importance of transportation in influencing the profitability of facilities, and the need to determine optimal site locations.

For cattle slurry, 38 plants sourced feedstock within an average distance of 10km (Figure 5-12), the overall average transportation distance of cattle slurry to all plants was 6.4km. The shortest distance to a plant for cattle slurry was 0.3km while the longest distance over which slurry was transported was 35.6km.

The average transportation distance of grass silage to all plants was 10.5 km. The shortest transportation distance was 0.3km while the longest transportation distance was 38.9km. A minor increase in transportation distance for grass silage can be seen as plants are constructed (Figure 5-12). The results in Figure 5-12 show that the first plants to be built are those with the shortest transportation distance and therefore the lowest annual transportation cost. Moving beyond the issue of profitability, the plants with the shortest transportation distance could also have

the least impact on traffic flows, which is a favourable aspect when developing a large energy infrastructure project.

In assessing the source locations of cattle slurry and grass silage for plants 34, 16, 24, and 20 (Figure 5-13) both grass silage and cattle slurry were sourced from the same location in a number of instances, as a result of a sufficient resource of each being available. The transportation of grass silage was viable over a greater distance than cattle slurry owing to the greater energy content per tonne of feedstock transported. The initial plants to be built, plant 34 and 16, are not located in regions with the absolute highest resource of either feedstock. Their location was determined by the model as the most profitable owing to the availability of both feedstocks in close proximity to the plants. Identification of these two injection points from visual inspection of the resource maps alone is difficult, which highlights the requirement for the development of the optimisation model.

5.5.7 Carbon dioxide intensity of biomethane

The gross carbon dioxide intensity of biomethane (70.74$gCO_2eq.kWh_{th}^{-1}$ to 81.36$gCO_2eq.kWh_{th}^{-1}$) is lower than the value determined by Korres et al. of ca. 206$gCO_2eq.kWh_{th}^{-1}$ (Korres et al. 2010). However, the underlying assumptions used in this work and the work by Korres et al. differ significantly, namely the specific methane yield, the methane slippage during upgrading, the type of upgrading system, the thermal energy requirement to heat the incoming feedstock, and the carbon intensity of electricity and natural gas used. Applying the same assumptions used in this work to the methodology applied in the work by Korres et al. yielded a carbon dioxide intensity of 98$gCO_2eq.kWh_{th}^{-1}$ which is similar to the gross carbon dioxide intensity calculated in this work.

The carbon dioxide intensities of biomethane derived from maize silage in work by the JRC ranged from 108$gCO_2eq.kWh_{th}^{-1}$ to 162$gCO_2eq.kWh_{th}^{-1}$ for biomethane with closed digestate storage (Guintoli et al. 2014). The lower carbon dioxide intensity of biomethane obtained in this work arose from emissions savings associated with

improved slurry management, this did not apply in the emission calculation carried out by the JRC for maize derived biomethane.

The carbon dioxide savings associated with improved slurry management ranged from 29-31gCO_2eq.kWh_{th}^{-1}. This CO_2eq saving is lower than the CO_2eq saving reported in work by the JRC for manures and slurries of 315gCO_2eq.kWh_{th}^{-1} (Guintoli et al. 2014). The difference in CO_2 saving from slurry management is a result of the calculation methodology. The JRC study only looked at the emission savings of the mono-digestion of slurry, this work involved the co-digestion of grass silage and cattle slurry, as such the CO_2 saving per unit of energy produced would be lower owing to the higher energy production of co-digestion plants.

The net carbon dioxide intensity of biomethane derived from grass silage and cattle slurry ranged from 40-52gCO_2eq.kWh_{th}^{-1}. In comparison to the carbon dioxide intensity of natural gas in Ireland, 204.7gCO_2eq.kWh_{th}^{-1}, biomethane derived from grass silage and cattle slurry could achieve a greenhouse gas reduction of 75-80%. The default fossil fuel comparator for biofuels in transport within Directive 2009/28/EC has a CO_2eq intensity of 83.8gCO_2eq.MJ^{-1} (301.68gCO_2eq.kWh_{th}^{-1}) (The European Parliament and the Council of the European Union 2009), biomethane produced from grass silage and cattle slurry could achieve a greenhouse gas saving of 73-77% gross, and 83-87% accounting for emissions savings from improved slurry management. Biomethane from grass silage and cattle slurry could meet the greenhouse gas reduction criteria of 50% in 2017, or 60% in 2018 to be classified as a sustainable biofuel (The European Parliament and the Council of the European Union 2009).

If the biomethane produced by the plants in the median scenario (ca. 2.248TWh_{th}) were to offset natural gas consumption in industry or households, there could be a potential saving of 366.1ktCO_2eq (this includes the CO_2 emitted during the biomethane production process), equivalent to 8% of the total energy related CO_2 emissions from industry in 2015.

If the biomethane production in the median scenario were to offset diesel (93.95gC_2.MJ^{-1} (Neeft & Ludwiczek 2016)) approximately 675ktCO_2 would be

avoided (this includes the CO_2 emitted during biomethane production), this is equivalent to 6% of CO_2 emissions in transportation in 2015.

5.5.8 Limitations of the work

The results of this work, in terms of the total biomethane production of plants with a positive NPV, and results pertaining to the LCOE, are dependent on a number of input assumptions such as capital costs, operating costs, gas prices, incentive levels, and feedstock prices to name but a few. As such, the results developed within this work are only relevant for the input assumptions used herein. Whilst the methodology developed in this work can be replicated for any given region, the input assumptions of capital cost, operating cost, feedstock cost etc. should be updated by whoever seeks to use this methodology in future work. Any use of the specific results obtained in this work should be treated with due caution by policy makers and developers.

5.5.9 Potential future considerations

The methodology utilised in this work did not account for potential learning rates in the construction of large scale centralised anaerobic digestion plants and the associated biogas upgrading systems. In reality, as subsequent plants are developed the costs associated with plant construction and operation will reduce owing to improve efficiency, thus lowering the overall cost of biomethane produced by plants. This was found to be the case for Danish biogas plants in work conducted by Junginer et al. (Junginger et al. 2006) in which the cost per unit of biogas produced was found to decrease as total cumulative biogas production increased. A similar cost reduction could be implemented in the optimisation model used in this work by reducing the capital and or the operation cost of anaerobic digesters processing grass silage and cattle slurry with subsequent upgrading of the biogas to biomethane as either the total number of facilities increases, or as the total quantity of biomethane increases as each new plant is built. The precise learning

rates and cost reductions remain to be elucidated and could form the basis of further works.

In addition to this, advances in anaerobic digestion technology such as high pressure anaerobic digestion, the use of enzymes, and the separation of the digestion process into multiple stages should be assessed in terms of increasing biomethane yields, and capital costs, thus altering the NPV of projects. These more novel technologies should be assessed in order to ascertain the future potential of biomethane from grass silage in Ireland.

The carbon dioxide intensity of biomethane calculated in this work did not consider the potential benefits of carbon sequestration in the root systems of grasslands, the inclusion of this additional carbon sink would greatly reduce the CO_2 intensity of the resulting biomethane. In work conducted by Korres et al. the impact of the ability of grassland to sequester carbon was assessed and was found to reduce the CO_2 intensity of biomethane produced from grass silage (Korres et al. 2010). A more indepth lifecycle assessment of the carbon intensity of biomethane derived from grass silage including for possible carbon sequestration should be conducted in future work.

The impact of societal acceptance of large scale anaerobic digestion plants processing grass silage and cattle slurry on NPV was not quantified in this work. In an Irish context, applications for planning permission to construct such facilities can be hindered due to public opposition on the grounds of increased traffic flows, visual and auditory hinderance and concerns on the impact of odours from plants. These concerns have resulted in the denial or withdrawal of planning permissions for anaerobic digestion facilities in Ireland in the past (Managh 2016; GalwayAdvertiser.ie 2013; Parsons 2008; Mulcahy 2012). The selection of potential locations on the gas network at which biomethane facilities are to be built could be further refined in future works by taking into consideration their proximity to large population areas or regions of strategic importance for certain economic sectors. Additional costs associated with protracted planning permission hearings and the inherent delays these cause could also be factored into the calculation of NPV in future works by assessing the delays that's prior applications have experienced.

A key finding of this work was the large potential resource of grass silage in Ireland in excess of livestock requirement, if land is fully utilised. In this work it was envisaged that the excess grass silage was to be used for the produciton of biomethane via anaerobic digestion however alternative uses for this resource do exist. The conversion of grass into valuable bio products such as proteins, organic acids, fibers, and energy has been assessed in literaure (KROMUS et al. 2004; Sharma et al. 2011). The biorefinery concept can marry the production of small volume, high value products such as proteins and ammino acids, with the produciton of large volume lower value products (such as biomethane) from the resulting residues remaining post processing of the raw material (Sharma et al. 2011). In an Irish context, a green biorefinery sytem in which grass and grass silage were processed into fiberous materials (to be used as insulative materials) and grass juices which were further processed into preotein rich products for animal feed as well as lactic acid for bioplastic production, with residues used for energy produciton via anaerobic digestion, was assessed by O'Keeffe et al. (O'Keeffe et al. 2012; O'Keeffe et al. 2011) . It was found that the grass biorefinery concept can be economically viable in an Irish context with the most suitable plant being one of medium scale processing grass silage only, wither with, or without protein produciton.

The optimal use of the poential resource of grass silage in Ireland, either for biomethane produciton, or for use as feedstock in biorefineries should be discerened future work to ensure that best use of the reosurce available is made.

5.6 Conclusions

The total theoretical biomethane resource of grass silage and cattle slurry identified in this work amounted to 128.4PJ.a^{-1} (35.67TWh.a^{-1}) and 9.6PJ.a^{-1} (2.67TWh.a^{-1}) respectively. The combined theoretical biomethane resource was equivalent to 76% of total natural gas consumption in 2015/16, 243% of industrial natural gas demand, and 69% of energy use in transport in 2015.

The results of the optimisation model showed that biomethane production of NPV positive plants ranged from 3.51 PJ.a^{-1} (0.975TWh.a^{-1}) to 12.19PJ.a^{-1} (3.385TWh.a^{-1}). The total production by NPV positive plants was equivalent to; 6% of energy use in transport, 6.7% of total natural gas consumption, 22% of industrial natural gas consumption, and 2.35 times the GNI renewable gas goal in 2025. The maximum production of biomethane in this work could supply up to 46.5% of the energy demand of HGVs in 2015, and 94-188% of the projected demand for CNG as a transport fuel in 2025.

Increased silage price was shown to result in increased LCOE while increased plant scale resulted in a lower LCOE. The impact of VSR was significant, with increased VSR resulting in a lower LCOE and an increase in biomethane production in all scenarios; additional biomethane production outweighed additional silage costs. The LCOE of biomethane ranged from 50.2-109€.MWh^{-1}. For plants to attain a positive NPV the monetary value of biomethane must be in excess of these values. At a VSR of 4-6 increasing the incentive increased plant profitability, not the total production of biomethane as no more plants could be developed. The average transportation distance for cattle slurry and grass silage was found to be 6.4km and 10.5 km respectively (in the median scenario). Plant profitability showed a strong correlation with annual transportation costs highlighting the need to take both plant and feedstock location into account. A high-level assessment of the carbon dioxide intensity of biomethane produced in the median scenario showed a potential greenhouse gas saving in the range of 75-80% when compared to natural gas primarily from avoided GHG emissions associated with slurry storage. Considering the large remaining portion of the total theoretical resource of grass silage and cattle slurry ca. 126PJ, alternative utilisation of the remaining resource

should be considered such as distributed biogas plants with mobile or centralised biogas upgrading.

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6 Chapter 6: An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network.

An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network.

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Abstract

For bioenergy installations producing heat, the minimum required GHG savings will be 85% from 2026. This is significant and a considerable challenge for biogas systems. This work investigates use of biogas from pig farms at a nearby milk processing facility, a large energy user. The work examines minimisation of greenhouse gas (GHG) emissions associated biogas production and delivery in particular in transporting slurry by road to a large centralised anaerobic digestion (CAD) facility or transporting biogas by low pressure pipe from decentralised anaerobic digestion (DAD) at the pig farms.

Four scenarios were assessed: "CAD1" road transport of slurry to a CAD located at the biogas end user (milk processing facility); "CAD2" transport of biogas by pipeline from an optimally located CAD located a distance from the biogas end user; "DAD1" DAD with biogas transportation in a biogas pipe network; and "DAD2" DAD with biogas transportation via a biogas pipe network of minimum length to reduce cost.

Scenario CAD2 (transporting biogas by pipe from optimally located CAD) reduced CO_2eq emissions associated with the road haulage of pig slurry by 49% compared to CAD1 (transporting slurry by road to a CAD at the milk processing facility) and 7% overall. Scenario DAD1 (distributed biogas production in DAD and transportation of the biogas by pipe) was shown to be the best scenario with CO_2eq emissions reduction of 19% compared to Scenario CAD1 (road transport of slurry with CAD at the biogas user). Scenario DAD2 (distributed biogas production in DAD while minimising length of the biogas network) reduced CO_2eq emissions by 18% relative to scenario CAD1, reduced the network length by 34% compared to scenario DAD1 but increasing total CO_2eq emissions by 1% compared to Scenario DAD1.

Keywords

Anaerobic digestion, biogas, biogas pipeline, biogas grid, centralised, distributed

6.1 Introduction

6.1.1 Background

The goal of reducing greenhouse gas (GHG) emissions by 20% in the EU is envisaged to be achieved by a reduction in GHG emissions in sectors governed by the Emission Trading Scheme (ETS) of 21% by 2020 (The European Parliament and the Council of the European Union 2009b), and a reduction in emissions from non-ETS sectors of 10% by 2020 relative to 2005 levels (European Environment Agency 2016). The ETS covers large energy users (such as electricity and heat production with a thermal rating more than 20MW). The non-ETS sectors include agriculture, residential energy consumption, and transportation. In addition to the GHG emission reduction targets, the EU also aims to ensure a renewable energy share of 20% by 2020 (The European Parliament and the Council of the European Union 2009a) and a minimum share of renewable energy in transport of 10% by 2020 (The European Parliament and the Council of the European Union 2009a).

A challenging aspect of meeting the non-ETS emission reduction targets in Ireland is the large role of agriculture in GHG production, accounting for 33.1% of total GHG emissions in 2015(Environmental Protection Agency 2017b), with 63% of agricultural emissions in the form of methane (CH_4) from enteric fermentation and manure management(Duffy et al. 2016). The Irish Environmental Protection Agency (EPA) predict that Ireland will not meet the 20% reduction in non-ETS emissions; reductions in non-ETS emissions are estimated to be 4%-6% relative to 2005 levels in 2020(Environmental Protection Agency 2017c). This predicted shortfall is due to growth in emissions from agriculture (4-5% of 2015 levels) and transport (10-12% of 2015 levels) to 2020 (Environmental Protection Agency 2017c).

For an energy source to count towards the renewable energy targets they must meet sustainability criteria, which specify the minimum required CO_2eq emissions saving compared to a standardised fossil fuel. These minimum required savings are set to increase from 50% for installations producing bioliquids and biofuels for use in transportation to 70% from 2021(European Commission 2017). For installations producing electricity, heating, and cooling, the minimum required GHG savings will be 80% from 2021, increasing to 85% in 2026 (European Commission 2017).

Meeting these emission savings criteria is critical in developing future renewable energy systems that can aid in meeting the GHG reduction targets.

To reduce GHG emissions in the non-ETS sector, reduce emissions in the ETS sector by offsetting fossil fuel use, and increase the share of renewable heat and transport (and the overall share of renewable energy) a promising technology pathway is the production of biogas via anaerobic digestion of livestock manures and slurries. Biogas and anaerobic digestion systems are a readily available commercial technology and are described in the literature(Wellinger et al. 2013; Al Seadi et al. 2013; Gerardi 2003). The benefits of digestion of animal manures and slurries are taken into consideration in the proposed revision to the Renewable Energy Directive (European Commission 2017), with a proposed bonus CO_2eq saving of -46gCO_2eq.MJ_{Manure}^{-1} arising from improved manure management(European Commission 2016).

Prior works have assessed the potential energy resource associated with livestock slurries and manures in Ireland(Singh et al. 2010; Wall et al. 2013; O'Shea, Kilgallon, et al. 2016). The resource identified was significant and ranged from 10.6-16.52 PJ/year (Singh et al. 2010; O'Shea, Kilgallon, et al. 2016)and could meet ca. 6-10% of natural gas demand in 2015/2016(Gas Networks Ireland 2016). Limitations on the distance over which livestock slurries can be hauled range from 10-30km(Bojesen et al. 2014; Dagnall 1995). In prior work by the authors the distance over which livestock slurries were transported to anaerobic digestion plants, which upgraded biogas to biomethane for injection to the gas network was found to be 10-20km(O'Shea, Wall, et al. 2016; O'Shea et al. 2017). The authors previously found that a significant portion of the livestock slurry resource was not utilised by anaerobic digestion plants producing biomethane for injection to the natural gas network owing to the resource being located too far a distance from potential gas grid injection points (O'Shea, Wall, et al. 2016; O'Shea et al. 2017).

A draw back associated with the use of animal slurries as a feedstock for anaerobic digestion is the high moisture content of slurry and low biogas yields per tonne of wet material. This increases the energy consumption associated with the road haulage of animal slurries to anaerobic digesters and results in a shorter feasible transportation distance to the biogas plant for slurries compared to feedstocks such

as slaughterhouse wastes (Berglund & Börjesson 2006) and other agro-industrial processing wastes (Dagnall et al. 2000) The transportation of feedstock to biogas plants can account for 30% of the total production costs (Bojesen et al. 2014) and can also be a limiting factor with respect to the sustainability of biogas production (Bekkering et al. 2010). The use of centralised anaerobic digestion facilities also presents issues in relation to bio-aerosols, odours, and heavy vehicle traffic (Righi et al. 2013).

One method to alleviate this issue is to transport the slurry to large CAD facility by pipeline as is the case for example, in Maabjerg Biogas plant in Denmark(IEA Task 37 2014). An alternative solution would be the use of DAD facilities processing slurry close to the point of production, and transporting biogas to a central point using low pressure biogas pipelines. Low pressure biogas pipelines have already been constructed in The Netherlands(IEA Bioenergy Task 37 2011; IEA Bioenergy Task 37 2017), Sweden(Persson & Svensson 2014; Biogas Brålanda n.d.), Germany, and Austria (European Biogas Association 2017) for the purpose of transporting biogas to a centralised upgrading facility or to a remote CHP unit.

The feasibility of using low pressure biogas pipelines to transport biogas to a centralised upgrading facility or biogas user has been assessed in prior literature. Results show that distributed biogas production and transportation to a centralised user via low pressure pipelines can be financially viable depending on the specific case in question (Van Eekelen et al. 2011; Prasodjo et al. 2013; Hengeveld et al. 2014; Hengeveld et al. 2016). It was also found that while the transportation of biogas (derived from maize silage) via low pressure pipelines reduced energy consumption associated with biomass transport, overall energy consumption in the biogas production process was not significantly altered(Hengeveld et al. 2014). Modelling of different network configurations showed that reducing overall pipeline length reduced cost, but increased energy consumed for gas compression (Hengeveld et al. 2016).

Different configurations of biogas production and delivery to an end user result in a different total emission of GHG and result in biogas systems with differing GHG emissions savings. Comparison of differing configurations is required when planning

a biogas production process to ensure that the biogas produced, or any energy derived therefrom, satisfies the GHG emission saving requirements.

6.1.2 Gap in state of the art

The main interest of prior works was the cost implication of differing biogas network configurations; the gap in the state of the art is the impact of network configuration on energy consumption and CO_2eq emissions in the production and delivery of biogas. The aim of this work is to assess the impact of different biogas production configurations on the energy consumption, GHG emissions, and biogas sustainability associated with biogas production from animal slurries in a region. This work is of importance owing to the need to ascertain methods in which the GHG savings associated with biogas production can be maximised to ensure that energy derived from the biogas is classified as being sustainable under the proposed increased GHG savings criteria of 85% from 2026(European Commission 2017).

6.1.3 Objectives

The aim of this work is to assess the impact of different biogas production configurations on the energy consumption and CO_2eq emissions associated with biogas production and delivery to an end user in a region. The implications of each configuration on the achievement of sustainability criteria will be assessed. This work will use a rural townland in the Republic of Ireland as an example, the region contains a large co-operative milk processing facility and several sources of pig slurry which could be used as feedstock for biogas production. A representation of the study region can be seen in Figure 6-1. The four scenarios of biogas production configuration assessed in this work are outlined in Table 6-1.
The methodologies used within this work can be applied in any region containing feedstock for biogas production, and a potential biogas user provided that sufficient data is available. The methodologies are not limited to the use of pig slurries as the sole feedstock, nor are they limited to biogas combustion as the end use of the biogas.

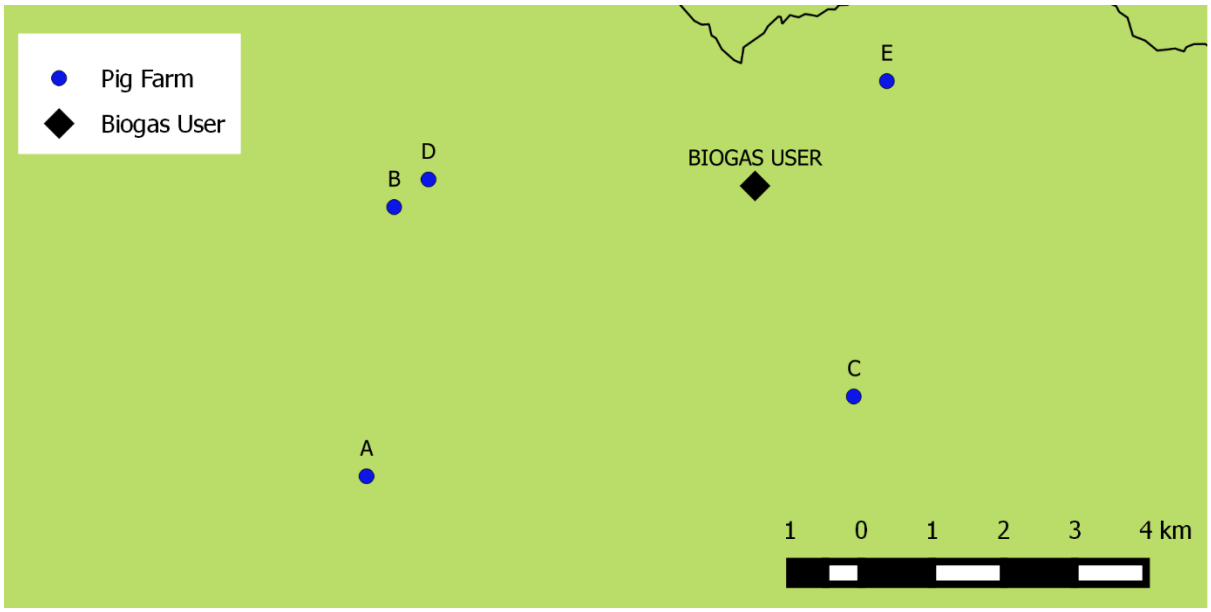


Figure 6-1 Location of pig farms and milk processing facility in the study region.

Table 6-1 Scenarios Assessed

Scenario	Description
CAD1	Transportation of pig slurry by road to a CAD facility co-located with a biogas end user
CAD2	Transportation of pig slurry by road to a CAD facility at a location to minimise road transportation energy use. Biogas is transported from the CAD facility to the end user through a biogas pipeline.
DAD1	Distributed anaerobic digestion (DAD) of pig slurry at each pig farm and transportation of the biogas to the biogas end user via biogas pipelines.
DAD2	DAD facilities processing pig slurry at each pig farm and transportation of the biogas to the biogas end user through a biogas grid of minimum length.

6.2 Methodology

6.2.1 Description of the study region

The region in which this work was conducted was a rural townland in the southern part of the Republic of Ireland. The major user of energy in this townland was a co-operative milk processing plant, which consumed ca. 292,511MWh of natural gas in 2016 (adapted from (Environmental Protection Agency 2017a)). The plant is required to reduce the emissions of CO_2eq generated on site relative to 2005 levels by 2020 as it is within the ETS. The estimated annual emission of CO_2eq from the facility was 59,724.1tCO_2eq (Environmental Protection Agency 2017a). The facility

already has an anaerobic digester onsite as part of a wastewater treatment system and burns the biogas in a boiler to provide process heat to the plant. Owing to the large thermal demand, and the pre-existing use of biogas at the milk processing plant it was deemed a suitable candidate for increased biogas use.

Pig slurry was identified as a potential source of feedstock for use in the production of biogas via anaerobic digestion in the region. The townland had 5 large pig farms within a 7km radius, with pigs housed indoors year-round enabling the collection of slurry. Slurry storage methods at the pig farms result in GHG emissions in the form of CH_4 and N_2O; anaerobic digestion of the pig slurry would help to mitigate these GHG emissions. Combustion of biogas produced from this pig slurry at the milk processing plant would reduce GHG emissions by replacing the consumption of natural gas.

6.2.2 Calculation of baseline greenhouse gas emissions from the study region

The population of pigs and the total production of slurry (M_{slurry}) in the study region was determined from annual environmental reports (AERs) of the 5 pig farms (Environmental Protection Agency 2017b). The farms housed a total of ca. 76,200 swine and produced ca. 122,000$t_{wwt}.a^{-1}$ of slurry. The total annual emissions of CH_4 ($ECH_{4\,i}$) and N_2O (EN_2O_i) arising from slurry management at each facility (i) were calculated using emissions factors for CH_4 ($eCH_{4\,j}$) and N_2O (eN_2O_j) per head of swine type (j) as per EPA guidelines (Environmental Protection Agency 2016b).
Pig slurry was transported over a distance (d_{Land}) of 12km for spreading on agricultural land (Fealy et al. 2012) using a diesel fuelled truck carrying a payload of 25t_{wwt} of pig slurry, with a specific energy consumption of transportation ($SE_{transport}$) of 0.876MJ.tkm_{slurry}^{-1} inclusive of empty return (adapted from(Guintoli et al. 2014b)). The emission of CH_4 ($eCH_{4\,tkm}$) and N_2O (eN_2O_{tkm}) per tonne-kilometre of slurry (tkm_{slurry}) were 0.003672gCH_4.tkm_{slurry}^{-1} and 0.00162gN_2O.tkm_{slurry}^{-1} respectively (adapted from (Guintoli et al. 2014b)). The emission intensity of diesel ($eCO_{2,\,Diesel}$) was taken to be 93.95gCO_2eq.MJ^{-1} (standard emission coefficient of diesel) as per Biograce II (Neeft & Ludwiczek 2016)).

The total equivalent CO_2 emissions ($ECO_2eqBase_{Total}$) were calculated using a global warming potential of 25 for CH_4 and 298 for N_2O (Guintoli et al. 2014b). Calculation of $ECO_2eqBase_{Total}$ from the storage of pig slurry ($ECO_2eqBase_{slurry,\ store}$), and its transportation to land for spreading ($ECO_2eqBase_{slurry,\ transport}$) was found using Equation 6-1.

Equation 6-1: Total CO_2eq emissions from baseline scenario

$$E\ CO_2eq\ Base = \left(\sum_i \sum_j eCH_{4\ j} * j_i * 25 + eN_2O_j * j_i * 298\right) + M_{slurry} * d_{Land} * \left(SE_{transport} * e_{CO_2,Diesel} + eCH_{4\ tkm} * 25 + eN_2O_{tkm} * 298\right)$$

6.2.3 Scenarios Investigated

The following sections describe in detail the four scenarios of biogas production in the study region outlined in section 6.1.3. To the authors' knowledge this is the first time that the four specific scenarios will be compared to one another in a single body of work.

6.2.3.1 Centralised anaerobic digestion facility located at the biogas end user (CAD1)

Scenario CAD1 assessed the road haulage of pig slurry to a CAD facility situated adjacent to the milk processing plant. Energy consumption and CO_2eq emissions were calculated according to the methodology outlined by the Joint Research Centre (JRC) (Guintoli et al. 2014b). The CO_2eq emissions arising from the transportation of slurry ($ECO_2eqCAD1_{Transport,\ slurry}$) were calculated using the annual mass of slurry available at each pig farm ($m_{slurry,\ i}$) and the Euclidian distance ($d_{farm,i\text{-}AD}$) between the pig farms and the proposed digester location according to Equation 6-2.

Equation 6-2: CO_2 emissions from transport of slurry to centralised anaerobic digester at the milk processing plant

$$E\ CO_2eq\ CAD1_{transport,slurry} = \left(\sum_i m_{slurry,i} * d_{farm_i-AD}\right) * \left(SE_{transport} * e_{CO_2,Diesel} + eCH_{4,tkm} * 25 + eN_2O_{tkm} * 298\right)$$

The energy resource associated with the digestion of pig slurry was calculated using a volatile solid (*VS*) content of 2.6%$_{wwt}$ and a specific methane yield (*SMY*) of 291LCH_4.kgVS^{-1} (Xie 2012; Thygesen et al. 2014; Asam et al. 2011; Angelidaki & Ellegaard 2003) at standard temperature and pressure (STP) of 273.15K and 101,325Pa. The density of methane at STP ($\rho CH_{4,\ STP}$) was taken as 0.714 kg.m^{-3} with a lower heating value of methane (LHV_{CH4}) of 50MJ.kg^{-1} (The European Parliament and the Council of the European Union 2009a).

The electrical energy consumed in the digestion process ($SE_{AD,elec}$) was 0.02MJ_e.$MJ_{biogas,\ gross}^{-1}$ and the heat energy consumed in the digestion process ($SE_{AD,heat}$) was 0.1MJ.$MJ_{biogas,\ gross}^{-1}$ (Guintoli et al. 2014b). Electricity was sourced from the electricity network with a CO_2 intensity ($e_{CO2,\ elec}$) of 164.4gCO_2eq.MJ_e^{-1} (BioGrace Additional Standard Values, Irish electricity, Version 4d). Heat used in the digestion process was supplied by burning biogas in a gas boiler with an efficiency (η_{boiler}) of 90%. Emissions of CH_4 ($e_{CH4,\ heat}$) and N_2O ($e_{N2O,\ heat}$) associated with heat production were 0.0028gCH_4.MJ_{Heat}^{-1} and 0.00112gN_2O.MJ_{Heat}^{-1} respectively (Guintoli et al. 2014b).

The total CO_2 emissions, associated with the digestion of pig slurry at a CAD facility located at the user ($ECO_2eqCAD1_{Digestion}$) was calculated as per Equation 6-3. Fugitive emissions of CH_4 from the digestion process were taken to be zero in this study as they were not the main focus off the work, emissions from digestate storage were not considered as the digestate was to be stored in a covered structure, enabling CH_4 recovery or thermal oxidation (Guintoli et al. 2014a).

Equation 6-3: CO_2 emission of digestion process

$$E\ CO_2eq\ CAD1_{Digestion} = \left(\sum_i m_{slurry,i} * VS * SMY)\right) * \rho CH_{4STP} * LHV_{CH_4} * \left(SE_{AD,Elec} * e_{CO_2,elec} + SE_{AD,heat} * \left(e_{CH_4,heat} * 25 + e_{N_2O,heat} * 298\right)\right)$$

The VS destruction (VS_{Dest}) of the digestion process was assumed to be 85% (Thamsiriroj & Murphy 2010); this resulted in a mass of digestate which was 97.8% of the total mass of slurry accepted by the CAD facility. Digestate was transported 12km to agricultural land (d_{land}), to ensure that the nutrient value of the digestate was utilised. The CO_2eq emission arising from the transportation of digestate by road to land for spreading was calculated using Equation 6-4.

Equation 6-4: CO_2 emissions from the transportation of digestate to land

$$E\ CO_2eq\ CAD1_{transport,digestate} = \left(\sum_i m_{slurry,i}(1 - * VS_{slurry} * VS_{Dest}) * d_{land}\right) * \left(SE_{transport} * e_{CO_2,Diesel} + eCH_{4,tkm} * 25 + eN_2O_{tkm} * 298\right)$$

The total CO_2eq emissions arising in scenario CAD1 ($E\ CO_2eq\ CAD1_{Total}$) were found as the sum of $ECO_2eq\ CAD1_{Transport,slurry}$, $E\ CO_2eq\ CAD1_{Digestion}$, $E\ CO_2eq\ CAD1_{Transport,\ digestate}$.

6.2.3.2 Centralised anaerobic digester remote from the biogas user combined with pipeline transportation of the biogas to the end user (CAD2)

Scenario CAD2 assessed the transportation of pig slurry to a CAD facility located at a point which would minimise the total slurry transportation energy consumption ($E^{Transport}{}_{Tot}$), this method is similar to finding the Weber point (Tellier 1972; ReVelle & Eiselt 2005). The location of this CAD facility was estimated using an iterative

method. The location of each pig farm was plotted on a Euclidian plane 9,000m x 5,000m, a 10m x 10m grid was overlaid on the plane, the corner points of each grid square were potential locations for the CAD facility. The value of $E^{Transport}{}_{Tot}$ was found knowing the Euclidian distance between the proposed facility location, the pig farm locations, and the mass of slurry to be transported from each pig farm. The energy consumption for road transportation was calculated as outlined in section 6.2.3.1. A flowchart illustrating the calculation process can be seen in Figure 6-2, the calculation was conducted using MATLAB. As a comparison, the problem was also formulated in Microsoft Excel, the objective was to minimise the total energy consumption associated with road haulage of slurry and was solved using the inbuilt GRG nonlinear solver.

The CO_2eq emissions associated with road transportation of slurry to the selected CAD facility ($E\ CO_2eq\ CAD2_{Transport,slurry}$) were calculated using Equation 6-2 with the distance between each pig farm and the CAD facility ($d_{farm,i\text{-}CAD}$) updated accordingly. The emissions of CO_2eq associated with the digestion of pig slurry ($ECO_2eqCAD2_{Digestion}$), and the transportation of digestate for land spreading ($ECO_2eqCAD2_{Transport,\ \mathrm{Digestate}}$) were calculated in the same manner as scenario CAD1.

The CAD facility in this scenario (CAD2) was not co-located with the end user of the biogas and thus, transportation of biogas to the user was required. The use of a pipeline to transport dewatered and de-sulphurised biogas to the user was assessed. The pipeline length was the Euclidian distance between the CAD facility and the user. The pipeline was modelled as a polyethylene pipe with an internal diameter (D) of 0.1m, and an absolute roughness (ε) of $3x10^{-6}$m. The delivery pressure (P_{user}) and temperature (T_{user}) of biogas to the user were 111,325$Pa_{absolute}$ at 288.15K, the biogas flow into the compressor from the anaerobic digester was assumed to be at 111,325$Pa_{abasolute}$ (P_{AD}) and 288.15K (T_{AD}). Flow of gas through the pipeline was modelled as being isothermal. The volumetric flow rate of biogas per hour (Q_{biogas}) from the digester, assuming 8,760 hours of operation per year, was calculated according to Equation 6-5. The density of CH_4 at the outlet conditions from the anaerobic digester ($\rho CH_{4,AD}$) was calculated to be 0.745$kg.m^{-3}$, the concentration of CH_4 in the biogas (Y_{CH4}) used in this work was 60%.

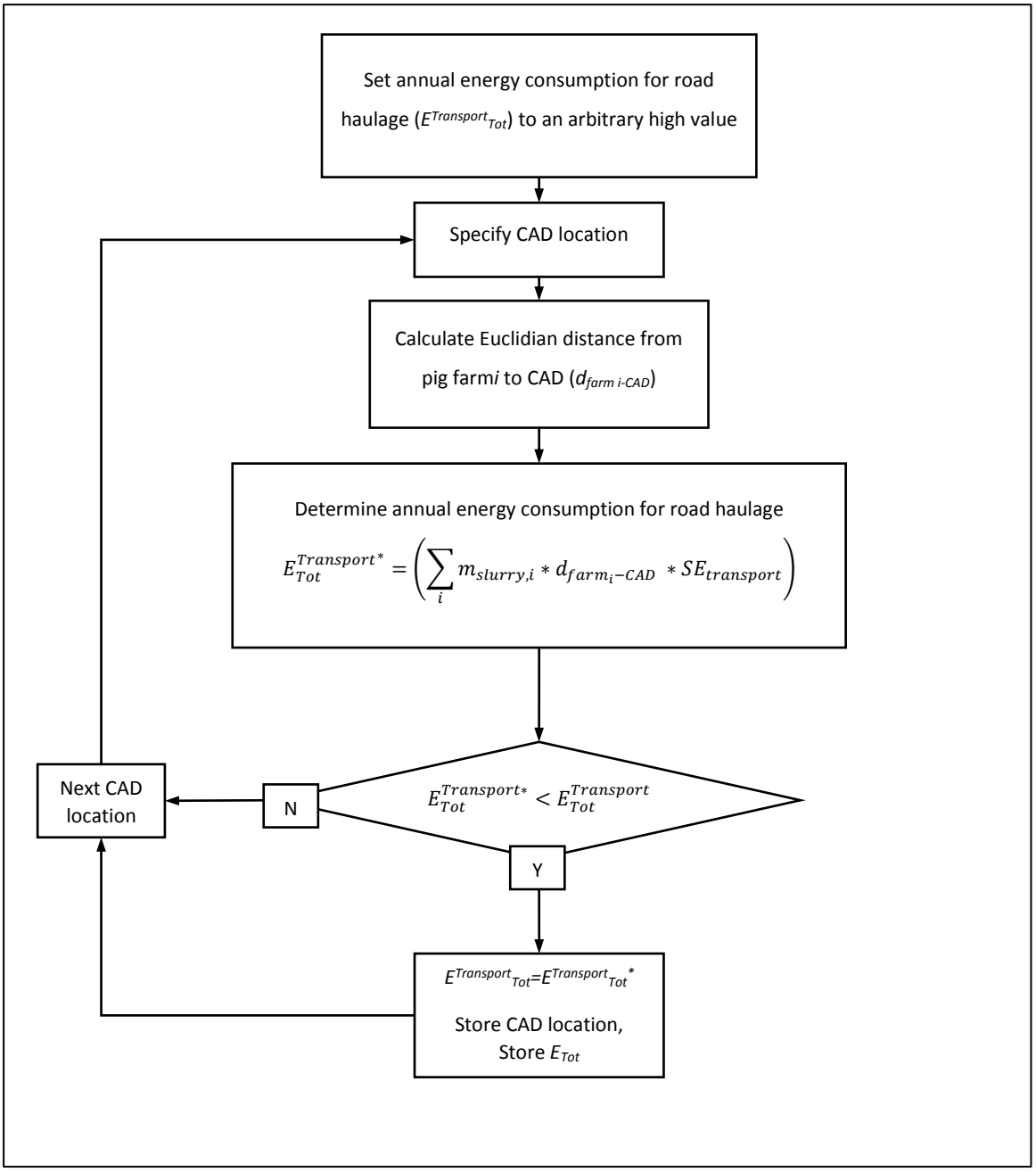


Figure 6-2: Flowchart for calculation of centralised anaerobic digester location to minimise road haulage energy consumption, scenario CAD2.

Equation 6-5: Hourly net flow rate of biogas from Centralised Anaerobic Digester

$$Q_{biogas} = \frac{\left(\frac{\left(\left(\sum_i m_{slurry,i} * VS * SMY\right)\right) * \rho CH_{4STP} * \left(1 - \frac{SE_{AD,Heat}}{\eta_{boiler}}\right)\right)}{\rho CH_{4_{AD}}}}{8760 * Y_{CH_4}}$$

6.2.3.2.1 Calculation of pressure drop in biogas pipeline

The calculation of frictional pressure drop (ΔP) along the biogas pipeline was conducted in two ways, the first considered the flow as being that of an incompressible ideal gas owing to the low pressures and temperatures involved. The second considered the flow was being that of a compressible ideal gas. Derivations of the governing equations are based on gas pipeline design literature (Coelho & Pinho 2007; Liu 2003; Shashi Menon 2005).

6.2.3.2.1.1 Incompressible ideal flow

The data required for the calculation of the pressure drop along the biogas pipeline if the flow of biogas in the pipeline can be considered as an incompressible and ideal flow is shown in Table 6-2.

Table 6-2 Data required for pressure drop calculation, incompressible flow

Data input	Symbol	Unit	Value	Reference
Pipe length	L	m	User specified	
Pipe Diameter	D	m	User specified	
Pipe roughness	ε	m	User specified	
Volumetric flowrate of biogas at digester outlet conditions	Q	$m^3.hour^{-1}$	User specified	
Temperature of biogas at digester outlet	T_{AD}	K	User specified	
Pressure of biogas at digester outlet	P_{AD}	Pa	User specified	
Volume fraction of methane in biogas	Y_{CH4}	%	User specified	
Volume fraction of carbon dioxide in biogas	Y_{CO2}	%	User specified	
Molar mass of CH_4	M_{CH4}	$g.mol^{-1}$	16.0425	(National Institute for Standards and Technology 2017b)
Molar mass of CO_2	M_{CO2}	$g.mol^{-1}$	44.0095	(National Institute for Standards and Technology 2017a)
Universal gas constant	Ru	$J.kmol^{-1}.K^{-1}$	8314.41	
Dynamic viscosity CH_4	μ_{CH4}	Pa.s	0.000010862	(National Institute for Standards and Technology 2017b)
Dynamic viscosity CO_2	μ_{CO2}	Pa.s	0.000014446	(National Institute for Standards and Technology 2017a)
Desired outlet pressure	P_{user}	Pa	User specified	
Initial guess for f in Prandtl von Karmann Equation	f	na	User specified	
Adiabatic efficiency	η Adiabatic	na	User specified	
Mechanical Efficiency	η Mechanical	na	User specified	

Pressure drop was calculated according to the Darcy Weisbach equation as per Equation 6-6.

Equation 6-6 Darcy Weisbach equation for pressure drop along gas pipeline, incompressible flow.

$$h_f = \frac{\rho_{Biogas_{AD}} f L V^2}{2D}$$

In Equation 6-6 $\rho_{Biogas,\ pipe}$ is the density of the biogas at the pipe inlet conditions, *f* is the Darcy friction factor, *L* is the pipeline length, *V* is the velocity of biogas flow in the pipeline, and *D* is the pipeline diameter.

The density of biogas was calculated using Equation 6-7.

Equation 6-7 Calculation of biogas density

$$\rho_{Biogas_{pipe}} = \frac{M_{Biogas} P_{Biogas_{AD}}}{R_u * T_{Biogas_{AD}}}$$

The molar mass of biogas was calculated based on the composition of biogas according to Equation 6-8.

Equation 6-8 Molar mass of biogas

$$M_{Biogas} = Y_{CH_4} * M_{CH_4} + Y_{CO_2} * M_{CO_2}$$

Biogas velocity in the pipeline is calculated according to Equation 6-9.

Equation 6-9 Biogas velocity in pipeline

$$V_{Biogas} = \frac{Q_{AD}}{A_{pipe}}$$

The Darcy friction factor, *f*, was calculated depending on the value of the Reynold's number (*Re*) of the flow, the Reynold's number was calculated according to Equation 6-10.

Equation 6-10 Reynold's number of biogas flow

$$Re = \frac{\rho_{AD} V D}{\mu_{biogas}}$$

The value of dynamic viscosity (μ_{biogas}) of biogas was calculated according to Equation 6-11 (Shashi Menon 2005).

Equation 6-11 Dynamic viscosity of biogas

$$\mu_{biogas} = \frac{\mu_{CH_4} * Y_{CH_4} * \sqrt{M_{CH_4}} + \mu_{CO_2} * Y_{CO_2} * \sqrt{M_{CO_2}}}{Y_{CH_4} * M_{CH_4} + Y_{CO_2} * M_{CO_2}}$$

Depending on the value of the Reynold's number, one of three methods were used to calculate the Darcy friction factor (Coelho & Pinho 2007). The value of Re_{Crit}, the Reynold's number at which there is a change between partially developed turbulent flow and fully developed turbulent flow was also determined as per (Coelho & Pinho 2007). The methodologies for the calculation of *f* can be seen in Table 6-3

Table 6-3 Calculation of Darcy Friction Factor 'f'

Value of Re	**Flow regime**	**Calculation of *f***
Re<2,100	Laminar	$f = \frac{64}{Re}$
		$\boldsymbol{Re_{crit} = 35.235\left(\frac{\epsilon}{D}\right)^{-1.1039}}$
2,100<Re<Re_{Crit}	Partially developed turbulent	$f = \left(-\frac{1}{2\log_{10}\left(\frac{2.825}{Re\sqrt{f}}\right)}\right)^2$ Prandtl-Von Karmann equation*
Re_{Crit}<Re	Fully developed turbulent	$f = \left(-\frac{1}{2\log_{10}\left(\frac{\epsilon}{3.7D}\right)}\right)^2$ Nikuradse Equation

*The calculation of *f* according to the Prandtl-Von Karmann equation required an initial guess for *f* and was solved iteratively until the difference between successive values of *f* was less than 0.0001.

A flow chart outlining the calculation of the pressure drop along the biogas pipeline assuming incompressible ideal flow can be seen in Figure 6-3.

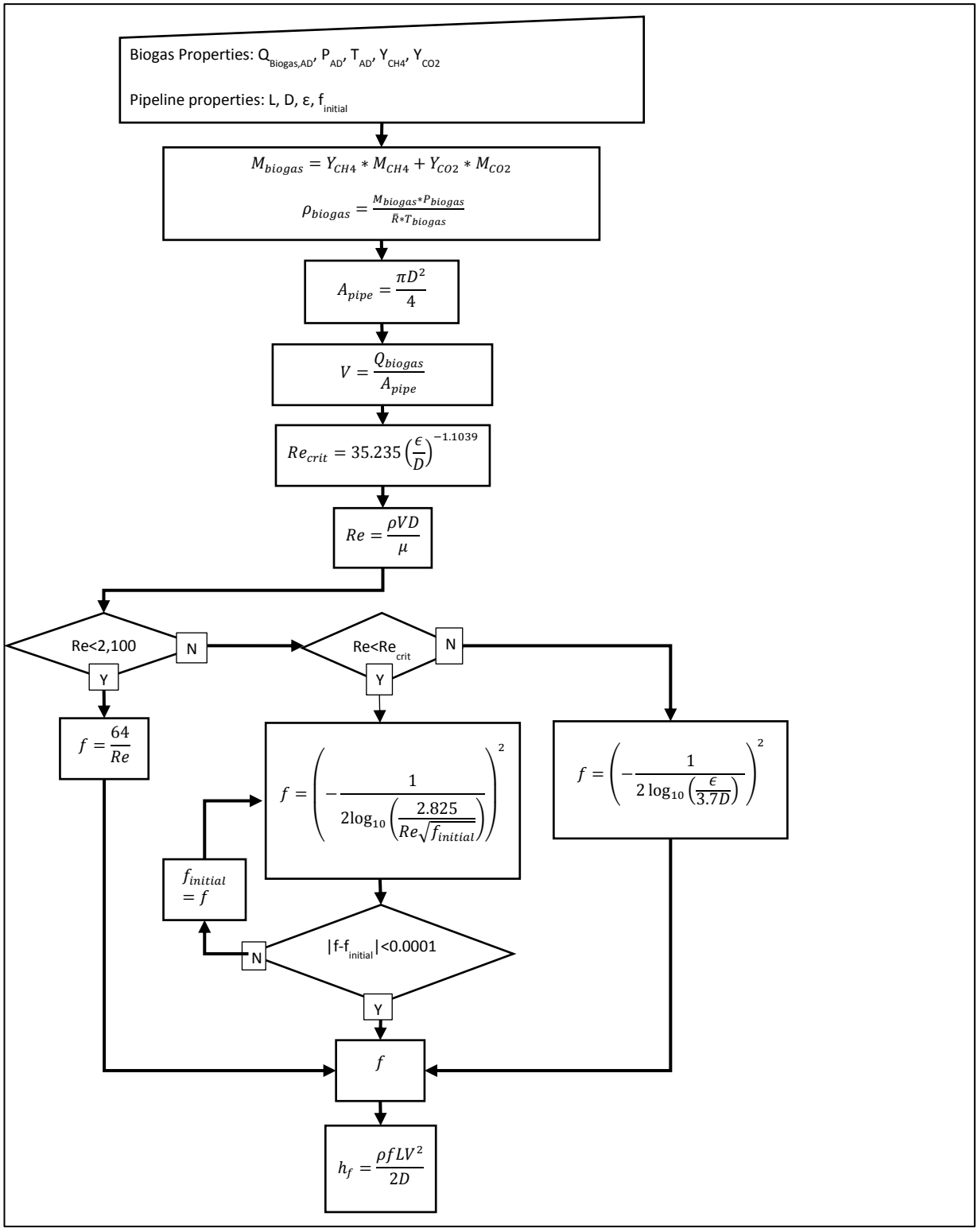


Figure 6-3 Flowchart of pressure drop calculation, incompressible ideal flow

An Excel spreadsheet and MATLAB code were developed (Appendix C) for the calculations.

6.2.3.2.1.2 Compressible ideal flow

The second methodology used to calculated pressure drop along the biogas pipeline considered the flow as being compressible and ideal. In this methodology the density of the biogas varies along the length of the pipeline and is not constant. A general flow equation for gas in a pipeline is shown in Equation 6-12 (Coelho & Pinho 2007).

Equation 6-12 General flow equation of gas in a pipeline

$$\frac{M_{Biogas}}{z_{avg}RT_{avg}}(P_1^2 - P_2^2) + \frac{gP_{avg}^2 M_{Biogas}^2}{z_{avg}^2 R^2 T_{avg}^2}(H_2 - H_1) + \frac{fL8P_{ST}^2 * M_{Biogas}^2 * Q_{ST}^2}{\pi^2 D^5 z_{ST}^2 R^2 T_{ST}^2} = 0$$

An explanation of the terms used in Equation 6-12 is shown in Table 6-4.

Table 6-4 Parameters used in general flow equation

Symbol	Parameter	Unit	Value
M_{Biogas}	Molar mass biogas	$g.mol^{-1}$	Calculated
Z_{avg}	Average biogas compressibility factor	na	1
R_u	Universal gas constant	$J.kmol.K^{-1}$	8314.41
T_{avg}	Average flow temperature	K	Calculated
P_1	Pressure at pipe inlet	Pa	Calculated
P_2	Pressure at pipe outlet	Pa	User specified
H_1	Elevation of pipe inlet	m	User specified
H_2	Elevation of pipe outlet	m	User specified
F	Darcy friction factor	na	Calculated
L	Pipe length	m	User specified
P_{ST}	Pressure at standard conditions	Pa	101,325
Q_{ST}	Flow at standard conditions	$m^3.s^{-1}$	Calculated
T_{ST}	Temperature at standard conditions	K	288.15
D	Pipe diameter	m	User specified
Z_{ST}	Biogas compressibility factor at standard conditions	na	1

If the inlet and outlet of the biogas pipeline are at the same elevation Equation 6-12 can be simplified yielding Equation 6-13.

Equation 6-13 General flow equation with equal elevation for inlet and outlet

$$\frac{M_{Biogas}}{z_{avg}RT_{avg}}(P_2^2 - P_1^2) + \frac{fL8P_{ST}^2 * M_{Biogas}^2 * Q_{ST}^2}{\pi^2 D^5 z_{ST}^2 R^2 T_{ST}^2} = 0$$

The compressible flow methodology calculates the frictional head loss in an iterative manner. A flowchart summarising the calculation can be seen in Figure 6-4.

Calculations were conducted using an Excel spreadsheet and MATLAB code developed by the authors (Appendix C)

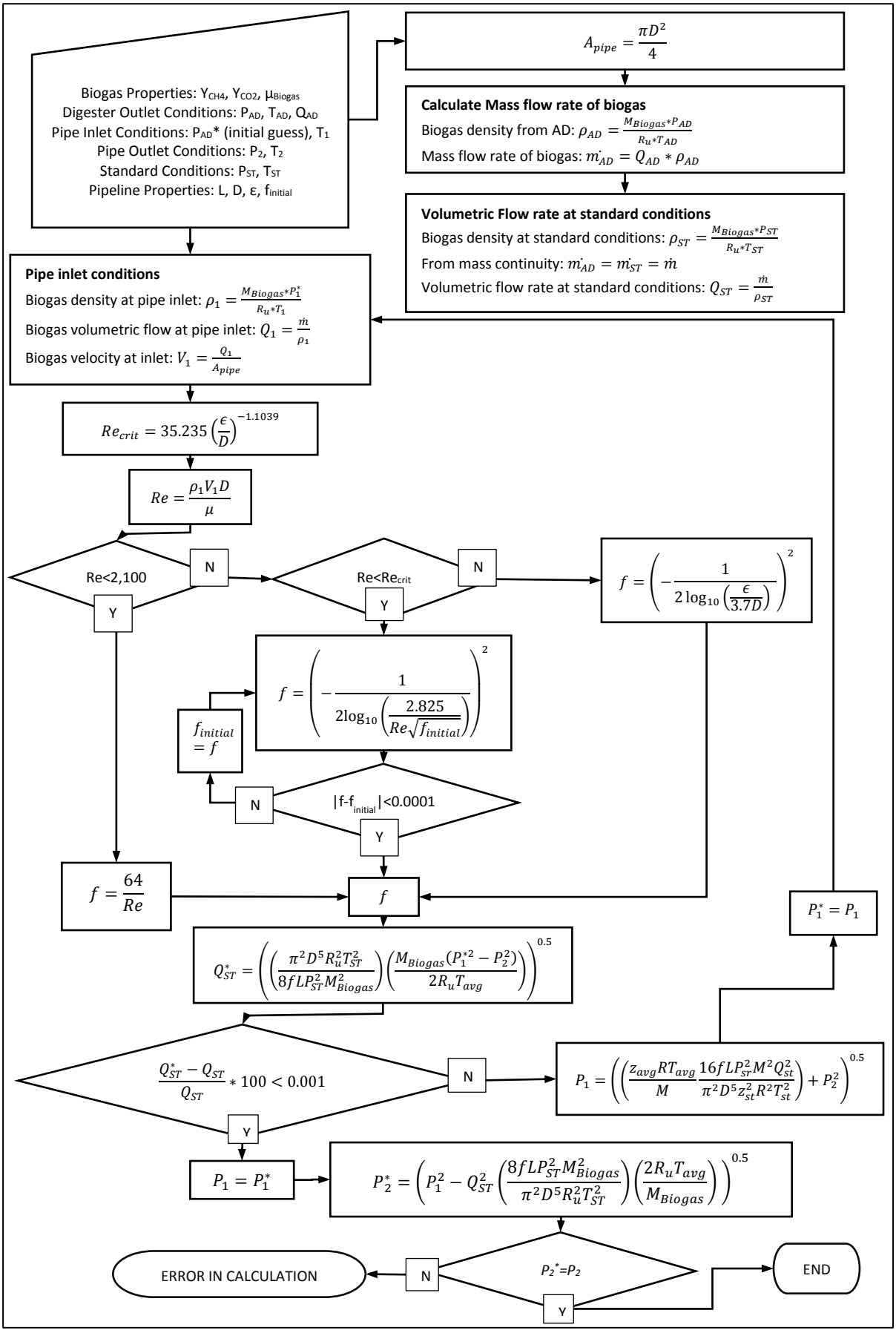


Figure 6-4 Flowchart of pressure drop calculation, compressible ideal flow

A range of calculated pressure drops for both the incompressible and compressible flow methodologies was calculated to compare the two methodologies. The flow rates used ranged from 20-120$m^3.hour^{-1}$, pipeline length was varied from 500-4,500m, and pipe diameter was set to 0.1m. The percentage difference between the pressure drop calculated using the incompressible methodology and the compressible methodology is shown in Figure 6-5.

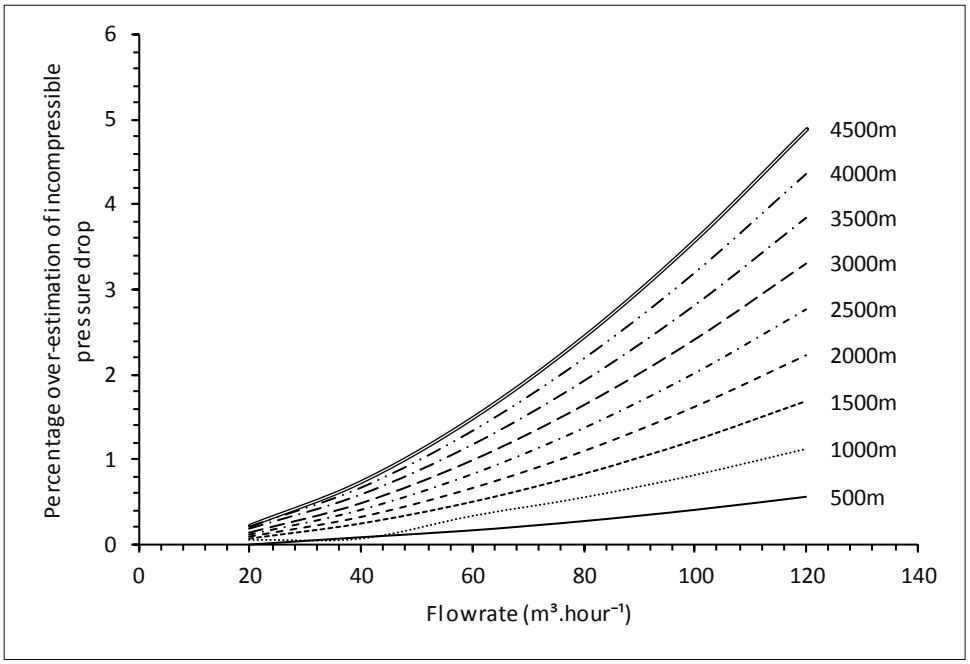


Figure 6-5 Percentage difference in pressure drop between incompressible, and compressible flow calculations

Similar pressure drops were calculated using both methodologies. The incompressible methodology overestimates the pressure drop by a maximum of 4.9% compared to the compressible flow methodology, as such, the compressible flow methodology was used in further calculations.

6.2.3.2.2 Electrical energy consumption of biogas compression

The electrical energy required for compression of biogas ($E_{compression}$) leaving the digester to the required pipeline inlet pressure was calculated as the energy consumption of an adiabatic compressor with an adiabatic efficiency (η_{adiab}) of 80% and a mechanical efficiency (η_{mech}) of 95%. The annual electrical energy consumption of the compressor (MJ.a^{-1}) was calculated according to Equation 6-14 adapted from (Liu 2003; Shashi Menon 2005).

Equation 6-14: Compressor electricity requirement

$$E_{compression} = \left(\frac{k}{k-1}\right)\left(\frac{1}{R}\right)T_1\left(\left(\frac{P_{outlet}}{P_{inlet}}\right)^{\frac{k-1}{k}} - 1\right)\left(\frac{1}{\eta_{mech}\eta_{adiab}}\right)\dot{m}_{biogas}\frac{(3600 * 8760)}{1{,}000{,}000}$$

In Equation 6-14 P_{inlet} corresponds to the pressure of the biogas entering the compressor from the digester, P_{outlet} corresponds to the pressure exiting the compressor flowing to the pipeline.

The ratio of specific heats, k, (C_p/C_v) for biogas was calculated using the values of C_p and C_v for methane and carbon dioxide. The specific heat at constant pressure for methane and carbon dioxide were calculated using the Shomate Equation with coefficients sourced from the National Institute of Standards and Technology (Chase 1998) at the inlet temperature to the compressor (i.e. the outlet temperature from the digester).

The specific heats at constant pressure for CH_4 and CO_2 were calculated according to Equation 6-15.

Equation 6-15 Calculation of molar heat capacity at constant pressure

$$C_p = A + B\left(\frac{T_{Biogas_{AD}}}{1000}\right) + C * \left(\frac{T_{Biogas_{AD}}}{1000}\right)^2 + D * \left(\frac{T_{Biogas_{AD}}}{1000}\right)^3 + \frac{E}{\left(\frac{T_{Biogas_{AD}}}{1000}\right)^2}$$

Values of the coefficients used in Equation 6-15 are shown in Table 6-5.

Table 6-5 Coefficient values for use in the Shomate equation to determine molar specific heat capacity for CH_4 and CO_2

Coefficient	CH_4	CO_2
A	-0.703029	24.99735
B	108.4773	55.48696
C	-42.52157	-33.69137
D	5.862788	7.948387
E	0.678565	-0.136638

The value of C_v for methane and carbon dioxide respectively was found by subtracting the individual gas constant (R_{CH4} and R_{CO2}) from the value of C_p for each gas. The individual gas constant of methane and carbon dioxide was the universal gas constant divided by the molar mass of each compound in question.

Emissions of CO_2 associated with the electricity used in the compressor ($ECO_2eqCAD2_{Biogas,\ compression}$) were calculated using the same value of $e_{CO2,\ elec}$ ($164.4gCO_2eq.MJ_e^{-1}$) as in Section 6.2.3.1. The total CO_2eq emissions arising in scenarioCAD2 ($E\ CO_2eq\ CAD2_{Total}$) were found as the sum of $E\ CO_2eq\ CAD2_{Transport.slurry}$, $E\ CO_2eq\ CAD2_{Digestion}$, $ECO_2eqCAD2B_{iogas\ compression,}$ and $E\ CO_2eq\ CAD2_{Transport,\ digestate}$.

6.2.3.3 Distributed anaerobic digestion, transportation of biogas to a central nexus point, and then transportation to the end user (DAD1)

The third scenario (DAD1) assessed the energy consumption and CO_2eq emissions associated with the digestion of pig slurry at each pig farm using DAD facilities. The energy requirement in the digestion process and the associated CO_2 emissions ($ECO_2eqDAD1_{Digestion}$) were calculated using Equation 6-3 on a per pig farm basis. The energy requirement and CO_2 emissions from the transportation of digestate from each pig farm ($ECO_2eqDAD1_{Digestate,\ transport}$) with an anaerobic digestion system was calculated using Equation 6-4 with a transportation distance of 12km as in prior scenarios.

Biogas was transported from each digester to the biogas end user via low pressure biogas pipelines. A simple approach would be to build a dedicated pipe from each DAD facility to the user in a “star” pattern as assessed by Hengeveld et al. (Hengeveld et al. 2014; Hengeveld et al. 2016). In this work, a modified approach was considered. A “nexus” point was proposed to which each DAD facility could pipe biogas, the biogas would then flow from the nexus point to the end user. The hypothesis was that it may require less energy to pipe biogas to the nexus and then to the user depending on the nexus location, than piping biogas directly to the user from the digesters at the pig farms. The layout of the simple “star” connection pattern and the connection pattern with a potential nexus is illustrated in Figure 6-6.

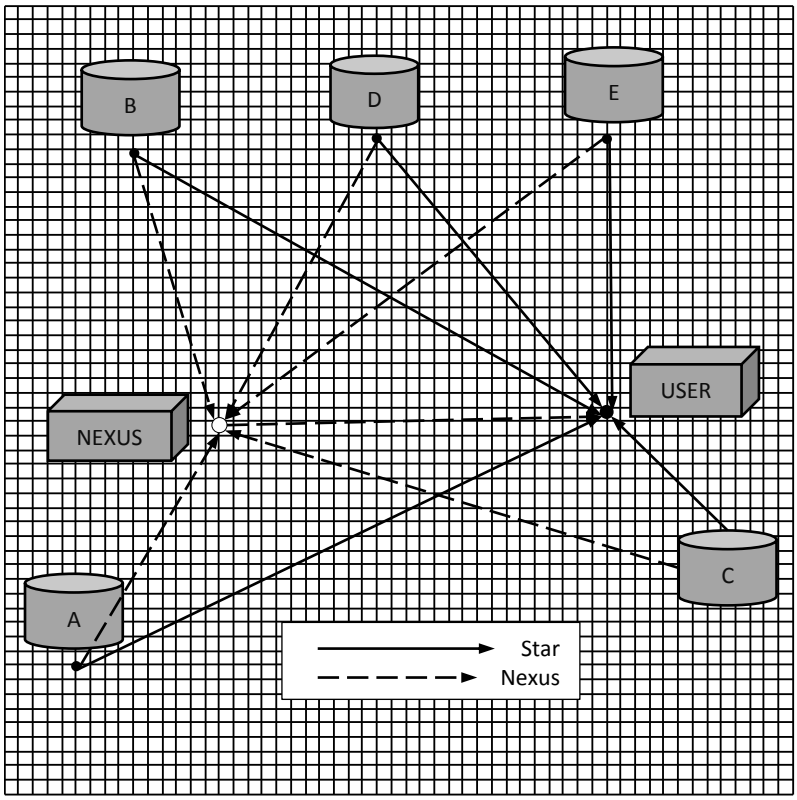


Figure 6-6: Biogas Pipeline configuration, star connection and nexus connection, scenario DAD1.

The location of the nexus point, which would minimise the total energy requirement for compression of biogas at all DAD facilities was found iteratively. A 10m x 10m grid was superimposed onto the plane containing the 5 pig farms and

the biogas end user; the corners of each 10m x 10m grid square were potential nexus points. Figure 6-7 outlines the calculation method used to determine the nexus point that would minimise the total electrical energy required for biogas compression ($E^{Compression}_{Tot}$).

The CO_2eq emissions associated with the electricity consumed for the compression of biogas ($ECO_2eqDAD1_{Biogas,\ compression}$) at each DAD facility was calculated as per Section 6.2.3.2.2. The total emission of CO_2eq in scenario DAD1 ($ECO_2eqDAD1_{Total}$) was the sum of $ECO_2eqDAD1_{Digestion}$, $ECO_2eqDAD1_{Digestate,\ transport}$, and $ECO_2eqDAD1_{Biogas,\ compression}$.

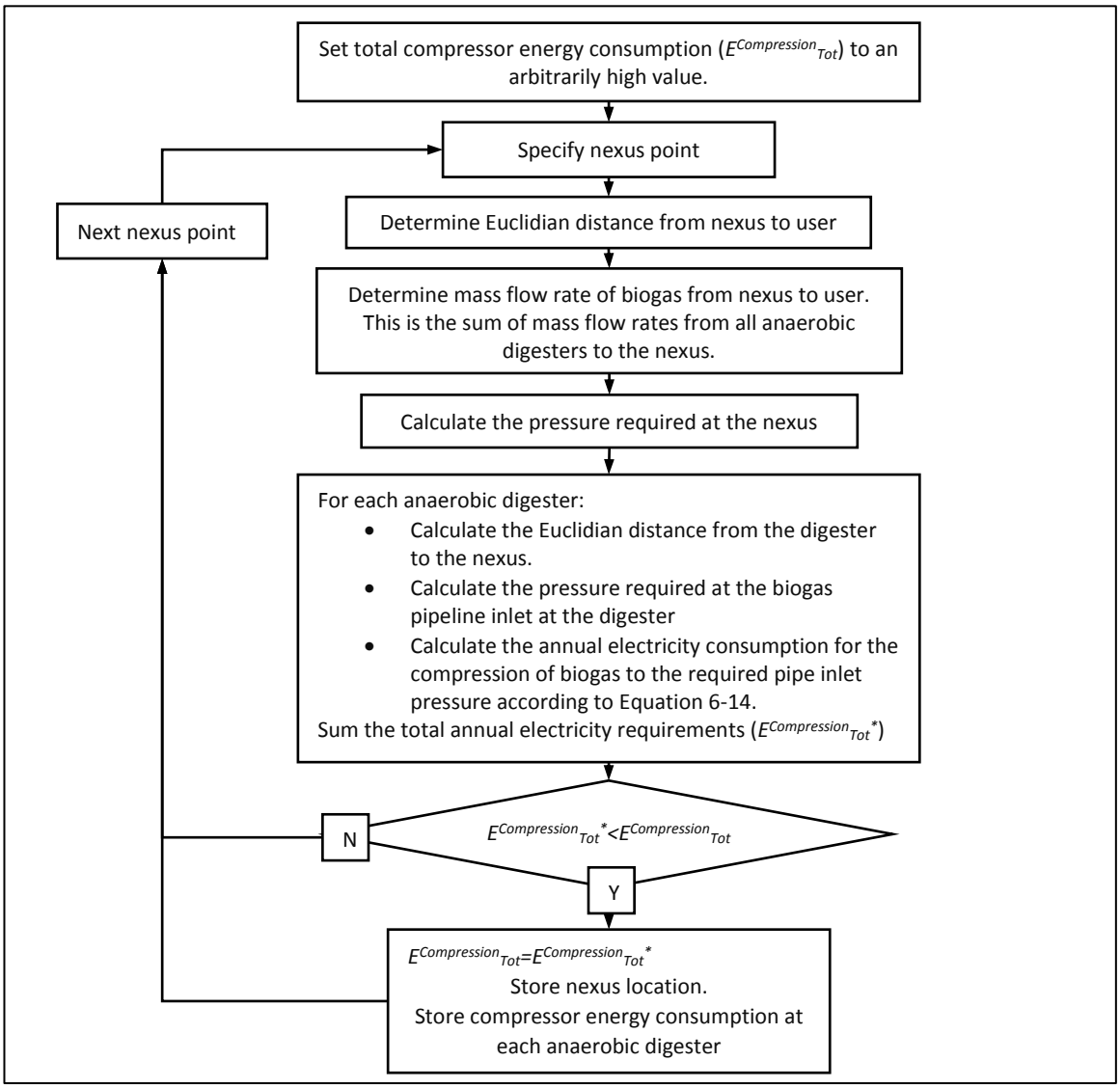


Figure 6-7: Flowchart outlining the method to determine the location of a biogas pipeline network that would minimise compressor energy consumption, scenario DAD1

6.2.3.4 Distributed anaerobic digestion and transportation of biogas to end user with minimisation of biogas pipeline length (DAD2)

Scenario (DAD2) assessed the impact of minimising the total length of biogas pipeline required (L_{Total}) to link DAD facilities at the pig farms and the biogas end user. A significant cost in the development of any pipeline network is the capital cost of the pipes, the installation cost of the pipes, and right of way payments ("way leaves") to access the pipes when they run through private lands.

Knowing the location of each pig farm and knowing the location of the end user, a Steiner Minimal Tree (SMT) was approximated to connect all the DAD facilities to the user in a network of minimum length with the inclusion of a Steiner point. A Steiner point is an additional vertex which when added to a network reduces the overall length (Gilbert & Pollak 1968).

The Steiner point location, which minimised total length (L_{Total}) was determined iteratively. Similar to section 6.2.3.3 a 10m x 10m grid was superimposed onto the plane containing the pig farms and the biogas user, corners of the grid squares were potential Steiner point locations. A flowchart of the calculation process to approximate the Steiner point can be seen in Figure 6-8. Computation of the minimum length network at each potential nexus location was conducted in MATLAB using code developed by the authors (Appendix C)

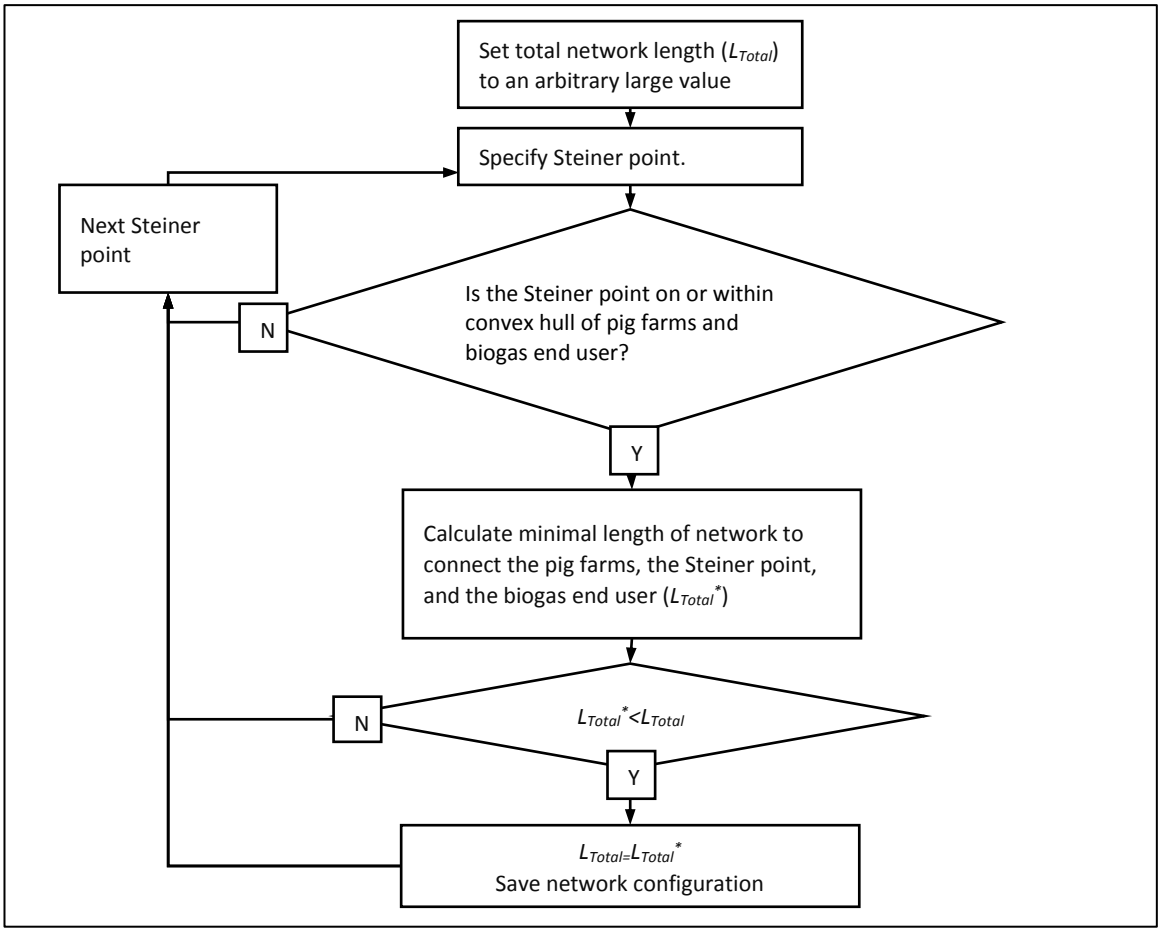


Figure 6-8: Flowchart outlining method to determine minimum network length with a Steiner point, scenario DAD2.

Once the location of the Steiner point, which minimised network length was known, the energy required for the compression of biogas at each DAD facility was determined. This was done by calculating the pressure at the upstream part of each pipe segment (*PS*) between an upstream point *a* and a downstream point *b* ($PS_{a\text{-}b}$). This required the mass flow rate of biogas through the pipe segment ($\dot{m}_{a\text{-}b}$), the pipe segment length ($L_{a\text{-}b}$), the downstream pressure (P_b) and temperature of the pipe segment being assessed. An illustration of a possible biogas network configuration is shown in Figure 6-9.

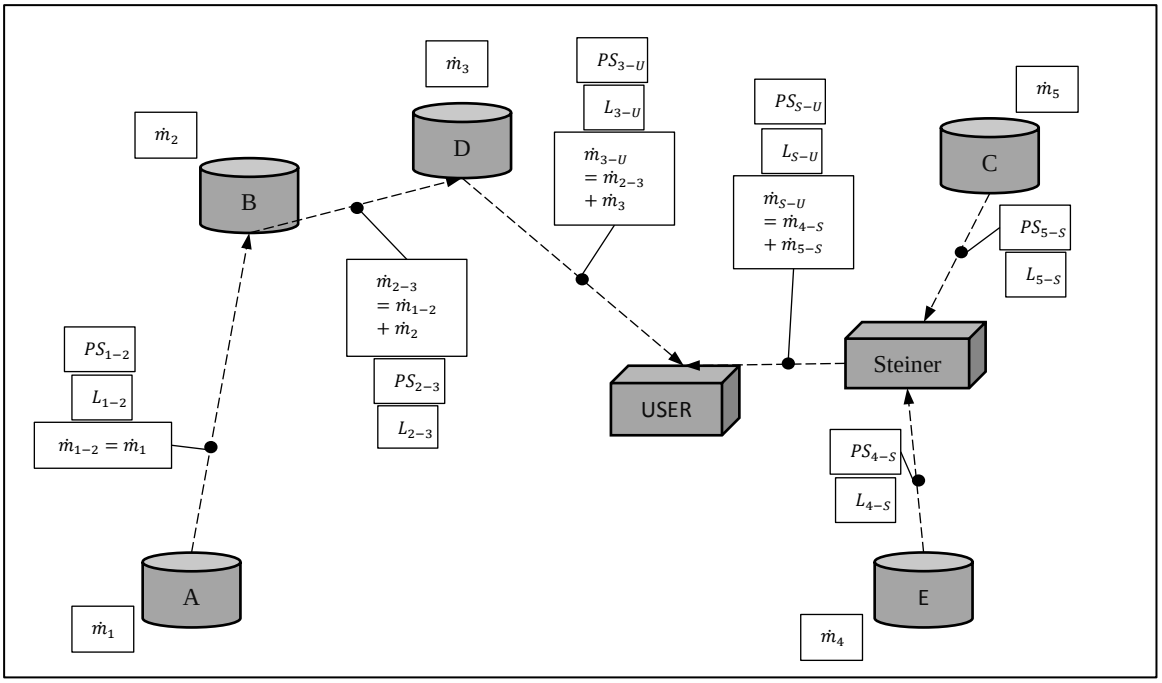


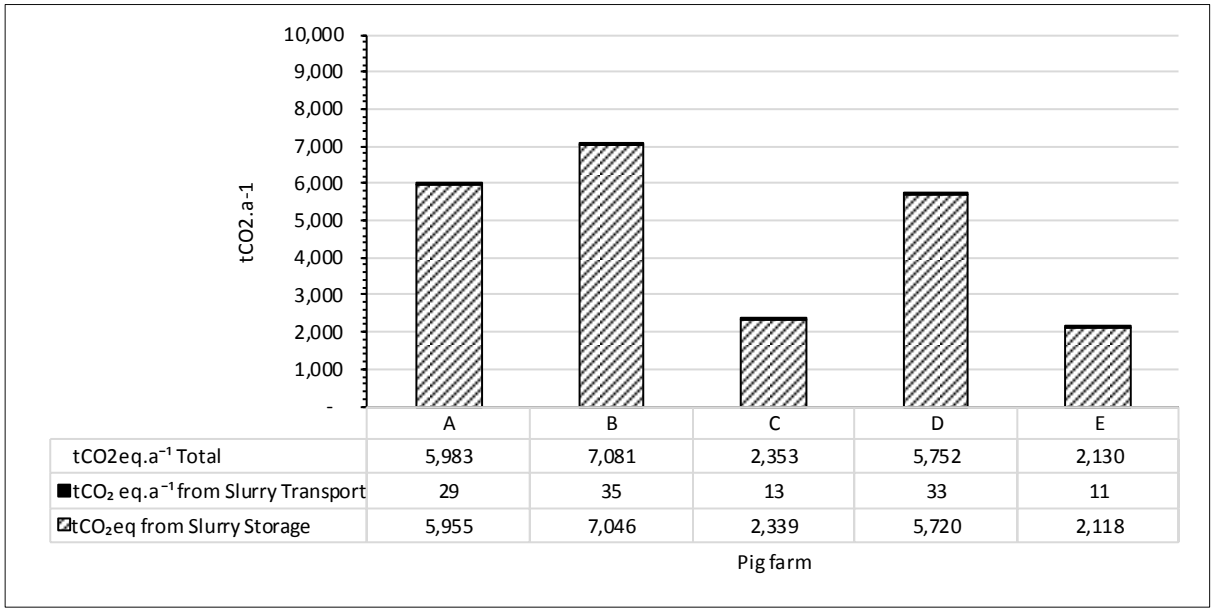
Figure 6-9: Possible biogas pipeline network configuration. Mass flow rates ($\dot{m}_{a\text{-}b}$) in each pipe segment from point a to point b ($PS_{a\text{-}b}$), and the length of each pipe segment ($L_{a\text{-}b}$) are specified

The pipeline inlet pressure at each DAD facility was calculated using a Microsoft Excel spreadsheet developed by the authors based on the pressure drop calculation methodology for a compressible ideal flow. The electrical energy required for the compression of biogas was calculated using Equation 6-14, CO_2eq emissions associated with the electrical energy used in the compression of biogas ($ECO_2eqDAD2_{Biogas,\ compression}$) were calculated as in Section 6.2.3.2.2. The emissions of CO_2eq during the digestion process ($ECO_2eqDAD2_{Digestion}$) and the emissions associated with the haulage of digestate to lands for spreading ($ECO_2eqDAD2_{Digestate,\ transport}$) were calculated in the same manner as prior scenarios. The total CO_2eq emissions associated with scenario DAD2 ($ECO_2eqDAD2_{Total}$) were the sum of $ECO_2eqDAD2_{Digestion}$, $ECO_2eqDAD2_{Biogas,\ compression}$, and $ECO_2eqDAD2_{Digestate,\ transport}$.

6.3 Results

6.3.1 Baseline greenhouse gas emissions from the study region

The emissions of CO_2eq associated with slurry storage at the pig farms and the transport of the slurry to land for spreading (*$ECO_2eqBase$*) in the study region are illustrated in Figure 6-10.



	A	B	C	D	E
tCO2eq.a^{-1} Total	5,983	7,081	2,353	5,752	2,130
■tCO$_2$ eq.a^{-1} from Slurry Transport	29	35	13	33	11
☑tCO$_2$eq from Slurry Storage	5,955	7,046	2,339	5,720	2,118

Pig farm

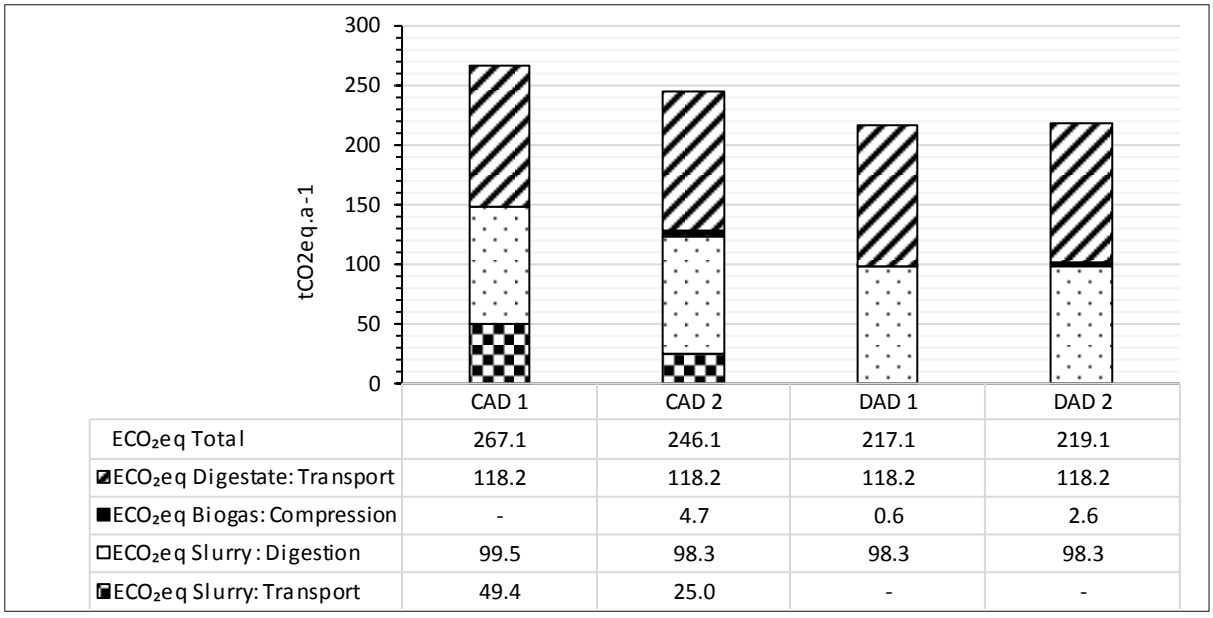
Figure 6-10: Greenhouse gas emissions from manure management at pig farms

The predominant source of CO_2eq emissions at each pig farm was the management of slurry generated at the facilities. The total emissions of CO_2eq arising from the storage of slurry in the study region was 23,178tCO_2eq.a^{-1} (99.5% of *$ECO_2eqBase$*) and the total emissions of CO_2eq associated with the transport of slurry to land for spreading was 121tCO_2eq.a^{-1} (0.5% of *$ECO_2eqBase$*) yielding a total of 23,299tCO_2eq.a^{-1}.

6.3.2 Comparison of CO_2eq emissions arising from biogas production in scenarios CAD1, CAD2, DAD1, and DAD2

The CO_2eq emissions arising from the biogas production process for scenarios CAD1 to DAD2 are illustrated in Figure 6-11.

The highest emissions of CO_2eq are associated with scenario CAD1 amounting to 267.1tCO_2eq.a^{-1}. Each of the remaining scenarios emitted a lower quantity of CO_2eq than scenario CAD1.



	CAD 1	CAD 2	DAD 1	DAD 2
ECO_2eq Total	267.1	246.1	217.1	219.1
ECO_2eq Digestate: Transport	118.2	118.2	118.2	118.2
ECO_2eq Biogas: Compression	-	4.7	0.6	2.6
ECO_2eq Slurry: Digestion	99.5	98.3	98.3	98.3
ECO_2eq Slurry: Transport	49.4	25.0	-	-

Figure 6-11: Emissions of CO_2eq from biogas production in scenarios CAD1, CAD2, DAD1, and DAD2

The location of the CAD facility in scenario CAD2 in relation to the pig farms and the milk processing plant is shown in Figure 6-12. Total CO_2eq emissions in scenario CAD2 were 246.1 tCO_2eq.a^{-1}, this was 20.9tCO_2eq.a^{-1} (8%) less than the total CO_2eq emissions arising in scenario CAD1. The location of the CAD facility in scenario CAD2 reduced the CO_2eq emissions (along with diesel consumption in trucks) arising from transportation of slurry to the digester by 49% compared to scenario CAD1.

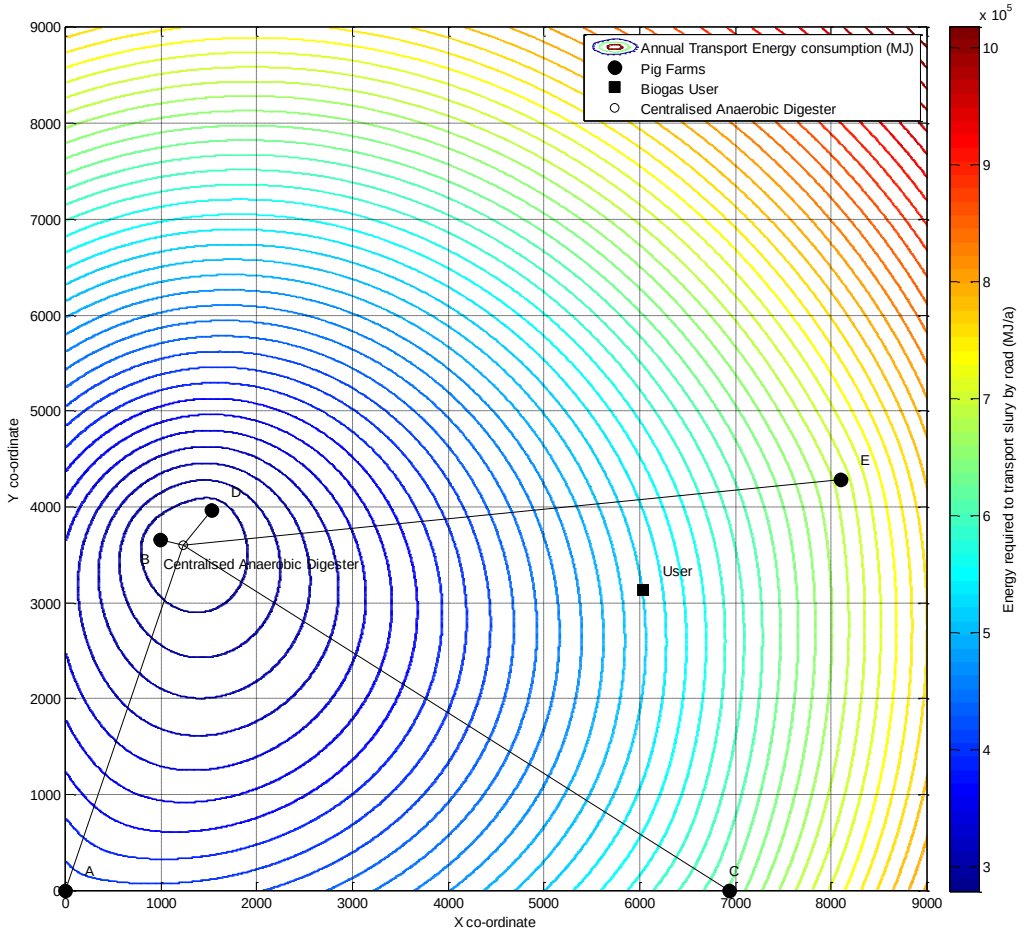


Figure 6-12: Location of centralised anaerobic digester in scenario CAD2 to minimise the energy requirement for road haulage of pig slurry, concentric circles signify locations of equal energy requirement

The location of the nexus point to which biogas is piped from individual DAD facilities at each pig farm, and from which biogas is piped to the milk processing plant (scenario DAD1) is shown in Figure 6-13. In this instance, the nexus point is located at the biogas end user (the milk processing plant). This corresponds to the scenario of building a dedicated biogas pipeline from each DAD facility directly to the biogas user in a star network configuration. The total emissions of CO_2eq in the production of biogas in scenario DAD1 was 217.1tCO_2.a^{-1}, this is 19% lower than the total CO_2eq emissions in scenario CAD1 and 12% lower than the total CO_2eq emissions in scenario CAD2. Scenario DAD1 completely removes the CO_2eq emissions (along with diesel consumption) associated with the haulage of pig slurry to a CAD facility in contrast to Scenarios CAD1 and CAD2.

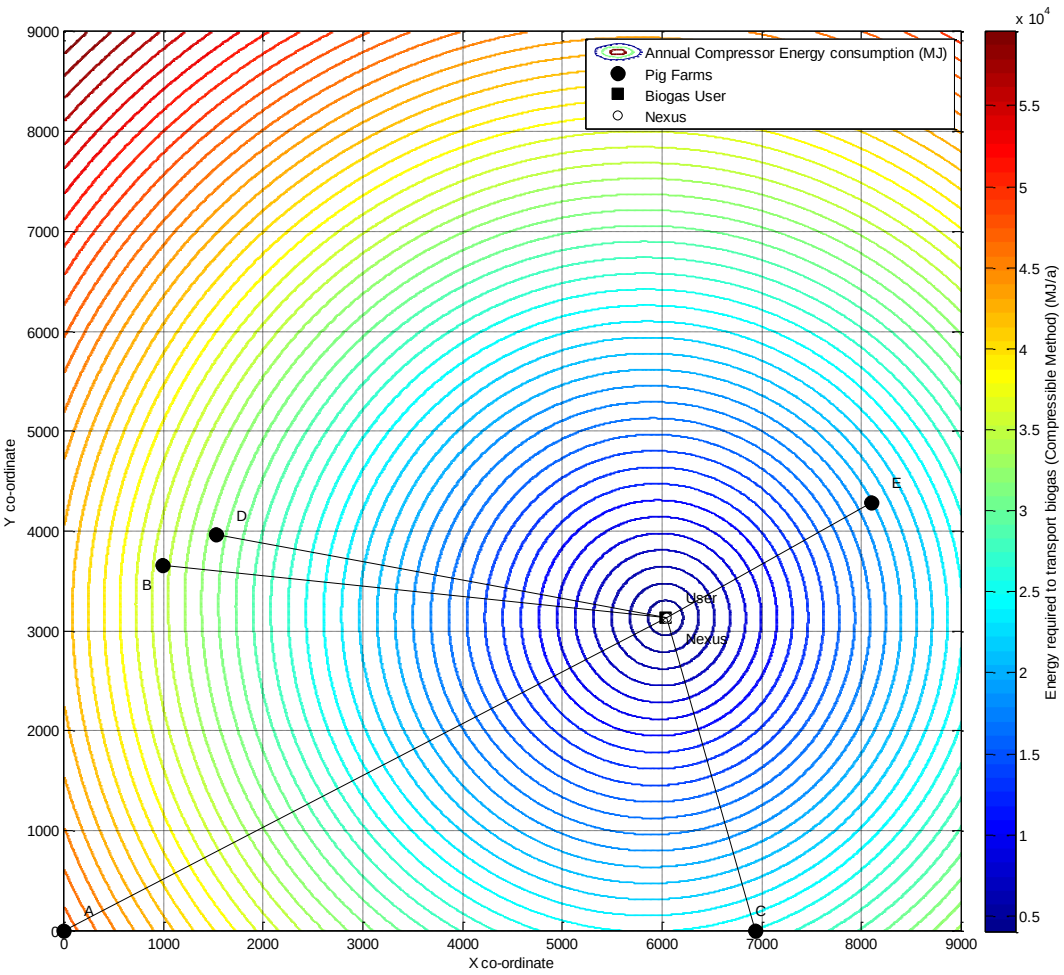


Figure 6-13: Location of nexus receiving biogas produced from decentralised anaerobic digesters at each pig farm and delivering to the milk processing plant (scenario DAD1). Concentric circles correspond to locations of equal total compressor energy requirement.

The network configuration that minimised the length of pipeline required to connect all the DAD facilities to the biogas user (Scenario DAD2) whilst considering the location of a potential Steiner point is illustrated in Figure 6-14.

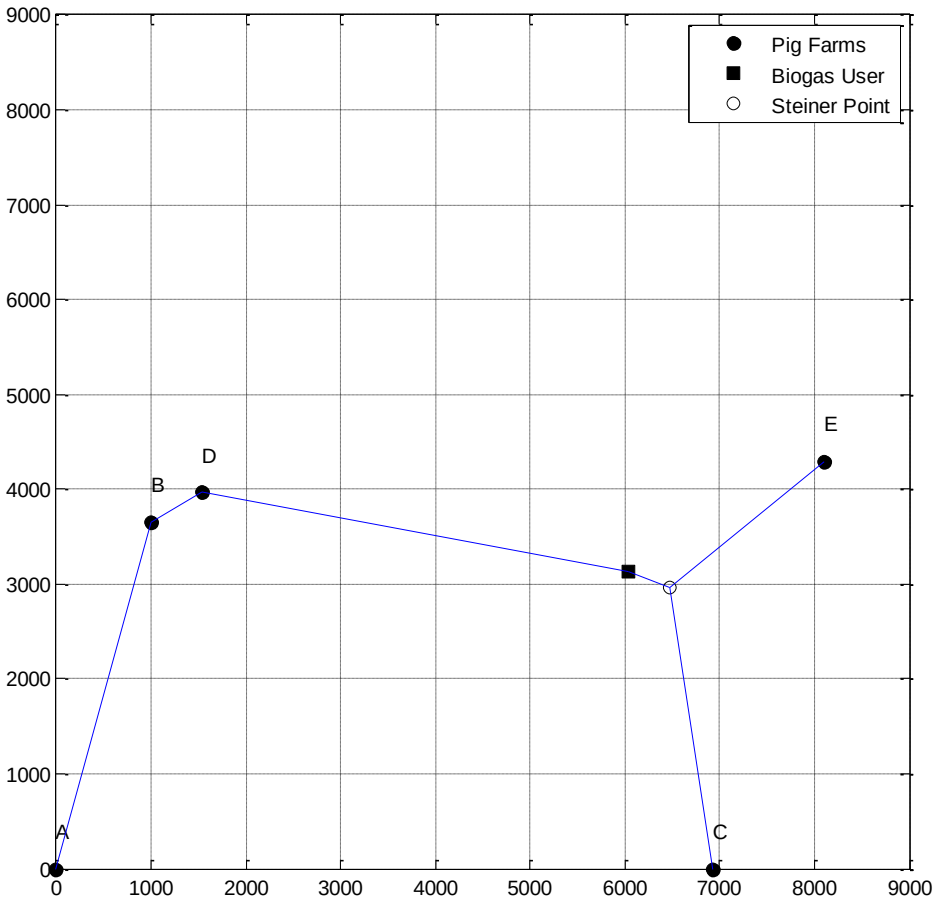


Figure 6-14: Network configuration of Steiner minimal tree with one Steiner point to minimise total network length, scenario DAD2.

Instead of building a dedicated biogas pipeline from each DAD facility to the milk processing plant (as in scenario DAD1), the three DAD facilities to the west of the user are connected to a common pipeline while the two facilities to the east of the milk processing plant are connected to a Steiner point which is then connected to the biogas end user. The total length of biogas pipeline required in scenario DAD2 (14.56km) was 34% lower than the total length of biogas pipeline in scenario DAD1 (22.09km). Reduction of the length of pipeline would reduce the capital cost associated with the purchase of pipelines, the installation cost of the biogas pipeline network, and the payments required for access to land through which the pipelines are routed.

The pressure to which biogas was compressed for injection to the biogas network at each DAD facilities in scenario DAD1 and DAD2 are given in Table 6-6 along with the electrical energy consumption and associated CO_2eq emissions.

Table 6-6: Biogas pressure required, electricity consumption for compression and CO_2eq emissions in scenarios DAD1 and DAD2

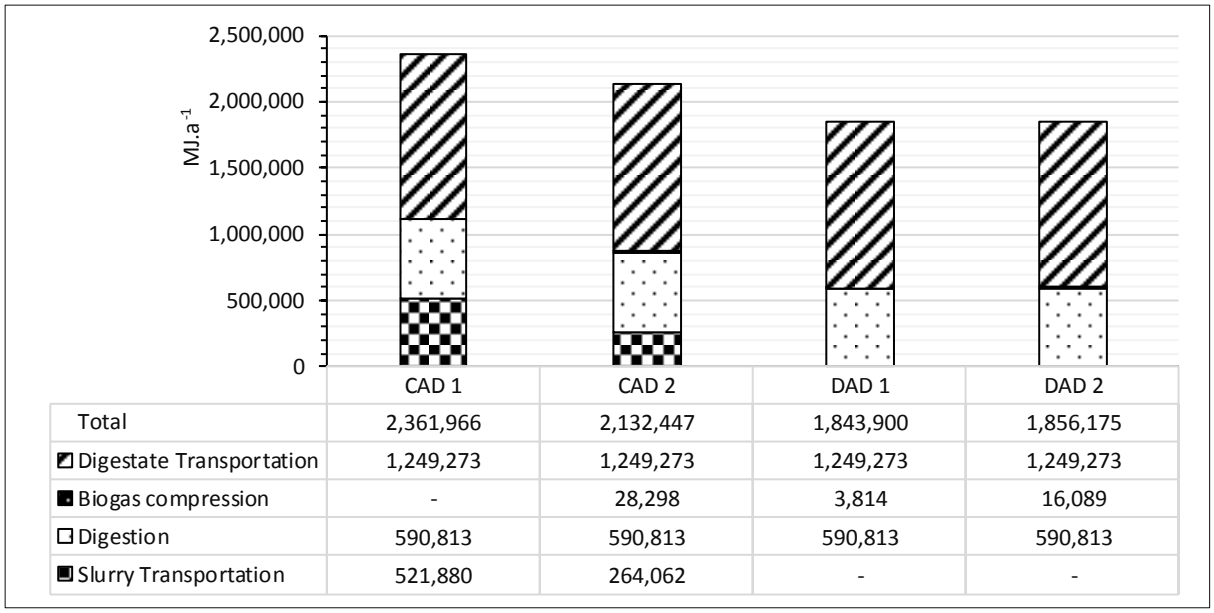
Pig Farm	**Biogas pressure required for injection to pipeline**		**Electrical energy consumption for compression**		**Emissions of CO_2eq associated with electrical energy consumption**	
	$Pa_{absolute}$		$MJ.a^{-1}$		$kgCO_2eq.a^{-1}$	
	Scenario DAD1	Scenario DAD2	Scenario DAD1	Scenario DAD2	Scenario DAD1	Scenario DAD2
A	113,828	124,267	1,142	5,133	188	941
B	113,939	123,221	1,447	5,742	238	944
C	111,657	111,657	70	63	12	10
D	113,467	122,533	1,120	5,155	184	841
E	111,518	111,544	35	35	6	6
Total			3,814	16,089	627	2,644

The total emissions of CO_2eq associated with the production of biogas in scenario DAD2 were 219.1tCO_2eq.a^{-1}, this was 18% lower than in scenario CAD1, 11% lower than in scenario CAD2, and 1% higher than in scenario DAD1. The emission of CO_2eq associated with biogas compression in scenario DAD2 was 3.21 times higher than the equivalent CO_2eq emission in scenario DAD1. However, the share of CO_2eq emitted from biogas compression is minor (0.3% of total CO_2eq emissions in scenario DAD1 and 1.2% in scenario DAD2) in comparison to the emission of CO_2eq associated with electrical and thermal energy use in the digestion process and the emission of CO_2eq arising from the transportation of digestate to land for spreading.

The reason for the difference in compressor energy consumption is that the pipelines in scenario DAD1 only convey the flow from one individual digester each. The pipelines in scenario DAD2 transported gas from more than one anaerobic digester, this increased the flow rate of biogas in the pipelines in scenario DAD2 and therefore increased the pressure drop as this is a function of the square of the flow rate.

6.3.3 Comparison of energy consumption in scenarios CAD1, CAD2, DAD1, and DAD2

The total final consumption of energy in scenarios CAD1, CAD2, DAD1, and DAD2 for; the transportation of pig slurry to the digestion facility(ies), the digestion of slurry, delivery of biogas to the milk processing facility, and transportation of digestate land for spreading is shown in Figure 6-15.



	CAD 1	CAD 2	DAD 1	DAD 2
Total	2,361,966	2,132,447	1,843,900	1,856,175
Digestate Transportation	1,249,273	1,249,273	1,249,273	1,249,273
Biogas compression	-	28,298	3,814	16,089
Digestion	590,813	590,813	590,813	590,813
Slurry Transportation	521,880	264,062	-	-

Figure 6-15: Total final energy consumption in scenarios CAD1, CAD2, DAD1, and DAD2

The largest share of energy consumption in all scenarios was the transportation of digestate to land for spreading; reduction of this energy requirement was not the focus of this work. Additionally, the energy consumed in the digestion process (in this case electricity) was identical for all scenarios as reduction of this energy requirement was not the focus of this work. The main components of energy consumption in each scenario, which did vary in this work, were the energy associated with the transportation of slurry to the digester(s) and the transportation of biogas to the milk processing plant.

Transporting slurry to a CAD facility in scenario CAD2 reduced the energy consumption associated with slurry transportation by 257,818MJ.a^{-1} (49%) as

compared to scenario CAD1. The location of the CAD facility in scenario CAD2 was not adjacent to the milk processing facility and required the use of a 4.8km pipeline to transport biogas to the milk processing plant. The energy required for the compression of biogas to the required inlet pressure of this pipeline (28,298MJ.a^{-1}) was sourced from the electricity network. The total reduction in energy consumption in scenario CAD2 was 229,520MJ.a^{-1} (10% of energy consumed in scenario CAD1).

The energy consumption in scenarios DAD1 and DAD2 were 288,547MJ.a^{-1} and 276,272 MJ.a^{-1} lower than that of scenario CAD2 owing to the use of DAD facilities at each site, thus avoiding the energy consumed in the road haulage of pig slurry. The main difference in energy consumption between scenarios DAD1 and DAD2 arises in the compression of biogas to the required pressure for injection to the biogas pipelines in each scenario, previously outlined in Table 6-6.

6.3.4 Comparison of GHG emissions savings from biogas produced in scenarios CAD1, CAD2, DAD1, and DAD2

The net energy production in the form of biogas in all scenarios was 29.504170 TJ.a^{-1}, this was equivalent to 2.8% of the natural gas consumption of the milk processing facility (end user). The CO_2eq intensity of biogas produced in all scenarios along with the emissions of CO_2eq that would be avoided by replacing natural gas (56.7gCO_2eq.$MJ_{Natural\ Gas}^{-1}$ for use in the ETS (Environmental Protection Agency 2016a)) in the milk processing plant can be seen in Table 6-7.

Table 6-7 Emissions intensity of biogas produced and CO_2eq avoided by replacing natural gas use at the milk processing plant

Scenario	Energy resource of biogas ($TJ.a^{-1}$)	GHG arising from biogas production ($tCO_2eq.a^{-1}$)	Emission intensity of biogas ($gCO_2eq.MJ_{Biogas}^{-1}$)*	CO_2eq saving by replacing natural gas ($tCO_2eq.a^{-1}$)**	Share of CO_2eq emission from milk processor (%)
CAD1	29.504	267.083	9.05	1,673.4	2.8
CAD2	29.504	246.137	8.34	1,673.4	2.8
DAD1	29.504	217.131	7.36	1,673.4	2.8
DAD2	29.504	219.149	7.43	1,673.4	2.8

*The emissions intensity of biogas in this calculation does not consider avoided emissions of GHGs resulting from improved slurry management.

**Calculation of CO_2eq saving by the replacement of natural gas consumption at the milk processing plant is based on a CO_2eq emission factor of 0 $tCO_2.TJ^{-1}$ for biogas according to EU Regulation 601/2012 Annex VI (European Commission 2012).

The minimum GHG emissions savings required for heat produced from bioenergy to be classified as a renewable, sustainable fuel is 85% for installations commencing operation from 2026 (European Commission 2017). This GHG emissions savings is based on the emissions per unit of final energy produced and takes the efficiency of the end user into consideration. In this work it was assumed that biogas was burned in a gas boiler (as is current practice) at the milk processing plant with an efficiency of 90%. The total GHG emissions per unit of heat energy produced, and the GHG emission savings per unit of heat energy produced (using a fossil fuel comparator of $80gCO_2eq.MJ_{Heat}^{-1}$ (European Commission 2017)) are shown in Table 6-8.

Table 6-8 GHG emission saving per unit of thermal energy produced from biogas

Scenario	GHG emissions per unit of thermal energy produced ($gCO_2eq.MJ_{Heat}^{-1}$)	GHG Emission saving (%)*
CAD1	10.06	87.4
CAD2	9.27	88.4
DAD1	8.18	89.8
DAD2	8.26	89.7

*Calculation of GHG emission saving according to Annex VI of (European Commission 2017)

The anaerobic digestion of pig slurry as opposed to storage using current practices would avoid the emission of 23,299tCO_2eq.a^{-1}, the overall GHG emission savings in the non-ETS sector (in which the biogas is produced) taking this into consideration can be seen in Table 6-9. The total CO_2eq intensity of biogas accounting for these savings is also shown, along with the total CO_2 intensity of heat produced from this biogas, and the GHG emissions savings (using a fossil fuel comparator of 80gCO_2eq.MJ_{Heat}^{-1} (European Commission 2017)).

Table 6-9 Total GHG emission saving accounting for avoided emissions from improved slurry management

Scenario	GHG emissions: Improved slurry management ($tCO_2eq.a^{-1}$)	GHG emissions: Production and delivery of biogas ($tCO_2eq.a^{-1}$)	GHG emission: Total ($tCO_2eq.a^{-1}$)*	CO_2eq intensity of biogas ($gCO_2e.MJ_{Biogas}^{-1}$)	CO_2eq intensity of final heat ($gCO_2eq.MJ_{Heat}^{-1}$)**	GHG Emission Saving (%)
CAD1	-23,299	267.083	-23,032	-780.63	-867.37	-1,184.21
CAD2	-23,299	246.137	-23,053	-780.31	-868.16	-1,185.20
DAD1	-23,299	217.131	-23,082	-782.33	-869.25	-1,186.57
DAD2	-23,299	219.149	-23,080	-782.26	-869.18	-1,186.47

*Negative values imply a reduction in greenhouse gas emissions per MJ of biogas or final heat

**Calculation of the CO_2eq intensity of the final heat energy is the CO_2eq intensity of the biogas divided by the efficiency of the gas boiler as per Annex VI of (European Commission 2017).

6.4 Discussion

The four scenarios assessed within the study showed that there can be significant differences in CO_2eq emissions arising from biogas production, and energy consumption in the biogas production process, depending on the configuration utilised. Minimising the distance over which pig slurry must be hauled has the greatest impact on the emissions of CO_2eq in the biogas production process. Location of a CAD facility to achieve this (scenario CAD2) resulted in an emissions reduction of 8% relative to locating a CAD facility at the milk processing facility (CAD1). In terms of the CO_2eq emissions associated with the haulage of slurry to the CAD facility, the reduction in CO_2eq emissions achieved was 49%, this would also reduce the consumption of diesel in the transportation of the slurry to the CAD facility by the same amount. It could be argued that these benefits should result in the preferential construction of a CAD facility at a location remote of the biogas end

user (the milk processing plant) with transportation of the biogas to the user via pipeline instead of building the CAD facility at the biogas user.

The distributed anaerobic digestion scenarios were found to result in substantially lower CO_2eq emissions than in the centralised processing of pig slurry for biogas production. The total CO_2eq emitted during the production and delivery of biogas in scenarios DAD1 and DAD2 (Processing of pig slurry in DAD facilities) were 19% and 18% lower than in scenario CAD1 (a CAD facility located at the biogas user). This altered the GHG emissions savings per unit of final heat produced from the biogas. Biogas produced in DAD facilities and transported to the biogas user via biogas pipelines achieved a GHG emissions saving of 89.8% to 89.7% (DAD1 and DAD2 respectively), an improvement compared to heat produced from biogas originating in a CAD facility achieved a GHG emission saving of 87.4% to 88.4% (CAD1 and CAD2 respectively). The benefit of alternative biogas production configurations could allow biogas production systems which use different feedstock and which struggle to meet the required GHG emission saving criteria to be classified as sustainable sources of energy if the alternative configuration provides a sufficient increase in GHG savings.

The construction of DAD facilities at each pig farm (scenarios DAD1 and DAD2) removed the energy required (along with associated CO_2eq emissions) to haul pig slurry to a CAD facility. The additional electrical energy required for the compression of biogas and injection to the biogas pipeline was found to be minor in comparison to the other energy uses in the digestion process.

Comparison of scenarios DAD1 and DAD2 showed that minimising the length of pipeline required does not lead to a reduction in electricity consumption for biogas compression, rather the opposite was true, this was also found to be the case in prior work (Hengeveld et al. 2016). The increase in electrical energy consumption for compression in scenario DAD2 compared to scenario DAD1 was inconsequential when compared to the total energy consumption in the biogas production process. The CO_2eq intensities of the biogas, and the heat produced from the biogas, were found to be within $0.07 gCO_2.MJ_{Biogas}^{-1}$ for DAD1 and DAD2. Minimising the length of pipeline required does not significantly influence the emissions intensity of either

the biogas or the heat produced from it. Additionally, the increased annual electricity consumption (resulting in increased annual cost) in scenario DAD2 could be outweighed by the cost savings associated with reduced biogas pipeline length.

The energy resource of biogas produced from pig slurry was 2.8% of the natural gas consumption of the milk processing plant, as such it is a relatively minor energy resource. Replacement of natural gas with biogas derived from pig slurry in the scenarios assessed could allow the milk processing facility to offset the emission of ca. 1,673.4tCO_2eq.a^{-1} equivalent to 2.8% of the total emission of CO_2eq from the milk processing plant. This would contribute toward the required reduction of CO_2eq emissions at the milk processing facility by 2020. The penalty per tonne of CO_2eq emitted for which no emission allowance has been surrendered is 100€ (European Parliament and the Council of the European Union 2014), therefore the maximum value of the CO_2eq emissions savings resulting from biogas use in the milk processing plant is €167,340. The market price per tonne of CO_2 in the EU-ETS at the time of writing was ca. €4.52 (Carbon Pulse 2017) therefore the value of the avoided CO_2eq emissions from biogas use would be €7,564.a^{-1}. The value associated with avoided carbon emissions is highly dependent on the market price of CO_2eq emission allowances.

This emissions savings of 1,673.4tCO_2eq.a^{-1} at the milk processing plant does not consider the avoided GHG emissions associated with improved slurry management.

The total emission of CO_2eq in the biogas production process ranged from 217 – 267 tCO_2eq.a^{-1}. The production of biogas occurs in the non-ETS sector, these emissions would result in an increase in the emissions of CO_2eq in the non-ETS sector, this appears to be detrimental to the required goal of reducing non-ETS emissions by 20% in Ireland by 2020. However, when the improved management of slurry using anaerobic digestion is considered (avoided CO_2eq emissions of ca. 23,299tCO_2eq.a^{-1}) the net emissions of CO_2eq in the non-ETS sector were reduced by 23,032 to 23,082tCO_2eq.a^{-1}.

As previously stated, reduction of agricultural CO_2eq emissions in Ireland is challenging owing to the high portion of CO_2eq emissions arising from enteric fermentation in livestock (55% of agricultural CO_2eq emissions) and manure

management (9% of agricultural CO_2eq emissions). As such, it could be argued that the savings of CO_2eq arising from anaerobic digestion of pig slurry (as opposed to storage of slurry in slurry pits) should remain in the agricultural sector as this is one of the only ways in which the emissions of CO_2eq in agriculture can be reduced.

From the point of view of the milk processor, the potential reduction in CO_2eq emissions is relatively small (2.8 %). It could be argued that in terms of improving the "green image" of the facility, utilising the biogas produced from the anaerobic digestion of pig slurry would be helping to reduce GHG emissions in agriculture. The milk processor would not accrue any of the emissions reductions resulting from improved slurry management, but would be enabling the reduction of GHGs to take place in agriculture by proving a year-round predictable use of the biogas produced by the anaerobic digester(s). As such the milk processor could enhance its corporate social responsibility by facilitating the reduction of GHG emissions in agriculture.

6.5 Conclusions

Four different scenarios of biogas production from pig slurry, and transportation to an end user were assessed. Anaerobic digestion of pig slurry at a CAD facility located at the biogas user (CAD1) resulted in the highest emission of CO_2eq in the biogas production process. Locating the CAD facility at a remote location from the biogas end user and transportation of the biogas via low pressure pipeline (CAD2) reduced the CO_2eq emissions arising in biogas production by 8%. Reduction in the transportation distance of pig slurry was found to significantly reduce energy requirement and CO_2eq emissions in the biogas production process. Removal of the need to transport slurry by using decentralised anaerobic digesters at each pig farm coupled with biogas pipelines significantly reduced energy consumption and CO_2eq emissions. In the region assessed ca. 2.8% of the CO_2eq emissions in the milk processing plant (1.67ktCO_2eq) could be avoided by using biogas from the 5 pig farms. Anaerobic digestion of pig slurry would also result in ca. 23.0 to 23.3ktCO_2eq of emissions savings in the agricultural sector in the region from improved slurry management. From this work, the most favourable scenario would be the digestion of pig slurry at each pig farm and the transportation of biogas to the milk processing plant via a biogas pipeline. The star biogas pipeline configuration (DAD1) minimised annual energy consumption and CO_2eq emissions, however, the minimum pipeline length configuration with an added Steiner point (DAD2) reduced the total length of pipe required by 34%, while only increasing annual energy consumption by 0.7% and annual CO_2eq emissions from biogas production by 1%. Alternative methods of biogas production and transportation could enable the use of feedstock that would otherwise be difficult to transport with respect to GHG savings, enabling a greater use of the resource associated with livestock slurries.

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7 Assessing the biomethane resource of microalgae cultivated using carbon dioxide from thermal power stations in a temperate oceanic climate

Assessing the biomethane resource of microalgae cultivated using carbon dioxide from thermal power stations in a temperate oceanic climate

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Abstract

The potential resource of biomethane derived from microalgae cultivated using CO_2 from thermal power stations was assessed in a temperate oceanic climate. A rudimentary assessment was compared to an in-depth assessment which accounted for the impact of weather and CO_2 availability on the rate of micro algae growth in race way ponds. There was a significant difference in the resource of microalgae in the study region depending on the assessment methodology. The rudimentary assessment indicated a biomethane resource potential of 9.76PJ (5.5% of thermal energy demand, or 4.87% of transport energy demand in 2015) derived from 983 x 10^3 tonnes of algal dry matter (DM) in Ireland. The in-depth assessment implied a biomethane resource of 1.75PJ (1% of thermal energy demand, or 0.87% of transport energy demand) arising from 176 x 10^3 t_{DM}Algae, a 6-fold reduction. Use of biomethane derived from microalgae in the in-depth assessment could offset the emission of 143,447tCO_2 or 97,946tCO_2 if used to replace diesel fuel or natural gas respectively. The authors recommend that resource assessments, which aim to quantify the total microalgae resource of a region, or indeed a power station, should consider the impact of weather on microalgae growth rates, as well as the operational schedule of the power stations or CO_2 sources being assessed. Ignoring the operation schedule of the CO_2 sources (in this case power stations) can lead to large over estimations of the potential microalgae resource that could be grown using CO_2 from the CO_2 sources being assessed.

Keywords: Microalgae; Resource assessment; Carbon capture; Biomethane; Carbon dioxide; Biomass

7.1 Introduction

7.1.1 Background

The use of microalgae as a feedstock in biofuel production offers a number of potential benefits, ranging from the use of non-arable land and water sources not favourable for conventional agriculture, to the potential recycling of carbon dioxide (CO_2) (U.S. DOE 2010). The use of microalgae as a feedstock in energy production was suggested as far back as 1959 by Golueke and Oswald (Golueke & Oswald 1959) who assessed the feasibility of using microalgae as a means of capturing solar energy and converting it to methane (CH_4) via anaerobic digestion. Microalgae can also be processed into renewable bio-diesel either through lipid extraction and transesterification (Bernard 2009; Campbell et al. 2011; Collet et al. 2014), or via hydrothermal liquefaction, pyrolysis and subsequent upgrading of the oil produced (Bennion et al. 2015).

The optimal conversion pathway from algal biomass to a renewable fuel remains to be determined. Collet et al. found that the conversion of microalgae to methane via anaerobic digestion could result in lower levels of abiotic depletion and eutrophication than conversion of microalgae to biodiesel while achieving similar levels of global warming potential (Collet et al. 2011). Ventura et al. compared conversion of microalgae to biodiesel via lipid extraction and trans-esterification (with and without anaerobic digestion of residue biomass), anaerobic digestion of microalgae for the production of biogas, and the super-critical gasification of microalgae for the production of synthesis gases. Ventura et al. determined that the net energy output of the anaerobic digestion pathway was higher than that of the traditional lipid extraction and trans-esterification pathway, however the supercritical water gasification pathway was better still (Ventura et al. 2013). Shimako et al. found that the anaerobic digestion of microalgae resulted in a higher net energy yield, higher energy return on investment, better environmental performance, and lower cumulative energy demand than the conversion of microalgae to biodiesel via lipid extraction using super critical CO_2 followed by trans-esterification (Shimako et al. 2016).

Owing to the simplicity of the anaerobic digestion process compared to other conversion pathways, favourable results from literature studies, and the ability of the anaerobic digestion pathway to mineralise nutrients contained in algal biomass for use in further cultivation (Singh & Olsen 2011) the anaerobic digestion pathway was selected for use in this work.

Numerous works such as that by Mussgnug et al. have assessed the suitability of microalgae as a feedstock in anaerobic digestion to produce biogas, a mixture of CH_4 and CO_2 (Mussgnug et al. 2010). Biogas produced from microalgae can be upgraded to biomethane by removing the CO_2 fraction, this biomethane can be used as a source of thermal energy, or as a transportation fuel in natural gas fuelled vehicles. As a further progression, life cycle assessments, techno economic studies, and mass balance evaluations have been conducted for systems combining microalgae and anaerobic digestion for the production of biogas (Collet et al. 2011; Zamalloa et al. 2011; Alcántara et al. 2013). Jacob et al. assessed the potential benefits of combining the cultivation of microalgae using CO_2 from power stations and anaerobic digestion. It was determined that 35% of the primary energy requirement of a $1GW_e$ coal fired power station could be recovered in the form of gaseous fuels derived from microalgae grown using CO_2 from the power station. This was found to be sufficient to fuel 600,000 cars (Jacob et al. 2015).

The production of microalgae using CO_2 from thermal power stations requires knowledge of the resource availability at potential sites, taking into account weather conditions, CO_2 availability, availability of nutrients and the availability of land (U.S. DOE 2010). Favourable weather conditions facilitate rapid microalgae growth and a long growing season to maximise the yield of biomass per unit area of land. The availability of CO_2 is also essential. CO_2 can only be assimilated by photoautotrophic microalgae whilst they are illuminated, for outdoor cultivation systems this corresponds to the hours of daylight (U.S. DOE 2010). Thus, the total quantity of CO_2 captured at the CO_2 source is only approximately 20-30% of the total CO_2 emissions owing to CO_2 production outside of the hours of daylight in temperate oceanic climates, such as Ireland, and losses of CO_2 from the cultivation system.

Many previous studies have assessed microalgae resource potential. However, the specific conditions under which the resources were examined varied. The main parameters considered by previous studies were; land suitability, weather conditions, water resources, access to nutrients, locations of CO_2 sources, proximity to CO_2 sources, and losses of CO_2 from the cultivation system. Some prior studies also incorporated the effect intra annual variations in weather on microalgae yields, while others used average annual values. Table 7-1 contains a list of prior resource assessments and the parameters they considered.

Table 7-1 Prior microalgae resource assessments

Region	Land suitability	Climate	Water Resources	Access to nutrients	CO_2 Source location	Proximity to CO_2 source	CO_2 loss from Cultivation	CO_2 availability	Algal yields	Reference
U.S.A.	Y	Y	Y	N	N	N	N	N	Not directly stated in the work	(Maxwell et al. 1985)
India	Y	Y	Y	Y	Y	Y	N	N	Assumed a yield of algal oil of 4-10t.ha^{-1}. Yield did not vary with climate parameters	(Milbrandt & Jarvis 2010)
U.S.A. (Detailed focus on California)	Y	Y	Y	Y	Y	Y	Y	N	Algae yield varied monthly from 4-38g_{DM}Algae.m^{-2}. Daily algal yield within each month was assumed to be the same. Average annual yield of 22g_{DM}Algae.m^{-2}	(Lundquist et al. 2010)
Australia	Y	Y	Y	Y	Y	Y	N	N	Algal yield was assumed to be constant throughout the year but did vary between locations depending on annual solar radiation. Algal yield of 19.5g_{DM}Algae.m^{-2}.day^{-1} was used in one region as an example.	(Boruff et al. 2015)
U.S.A.	Y	Y	Y	N	N	N	N	N	Varied depending on climactic parameters. Mean daily yield of 15.8-50.3g_{DM}Algae.m^{-2}.day^{-1} over 30 years of simulation for the entire USA depending on input parameters	(Wigmosta et al. 2011)
U.S.A.	Y	Y	Y	N	Y	Y	N	N	Algal yield varied with climatic conditions. Specific yields not stated.	(Quinn et al. 2012; Quinn et al. 2013)
U.S.A.	Y	Y	Y	N	N	N	N	N	Algal yield varied with climatic conditions. Yields ranged from 3-24g_{DM}Algae.m^{-2}.day^{-1} depending on the season.	(Davis et al. 2014)
U.S.A.	Y	Y	Y	Y	Y	Y	Y		Algal yield varied with climatic conditions. Yields ranged from 2-28g_{DM}Algae.m^{-2}.day^{-1} depending on time of year and location.	(Orfield et al. 2014)
U.S.A.	Y	Y	Y	Y	Y	Y	N	N	Algal yield varied with climatic conditions. Average annual yields ranged from 2-21g_{DM}Algae.m^{-2}.day^{-1}	(Venteris et al. 2014)

The yields of microalgae within prior literature typically fall within the range of 2-28g_{DM}Algae.m^{-2}.day^{-1}, with a reduction in algae production in winter months as compared to summer months as would be expected. A consistent assumption in prior works is the constant availability of CO_2 to be used in the microalgae cultivation system. This assumption does not consider the operational schedule of sources of CO_2 such as power stations, which could potentially lead to an overestimation of the available CO_2 source and associated microalgae resource. An example of such an occurrence would be if the power station was mostly operational during periods of low algal productivity such as during winter months or at night.

In an Irish context, to date the only study which attempted to assess the potential resource of microalgae in Ireland was conducted by Bruton et al. (Bruton et al. 2009) who identified that the largest unknown in Ireland was whether or not it was possible to achieve reasonably high levels of algae productivity given the prevailing temperatures and light availability. The work by Brutton et al. also found that there was little or no existing research which attempted to quantify the potential scale f microalgae for biofuel production in Ireland (Bruton et al. 2009). Calculation of the net energy ratio of microalgae cultivation and by extension the cost and economic viability of microalgae cultivation systems for the production of biofuels requires a sound estimate of the productivity of microalgae cultivation systems in a region. Thus the first step of any assessment of microalgae should be an estimate of the available resource in a region as this forms the basis for all further analyses. It is this initial assessment of the resource of microalgae in a region that is the main focus of this work.

7.1.2 Gap in state of the art

A gap in the state of knowledge is the impact of CO_2 availability on the microalgae growth. The underlying assumption of previous literature has been that CO_2 was always available when conditions were favourable for microalgae growth (Table 7-1). This assumption ignores the impact of the operational schedule of the CO_2 source on microalgae growth. The innovation in this work is that it considers the impact of weather, solar radiation, CO_2 losses in the cultivation system, and CO_2 availability simultaneously. The majority of literature, concerning national resource assessments of microalgae has been undertaken for the USA (Table 7-1); little such work has taken place in other locations. This work aims to fill these knowledge gaps by considering weather and CO_2 availability in a microalgae resource assessment of a temperate oceanic climate, specifically, Ireland, which is situated in the North East Atlantic Ocean.

The work also aims to use this resource assessment to determine the relative scale of the potential biomethane resource, which could be obtained from microalgae, the potential fossil fuel savings, and the potential greenhouse gas emission reductions.

The main objectives of this work are to:

1. Determine the total potential resource of microalgae in a temperature oceanic climate from CO_2 produced in electrical power generation stations using a rudimentary methodology;
2. Refine the resource assessment by considering the impact of weather on microalgae growth and the effect of CO_2 availability;
3. Provide a high-level assessment of the energy resource associated with microalgae when used as a feedstock in anaerobic digestion for the production of biomethane, and the potential CO_2 savings associated with the use of this biomethane as a transport fuel or in the production of heat.

7.2 Methodology

7.2.1 Rudimentary microalgae resource

7.2.1.1 CO_2 resources

The sources of CO_2 assessed for use in microalgae production was taken to be large scale fossil fuel fired power stations in Ireland. The annual mass of CO_2 emitted from 13 power stations was sourced from the annual environmental reports (AERs) of each power station which were submitted to the Environmental Protection Agency (EPA) for the year 2014 (Environmental Protection Agency 2015). The total electrical energy generated per annum by each power station was also sourced from AERs; these data were used to calculate the CO_2 intensity of electricity generated by each of the power stations according to Equation 7-1.

Equation 7-1 CO_2 intensity of electricity

$$CI_i^{Elec} = \frac{mCO_{2i}}{Elec_i^{Gen}}$$

Where CI_i^{Elec} is the CO_2 intensity ($kgCO_2.MWh^{-1}$) of electricity from power station *i*, mCO_{2i} is the annual mass of CO_2 emitted ($kgCO_2$) from power station *i,* and $Elec^{Gen}_i$ is the annual electricity generation of power station *i* (MWh).

To account for the mass of CO_2 emitted in a particular hour, the total electricity production of each power station in each hour for a given year (in this case 2014) was sourced from the Single Electricity Market Operator (SEMO) (Single Electricity Market Operator 2016) for the island of Ireland. The CO_2 intensity of electricity (from Equation 7-1) for a power station, and the electricity generation of that station in an hour (according to data from the SEMO) allowed for the evaluation of Equation 7-2.

Equation 7-2 Recalculated CO_2 emission from power station

$$mCO_{2_{i_h}}^{*} = CI_i^{Elec} * E_{i_h}^{gen}$$

In which $mCO_{2i,h}^{*}$ is the CO_2 emission from power station *i* ($kgCO_2$), in hour *h*, $E_{i,h}^{gen}$ is the electricity generated by power station *i* in hour *h* (MWh_e), and CI_i^{Elec} is the CO_2 intensity of electricity from power station *i* ($kgCO_2.MWh^{-1}$) assumed to be constant for all modes of plant operation as data on a finer temporal scale was not available.

The total annual emissions of CO_2 from all power stations based on hourly electrical output was calculated as follows;

Equation 7-3 Total annual carbon dioxide emissions

$$MCO_2 = \sum_{i=1}^{n} mCO_{2i}^{*}$$

Where MCO_2 ($kgCO_2.a^{-1}$) is the total annual CO_2 emissions from all power stations (*n*) used in this assessment.

7.2.1.2 Resource of microalgae and land area requirement

The CO_2 requirement of microalgae (CO_2Req_{Algae}) was taken to be 1.758 $gCO_2.g_{DM}Algae^{-1}$, an average of CO_2 requirements sourced from literature (Chisti 2007; Lardon et al. 2009; Campbell et al. 2011; Collet et al. 2011; Khoo et al. 2011; Passell et al. 2013). This is similar to the theoretical CO_2 requirement of 1.686 $gCO_2.g_{DM}Algae^{-1}$ based on a stoichiometric formulae of algae (Dalrymple et al. 2013; Delrue et al. 2012; Binaghi et al. 2003). Microalgae are generally only capable of assimilating CO_2 during hours of illumination, that is, daylight periods for outdoor cultivation systems. Prior estimates of the amount of CO_2, which can be absorbed by the microalgae, are in the range of 10-30% of the total annual CO_2 production of a power station (U.S. DOE 2010; Lundquist et al. 2010; Orfield et al. 2014). To allow for the impact of daylight hours, this rudimentary analysis assumes that CO_2 sourced from the flue gas of power stations is added to the microalgae cultivation system for 8 hours per day during the period of highest photosynthetic activity

($hrCO_2^{add}$), throughout the year assuming a growing season of 365 days (Stephenson et al. 2010). As such one third of the annual CO_2 emissions could be captured and sent to the microalgae cultivation system. Following the addition of CO_2 to the microalgae cultivation system, a certain portion of the added CO_2 will escape to the atmosphere (Lundquist et al. 2010). The portion of CO_2 typically captured by the cultivation system in this work was taken to be 65.2% ($CO_2^{capture}$), an average of values reported in literature (Lundquist et al. 2010; Delrue et al. 2012; Collet et al. 2011; Cheng et al. 2015; Stephenson et al. 2010; Jonker & Faaij 2013) as such, 21.5% of CO_2 available at a power station could be absorbed by the cultivation system, within the 10-30% range previously mentioned. To ensure carbon replete conditions in the cultivation system, the total mass of CO_2 absorbed by the cultivation system was taken to be 120% ($CO_2^{replete}$) of the CO_2 requirement of the microalgae (Stephenson et al. 2010). The total fraction of CO_2 absorbed by the microalgae is approximately 17.9% of the total CO_2 available from a power station. Thus, the total theoretical annual microalgae resource ($kg_{DM}Algae.a^{-1}$) for each power station can be calculated as follows:

Equation 7-4 Total theoretical microalgae resource

$$mAlgae_i^{theoretical} = \frac{mCO_{2_i}^{*} * \frac{hrCO_2^{add}}{24} * \frac{CO_2^{Capture}}{100} * \frac{100}{CO_2^{replete}}}{1000 * CO_2Req_{Algae}}$$

The land area (hectares) required for the cultivation of this mass of microalgae can be estimated using Equation 7-5:

Equation 7-5 Land area required for theoretical microalgae growth

$$A_i^{cultivation\ (theoretical)} = \frac{MAlgae_{theoretical}}{Growth_{Algae} * 10}$$

A maximum daily growth ($Growth_{Algae}$) of 23.73 $g_{DM}Algae.m^{-2}.day^{-1}$ applied to every day in a year was used, this was an average of values obtained for raceway ponds (Lardon et al. 2009; Jorquera et al. 2010; Campbell et al. 2011; Clarens et al. 2010; Stephenson et al. 2010; Quinn et al. 2011; Razon & Tan 2011; Collet et al. 2011; Batan et al. 2010; Passell et al. 2013; Delrue et al. 2012). The number 10 in the denominator is to facilitate conversion to hectares. As such, this method ignores the influence of daily or seasonal weather fluctuations on microalgae growth yields, as was the case in prior works (Boruff et al. 2015; Bravo-Fritz et al. 2015; Jacob et al. 2015; Stephenson et al. 2010).

7.2.1.3 Biomethane resource of microalgae

It is proposed that the microalgae biomass is biologically converted to biogas, a renewable gaseous fuel source containing approximately 55% CH_4 and 45% CO_2, via the process of anaerobic digestion (AD). The portion of volatile solids (VS) as a fraction of dry matter was taken to be 84%, an average of values obtained in Ward et al. (Ward et al. 2014). The biomethane yield of microalgae when used as a feedstock in AD was taken as $313LCH_4.kgVS^{-1}$, an average of values obtained in literature (Zhao et al. 2014; Inglesby & Fisher 2012; Mussgnug et al. 2010; Golueke & Oswald 1959; Polakovičová et al. 2012; Lü et al. 2013; Lakaniemi et al. 2011; Ras et al. 2011; Yang et al. 2011). As such, the anaerobic digestion of $1kg_{DM}Algae$ would yield $0.263Nm^3$ of methane gas. The gross energy yield (the total energy contained in the methane produced in the anaerobic digestion of the microalgae whilst ignoring upstream energy inputs to the cultivation system and electrical and thermal demand of the anaerobic digester) was determined using a calorific value of $37.78MJ.Nm^{-3}$ for methane (Murphy et al. 2004). Thus, the digestion of $1kg_{DM}Algae$ would yield a gross energy yield in the form of methane of 9.9MJ. The volume of diesel fuel which could be replaced by the biomethane was calculated on an energy basis using a volumetric energy content of $36MJ.L^{-1}$ for diesel (The European Parliament and the Council of the European Union 2009). The gross energy yield on a per unit area basis was found by dividing the annual energy

resource of the microalgae from each power station by the cultivation area required to produce the microalgae.

The capture of CO_2 by microalgae growth is temporary when, the algae are digested CO_2 is released to the atmosphere either when the biogas is burned in an engine for energy production, or when the CO_2 is separated from the biogas during an upgrading process in which the purified methane can be compressed and injected into gas cylinders or a natural gas grid. Combustion of the methane fraction of the biogas releases the remainder of the CO_2 captured by the microalgae. As such, this system represents carbon capture and reuse with captured CO_2 eventually emitted, as opposed to carbon capture and sequestration in which the captured CO_2 is stored and not permitted to enter the atmosphere(U.S. DOE 2010).

There are however carbon savings associated with the replacement of fossil fuels by methane (referred to as biomethane from this point onward) derived from microalgae grown using CO_2 from fossil fuel power stations. The CO_2 saving is calculated using the CO_2 intensity of the fuel replaced; this was taken to be $94gCO_2.MJ^{-1}$ for diesel (Neeft & Ludwiczek 2016), and $56.9gCO_2.MJ^{-1}$ for natural gas (Howley et al. 2015)**.** This carbon saving calculation assumes that the CO_2 intensity of biomethane derived from microalgae is zero, as such, it is a best case scenario and does not consider the lifecycle emissions of greenhouse gases from the microalgae production and anaerobic digestion process. A full lifecycle assessment of the CO_2 emissions associated with the cultivation of microalgae was not the focus of this work.

Within this rudimentary analysis the impact of weather and solar radiation on the growth rate of microalgae was not considered, nor was the impact of CO_2 availability, it was assumed in this simplistic analysis that for 8 hours a day, every single day, CO_2 would be available which could then be added to the microalgae cultivation system.

7.2.2 Microalgae growth model for raceway ponds

7.2.2.1 Effect of temperature and solar radiation on microalgae growth

In order to gain a better insight into the potential resource of microalgae which could be grown using CO_2 from power stations in a temperate oceanic climate a more in-depth assessment was conducted. The main parameters which influence the growth rate of microalgae are solar radiation levels, nutrient availability, and culture temperature. Additionally, different strains of microalgae will exhibit different growth rates. A number of models of microalgae growth have been developed over the years, each with differing degrees of complexity. Models used to predict microalgae growth range from those which use; author experience and literature reviews of likely growth rates (Lundquist et al. 2010), recorded growth rates for a region as a function of light intensity (Boruff et al. 2015), and basic physical laws (Weyer et al. 2010; Wigmosta et al. 2011), to those which use species specific parameters such as light attenuation coefficients and growth rates as a function of light intensity (Quinn et al. 2011; Huesemann et al. 2013; Orfield et al. 2014; Huesemann et al. 2016; Jonker & Faaij 2013). Owing to the lack of data on the species specific parameters which are used in more intricate growth models (Quinn et al. 2011; Huesemann et al. 2013; Huesemann et al. 2016) for microalgae species in Ireland, the methodology developed by Wigmosta et al. was implemented in this work (Wigmosta et al. 2011). The following equations outline the growth model developed by Wigmosta et al. and are directly taken from their prior publication, the equations were not adapted prior to use in this work (Wigmosta et al. 2011).

The rate of biomass growth per unit area was described according to Equation 7-6;

Equation 7-6 Biomass growth per unit area per unit of time

$$p_{mass} = \frac{\tau_p C_{PAR} \epsilon_a E_s}{E_a}$$

In which p_{mass} ($kg_{DM}Algae.m^{-2}.hr^{-1}$) is the area specific algae biomass productivity per hour, τ_p is the transmission co-efficient of solar radiation, C_{PAR} is the fraction of

photosynthetically active radiation (PAR) in sunlight, ε_a is the efficiency with which microalgae convert photons to biomass, E_s is the full spectrum solar energy at the land surface in a given time period ($MJ.m^{-2}.hr^{-1}$), and E_a is the energy content per unit of biomass in $MJ.kg_{DM}^{-1}$.

The efficiency with which photons are converted to biomass is given by Equation 7-7;

Equation 7-7 Photon conversion efficiency

$$\epsilon_a = \frac{E_c \epsilon_p \epsilon_b}{Q_r E_p}$$

E_c is the conversion of light energy into chemical energy, ε_p is a factor which estimates the impact of light level and temperature on photon conversion efficiency, ε_b is the biomass accumulation efficiency with which energy captured by the cell is converted to biomass, Q_r is the quantum requirement, the number of photons required to produce one mole of oxygen through photosynthesis, whilst E_p converts the incoming PAR to the corresponding number of photons.

The impact of light level and temperature on the photon conversion efficiency is captured by Equation 7-8;

Equation 7-8 Light and temperature coefficient

$$\epsilon_p = \epsilon_s \epsilon_T$$

In which ε_s is the light utilisation coefficient, and ε_T is the culture temperature coefficient.

The light utilisation coefficient is given by Equation 7-9;

Equation 7-9 Light utilisation coefficient

$$\epsilon_s = \frac{E_s}{S_o}\left(\ln\left(\frac{S_o}{E_s}\right) + 1\right)$$

Where S_O is the light saturation constant.

The culture temperature coefficient is given by the following clauses outlined in Equation 7-10;

Equation 7-10 Culture temperature coefficient

$$\epsilon_t = 0, \ T < Tmin$$

$$\epsilon_t = \frac{T - T_{min}}{T_{opt\ low} - T_{min}}, \quad Tmin \leq T < Toptlow$$

$$\epsilon_t = 1, \quad T_{opt\ low} \leq T \leq T_{opt\ high}$$

$$\epsilon_t = \frac{T_{max} - T}{T_{max} - T_{opt\ high}}, \quad T_{opt\ high} < T \leq Tmax$$

$$\epsilon_t = 0, \ T > Tmax$$

With T representing the culture temperature, T_{min} and T_{max} as the minimum, and maximum, temperatures at which microalgae can grow, and $T_{opt\ low}$ and $T_{opt\ high}$ as the minimum and maximum optimal temperatures for microalgae growth.

Input parameters used are shown in Table 7-2.

Table 7-2 Input parameters for microalgae growth model

Parameter	Unit	Value	Source
τ_p	-	0.9	(Wigmosta et al. 2011)
C_{PAR}	-	0.46	(Wigmosta et al. 2011)
E_a	$MJ.kg^{-1}$	21.7	(Wigmosta et al. 2011)
E_c	$MJ.mol^{-1}$	0.4825	(Wigmosta et al. 2011)
ε_b	-	0.5	(Weyer et al. 2010)
Q_r	$mol.mol^{-1}$	8	(Wigmosta et al. 2011)
E_p	$MJ.mol^{-1}$	0.2253	(Wigmosta et al. 2011)
S_O	$\mu mol.m^{-2}s^{-1}$	150	(Wigmosta et al. 2011)
T_{min}	°C	10	(Wigmosta et al. 2011)
T_{max}	°C	35	(Wigmosta et al. 2011)
$T_{opt\ low}$	°C	20	(Wigmosta et al. 2011)
$T_{opt\ high}$	°C	30	(Wigmosta et al. 2011)

A full description of the development of the growth model can be found in Wigmosta et al. (Wigmosta et al. 2011) and Weyer et al. (Weyer et al. 2010).

7.2.2.2 Thermal model of raceway pond

Culture temperature can influence the productivity of microalgae, as well as the length of the growing season (U.S. DOE 2010). The model of microalgae growth used in this work allows for an approximation of the impact of culture temperature on microalgae growth. Microalgae cultivation was assumed to take place in open raceway ponds owing to the favourable net energy yield of these systems, their lower cost, improved environmental sustainability when compared to closed tubular or flat plate photobioreactors, and the fact that commercial production of microalgae in such systems is already underway (Jorquera et al. 2010; Stephenson et al. 2010; Lundquist et al. 2010; Lam et al. 2012; Jonker & Faaij 2013).

The raceway pond cultivation system modelled in this work was similar to that proposed by Stephenson et al. and consisted of two parallel channels with a 180° bend at either end (Stephenson et al. 2010). The width of each channel was 10m, with each channel section being 150m in length, the depth of the culture was set to 0.3m, as is the case in literature (Jorquera et al. 2010; Stephenson et al. 2010; Lundquist et al. 2010; Collet et al. 2014; Campbell et al. 2011; Cheng et al. 2015). The total surface area and volume of the raceway pond were ca. 3,314m^2 and 994m^3 respectively. Mixing of the raceway pond was carried out using a paddle wheel mixing system to achieve an average flow velocity of 0.3$m.s^{-1}$ (Lundquist et al. 2010; Stephenson et al. 2010; Chisti 2008; Cheng et al. 2015). The structure of the pond was assumed to comprise of two layers of concrete on either side of an internal layer of insulation, each layer was 0.215m thick. The entire structure of the raceway pond was assumed to be surrounded by soil in order to minimise the effect of fluctuating air temperature (Laamanen et al. 2014).

A literature review on the energy balances of open bodies of water was conducted in order to select an appropriate methodology for calculating raceway pond temperature. Prior works dealt with the thermal energy balance of rivers (Troxler et al. 1977), cooling ponds for power stations (Codell & Nuttle 1980), aeration basins for waste water treatment (Talati & Stenstrom 1990; Makinia et al. 2005), outdoor swimming pools (Lam & Chan 2001; Woolley et al. 2011; Luminosu & De Sabata

2013), seas (Omstedt & Axell 2003), and microalgae cultivation ponds (Béchet et al. 2011; Quinn et al. 2012; Laamanen et al. 2014).

Based on the literature review the energy balance of the raceway pond used in this work is as follows;

Equation 7-11 Energy balance of raceway cultivation system

$$E_{net} = E_{solar} + E_{evaporation} + E_{convection} + E_{long-wave} + E_{soil} + E_{medium}$$

Where E_{net} is the net energy supplied to the raceway pond; a negative net energy flow is defined as a heat input to the pond, whilst a positive net energy flow is defined as a heat loss from the pond in this work. In Equation 7-11, $E_{evaporation}$ is the heat flux due to evaporation, $E_{convection}$ is the heat flux due to convection, $E_{long\text{-}wave}$ is the net long-wave radiative heat flux, E_{solar} is the absorbed solar energy, E_{soil} is the heat loss via conduction to the soil surrounding the raceway pond, and E_{medium} is the heat required to bring fresh culture medium to the pond temperature. Figure 7-1 summarises the energy balance in graphical terms.

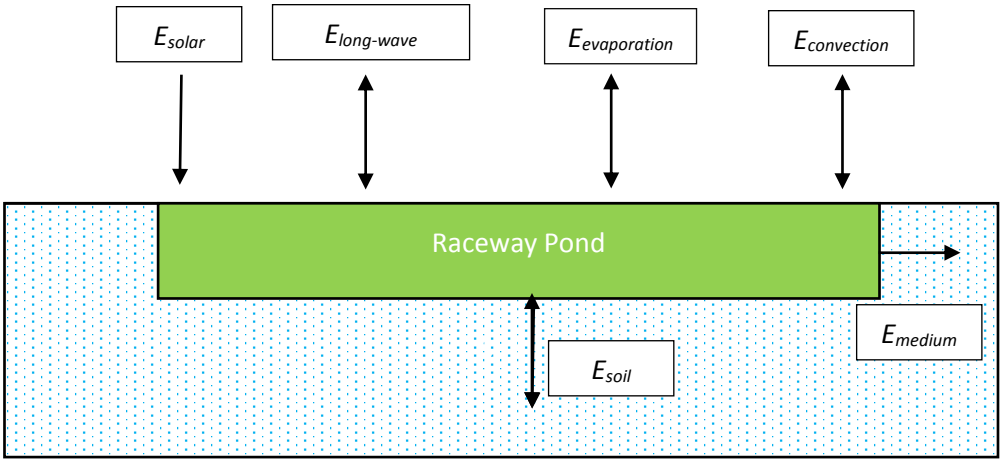


Figure 7-1 Energy balance of raceway pond (colour print not required)

Equation 7-13 to Equation 7-19 describe the calculation of each term in the energy balance, with the standard units of each parameter, and value of constants used in

their calculation outlined in Table 7-3. The calculation of the first four terms in the energy balance was carried out by first determining the rate of energy flux ($W.m^{-2}$) of the raceway pond surface at the start of each hour. This value was assumed to be constant for the hour in question. The energy flux in one hour was found by multiplication of the rate of energy flux at the start of the hour, by the number of seconds in one hour (3,600). To determine the total energy gained or lost by the raceway pond in an hour, the energy flux in one hour was multiplied the surface area of the pond. The same methodology was used in the calculation of the energy gained or lost by the raceway pond via conduction to the soil, except that the combined area of the walls and base were used instead of the water surface area. The energy lost or gained by the pond owing to the addition of new medium to the raceway pond was assumed to occur in the hour of harvest of culture from the raceway pond, and used the pond temperature at the start of that hour in its calculation. The temperature of the culture in the raceway pond at the end of each hour was then found according to Equation 7-12;

Equation 7-12 Pond temperature calculation

$$T_p^{end} = T_p^{start} - \frac{E_{net}}{V_{culture} * \rho_{culture} * Cp_{culture}}$$

In which T_p^{end} (K) is the pond temperature at the end of each hour, T_p^{start} (K) is the pond temperature at the start of each hour, $V_{culture}$ (m^3) is the volume of culture in the raceway pond, $\rho_{culture}$ ($kg.m^{-3}$) is the density of the culture, and $Cp_{culture}$ ($J.kg^{-1}.K^{-1}$) is the specific heat capacity of the culture. The pond temperature at the end of each hour was then used as the temperature of the pond at the start of the next subsequent hour in the heat balance calculation.

The methodology for the calculation of $E_{evaporation}$, $E_{convection}$, $E_{long\text{-}wave}$, and E_{solar} used in this work is based on the work by Béchet et al. (Béchet et al. 2011) as the model developed therein was aimed at being a universal model, applicable in different localities and climates. The equation describing the energy transfer due to evaporation is as follows as per Béchet et al. (Béchet et al. 2011);

Equation 7-13 Evaporative energy flow

$$E_{evaporation} = A_{pond} * 3600 * L_w * K * \left(\frac{P_w}{T_p} - \frac{RH * P_a}{T_a}\right) * \frac{M_w}{R}$$

In which A_{pond} is the pond surface area, L_w is the latent heat of evaporation of water, P_w and P_a are the saturated vapour pressures at the pond temperature (T_p) and air temperature (T_a) respectively, RH is the relative humidity of the air over the pond surface, M_w is the molecular mass of water, R is the ideal gas constant, and K is a mass transfer coefficient. A detailed explanation of the terms, and their derivation is given in the work by Béchet et al. (Béchet et al. 2011).

The equation governing convective energy transfer is;

Equation 7-14 Convective energy flow

$$E_{convection} = A_{pond} * 3600 * h_{convection} * (T_a - T_p)$$

In which $h_{convection}$ is the convection coefficient, and depends on; the thermal conductivity of air, the characteristic length of the pond, and the Nusselt number, which in turn depends on the Reynolds number, Prandtl number, the derivation of which is given in Béchet et al. (Béchet et al. 2011).

The net long wave radiative energy transfer is given by the following equation;

Equation 7-15 Net long-wave energy flow

$$E_{long-wave} = A_{pond} * 3600 * (\epsilon_w * \sigma * T_p^4 - * \epsilon_a * \sigma * T_a^4)$$

Where ε_w is the emissivity of the water surface, σ is the Stefan-Boltzman constant, and ε_a is the atmospheric radiation factor. This methodology is that used by Béchet et al. (Béchet et al. 2011) and when compared to other methodologies (Talati & Stenstrom 1990; Makinia et al. 2005; Smith et al. 1994; Woolley et al. 2011; Lam &

Chan 2001) (data not shown), yielded similar results for the net radiative long-wave heat transfer.

The energy input to the pond due to incoming solar radiation is given by the following equation;

Equation 7-16 Solar energy input

$$E_{solar} = A_{pond} * 3600 * (1 - f_s) * H_s$$

Where f_s is the fraction of solar energy captured by the microalgae and H_s is the total solar irradiance at ground level; this methodology is based on work by Béchet et al. (Béchet et al. 2011).

The energy transfer to the soil surrounding the raceway pond cultivation system is given by Equation 7-17 as per work carried out by Laamanen et al. (Laamanen et al. 2014);

Equation 7-17 Energy transfer to soil

$$E_{soil} = h_{wall} * A_{wall} * 3600 * (T_p - T_{soil})$$

In which h_{wall} is the wall heat transfer coefficient, calculated assuming a three layer wall and base construction consisting of a layer of insulation between two layers of concrete (with thicknesses of $L_{concrete}$ and $L_{insulation}$ respectively, and thermal conductivities of $k_{concrete}$ and $k_{insulation}$ respectively), as per Equation 7-18, A_{wall} is the area of the external walls and base of the raceway pond, and T_{soil} is the soil temperature.

Equation 7-18 Wall heat transfer coefficient

$$h_{wall} = \frac{1}{\frac{L_{concrete}}{k_{concrete}} + \frac{L_{insultaion}}{k_{insulation}} + \frac{L_{concrete}}{k_{concrete}}}$$

The energy transfer to the incoming medium supplied to the raceway pond is given by Equation 7-19;

Equation 7-19 Energy to incoming medium

$$E_{medium} = m_{medium} * Cp_{medium} * \left(T_p - T_{medium}\right)$$

In which m_{medium} is the mass of fresh medium added to the raceway pond, Cp_{medium} is the specific heat capacity of the medium, and T_{medium} is the temperature of the incoming medium (assumed to equal the surrounding soil temperature).

Table 7-3 Constant parameter values

Parameter	Unit	Value	Source
A_{pond}	m^{-2}	3,314	This work
L_w	$J.kg^{-1}$	$2.45x10^6$	(Béchet et al. 2011)
K	$m.s^{-1}$	Calculated herein	(Béchet et al. 2011)
P_w	Pa	Calculated herein	This work
P_a	Pa	Calculated herein	This work
T_p	K	Calculated herein	This work
T_a	K	Calculated herein	This work
RH	-	Calculated herein	This work
M_w	$kg.mol^{-1}$	0.018	(Béchet et al. 2011)
R	$Pa.m^3.mol^{-1}.K^{-1}$	8.314	(Béchet et al. 2011)
$h_{convection}$	$W.m^{-2}.K^{-1}$	Calculated herein	(Béchet et al. 2011)
ε_w	-	0.97	(Béchet et al. 2011)
ε_a	-	0.8	(Béchet et al. 2011)
σ	$W.m^{-2}.K^{-4}$	$5.67x10^{-8}$	(Béchet et al. 2011)
f_s	%	2.5	(Béchet et al. 2011)
H_s	$W.m^{-2}$	Calculated herein	This work
h_{wall}	$W.m^{-2}.K^{-1}$	0.59	This work
A_{wall}	m^2	3,423	This work
T_{soil}	K	Calculated herein	This work
$L_{concrete}$	M	0.215	This work
$L_{insulation}$	M	0.215	This work
$k_{concrete}$	$W.m^{-1}.K^{-1}$	1	(Laamanen et al. 2014)
$k_{insulation}$	$W.m^{-1}.K^{-1}$	0.17	(Laamanen et al. 2014)
m_{medium}	Kg	Calculated herein	This work
Cp_{medium}	$J.kg^{-1}.K^{-1}$	4180	(Béchet et al. 2011)
T_{medium}	K	Calculated herein	This work

7.2.2.3 Weather data

The weather dependant inputs required in the temperature model of the raceway pond were; air temperature, wind speed, relative humidity, air pressure, and total solar irradiance. The hourly values of these parameters were sourced from a number of weather stations spread across Ireland for 2014 with data sourced from Met Éireann (The Irish meteorological service). The values of these parameters were then estimated at the location of each power station using the inverse distance weighting average (IDWA) method outlined in literature (Hartkamp et al. 1999; Noori et al. 2014). Quinn et al. also used this method (Quinn et al. 2012).

In brief, the IDWA method estimates the value of a parameter at an un-sampled point (in this case a power station) as a linear combination of values at known sample points (at weather station locations). The weighting of each known data point, in the linear combination, is a function of the distance between the known sample point and the unknown sample point. A full description of the IDWA methodology can be found in literature (Hartkamp et al. 1999) and is summarised in Equation 7-20.

Equation 7-20 Inverse distance weighting average formula

$$\hat{y}(x) = \sum_{i=0}^{n} \left(\lambda_i * y(x_i)\right)$$

Where $\hat{y}(x)$ is the value of the parameter to be estimated at the un-sampled location x, and λ_i is the weight applied to the value of the parameter at the known point x_i, for n sampled points. The weight applied to the value of the parameter at each sampled point is solely dependent on the distance of the sampled point to the un-sampled point of interest and is given by Equation 7-21.

Equation 7-21 Calculation of weights for inverse distance weighting average

$$\lambda_i = \frac{d_i^{-\alpha}}{\sum_{i=1}^{n} d_i^{-\alpha}}$$

In Equation 7-21, d_i is the Euclidian distance between the un-sampled point of interest and the sampled point at which the parameter value to be estimated is known. The power parameter α is used to determine the degree with which the parameters at sampled points influence the value of the parameter to be estimated at the un-sampled point.

The value of the power parameter in the IDWA equation and the search radius (the radius within which values at known locations were considered) were found using "leave one out cross-validation" for each individual weather station in order to find the value of α which minimised the overall root mean square error (RMSE) for a given search radius, using the built in solver function in Excel. The combination of power parameter and search radius that resulted in the lowest RMSE was chosen for each weather parameter. The number of weather stations, and the values of the power parameter and search radius used in the IDWA method for each parameter can be seen in Table 7-4.

The estimated hourly values of each weather parameter were then used in the calculation of pond temperature and microalgae growth, outlined in previous sections, using Microsoft Excel 2013.

Table 7-4 Parameters of inverse distance weighting average method

Parameter	Unit	No. Weather stations	Power parameter	Search radius (km)
Air temperature	°C	17	2.0748	450
Wind speed	$m.s^{-1}$	17	1.7009	500
Relative humidity	%	17	1.8293	400
Air pressure	hPa	17	6.8754	400
Total solar irradiance	$W.m^{-2}$	21	1.9645	550

7.2.2.4 CO_2 Requirement of microalgae

The hourly growth of microalgae per unit area, p_{mass} ($kg.m^{-2}.hr^{-1}$) was calculated from the growth model, accounting for culture temperature and solar irradiation. This value was then multiplied by the raceway pond area, A_{pond}, to give the total hourly algal biomass production, P_{mass} ($kg.hr^{-1}$). The mass of CO_2 required by the

raceway pond per hour, mCO_2^{hourly} (kg.hr^{-1}), was calculated in the same manner as that used in the rudimentary model (section 7.2.1.2) assuming a CO_2 requirement (CO_2Req_{Algae}) of 1.758gCO_2.g$_{DM}$Algae^{-1}, a CO_2 capture efficiency ($CO_2^{capture}$) of 65.2% for the raceway pond system, and supplying 120% of the required CO_2 to the culture to ensure CO_2 replete conditions ($CO_2^{replete}$). Thus, the hourly CO_2 requirement of a single raceway pond was found using Equation 7-22;

Equation 7-22 Hourly CO_2 requirement of raceway pond

$$mCO_2^{hourly} = \frac{\left(\frac{p_{mass} * A_{pond} * CO_2Req_{Algae}}{\frac{CO_2^{replete}}{100}}\right)}{\left(\frac{CO_2^{capture}}{100}\right)}$$

The addition of CO_2 to the raceway pond only occurred during hours of sunlight, as this is generally the only period in which microalgae can assimilate inorganic carbon through photosynthesis (U.S. DOE 2010), an hour of sunlight was defined as an hour in which the solar irradiation was greater than zero, the hours of sunlight per day vary throughout the year, based on data obtained from meteorological stations.

7.2.2.5 Microalgae Harvesting

Harvesting of the microalgae culture was assumed to take place once a day, following the last hour of sunlight. The volume of culture removed and the fresh medium added was calculated so as to ensure that the concentration of microalgae biomass in the pond was always 1kg.m^{-3} immediately following culture harvest (Stephenson et al. 2010). This resulted in a variable dilution rate (quotient of volume of culture removed and total culture volume) of the raceway pond throughout the year as a result of variations in daily yields of microalgae; as the daily yield of microalgae increased, so too did the volume of culture withdrawn, which resulted in a higher dilution rate. The maximum daily volume of culture harvested from the raceway pond was found to be ca. 100m^3.day^{-1}, this is in

agreement with the work by Stephenson et al. for a similarly sized raceway cultivation system (Stephenson et al. 2010) and yielded a dilution rate of 0.09day^{-1}.

7.2.3 Resource of microalgae accounting for growth and variable CO_2 availability

7.2.3.1 Case 1: Annual microalgae production assuming constant CO_2 availability

The annual production of micro-algae by an individual raceway pond cultivation system at each of the power station locations was determined under the assumption that CO_2 could always be supplied to the microalgae when required. This gave the upper limit on the productivity of a single raceway pond cultivation system at each power station.

7.2.3.2 Case 2: Annual microalgae production taking CO_2 availability into account

As previously stated, prior works do not account for the impact of power station operational schedule on the availability of CO_2 for the cultivation of microalgae. To take CO_2 availability into account, hourly electricity generation data from each power station was sourced from the SEMO (Single Electricity Market Operator 2016). The hourly electricity generation was multiplied by the annual average CO_2 intensity of electricity from each power station (obtained in annual environmental reports from the EPA (Environmental Protection Agency 2015)) in order to determine the hourly CO_2 production of each power station.

In hours where the CO_2 production of power stations was in excess of the CO_2 requirement of the single raceway pond, the growth of microalgae was assumed to be un-constrained and occurred in CO_2 replete conditions. During hours in which microalgae could grow, but during which there was no CO_2 available from the power station, the growth of micro algae was taken to be zero. In hours when the CO_2 requirement of the single raceway pond exceeded the CO_2 production of the power station, the growth of microalgae was reduced pro-rata depending on the degree of under supply of CO_2 to the cultivation system. This reduction in growth was unlikely to occur for a single raceway pond as the hourly generation of CO_2 generally exceeded the CO_2 requirement of a single raceway pond. The third

scenario did come into effect when the resource from multiple ponds was assessed at each power station (see section 7.2.3.3).

The annual algae yield of a single raceway pond in the immediate vicinity of a power station was thus determined and compared to the yield obtained assuming CO_2 was constantly available, in order to quantify the impact of plant operational schedule on microalgae yield. In reality multiple raceway ponds would be developed in a microalgae production facility, however, the analysis carried out for a single raceway pond was done to highlight the maximum possible microalgae yield per unit area, before limitations on CO_2 availability came into play, as outlined in the following section.

7.2.3.3 Case 3: Annual microalgae production from multiple raceway ponds accounting for CO_2 availability

Microalgae cultivation systems typically comprise of a number of raceway pond units. For case 3, alteration of the number of ponds (and thus land area) required was carried out manually. The number of ponds was altered in order to achieve a total cultivation area of 100ha, 200ha, 400ha, 800ha, 1600ha, and 3,200ha. These area values assume that the ponds are arranged end to end, and side to side, with no space between them for vehicle access and egress. This is not realistic, but was carried out in order to be coherent with the rudimentary analysis which also did not consider the land area required for vehicular access and egress to the cultivation ponds, as such, land area estimates are optimistic. An improved estimate of the total foot print of the microalgae cultivation system should include the area required for such access.

The cultivation areas assessed were selected to allow for ease of comparison between areas to determine whether the yield of microalgae doubled each time the area was doubled. As previously indicated, increasing the number of ponds may result in an undersupply of CO_2 to the cultivation system. Therefore the algae yield per hectare of cultivation system was compared for each cultivation area to determine the area at which the algae yield per hectare started to reduce markedly.

This was seen as the maximum cultivation area of the multiple raceway pond system for each power station. This assessment factored in the availability of CO_2 to the cultivation system. The total microalgae biomass resource, the gross energy yield, gross energy yield per hectare, and the CO_2 avoided by replacing diesel or natural gas with biomethane from the microalgae was then determined for this cultivation area.

7.2.4 Energy resource of microalgae

The cultivated microalgae was assumed to be converted to biomethane via the process of anaerobic digestion as was the case in the rudimentary resource assessment. The VS content (84%$_{DM}$) and the biochemical methane potential (313 $LCH_4.kgVS^{-1}$) of the microalgae were outlined in the rudimentary analysis. For this assessment, the electrical and thermal energy demand of the anaerobic digestion of the microalgae was not considered. The electrical energy requirement of the raceway pond cultivation system for powering the paddle wheel and compressing and injection of flue gas into the cultivation system was also not considered. Thus, the energy yield obtained herein is a gross energy yield. This was done to allow for comparison between; the energy resource identified in the rudimentary analysis, the analysis assuming constant CO_2 availability, and the analysis considering actual CO_2 availability. The gross energy yield on a per unit area basis was determined for a singular pond by dividing the annual energy resource of microalgae from a pond by the footprint of a pond. A similar calculation was applied for the gross energy yield per unit area for a multi-pond cultivation system by dividing the annual energy resource of the system by the footprint of the system. Here a cultivation system was defined as a number (greater than one) of ponds.

Calculation of the volume of diesel replaced and the CO_2 emission savings associated with diesel and natural gas replacement respectively were undertaken as stated in section 7.2.1.3.

7.3 Results and discussion

7.3.1 Total microalgae resource based on rudimentary assessment

The total annual CO_2 emissions of the power stations assessed and the total theoretical resource of microalgae from the rudimentary assessment can be seen in Table 7-5. Additionally, the gross energy resource of this microalgae, the cultivation area required, and the gross energy yield per hectare, based on the rudimentary resource assessment for each power station assessed can be seen in Table 7-5. Table 7-5 also shows the volume of diesel fuel, which could be offset if all of the biomethane derived from algae were used, as well as the potential CO_2 saving associated with not burning this diesel. The CO_2 saving associated with offsetting natural gas with all of the biomethane produced from the microalgae is also shown.

Table 7-5 Microalgae resource: rudimentary analysis

Power station	CO_2 emissions	Theoretical microalgae resource[a]	Gross methane yield	Gross energy yield[b]	Cultivation area required	Gross energy yield per hectare	Diesel replaced [c]	CO_2 avoided from diesel [d]	CO_2 avoided from natural gas [e]
	$tCO_2.a^{-1}$	$t_{DM}Algae.a^{-1}$	$Mm^3CH_4.a^{-1}$	$GJ.a^{-1}$	$ha.a^{-1}$	$GJ.ha^{-1}.a^{-1}$	Million litres	$t.a^{-1}$	$t.a^{-1}$
Aghada Boiler	113,687	11,707	3,076,003	116,211	135	860	3.2	10,918	6,518
Aghada CCGT	477,179	49,138	12,910,911	487,774	567	860	13.5	45,826	27,357
Dublin bay	1,072,466	110,440	29,017,432	1,096,279	1275	860	30.5	102,995	61,485
Edenderry	699,593	72,042	18,928,716	715,127	832	860	19.9	67,186	40,108
Huntstown	39,236	4,040	1,061,584	40,107	47	860	1.1	3,768	2,249
Lough Ree	732,811	75,463	19,827,466	749,082	871	860	20.8	70,376	42,012
Moneypoint	3,471,649	357,501	93,931,498	3,548,732	4127	860	98.6	333,403	199,031
Poolbeg	764,447	78,721	20,683,432	781,420	909	860	21.7	73,414	43,826
Rhode	737	75.9	19,944	754	1	860	0.02	71	42
Tawnaghmore	725	74.7	19,625	741	1	860	0.02	70	42
Tynagh	434,194	44,712	11,747,869	443,835	516	860	12.3	41,698	24,893
Shannon Bridge	1,098,168	113,086	29,712,857	1,122,552	1306	860	31.2	105,463	62,958
Whitegate	640,665	65,974	17,334,317	654,891	762	860	18.2	61,527	36,730
Total	9,545,556	982,974	2588,271,653	9,757,503	11,349		271	916,717	547,250

[a] Microalgae resource was calculated using Equation 7-4 as follows for Aghada Boiler: [113,687.1*(8/24)*(65.2/100)*(100/120)]/(1.758*1000)=11,707.2$t_{DM}Algae.a^{-1}$

[b] Gross energy yield does not consider the energy consumption in the cultivation of microalgae or the anaerobic digestion process. It is the upper limit on energy which can be obtained.

[c] Diesel replaced calculated as follows: (11,707.2*(84/100)*313*37.78)/(36)=3,228,093 litres of diesel

[d] CO_2 avoided from diesel replacement: 3,228,093*36*94/(1,000,000)=9,738,513kgCO_2. This value is the gross emissions savings and does not consider CO_2 emissions arising from the use of energy in the cultivation or anaerobic digestion process.

[e] CO_2 avoided from natural gas replacement: (116,211.4*1000)*(56.085)/1,000,000=6,517.7tCO_2. This value is the gross emissions savings and does not consider CO_2 emissions arising from the use of energy in the cultivation or anaerobic digestion process

Based on the rudimentary resource assessment the total theoretical microalgae resource amounted to $983x10^6t_{DM}$ of algae biomass, which could yield 9.76PJ (2.7TWh) of energy in the form of biomethane. The total primary energy requirement of natural gas in Ireland was ca. 181.26PJ in 2015, the total end use of natural gas was approximately 57PJ by industrial and commercial users, and 26PJ by residential users (Gas Networks Ireland 2016). Based on the rudimentary assessment, up to 5.4% of the total primary natural gas demand could theoretically be offset by biomethane derived from microalgae, equivalent to 17% of industrial natural gas demand or 38% of residential natural gas demand. If the biomethane produced from the cultivated microalgae were to offset natural gas consumption in the production of heat by industrial or residential consumers (requiring no infrastructural changes on the part of the gas user), it could supply up to 5.5% (renewable energy share of heat, RES-H) of the final thermal energy requirement in 2015 (Howley & Holland 2016) and result in a maximum avoided CO_2 emissions of 547,250tCO_2.

An alternative use of the biomethane would be as a vehicle fuel in compressed natural gas fuelled vehicles, especially heavy goods vehicles (HGVs). If the biomethane resource were to be used in HGVs it would offset the consumption of ca. 271 million litres of diesel, equivalent to ca. 9% of the total diesel consumption in Ireland in 2015 (Howley & Holland 2016), and ca. 37% of the energy consumption of HGVs in 2015 (Howley & Holland 2016). The total energy consumption of public transportation in 2015 was 5.7PJ, the potential biomethane resource of microalgae in the rudimentary assessment could meet this energy demand 1.7 times over. Of interest is that the potential for avoided CO_2 emissions when biomethane is used to replace diesel (916,717tCO_2) are significantly higher than if the biomethane were used to replace natural gas (547,250tCO_2) owing to the higher carbon intensity of diesel. The total theoretical biomethane resource of microalgae based on the rudimentary assessment was equivalent to a renewable energy in transportation (RES-T) contribution of approximately 4.9% of total final consumption. This becomes 9.8% when a double weighting is applied to the energy contribution of

microalgae as per Directive (EU) 2015/1513 (The European Parliament and the Council of the European Union 2015).

The land area required for the cultivation of this microalgae resource in the rudimentary assessment was found to be ca. 11,384ha. This land area is equivalent to 0.25% of Ireland's total agricultural land area (ca. 4.6 million hectares (Central Statistics Office 2012)). The small land area required results in a high gross energy yield per hectare of 860GJ.ha^{-1}.a^{-1} in the rudimentary analysis. The theoretical gross energy yield of biomethane derived from grass silage in Ireland was previously calculated as 122GJ.ha^{-1}.a^{-1} (Smyth et al. 2009), while that of sugar beet derived biomethane was estimated as 155GJ.ha^{-1}.a^{-1} (Murphy & Power 2009). The theoretical gross energy yield per hectare of biodiesel derived from oil seed rape has been estimated to be 47GJ.ha^{-1}.a^{-1} (Thamsiriroj & Murphy 2011). Compared to the gross energy yields of these other fuel sources, biomethane derived from microalgae, according to the rudimentary assessment, is very attractive. However, the high gross energy yield per hectare of microalgae derived biomethane is a direct result of the growth rate of microalgae, assumed to be 23.73 g_{DM}Algae.m^{-2}.day^{-1}, and the assumption that this growth rate was constant throughout the year, irrespective of weather conditions, or the availability of CO_2 from each power station.

7.3.2 Total microalgae resource accounting for growth model, culture temperature, and CO_2 availability

7.3.2.1 Results and discussion of Case 1 and Case 2

The hourly microalgae growth assuming constant CO_2 availability (Case 1) and hourly microalgae growth taking CO_2 availability into account (Case 2), for a single raceway pond is shown in Figure 7-2. The actual CO_2 production of the power station Shannon Bridge is also shown in Figure 7-2. The example of Shannon Bridge was selected as it is a peat fired power station with a relatively high number of operational hours per year (7,920 hours), and can be considered a base load power station. The cumulative microalgae resource of both Case 1 and Case 2 are also

displayed. The hourly production of CO_2 is shown on the primary y-axis, whilst the hourly microalgae growth, and cumulative microalgae grown are shown on the secondary y-axis. Similar results are shown for two additional power stations, Whitegate (a mid-merit combined cycle gas turbine power station with approximately 5,896 operational hours per year) and Huntstown (an open cycle gas turbine operating as a peaking plant with a low number of operation hours per year ca. 88) in order to highlight the impact of different plant operating regimes. Additional results can be seen in Appendix D for the remaining power stations which were assessed.

The results of these graphs are shown in Table 7-6, which contains the annual microalgae yield of a single pond and the number of days in which growth occurred, under the assumption of constant CO_2 availability (Case 1), and taking CO_2 availability into account (Case 2). The difference in microalgae yield for Case 1 and Case 2 is also presented in Table 7-6. Additionally, the gross energy resource (in the form of biomethane) and gross energy yield per area of raceway pond is reported.

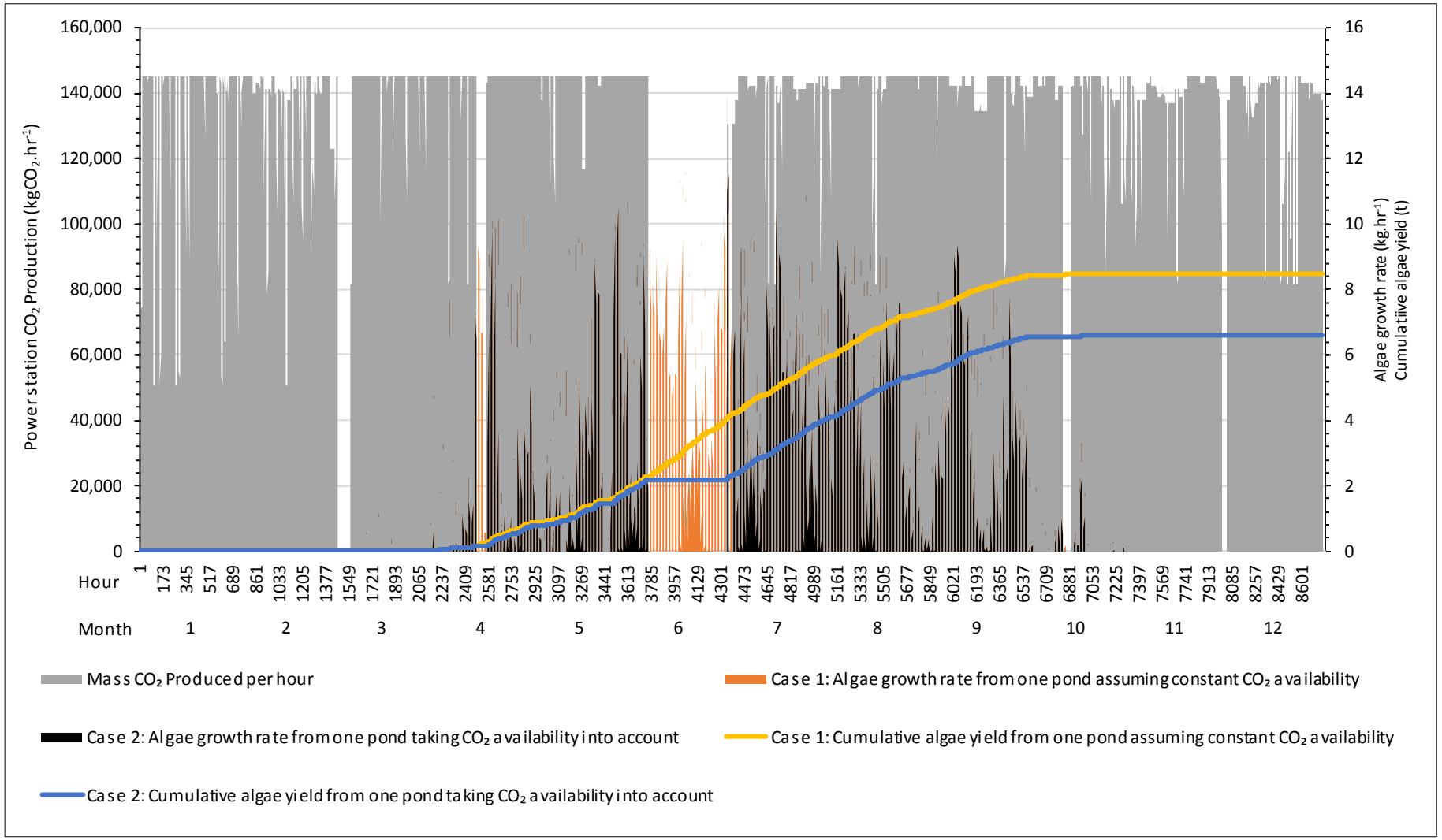


Figure 7-2 Carbon dioxide (CO_2) production and microalgae growth for one year at Shannon Bridge power station

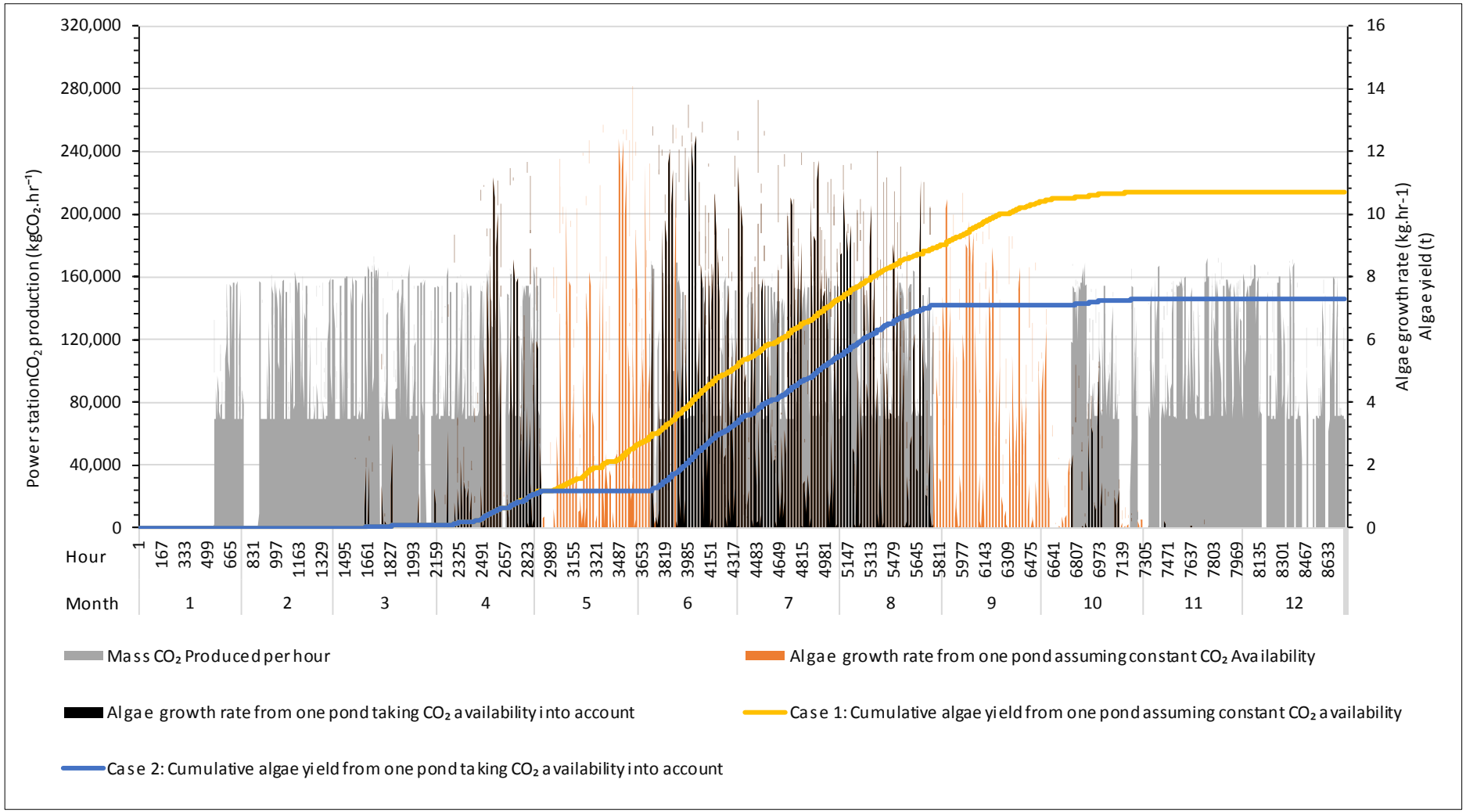


Figure 7-3 Carbon dioxide (CO_2) production and microalgae growth for one year at Whitegate power station

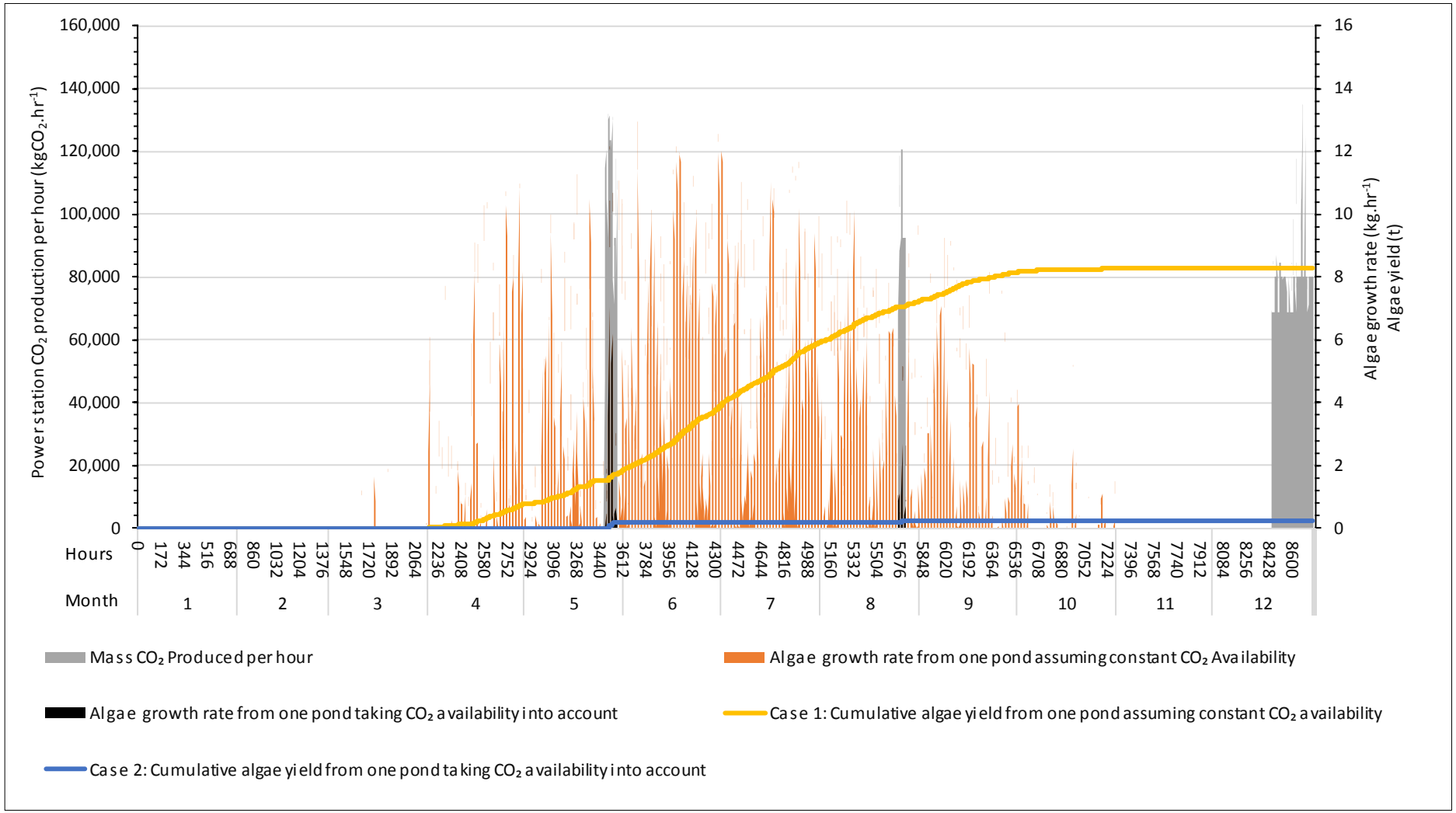


Figure 7-4 Carbon dioxide (CO_2) production and microalgae growth for one year at Huntstown power station

Table 7-6 Microalgae resource of a single pond assuming constant CO_2 availability (Case 1), and taking CO_2 availability into account (Case 2)

	Case 1	**Case 1**	**Case 1**	**Case 1**	**Case 2**	**Case 2**	**Case 2**	**Case 2**	**Case 2 vs. Case 1**
Power station	Microalgae yield	Days of growth	Gross energy resource[a]	Gross energy per unit area	Microalgae yield from a single pond	Days of growth	Gross energy resource[a]	Gross energy per unit area	Reduction in microalgae yield in Case 2 compared to Case 1
	$t_{DM}Algae.a^{-1}$	days	$GJ.a^{-1}$	$GJ.ha^{-1}.a^{-1}$	$t_{DM}Algae.a^{-1}$	days	$GJ.a^{-1}$	$GJ.ha^{-1}.a^{-1}$	% Reduction
Aghada Boiler	10.658	228	105.800	319.233	3.903	82	38.741	116.895	63
Aghada CCGT	10.658	228	105.800	319.233	6.760	119	67.104	202.474	37
Dublin bay	8.340	212	82.788	249.797	7.317	197	72.632	219.155	12
Edenderry	8.553	207	84.897	256.160	6.986	178	69.348	209.245	18
Huntstown	8.275	210	82.140	247.842	0.242	7	2.403	7.249	97
Lough Ree	7.961	201	79.022	238.435	6.519	160	64.711	195.254	18
Moneypoint	9.244	218	91.758	276.863	9.244	218	91.758	276.863	0
Poolbeg	8.366	212	83.048	250.584	7.696	175	76.393	230.502	8
Rhode	8.437	207	83.746	252.689	0.029	13	0.285	0.860	99
Tawnaghmore	8.112	207	80.521	242.957	0.042	12	0.415	1.254	99
Tynagh	8.576	212	85.125	256.849	4.504	114	44.714	134.916	47
Shannon Bridge	8.483	209	84.207	254.080	6.601	182	65.522	197.702	22
Whitegate	10.684	228	106.052	319.994	7.272	149	72.182	217.796	32

[a]Gross energy yield does not consider the energy consumption of the cultivation process or the energy consumed in the anaerobic digestion process.

It is evident from Figure 7-2 to Figure 7-4 that the hourly growth rate of microalgae varied throughout the year as a result of changing solar irradiation and culture temperature, with the highest growth rates occurring during the summer months and no growth taking place during the winter months. This is to be expected and highlights the inaccuracy of assuming a constant microalgae growth rate as used in the rudimentary assessment. Furthermore, the daily growth rate assumed in the rudimentary assessment (23.73 $g_{DM}Algae.m^{-2}.day^{-1}$) is higher than the daily growth rates determined in the microalgae growth model for approximately 95% of the days in a year. An example of this can be seen in Figure 7-5 for Shannon Bridge power station.

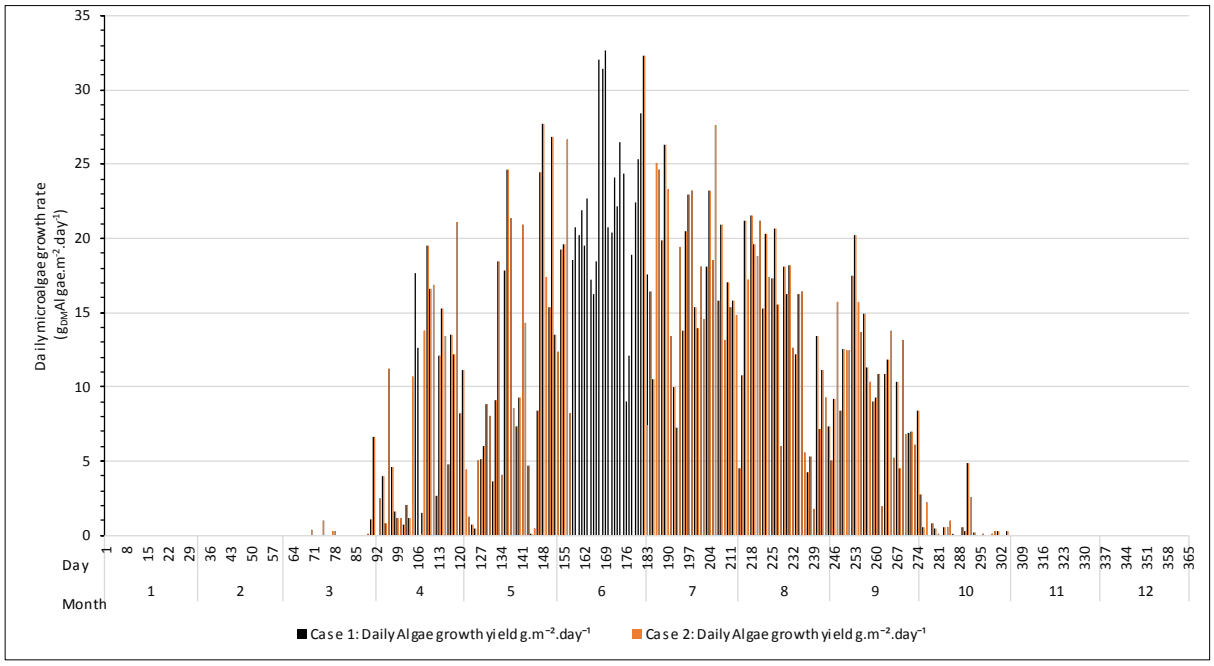


Figure 7-5 Daily microalgae growth rate for Shannon Bridge power plant assuming constant CO_2 availability (Case 1)

A potential reason for the reduced daily growth rates calculated by the growth model as compared to previous literature which used constant average annual growth rates is that such literature values are typically obtained for different climatic regions, such as the south-western regions of the USA or continental Europe, and not for temperate oceanic climates as exemplified by Ireland. Based on

the lower microalgae growth rates, which also vary throughout the year, it was expected that the gross energy yield of microalgae derived biomethane would be lower for a single raceway pond in Case 1 (assuming constant CO_2 availability) and in Case 2 (accounting for CO_2 availability) than in the rudimentary assessment.

In Figure 7-2 to Figure 7-4 it can be seen that the assumption that CO_2 produced from power stations would be constantly available to microalgae cultivation systems is not fully accurate. There is a variation in the production of CO_2 from power stations depending on the quantity of electricity generation, and whether the power station is operational or not. In the case of Shannon Bridge (Figure 7-2), production of CO_2 occurs almost constantly, with the exception of the summer months.

Shutdown of Shannon Bridge during this period is potentially a result of lower electricity demand during the summer months, or as a result of maintenance work. In the case of Whitegate (Figure 7-3), the degree of variation in the quantity of CO_2 produced can be seen to vary significantly, almost doubling in periods of high electricity generation. This is in agreement with the classification of the Whitegate power station as a mid-merit plant which is likely to increase and decrease electricity output in response to total electricity demand.

There are significantly more periods of the year when no CO_2 is produced at the Whitegate power station than at Shannon Bridge (2,864 hours vs. 840 hours respectively). Thus, assuming that the CO_2 production of Whitegate power station would be constantly available to a microalgae cultivation system would lead to an erroneous result in terms of the potential yield of microalgae. Variation in the production of CO_2 from the Huntstown power station is significant. As this power station operates as a peaking plant (being dispatched only at times of high electricity demand) the total number of run hours is low, with a correspondingly low number of hours during which CO_2 is produced. Assuming that the total annual CO_2 emissions from such a power station would be constantly available to cultivate microalgae is inaccurate.

The reduction in the annual microalgae yield between Case 1 and Case 2 for a single raceway pond ranged from 0% (no reduction) for Moneypoint (a base load coal

fired power station consisting of three separate units, one of which was always running), to a reduction in excess of 97% for three peaking power stations (Huntstown, Rhode, and Tawnaghmore) when CO_2 availability is considered. The reduction in microalgae yield between Case 1 and Case 2 ranged from 8 - 63% for the remaining power stations, depending on both the number of hours without CO_2 production, and when these hours of no CO_2 production occurred, owing to the variation in microalgae growth rate throughout the year. In theory, if the hours in which no CO_2 production occurred were to take place at night time, no reduction in microalgae yield would occur between Case 1 and Case 2, however, this is not the case. The total annual microalgae yield in Case 1 ranged from 7.96t_{DM}Algae.pond^{-1}.a^{-1} to 10.68 t_{DM}Algae.pond^{-1}.a^{-1}, compared to 0.029-9.244 t_{DM}Algae.pond^{-1}.a^{-1} for Case 2. Ignoring the impact of CO_2 availability resulted in an overestimation of the microalgae yield associated with a single raceway pond at almost all power stations in Case 1.

Based on the annual algae yield per pond, the gross energy yield per hectare of a single raceway pond ranged from 238GJ.ha^{-1}.a^{-1} to 320GJ.ha^{-1}.a^{-1} for Case 1, and from 0.86GJ.ha^{-1}.a^{-1} to 277GJ.ha^{-1}.a^{-1} for Case 2. Comparing the gross energy yield per hectare from Case 1 and Case 2 to that obtained in the rudimentary analysis illustrates the potential over estimation of the microalgae resource in the rudimentary assessment. The gross energy yield per hectare obtained in the rudimentary analysis was 2.68 times greater than the maximum gross energy yield of any raceway pond assessed in Case 1, and 3.11 times greater than the maximum gross energy yield of any raceway pond in Case 2. This highlights the requirement to consider the impact of weather conditions and CO_2 availability when conducting microalgae resource assessments. Whilst the gross energy yield per hectare was found to be lower in Case 2 than that obtained in the rudimentary assessment, the gross energy yield per hectare of a single pond was still significantly higher than that of biomethane derived from grass silage, sugar beet, and biodiesel obtained from oil seed rape for the majority of power stations.

7.3.2.2 Results and discussion of Case 3

The maximum cultivation area of each raceway pond cultivation system, as well as the gross energy yield, and energy yield per hectare for each power station whilst considering the availability of CO_2 (Case 3) can be seen in Table 7-7. Case 3 illustrates the impact of increasing the number of ponds on the achievable microalgae yield. Supplying more microalgae cultivation ponds with CO_2 from a single power station would result in an under supply of CO_2 when the number of ponds increased beyond a certain point. This would result in a reduced microalgae yield per unit area, and a lower gross energy yield per hectare. Additionally, the equivalent volume of diesel which could be replaced by biomethane (on an energy basis), and the gross CO_2 savings associated with replacing diesel and natural gas with biomethane derived from microalgae are also contained in Table 7-7. The power stations Huntstown, Rhode, and Tawnaghmore were excluded from this analysis as they were deemed unsuitable for microalgae cultivation owing to their operational nature (peaking electricity production plants) and the impact of this on the potential microalgae yields when taking CO_2 supply into account.

The gross energy resource associated with biomethane derived from microalgae cultivated at each power station in Case 3 ranged from 23TJ.a^{-1} to 443TJ.a^{-1}, this is considerably lower than the biomethane resource obtained in the rudimentary resource which ranged from 116TJ.a^{-1} to 3,548TJ.a^{-1}. A comparison of the energy resource at each power station can be seen in Figure 7-6.

Table 7-7 Maximum microalgae cultivation area, gross energy yield, energy yield per unit area, diesel replacement, and CO_2 savings for each power station for Case 3 (multiple ponds)

Power station	Maximum no. of raceway ponds	Maximum cultivation area [a]	Microalgae yield [b]	CO_2 captured by microalgae[c]	CO_2 capture as fraction of annual CO_2 production	Gross energy yield	Gross energy yield per hectare	Volume of replaced diesel	CO_2 saving from replacing diesel	CO_2 saving from replacing natural gas
	no.	Ha	$t_{DM}Algae.a^{-1}$	$tCO_2.a^{-1}$	%	$GJ.a^{-1}$	$GJ.ha^{-1}.a^{-1}$	Million litres	$tCO_2.a^{-1}$	$tCO_2.a^{-1}$
Aghada Boiler	603	200	2,340	4,115	3.6	23,224	116	0.645	2,182	1,303
Aghada CCGT	2,413	800	16,173	28,445	6.0	160,543	201	4.460	15,083	9,004
Dublin bay	2,413	800	17,612	30,975	2.9	174,825	219	4.856	16,425	9,805
Edenderry	2,413	800	16,824	29,590	4.2	167,007	209	4.639	15,690	9,367
Lough Ree	2,413	800	15,626	27,482	3.8	155,110	194	4.309	14,573	8,699
Moneypoint	4,827	1,600	44,597	78,435	2.3	442,695	277	12.297	41,591	24,829
Poolbeg	2,413	800	18,566	32,653	4.3	184,294	230	5.119	17,314	10,336
Tynagh	2,413	800	10,823	19,035	4.4	107,436	134	2.984	10,094	6,026
Shannon Bridge	2,413	800	15,911	27,983	2.5	157,936	197	4.387	14,838	8,858
Whitegate	2,413	800	17,460	30,708	4.8	173,320	217	4.814	16,283	9,721
Total		8,200	175,932	309,420		1,746,390		48.51	164,073	97,946

[a] Maximum cultivation area found by multiplication of maximum number of raceway ponds by the area of each pond.

[b] Microalgae yield was calculated using the hourly growth rate at each power station location while also taking CO_2 supply into account.

[c] The mass of CO_2 captured by the microalgae was found by multiplication of the microalgae biomass by $1.758gCO_2.g_{DM}Algae^{-1}$

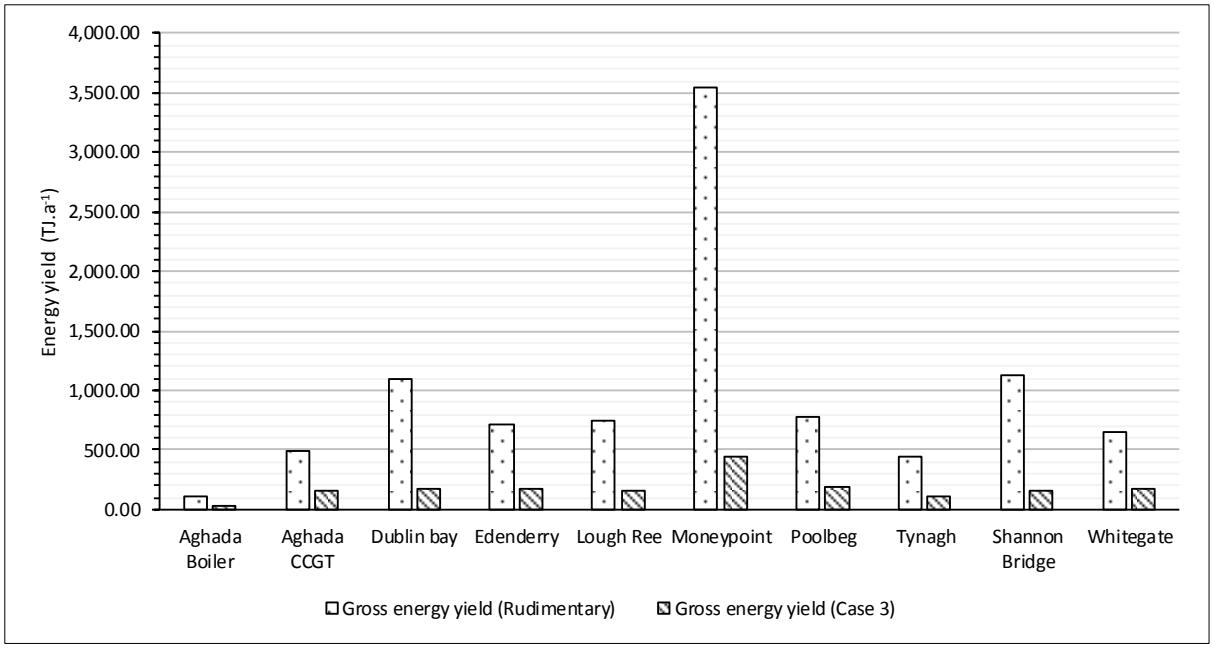


Figure 7-6 Gross energy yield of microalgae derived biomethane, rudimentary assessment and Case 3

The gross energy yield of biomethane derived from microalgae at each power station in Case 3 is consistently lower than in the rudimentary assessment owing to lower microalgae growth rates as a result of weather conditions, and the impact of considering CO_2 availability on microalgae yield. The total biomethane resource based on the microalgae yield obtained in Case 3 was approximately 1,746TJ.a^{-1}, approximately 17.9% of the biomethane resource identified in the rudimentary assessment.

The gross biomethane resource in Case 3 is equivalent to 1% of the total primary gas demand of Ireland in 2015. In this respect biomethane from microalgae in Case 3 could replace 3% of the natural gas demand of industrial consumers of natural gas or 7% of the residential natural gas demand. If the total biomethane were used to offset natural gas approximately 97,946tCO_2 could be avoided. The biomethane resource of microalgae identified in Case 3 was equivalent to approximately 1% of thermal energy consumption in Ireland in 2015, giving a RES-H of 1%.

If the biomethane resource identified in Case 3 were used to replace diesel fuel in transportation, it could offset the consumption of ca. 48.51 million litres of diesel on an energy basis, approximately 1.5% of the total diesel consumption in Ireland in 2015 (Howley & Holland 2016). Alternatively, if the biomethane were to be used as

a fuel in HGVs it could replace 7% of HGV energy consumption in 2015 (Howley & Holland 2016). In terms of the energy consumption of public transportation in Ireland, the microalgae derived biomethane resource in Case 3 could replace 31% of the energy consumption of public transportation in 2015. The majority of energy use in public transportation is diesel, replacement of this quantity of diesel would result in avoided emissions of approximately 164,073tCO_2, equivalent to 1.4% of CO_2 emissions from transportation in 2015 (United Nations Framework Convention on Climate Change 2017). In terms of RES-T, offsetting diesel with biomethane derived from microalgae in Case 3 would have a contribution of 0.87% RES-T on an energy basis, which increases to 1.74% when double weightings are applied.

The total cultivation area required at each power station ranged from 200-1,600 hectares, with a total cultivation area of 8,200ha required. This assumes that the raceway ponds can be arranged end on end and side to side, with no consideration for vehicle access and egress to and from raceway ponds away from the immediate edges. Whilst the total cultivation area required is small in comparison to the total agricultural land area of Ireland (c.a. 4.6million ha), the use of land in the immediate vicinity of the power stations may be impractical. In cases of unsuitable land use next to power stations transportation of CO_2 via pipelines to more suitable locations would be required (Kadam 1997; Kadam 2001).

Transportation of CO_2 to cultivation ponds located away from a power station would result in energy consumption in the separation of CO_2 from the exhaust gas stream, CO_2 compression, dehydration, and transportation to the cultivation ponds. This increase in energy consumption would lower the net energy ratio, the ratio of energy output of the microalgae cultivation system to the energy required in the operation of the system, and reduce the benefits of offsetting fossil fuels with fuels derived from microalgae. The model developed herein would need to be updated to take these effects into account. However, if there was sufficient land with little or no use in close proximity to the power station, this model would be applicable, provided the data inputs are updated to match the area in question . This may occur in regions such as the South-western USA and Australia.

A particular point of interest is the fact that the majority of "land" use surrounding 5 of the plants assessed consists of seas, port areas, intertidal flats, and estuarine areas. The development of potential technologies such as the floating microalgae cultivation systems proposed by Trent et al. (Trent & NASA Ames research Center 2012) could facilitate the production of microalgae at these sites, without causing any land use change, considerations toward wildlife habitats and sea-faring capabilities will however be required.

An important point of note is that the results in this work are not derived from growth rates of a specific algae species or taxa owing to the lack of information available as to which species or taxa would be most suitable for the region in question (Ireland). If more detailed information were available on the growth rates of various microalgae species and taxa as a function of weather conditions this would yield more accurate and realistic results.

7.4 Further Work

The methodology developed for the in-depth analysis in this work can be used as a basis for further assessments of the viability of microalgae cultivation systems for the production of biofuels. These further assessments include; net energy ratio analysis to determine whether the cultivation system produces more energy than it consumes, and economic viability assessments to discern whether the production of biofuels form microalgae is a viable economic venture. These assessments should be conducted in future work to further refine the initial analysis conducted herein. Refinement of the methodology developed in this work for the in-depth analysis is also possible. The methodology in this work did not use species specific responses in growth rate to either cultivation temperature or light intensity as no such information for indigenous Irish species was available and generic responses were used. Future work which considers species specific responses in growth rate to temperature and light intensity would increase the applicability and accuracy of the methodology. Additional future work should also assess the impact of utilising waste heat from possible sources of CO_2 in-order to increase culture temperature to the optimal range if required.

7.5 Conclusions

The impact of CO_2 availability and varying microalgae growth rates on the potential biomethane resource derived from microalgae grown using CO_2 from power stations was found to be significant. The results of the rudimentary analysis indicated that a potential biomethane resource of 9.76PJ (21% of industrial natural gas demand) derived from $983x10^3$ t_{DM}Algae could be available under the assumption of constant CO_2 availability and a constant microalgae growth rate of 23.73 $g_{DM}Algae.m^{-2}.day^{-1}$. This resource could offset 4.87% of energy use in transportation. The rudimentary assessment resulted in a 6-fold over estimation of the potential resource of biomethane derived from microalgae grown using CO_2 from thermal power stations compared to Case 3 (including the effects of CO_2 availability and varying microalgae growth yields). Growth rates assumed in the rudimentary assessment were only achieved 5% of the time in the in-depth assessment, which accounted for the effects of weather and CO_2 availability. The biomethane resource identified in the in-depth assessment, which considered CO_2 availability and weather was 17.9% of the resource identified in the rudimentary assessment.

The results of the analysis which incorporated the effects of CO_2 availability and varying microalgae growth yields (Case 3) indicated a potential resource of 1.746PJ arising from $176x10^3$ t_{DM}Algae, equivalent to 0.87% of energy use in transport which could offset a maximum of 146,347tCO_2 (1.4% of total CO_2 emissions from transport) if it were to replace diesel use. The total biomethane resource, when taking CO_2 availability and variations in microalgae growth rate into account (Case 3), was equivalent to 3% of industrial natural gas demand and 6.8% of residential gas demand, of the Republic of Ireland. Use of biomethane derived from microalgae to replace natural gas use could avoid the emission of a maximum of 97,946tCO_2.

The minor resource of microalgae calculated in this work for Ireland leads to the conclusion that microalgae is not the panacea of biofuel production in an Irish context. However, the production of microalgae for use as a raw material in a biorefinery for the production of high value products may be viable.

The methodology developed in this work, which incorporated the variation in microalgae growth rate and the availability of CO_2, can be applied in any region provided that sufficient data on climactic conditions and power station operation are available and should yield more realistic results than prior methodologies which assumed a constant availability of CO_2 and constant microalgae growth yields.

7.6 References

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8 Chapter 8: The potential of power to gas to provide green gas utilising existing CO_2 sources from industries, distilleries and wastewater treatment facilities

The potential of power to gas to provide green gas utilising existing CO_2 sources from industries, distilleries and wastewater treatment facilities

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Abstract

The suitability of existing sources of CO_2 in a region (Ireland) for use in power to gas systems was determined using multi criteria decision analysis. The main sources of CO_2 were from the combustion of fossil fuels, cement production, alcohol production, and wastewater treatment plants. The criteria used to assess the suitability of CO_2 sources were: annual quantity of CO_2 emitted; concentration of CO_2 in the gas; CO_2 source; distance to the electricity network; and distance to the gas network. The most suitable sources of CO_2 were found to be distilleries, and wastewater treatment plants with anaerobic digesters. The most suitable source of CO_2, a large distillery, could be used to convert 461GWh.a^{-1} of electricity into 258GWh.a^{-1} of methane. The total electricity requirement of this system is larger than the 348GWh of renewable electricity dispatched down in Ireland in 2015. This could allow for the conversion of electricity that would otherwise be curtailed into a useful energy vector. The resulting methane could fuel 729 compressed natural gas fuelled buses per annum. Potential synergies in integrating power to gas at a wastewater treatment plant include use of oxygen in the wastewater treatment process.

Keywords: Power to gas; Multi Criteria Decision Analysis; Renewable Energy; Energy Storage; Bioresource; Renewable Gas.

8.1 Introduction

The 2020 climate and energy package aims to achieve by 2020: a reduction in greenhouse gas emissions of 20% compared to 1990 levels (The European Parliament and the Council of the European Union 2009); a supply of 20% of energy consumed in the EU from renewables (The European Parliament and the Council of the European Union 2009); and a 20% increase in energy efficiency (European Parliament 2012). In Ireland, the target for renewable energy by 2020 as a share of gross final consumption (GFC) is 16% (The European Parliament and the Council of the European Union 2009). This is to be achieved through a renewable energy supply in electricity (RES-E) of 40% of GFC, a renewable energy supply in transport (RES-T) of 10% of total final consumption (in line with Directive 2009/28/EC (The European Parliament and the Council of the European Union 2009)), and a renewable energy supply in heat (RES-H) of 12% of total final consumption.

In 2015, Ireland's RES-E was 25.3%, with 84% of all of the renewable electricity generated by wind turbines (Howley & Holland 2016). The intermittent nature of the renewable electricity generated in the Irish electricity system presents difficulties in matching supply with demand. The permitted quantity of non-synchronous variable renewable generation is governed by the system non-synchronous penetration (SNSP) metric as calculated as in Equation 8-1.

Equation 8-1: Calculation of system non-synchronous penetration

$$SNSP = \frac{Wind\ Generation + High\ Voltage\ DC\ Imports}{System\ Demand + High\ Voltage\ DC\ Exports}$$

When SNSP limits are reached the output of wind farms must be curtailed, also termed as being "dispatched down". In 2015, ca. 348GWh was dispatched down, approximately 5% of the total wind generation in Ireland (EIRGRID & SONI 2016).

Increased limits for SNSP would result in a lower quantity of electricity being dispatched down, as a greater portion of system demand could be met by wind generation. Alternatively, increasing system demand for a given quantity of wind

generation would reduce the instantaneous SNSP. Efforts to increase the SNSP limit in Ireland from 50% are underway with an expected SNSP limit of 75% to be achieved (Eirgrid Group 2015) by 2020; despite this, a certain amount of curtailment will occur, with estimates at 7% of total electricity generation from wind turbines (Mc Garrigle et al. 2013).

Based on work conducted by Chiodi et al. non-dispatchable renewable electricity generation (predominantly from on-shore and off-shore wind turbines) could amount to 70% of total electricity production in 2050 (Chiodi et al. 2013) in order to meet target of reducing GHG emissions by 80%. No modelling of the implications of this high level of variable renewable electricity generation on the operational stability of the electricity network was conducted. Similar work conducted at a pa-European level by Capros et al. which found that renewable sources of electricity amounted to 51% of total electricity generation (Capros et al. 2012). In the work by Capros et al. potential curtailment of variable renewable electricity generators was addressed by using surplus renewable electricity for the production of hydrogen (via the electrolysis of water) with subsequent injection to the natural as network at concentrations up to 30% by volume (Capros et al. 2012). It can be assumed that the production of hydrogen from surplus renewable electricity will also play a role in the Irish energy systemin the future.

A number of potential pathways for the use of excess renewable electricity have been proposed which include: use as source of energy and a reducing agent in the steel manufacturing industry (Otto et al. 2017), use in coal to liquid facilities to produce methane gas (Chiuta et al. 2016), and production of hydrogen with subsequent injection into the natural gas network (Lo et al. 2017).

The conversion of surplus renewable electricity to hydrogen and the subsequent injection to the natural gas network enables the gas network to act as an additional means of conveying renewable energy to end users. Use of the hydrogen-natrual gas blend would also allow for the use of renewable energy in sectors that are difficult to decarbonise through the use of renewable electricity alone e.g. heavy goods vehicles (Capros et al. 2012). The injection of hydrogen into the natural gas network as proposed by Capros et al. does present some technical difficulties, chief

among them is the fact that currently the maximum allowable concentration of hydrogen in the natural gas transmission system in Ireland is less than 0.1% by volume (Gas Networks Ireland 2017). To overcome this operational limitation on hydrogen injection, conversion to methane via combination with CO_2 via the Sabatier process is a viable mechanism.

Power to gas (PtG), in this case power to methane, is the conversion of electrical energy into hydrogen (H_2) via electrolysis, followed by the conversion of this H_2 and carbon dioxide (CO_2) to methane (CH_4) via the Sabatier process ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$). While the conversion of electrical energy to CH_4 is a less efficient process than utilising the H_2 directly, CH_4 can be injected into the existing natural gas infrastructure. This allows for easier transportation, distribution, and use of the resulting energy carrier.

Issues with integrating high levels of variable renewable electricity generation, and deploying PtG systems as a potential storage solution for surplus electricity have been discussed in several countries (Grond et al. 2013; Benjaminsson et al. 2013; Consulatant Environnement Énergie et al. 2014; Jürgensen et al. 2014; Hashimoto et al. 2014; Schneider & Kötter 2015).

In investigating PtG systems, prior work by Schneider and Kotter identified sources of CO_2 which were in close proximity to both the gas network and renewable electricity generators in Germany (Schneider & Kötter 2015). A similar assessment was conducted for Austria by Reiter and Lindorfer (Reiter & Lindorfer 2015). However, neither study identified the most suitable sites for PtG facilities. Furthermore, the total potential use of electricity in PtG systems was not compared to the quantity of electricity dispatched down in either region. Ahern et al. assessed the potential PtG resource in Ireland based on the theoretically available biogas resource (E. Ahern et al. 2015). No assessment of the resource of PtG from existing CO_2 sources in Ireland was conducted.

The innovation in this work is associated with meeting the objectives of the paper, which are:

- To assess the suitability of existing sources of CO_2 for use in a PtG system in a region with a high level of installed wind capacity, in this case Ireland;
- Determine the possible energy resource of the most suitable CO_2 sources (in terms of CH_4 produced) and estimate the electrical energy required by the PtG systems;
- Compare the energy resource to natural gas demand and energy used in transportation;
- Outline potential configurations for the integration of PtG facilities with the identified CO_2 sources.

8.2 Methodology

8.2.1 Analysis criteria

The methodology used to assess the suitability of CO_2 sources for use in PtG systems was the Multi Criteria Decision Analysis (MCDA) method (Kumar et al. 2017). The MCDA method determines the suitability (S_i) of a given source of CO_2 (i) based on the score ($x_{i,j}$) that a given source of CO_2 achieves for a number of criteria ($j=1 \rightarrow M$). The relative importance of each criterion can also be accounted for in the MCDA method by the application of weightings (w_j) to each. In this assessment each criterion was assigned an equal weighting, in the same manner as that applied by Smyth et al. (Smyth et al. 2011) in assessing the biomethane potential of regions in Ireland. The suitability of a given CO_2 source was calculated using Equation 8-2.

Equation 8-2: Calculation of CO_2 Source Suitability

$$S_i = \frac{\left(\sum_{j=1}^{M} x_{i,j} * w_j\right)}{M}$$

Five criteria were selected to determine the suitability of CO_2 sources for use with PtG systems: total annual quantity of CO_2 produced (m_{CO2}); volumetric concentration of CO_2 in the gas stream (C_{CO2}); biological or fossil production of CO_2 (P_{CO2}); distance to the electricity network (D^{Elec}_{CO2}); and distance to the gas transmission network (D^{Gas}_{CO2}). The scoring system was on a scale of 1 to 10, with 1 being the least suitable and 10 being the most suitable. The range of values for each criterion was divided into 10 equal segments with the exception of biological or fossil production of CO_2 in which biological production was assigned a value of 10 and fossil production of CO_2 was assigned a value of 1 (elaborated upon in Section 8.2.3).

8.2.2 Annual quantity of CO_2 produced

8.2.2.1 Energy related CO_2 production

Annual energy related CO_2 production from the combustion of fuels for 76 of the largest emitters of CO_2 in Ireland, registered in the Emission Trading System (ETS), was obtained from annual environmental reports (AERs) from the Environmental Protection Agency (EPA) for 2015 (Environmental Protection Agency 2015). Each facility had an installed thermal capacity in excess of 20MW. The activity class of each source was identified; the number of facilities in each activity class and the total CO_2 emissions per activity class can be seen in Table 8-1. The total annual emission of energy related CO_2 from each potential source was compared to the ETS licence for each site ((EPA) 2016), to ensure that the figures were consistent.

Table 8-1 Industrial Sources of CO_2

Activity Class	**Number of Facilities**	**Energy Related CO_2 emissions ($t.a^{-1}$)**
Brewing[a]	1	56,020
Cement Production	6	2,369,507
Confectionary	2	4,555
Dairy Processing	16	479,733
Distilling[a]	1	37,866
Meat Processing	7	34,288
Medical Devices	1	7,465
Mineral Extraction	2	216,295
Oil Refining	1	279,270
Pharmaceuticals	17	174,203
Power Generation	18	11,099,006
Processor Manufacturing	1	28,429
Wood Processing	3	7,510

[a] Emissions of energy related CO_2 from brewing and distilling in this instance are from the combustion of fuel onsite for energy production and do not include CO_2 emissions from the fermentation process

8.2.2.2 Alcohol production industry

Three large breweries and three large distilleries were identified as sites with high purity CO_2 generated in the production of alcohol. The three breweries were disregarded due to the on-site capture and use of CO_2 from the fermenters as outlined in their respective AERs. The annual CO_2 production of two of the distilleries (Distillery DA and Distillery DB) was based on information from personal communications with plant staff. Weekly production of pure alcohol was provided from Distillery DA and Distillery DB, this was used to estimate weekly and annual CO_2 production as outlined in Box 8-1 for Distillery DA.

Production of ethanol $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

Producing 1 mol C_2H_5OH produces 1 mol CO_2

46gC_2H_5OH also yields 44gCO_2

1gC_2H_5OH also yields 44/46=0.957gCO_2

Density of C_2H_5OH: 0.7893t/m^3

Weekly ethanol production: 1.23*10^6L

Weekly CO_2 production:

(1.23*10^6/1000)*0.7893*0.957=929.1tCO_2

Box 8-1: Calculation of CO_2 production based on distillery output for Distillery DA

Weekly production of CO_2 was sourced directly from Distillery DC (personal communication Distillery DC) and amounted to 92tCO_2 per week. Annual production of CO_2 from the distilleries assuming 52 weeks of operation per year can be seen in Table 8-2.

Table 8-2 Production of CO_2 at distilleries

Distillery	**Annual CO_2 Production (kt.a^{-1})**
DA	48.3
DB	1.58
DC	4.71

Note on distilleries: Only one distillery was large enough to be included in the ETS, the remaining two facilities have a thermal rating of less than 20MW

None of the distilleries capture the CO_2 produced in the fermentation process, as such it could be considered available for use in a PtG system as there is no significant on-site use for CO_2 at the distilleries.

8.2.2.3 Wastewater treatment

An additional source of CO_2 was biogas from the anaerobic digestion of sewage sludge at wastewater treatment plants (WWTPs). A total of 9 WWTPs with anaerobic digestion of sewage sludge were identified. Data on the annual biogas production by WWTPs was estimated using a biogas production per population equivalent (PE) of $24L_{Biogas}.PE^{-1}.day^{-1}$ (Bachmann et al. 2015). Biogas was assumed to be $40\%_{vol}$ CO_2 (Bachmann et al. 2015; Fernandes et al. 2007). The PE loading of each WWTP in 2015 was calculated using the total influent biological oxygen demand (kg BOD_{in}) in 2015 (Environmental Protection Agency 2015) and the BOD production per population equivalent of $60gBOD.day^{-1}$ (Department of The Environment Heritage and Local Government 2007) as per Equation 8-3.

Equation 8-3 Calculation of PE loading of wastewater treatment plants

$$PE\ Loading = \frac{(kgBOD_{in}) * 1000}{60 * 365}$$

Calculation of the biogas production from WWTPs was also carried out based on the calculated sludge production and biogas yield outlined in Fernandes et al. (Fernandes et al. 2007) as a check. Both methodologies yielded similar results. The biogas production and associated CO_2 resource of each WWTP is shown in Table 8-3.

Table 8-3 Production of CO_2 at wastewater treatment plants

Wastewater Treatment Plant	Loading (PE.day^{-1})	Biogas production (m^3.a^{-1})	CO_2 Production (t.a^{-1})[a]
WWTP1	1,933,205	1.69x10^7	13,299
WWTP2	250,011	2.19x10^6	1,720
WWTP3	214,409	1.88x10^6	1,475
WWTP4	97,832	8.57x10^5	673
WWTP5	88,876	7.78x10^5	611
WWTP6	84,820	7.43x10^5	583
WWTP7	72,226	6.33x10^5	497
WWTP8	54,322	4.76x10^5	374
WWTP9	45,503	3.99x10^5	313

[a]Annual mass of CO_2 produced based on 40%$_{vol}$ concentration of CO_2 in biogas, a molar mass of 44g, and a molar volume of 22.414L.mol^{-1}.

8.2.2.4 Weightings applied to CO_2 emissions

For the MCDA, the range of CO_2 emissions was divided into 10 equal bands with a score of 1 to 10 applied to each, the highest CO_2 emission band was assigned a score of 10, the lowest CO_2 emission band was assigned a score of 1. The emission band of each source of CO_2 was determined and its score was found.

8.2.3 Volumetric concentration of CO_2 in gas stream

The volumetric concentration of CO_2 in exhaust gas from the combustion of fuel is dependent on the fuel type, the combustion technology, and the level of excess air used. This can be seen in Table 8-4, which is taken from scientific literature.

Table 8-4 Concentration of CO_2 in exhaust gas stream

Fuel	**Combustion method**	**CO_2 concentration (%volume)**	**CO_2 concentration (%volume)**	**CO_2 Concentration (%volume)**
Reference		(Metz et al. 2005)	(Schneider & Kötter 2015)	Values used in this work
Natural Gas	Boiler	7-10	5-15	6.5
Natural Gas	Turbine	3-4	5-15	4
Oil	Boiler	3-8	5-15	3.5
Coal	Boiler	12-15	5-15	13.5
Cement kiln off gas		14-33		20
Biomass	Boiler	3-8		NA

Biogas was assumed to be 60% CH_4 and 40% CO_2 (Bachmann et al. 2015; Fernandes et al. 2007), while the concentration of CO_2 in gas from fermenters in distilleries was taken to be 99%. CO_2 present in the exhaust gas stream from a boiler or a turbine must be separated from the remainder of the gases present (such as N_2, O_2 and H_2O) before it can be sent to the methanation phase of a PtG system. The concentration of CO_2 in a gas stream influences the energy required to separate the CO_2 from the other gases present with higher concentrations of CO_2 reducing the energy requirement for separation and vice versa.

The minimum theoretical thermodynamic work required, in an isobaric and isothermal process, for separation into a stream with a high concentration of CO_2 (for use in a PtG system) and a waste gas stream (with low CO_2 concentration), can be calculated as the negative of the difference of the Gibbs free energy of the final separated streams (Wilcox 2012). The work required per kg of CO_2 separated from each source of CO_2 can be seen in Figure 8-1. The sources of CO_2 were reclassified depending on the fuel they used and the combustion method if the exhaust gas originated from fuel combustion. The energy requirement was calculated according to the methodology outlined in Wilcox (Wilcox 2012). The concentrations of CO_2 in each gas stream were varied by +/-5% of the original concentrations to give an estimate of the variation in energy required for CO2 separation. A variation of +/-5%

in the percentage of CO_2 captured and the CO_2 purity was also conducted where applicable to indicate the range of potential energy requirements.

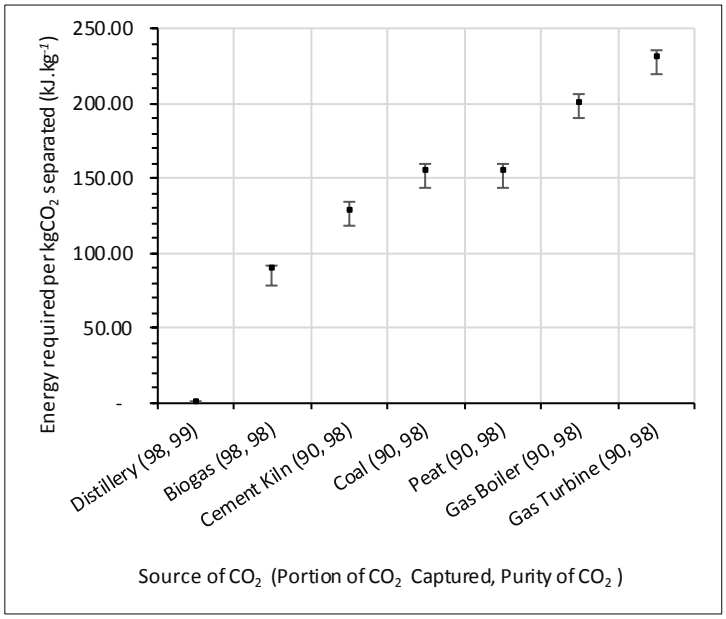


Figure 8-1: Theoretical work (kJ) required per kg of CO_2 separated from each source. Values in brackets correspond to the percentage of total CO_2 that is captured from a source, and the purity of the captured CO_2 respectively. Error bars illustrate the range in values for a variation of +/-5% of CO_2 concentration in the original gas stream and in the percentage of CO_2 captured and the CO_2 purity where applicable.

The range of energy requirement for CO_2 separation was divided into 10 equal bands, the band with the lowest energy requirement was assigned a score of 10, and the band with the highest energy consumption was assigned a score of 1. With respect to the MCDA, the score assigned to each source for the CO_2 concentration criteria was based on the band of energy consumption for CO_2 separation in which it was located.

8.2.4 Biological or fossil production of CO_2

The source of CO_2 used in power to gas systems can impact overall CO_2 emissions from the system. Approximate CO_2 emissions from 4 scenarios depending on whether the source of CO_2 used in the PtG system was biogenic (i.e. arising from a biological process) or non-biogenic (the combustion of fossil fuels) were determined based on the final quantity of CO_2 emitted by: the CO_2 source; PtG facility; and end user of the produced CH_4. Four idealised scenarios were considered as per Table 8-5.

Table 8-5 Scenarios of biogenic and non-biogenic CO_2 use in power to gas systems

Scenario	Source of CO_2	Fuel used in vehicle
S1	Combustion of fossil fuel at a power station	Combustion of diesel in a vehicle producing CO_2
S2	Capture of the CO_2 from combustion of fossil fuel at a power station and conversion to CH_4	Combustion of CH_4 offsetting diesel use in a vehicle.
S3	Production of CO_2 at a distillery	Combustion of diesel in a vehicle producing CO_2.
S4	Capture of CO_2 from the distillery and conversion to CH_4	Combustion of CH_4 offsetting diesel use in a vehicle.

The assumption in these scenarios is that $1m^3$ CO_2 can produce $1m^3$ CH_4 with an energy content of $37.78MJ.m^{-3}CH_4$. The scenarios are based on the emission of $1m^3$ CO_2 from a fossil fuel fired power station, and the emission of CO_2 from the combustion of 30.98MJ of diesel (to account for a reduction in efficiency of CNG fuelled engines of ca. 18% (Korres et al. 2010)) with an emission factor of $94gCO_2.MJ^{-1}$ (Neeft & Ludwiczek 2016; European Commission 2016)) in a diesel vehicle. The scenarios with a biogenic CO_2 source (a distillery) assume that the emission of $1m^3$ CO_2 is a result of the input of $1m^3$ CO_2 into the distillery in the form of the biomass accepted by the distillery. The CO_2 intensity of electricity used in the PtG system was taken to be $130gCO_2eq.MJ^{-1}$ for Ireland (Howley & Holland 2016). The efficiency of the PtG system was taken to be 56% as per section 8.2.6. Scenarios S1 to S4 are illustrated in Figure 8-2.

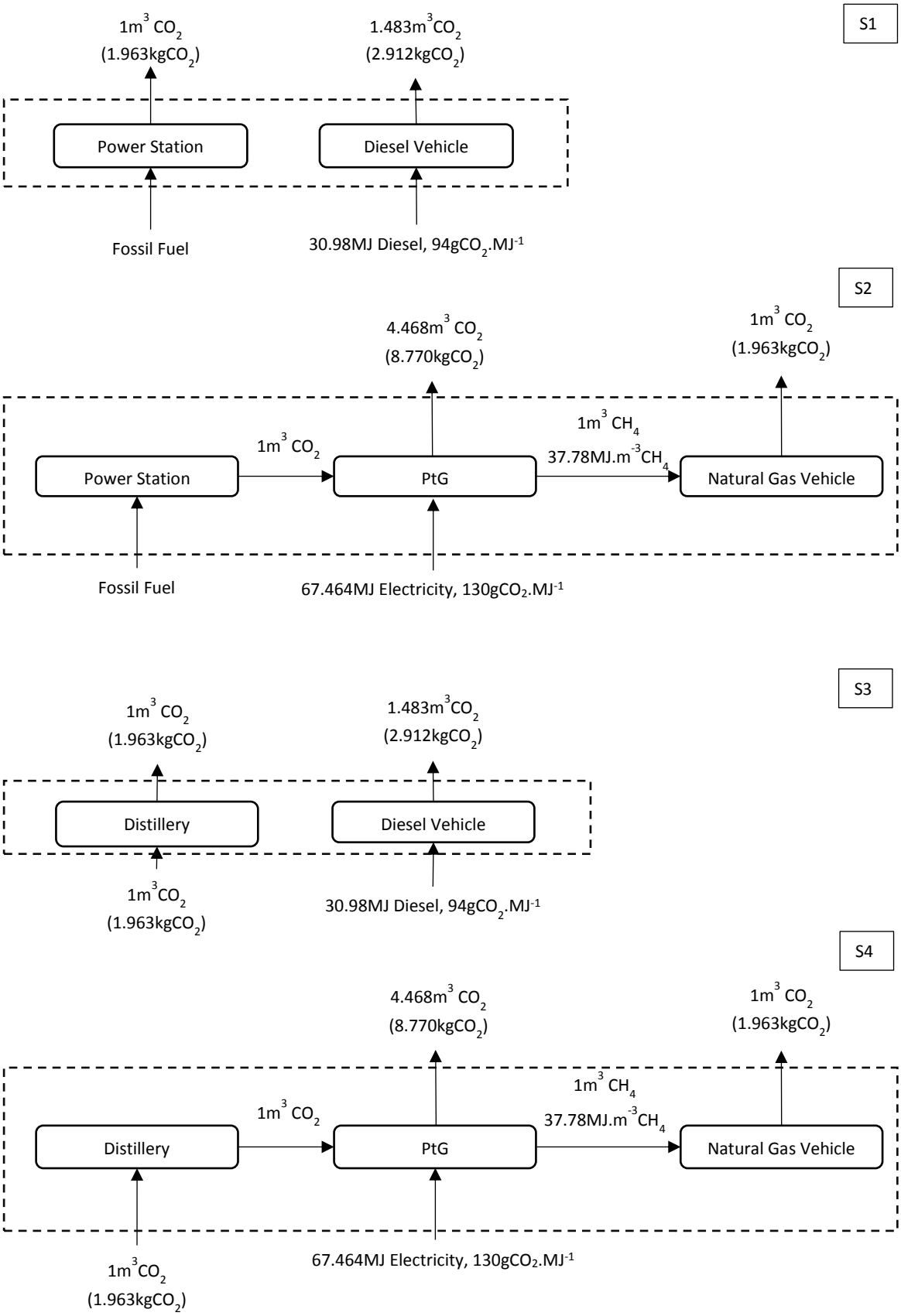


Figure 8-2: Scenarios for the use of non-biogenic or biogenic CO_2 in a PtG system.

The total amount of CO_2 emitted in each of the scenarios S1, S2, S3, and S4 is 4.875kgCO_2, 10.733kgCO_2, 1.483kgCO_2, and 8.77kgCO_2, respectively. The increase in CO_2 emissions in the system with PtG is a result of the CO_2 intensity of electricity used. If renewable electricity that would otherwise have been dispatched down is used the CO_2 emissions in S1, S2, S3, and S4 reduce to 4.875kgCO_2, 1.963kgCO_2, 1.483kgCO_2, and 0kgCO_2 respectively. Alternatively, guarantees of origin could be used to ensure that all of the electricity consumed by the PtG plant is sourced from renewable generators. In reality the CO_2 emissions from systems will be higher (owing to CO_2 arising in the operation of the process and the electricity used to produce the H_2 in the PtG system) however the total CO_2 emissions from a PtG system using biogenic CO_2 will be less than those from a PtG system using non-biogenic CO_2. As such, it was deemed important to distinguish whether the CO_2 source was in fact biogenic or non-biogenic. A biogenic source of CO_2 would result in lower emissions of CO_2 in the power to gas system than if a non-biogenic source of CO_2 were to be used. A similar conclusion was reached in work by Blanco & Faaij (Blanco & Faaij 2018). The score assigned to biogenic sources of CO_2 (distilleries, and WWTPs with anaerobic digestion systems) was 10 and the score assigned to a non-biogenic source of CO_2 (all other sources of CO_2 considered) was 1 as outlined in section 8.2.1.

8.2.5 Distance to electricity and gas networks

Proximity to both energy grids is important for the economic viability of PtG. Increased distance from each of the energy transmission grids leads to an increased cost of developing infrastructure to access these networks. The location of each source of CO_2 was determined from the AERs for each facility. A map of the electricity transmission network (Eurgrid 2016) was digitised manually in QGIS and the shortest distance from each potential CO_2 source to the network was determined.

Similarly, a map of the gas network, sourced from Gas Networks Ireland (GNI) was digitised manually in QGIS to allow for the calculation of the shortest distance from each potential source of CO_2 to the gas network. A map of the location of each of

the identified CO_2 sources along with the electricity and gas transmission networks can be seen in Figure 8-3.

The distances from each energy grid were divided into 10 equal bands. The band with the shortest distance was assigned a score of 10, the band with the longest distance was assigned a score of 1 for these criteria. The score of each CO_2 source with respect to the distance to the electricity network, and gas network respectively, was based on the distance band it was allocated to.

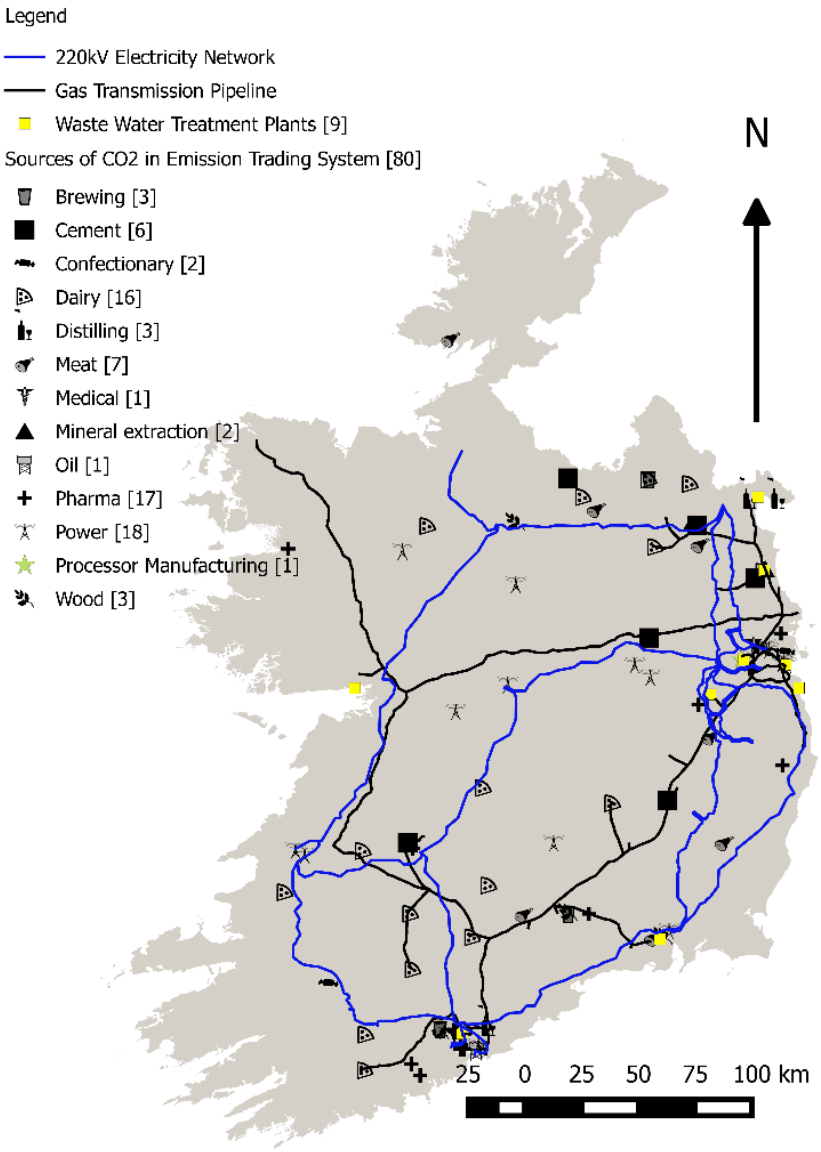


Figure 8-3: Map of sources of CO_2, electricity network, and gas transmission network. Energy transmission networks were manually digitised in QGIS and are a general guide of network locations only.

8.2.6 Energy resource associated with sources of CO_2

The production of CH_4 from CO_2 according to the Sabatier process can be seen in Equation 8-4.

Equation 8-4: Production of CH4 from CO_2 according to the Sabatier process

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The production of 1m^3 CH_4 requires 1m^3 CO_2. Knowing the annual mass of CO_2 ($m^{CO2}{}_i$) emitted at each CO_2 source (i), the potential volumetric resource of CH_4 ($V^{CH4}{}_i$) of each source was calculated according to Equation 8-5. In Equation 8-5 "M_{CO2}" corresponds to the molar mass of CO_2 (44g.mol^{-1}) and "V_m" is the molar volume at STP, taken to be 22.414 L.mol^{-1}.

Equation 8-5: Calculation of volumetric CH_4 resource associated with source of CO_2.

$$V_i^{CH_4}(m^3) = \frac{m_i^{CO_2}}{M_{CO_2}} * V_m$$

The energy associated with the potential resource of CH_4 at each CO_2 source was determined using an energy content of 37.78MJ.m^{-3} for CH_4 (e^{CH4}). Calculation of the electrical energy (E^{elec}) required (GWh) for the production of H_2 at each source was determined as per Equation 8-6 based on an 80% efficiency (η_{Meth}) of methanation, an average of efficiencies sourced from literature (Benjaminsson et al. 2013; Grond et al. 2013; Müller et al. 2013; Schmack et al. 2014; E. P. Ahern et al. 2015; Breyer et al. 2015; Kötter et al. 2015; Reiter & Lindorfer 2015; Schiebahn et al. 2015; Grond et al. 2015; Vlap et al. 2015; Götz et al. 2016; Kötter et al. 2016; Tsupari et al. 2016) and seen to be a conservative estimate, and a 70% electrolyser efficiency ($\eta_{Electro}$), the average of alkaline electrolysis system efficiencies sourced from literature (Gahleitner 2013; Benjaminsson et al. 2013; Grond et al. 2013; Smolinka et al. 2010; Bailera et al. 2015; Schiebahn et al. 2015; Götz et al. 2016;

Buchholz et al. 2014; Qadrdan et al. 2015; Vandewalle et al. 2015). Thus, the overall efficiency of PtG was 56%.

Equation 8-6: Calculation of electrical energy required for the production of H2 to be used in the PtG system. Division by a factor of 3,600,000 is to facilitate the conversion from MJ to GWh

$$E_i^{elec} = \frac{V_i^{CH_4} * e^{CH_4}}{\eta_{Meth} * \eta_{Electro}} * \frac{1}{3{,}600{,}000}$$

The efficiency of electrolysis and methanation were also varied by +/-5% of the values stated above to indicate the range of possible results.

The electrolyser size ($P_{electro}$) in MW_e required in a PtG facility was calculated assuming a number of full load run hours ($FLH_{electro}$) as per Equation 8-7. The value of $FLH_{electro}$ will depend upon a number of factors such as: electricity prices; gas prices; incentives; and maintenance schedules. Calculation of the value of $FLH_{electro}$ incorporating these parameters is beyond the scope of this work and a value of 8,000, which can be considered optimistic was used in this work. The number of full load hours was also varied by +/-5%, again to given an indication of the range of potential results.

Equation 8-7: Calculation of electrolyser size required at a potential PtG facility. Multiplication by 1,000 facilitates the conversion from GWe to MWe

$$P_i^{electro} = \frac{E_i^{elec}}{FLH_{electro}} * 1{,}000$$

8.2.7 Scale of potential energy resource and potential uses

The potential electricity consumption and CH_4 resource associated with the most suitable sites were compared to national values of curtailed electricity and natural gas demand. The total electrical energy dispatched down in the Republic of Ireland in 2015 amounted to ca. 348GWh (EIRGRID & SONI 2016). Potential uses of the CH_4 produced in PtG facilities at the identified sources of CO_2 include combustion in gas boilers to produce heat, and use as a transport fuel in heavy goods vehicles and

buses. Total natural gas consumption in the Republic of Ireland in 2015 was approximately 47,136GWh with 15,013GWh consumed in the industrial commercial sector (Gas Networks Ireland 2016). The final energy consumption of road freight activities in 2015 for the Republic of Ireland was approximately 7,268GWh (Howley & Holland 2016) of which 557GWh arose from the two main bus fleets in the country (Central Statistics Office 2016).

The number of Compressed Natural Gas (CNG) powered buses that could be fuelled using CH_4 from a PtG facility was based on a bus traveling 58,163 km per year (Dublin Bus 2015) with a specific energy consumption of 22 $MJ.km^{-1}$ (MJB&A 2013; Gerbec et al. 2015; Ryan & Caulfield 2010; Ally & Pryor 2007; Zhang et al. 2014; Johnson 2010).

8.3 Results

The suitability score of the 12 highest ranking CO_2 sources can be seen in Table 8-6 along with the potential CH_4 resource available at each facility, the electrical energy required, and the electrolyser size. The locations of these facilities are also shown in Figure 8-4. The electrical energy required by each potential facility as a fraction of the total dispatched down electricity in 2015 in the Republic of Ireland can be seen in Table 8-6 coupled with a comparison to the total consumption of natural gas by industry, and the total energy consumed in heavy goods vehicles and buses in Ireland.

Table 8-6: Suitability score of 12 highest scoring CO_2 sources. Values shown are baseline results with results for -5% variation in input parameters and +5% variation in input parameters in parenthesis respectively.

Facility	Facility Number	m_{CO2}	C_{CO2}	P_{CO2}	D^{Elec}_{CO2}	D^{gas}_{CO2}	Suitability[a]	Potential CH_4 Resource ($GWh.a^{-1}$)[b]	Electrical Energy Required ($GWh.a^{-1}$)[c]	Electrolyser size (MW)[d]
Distillery DA ($64ML.a^{-1}$)	1	1	10	10	10	10	8.2	258.21 (245.3, 258.21)	461.09 (485.36, 418.23)	57.637 (63.83, 49.78)
Distillery DC ($6.24ML.a^{-1}$)	2	1	10	10	9	10	8	25.18 (23.92, 25.18)	44.96 (47.32, 40.78)	5.62 (6.23, 4.85)
WWTP2 (PE of 250,011)	3	1	8	10	10	10	7.8	9.19 (8.73, 9.19)	16.42 (17.28, 14.89)	2.052 (2.27, 1.77)
WWTP5 (PE of 88,876)	4	1	8	10	10	10	7.8	3.27 (3.11, 3.27)	5.84 (6.14, 5.29)	0.73 (0.81, 0.63)
WWTP7 (PE of 72,226)	5	1	8	10	10	10	7.8	2.66 (2.52, 2.66)	4.74 (4.99, 4.30)	0.593 (0.66, 0.51)
WWTP4 (PE of 97,832)	6	1	8	10	10	10	7.8	3.6 (3.42, 3.60)	6.42 (6.76, 5.83)	0.803 (0.89, 0.69)
WWTP6 (PE of 84,820)	7	1	8	10	10	10	7.8	3.12 (2.96, 3.12)	5.57 (5.86, 5.05)	0.696 (0.77, 0.6)
WWTP1 (PE of 1,933,205)	8	1	8	10	9	10	7.6	71.1 (67.54, 71.1)	126.96 (133.64, 115.15)	15.87 (17.58, 13.71)
Distillery DB ($2.1ML.a^{-1}$)	9	1	10	10	7	9	7.4	8.47 (8.05, 8.47)	15.13 (15.93, 13.72)	1.891 (2.1, 1.63)
WWTP9 (PE of 45,503)	10	1	8	10	8	10	7.4	1.67 (1.59, 1.67)	2.99 (3.15, 2.71)	0.374 (0.41, 0.32)
WWTP8 (PE of 54,322)	11	1	8	10	8	10	7.4	2 (1.9, 2.0)	3.57 (3.76, 3.24)	0.446 (0.49, 0.39)
WWTP3 (PE of 214,409)	12	1	8	10	8	10	7.4	7.89 (7.48, 7.89)	14.08 (14.82, 12.77)	1.76 (1.95, 1.52)

[a] Suitability = $(m_{CO2}+C_{CO2}+P_{CO2}+D^{Elec}_{CO2}+D^{gas}_{CO2})/5$ as per Equation 8-2

[b] Sample calculation for Distillery DA: *$(48{,}300{,}521kgCO_2)*(22.414/44)*(37.78)/(3{,}600{,}000)=258.21\ GWh$* as per Equation 8-5

[c] Sample calculation for Distillery DA: *$(258.21)/(0.7*0.8)=461.09\ GWh$* as per Equation 8-6

[d] Sample calculation for Distillery DA: *$(461.09*1000)/8000=54.637\ MW$* as per Equation 8-7

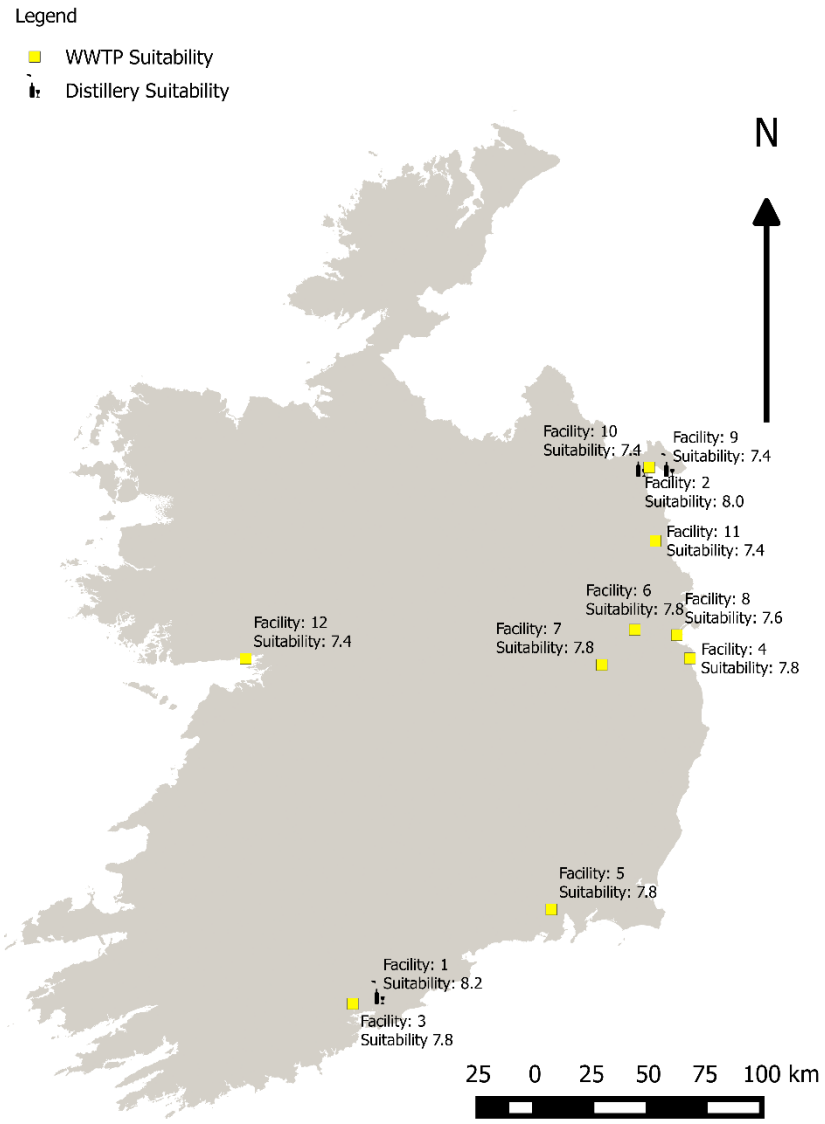


Figure 8-4 Location of most suitable CO_2 sources

Table 8-7: Comparison of results to annual figures of electricity dispatch down, industrial gas demand, freight transport energy use, and energy use in the main bus fleets in Ireland. Values shown are baseline results with results for -5% variation in input parameters and +5% variation in input parameters in parenthesis respectively.

Facility	**Facility Number**	**Share of dispatched down electricity in 2015 (%)**	**Share of industrial natural gas use in Ireland in 2015 (%)**	**Share of fuel consumption of heavy goods vehicles in Ireland in 2015 (%)**	**Share of fuel consumption of diesel buses in main fleets in 2015 (%)**
Distillery DA (64ML.a^{-1})	1	132.6 (139.6, 120.29)	1.72 (1.63, 1.72)	3.55 (3.37, 3.55)	46.38 (44.06, 46.38)
Distillery DC (6.24ML.a^{-1})	2	12.9 (13.61, 11.73)	0.17 (0.16, 0.17)	0.35 (0.33, 0.35)	4.52 (4.30, 4.52)
WWTP2 (PE of 250,011)	3	4.7 (4.97, 4.28)	0.06 (0.06, 0.06)	0.13 (0.12, 0.130	1.65 (1.57, 1.65)
WWTP5 (PE of 88,876)	4	1.7 (1.77, 1.52)	0.02 (0.02, 0.02)	0.04 (0.04, 0.040	0.59 (0.56, 0.59)
WWTP7 (PE of 72,226)	5	1.4 (1.44, 1.24)	0.02 (0.02, 0.02)	0.04 (0.03, 0.04)	0.48 (0.45, 0.48)
WWTP4 (PE of 97,832)	6	1.8 (1.95, 1.68)	0.02 (0.02, 0.02)	0.05 (0.05, 0.05)	0.65 (0.61, 0.65)
WWTP6 (PE of 84,820)	7	1.6 (1.69, 1.45)	0.02 (0.02, 0.02)	0.04 (0.04, 0.04)	0.56 (0.53, 0.53)
WWTP1 (PE of 1,933,205)	8	36.5 (38.44, 33.12)	0.47 (0.45, 0.47)	0.98 (0.93, 0.98)	12.77 (12.13, 12.77)
Distillery DB (2.1ML.a^{-1})	9	4.4 (4.58, 3.95)	0.06 (0.05, 0.06)	0.12 (0.11, 0.12)	1.52 (1.45, 1.52)
WWTP9 (PE of 45,503)	10	0.9 (0.9, 0.78)	0.01 (0.01, 0.01)	0.02 (0.02, 0.02)	0.3 (0.29, 0.3)
WWTP8 (PE of 54,322)	11	1 (1.08, 0.93)	0.01 (0.01, 0.01)	0.03 (0.03, 0.03)	0.36 (0.34, 0.36)
WWTP3 (PE of 214,409)	12	4 (4.26, 3.67)	0.05 (0.05, 0.05)	0.11 (0.1, 0.11)	1.42 (1.35, 1.42)
Total		203.5 (214.29, 184.65)	2.63 (2.51, 2.63)	5.46 (5.18, 5.46)	71.62 (67.64, 71.62)

Based on Table 8-6, the facilities with the highest suitability and potential energy resource are Distillery DA, Distillery DC (see Figure 8-4). Both facilities currently burn natural gas; the total consumption of natural gas of each facility in 2015 was approximately 188GWh and 60GWh respectively. The potential CH_4 resource available at Distillery DA and Distillery DC could meet 137% and 42% of the in house

natural gas demand of each facility, respectively. The total number of CNG buses that could be fuelled by CH_4 from Distillery DA and Distillery DC would be 729 and 71 per annum, respectively.

Of the remaining facilities, all but one are WWTPs with existing anaerobic digestion facilities. The two WWTPs with the largest potential CH_4 resource areWWTP1 (PE of 1,933,205) and WWTP2 (PE of 250,011). Both plants thermally dry the digestate produced onsite using a combination of natural gas and biogas. The thermal energy required for the evaporation of 1kg of water from dewatered digestate was taken to be 0.98kWh (drying from 23% to 95% dry matter content). The total annual energy demand for the thermal drying of sludge was calculated to be ca. 49GWh and 8GWh for the WWTP1 and WWTP2 respectively. The potential energy resource associated with converting CO_2 from these facilities to CH_4 could meet 146% and 111% of the thermal demand for sludge drying in each WWTP. The total number of CNG fuelled buses that could be fuelled from each facility was found to be 200 and 26 per annum, respectively.

8.4 Discussion

8.4.1 Scale of resource and potential CO_2 emission reductions

The results of the MCDA show that the most suitable sources of CO_2 for the development of PtG facilities in Ireland were those which had high concentrations of CO_2 and produced the CO_2 in a biological process such as alcohol fermentation and anaerobic digestion. This is in agreement with work by Reiter and Lindorfer (Reiter & Lindorfer 2015). Additionally, these facilities were in close proximity to both the gas and electricity networks. The total resource of CH_4 (396GWh), which could potentially be produced by PtG systems was ca. 2.6% of industrial natural gas consumption, or 5.5% of the energy consumption of heavy goods vehicles in Ireland in 2015. The total electrical energy required to produce this potential CH_4 resource was found to be greater than the total quantity of dispatched down electricity from renewable sources (mainly wind turbines) in 2015. As such, PtG could be seen as an energy conversion mechanism to use significant quantities of renewable electricity

that would otherwise be dispatched down. As Ireland (as an EU state) heads to an 80% reduction in GHG by 2050, generation from intermittent renewable electricity is likely to increase, as an island nation with limited interconnection the levels of electricity that will be dispatched down are likely to increase.

In terms of industrial gas use, the total theoretical resource of CH_4 arising from PtG facilities identified in this work could meet the annual energy requirement of the largest brewery in the country which consumed 291.5MWh of natural gas and has publicly expressed interest in the use of renewable gas. It should also be noted that whiskey production in Ireland is undergoing significant growth, estimated to be approximately 220% between 2002 and 2012, with plans in place for up to 20 new distilleries and expansion of existing distilleries in order to increase production by 41% from 2015 levels (Irish Whiskey Association 2015). GNI aim to supply approximately 1,440GWh of renewable gas in 2025 (Gas Networks Ireland 2016), the theoretical resource potential of PtG identified in this work could meet 28% of this goal.

In terms of energy consumption in transport, the total potential CH_4 resource identified could meet 71.6% of the energy consumption of the two main bus fleets in the country (the capital city bus service and the national bus service). The total theoretical CH_4 resource identified of 396GWh could fuel a total of 1,119 CNG fuelled buses. If the same number of buses, traveling the same distance were to be fuelled by diesel, with an approximate fuel efficiency of 17.36MJ.km^{-1}, a total of 314GWh of diesel would be required. GNI have secured funding for the development of CNG service stations in line with Directive 2014/94/EU (The European Parliament and the Council of the European Union 2014) to promote the use of natural gas as a transport fuel in Ireland, specifically in heavy goods vehicles and buses (Comission for Energy Regulation 2016). Development of a market for the use of CNG transport fuel would also allow for the use of methane gas produced in PtG systems in vehicles. GNI have a goal of supplying between 1,801-3,603GWh of CNG as a transport fuel in 2024-2025 (Gas Networks Ireland 2016). CH_4 produced in the potential PtG facilities identified in this work could meet 11-22% of the projected CNG demand in transport.

8.4.2 Energy policy implications

The use of PtG systems to produce CH_4 from excess renewable electricity has a number of energy policy implications. Firstly, the use of PtG systems to convert renewable electricity into CH_4 acts as an energy storage mechanism for electricity that would otherwise have been wasted. Within Ireland this is significant as the only largescale energy storage system in existence is a pumped hydroelectric system (PHES), Turlough Hill. While new systems have been mooted, none have been developed in recent years. Within the EU, future potential for large scale energy storage systems such as PHES range from 4GWh to 123TWh depending on constraints considered (Gimeno-gutiérrez & Lacal-arántegui 2013). There are concerns regarding the further development of PHES systems including the availability of environmentally acceptable sites (Yang & Jackson 2011). In contrast the small footprint of PTG systems reduces the impact on the surrounding landscape and environment.

Secondly, PtG systems allow for the stored energy (in the form of CH_4) to be used in either the heat, transportation, or electricity sector (Stor & Sto 2016). In the case of transportation, the renewable CH_4 produced from excess renewable electricity can be used as a source of renewable transport fuel within the EU and is classified as a renewable gaseous transport fuel of non-biological origin (Directive 2015/1513). The use of such renewable gaseous fuels is incentivised by weighting their energy contribution by a factor of 2 toward the target of renewable energy use in transportation of 10% by 2020 (Directive 2015/1513) (The European Parliament and the Council of the European Union 2015). Proposals for new EU legislation promoting the use of energy from renewable sources indicate that from 2021 fuel suppliers will be required to ensure that a minimum share of 1.5% of the fuel that they supply be in the form of advanced biofuels, these include renewable transport fuels of non-biological origin i.e. power to gas (European Commission 2017). The proposed minimum share of advanced biofuels will increase to 6.8% by 2030, development of power to gas systems providing renewable transport fuel would aid in achieving this proposed target.

Thirdly, the implementation of PtG systems in Ireland would increase energy security in the transportation sector if the resulting CH_4 were to be used as a gaseous transport fuel. Ireland is heavily dependent on imported energy, 97.2% of the energy used in transportation in Ireland is derived from oil, all of which is imported (Howley & Holland 2016) and 83% of biofuels (on an energy basis) currently used in Ireland are imported (Byrne Ó'Cléirigh & LMH Casey McGrath 2016). The potential resource of CH_4 from PtG systems that use existing sources of CO_2 could supply 71.6% of the current energy consumption of the two major public transportation bus fleets in the country if used in CNG fuelled buses. This would ensure that these public transportation fleets (which provided a total of 201.3 million passenger journeys in 2015 (Dublin Bus 2015; Bus Éireann 2015)) could be supplied with indigenously produced renewable energy. The potential to use excess renewable electricity in PtG systems to produce indigenous renewable transport fuel is not limited to Ireland, it is possible in any jurisdiction in which there is excess renewable electricity that cannot be stored.

8.4.3 Integration of a PtG facilities at a Distillery

Distillery DA, which has a theoretical CH_4 resource of 258GWh, could potentially fuel 729 CNG fuelled buses per annum. The bus fleet of the nearest city (24.7 km distant from Distillery DA) consists of 88 buses as of 2015, as such, if these buses were to convert run to on CNG, their annual fuel requirement would be a small fraction of the total theoretical CH_4 resource available at Distillery DA. It is also possible for the gas to be injected into the gas grid and become available for sale to any natural gas users on the natural gas grid, including other bus fleets in the country.

Integration of a PtG facility at Distillery DA could also result in potential synergies. One possible concept for the integration of a PtG facility at Distillery DA can be seen in Figure 8-5.

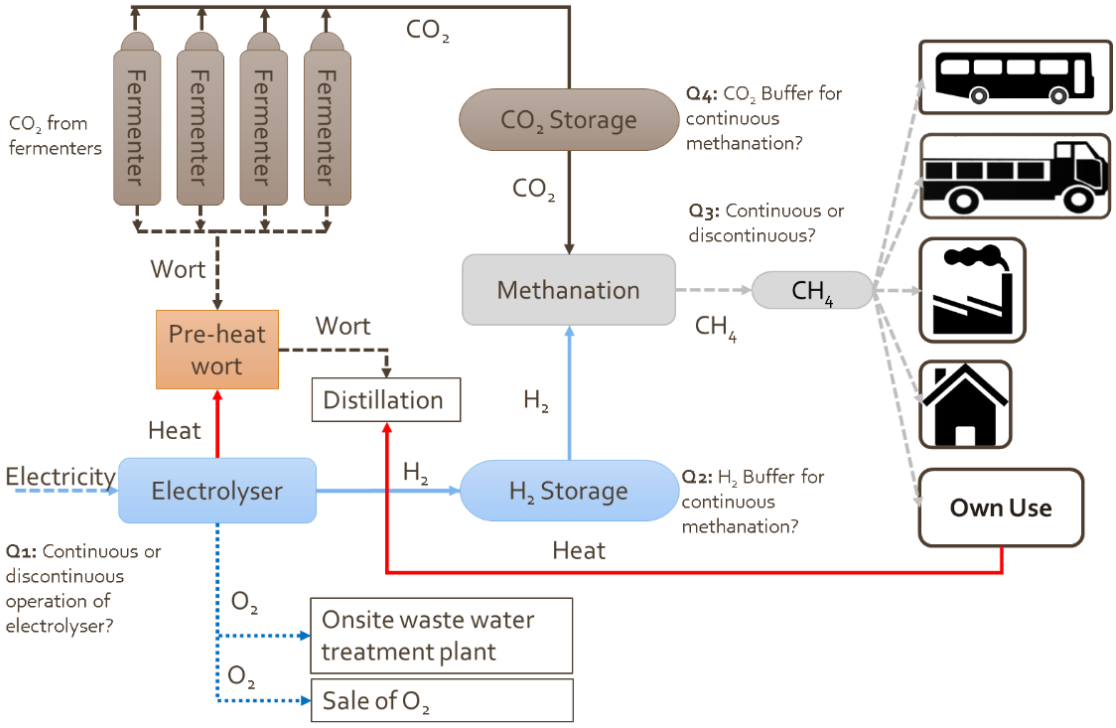


Figure 8-5: Possible integration of PtG facility with a distillery.

Integration of the PtG facility could allow for the use of waste heat from the electrolyser (or catalytic methanation system) to be used as a source of energy to pre-heat wort leaving the fermenters en-route to the distillation process. Potentially reducing the consumption of natural gas by the distillery. Additionally, O_2 produced by the electrolyser could either be used in the on-site wastewater treatment plant, reducing the electricity demand for supplying air to the activated sludge (AS) process, or the O_2 could be captured and sold as a commodity. The produced CH_4 could be compressed and used as a transport fuel in CNG fuelled buses as outlined in prior sections, or it could be used as a transport fuel for heavy goods vehicles for transporting either raw materials to the distillery, or finished product from the distillery. Alternatively, the CH_4 could be compressed and injected into the gas network to be used by other industries, residential gas customers, or on-site to reduce the distillery's natural gas consumption. The optimal use of the produced CH_4 is outside the scope of this work. A number of questions (Q1 to Q4 in Figure 8-5) regarding the operation of the PtG plant remain. They relate to the optimal price that the PtG system pays for electricity, and whether the various components

operate continuously or discontinuously. The answers to these questions would require a techno-economic model to determine the most cost-effective mode of operation.

8.4.4 Integration of a PtG facilities at a Wastewater Treatment Plant

With regards to WWTP2, approximately 26 CNG fuelled buses could be fuelled by the CH_4 resource from a PtG facility at the plant. The integration of a PtG facility at the WWTP could have a number of configurations; three of these can be seen in Figure 8-6 outlined by the dashed boxes A, B, and C.

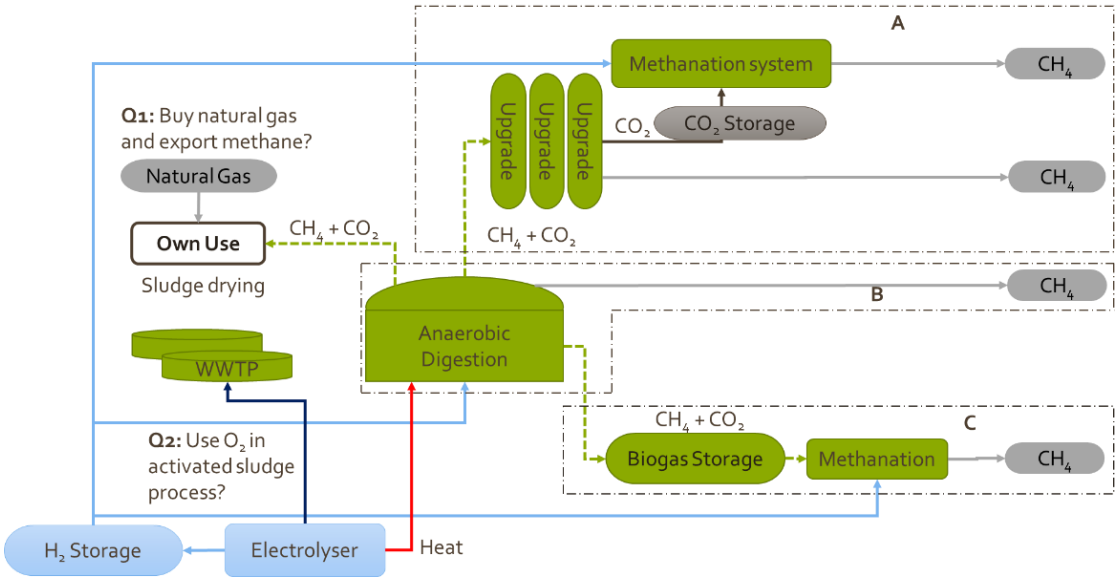


Figure 8-6: Potential integration of PtG facility with wastewater treatment plant

Box A outlines a setup in which biogas from the WWTP is separated into CO_2 and CH_4 in an upgrading plant. The CO_2 is then sent to an ex-situ methanation reactor via a possible intermediate CO_2 storage mechanism depending on whether or not the methanation system runs continuously. Such a system is similar to the Audi e-gas plant in Werlte, which utilises CO_2 from the upgrading system of a biogas plant adjacent to the PtG facility and is equipped with a catalytic methanation system. The Audi system (developed by ETOGAS GmBh) uses the waste heat from the methanation system in the biogas plant; a similar heat recovery system could be

integrated at WWTP2 if a catalytic methanation system was used. The BioCat project in Denmark is aiming to trial a similar system. It will utilise CO_2 separated from biogas generated in a wastewater treatment plant and H_2 in an ex-situ biological methanation reactor to produce CH_4. The BioCat project also aims to investigate the use of O_2 produced by the electrolyser in the activated sludge process.

Box B outlines an in-situ biological methanation system in which H_2 is injected directly into the digester where it is consumed by hydrogenotrophic methanogenic archaea along with CO_2 to produce CH_4. Such systems have been proposed in the past; however, the impact of direct H_2 addition on the stability of the digestion process may be a limiting factor in the quantity of H_2 that can be added. Additionally, if the produced gas is to be compressed and injected into the natural gas network, the quantity of H_2 in the gas must be below the limits set by gas network operators.

Box C outlines an ex-situ methanation system, which is supplied with biogas directly from the digester (following a desulphurisation step). The methanation system can be either biological or catalytic; such systems have been proposed and developed by MicrobEnergy and BioCat using biological methanation systems, and by ETOGAS using catalytic methanation systems.

The most suitable method of integrating a PtG facility at WWTP2 is beyond the scope of this work, but would potentially take one of the routes proposed. Several questions concerning the operation of the system need to be investigated. These relate to the continuous or discontinuous operation of PtG system components, how the WWTP compensates for the electrical and thermal energy that was previously generated by biogas which is now sent to a PtG system, and what is the best use of the CH_4 produced in a PtG system. A techno-economic analysis of all the above scenarios should be carried out to determine the most suitable system.

8.5 Conclusions

Existing sources of CO_2, which could be used in PtG systems in Ireland were identified and their suitability was assessed using the MCDA method. The most suitable sources of CO_2 identified were distilleries and WWTPs. The potential CH_4 resource associated with the 12 sources of CO_2 with the highest suitability was approximately 396GWh, which would require over twice the total quantity of dispatched down renewable electricity in Ireland in 2015. The potential CH_4 resource represents 2.6% of the total natural gas consumption of Ireland in 2015, and 71.6% of the total energy consumption of the two main bus fleets in the country in 2015. The most suitable source of CO_2 for use in a PtG plant, Distillery DA, could in theory produce 258GWh of CH_4, which would require 132.6% of the total dispatched down electricity in 2015. This represents a significant possibility for the storage of renewable electricity that would otherwise have been wasted. The potential CH_4 resource from this single plant could fuel approximately 729 CNG fuelled buses, or completely offset its own natural gas consumption. Integration of a PtG facility in a distillery or WWTP can be achieved through several potential configurations, with potential synergies arising from the use of waste heat and O_2 produced by the electrolyser and methanation process. Further work is required in discerning the optimal method of integrating PtG plants with distilleries or WWTPs, as well as determining the optimal operational strategy to maximise plant profitability.

Additionally, an in-depth life cycle assessment of power to gas facilities in order to quantify the CO_2 intensity of the gas produced is required, this may vary depending on the time at which electricity is purchased owing to the fluctuating nature of CO_2 intensity. A full techno-economic analysis conducted in tandem with an LCA should be conducted to assess how to best operate a power to gas facility in terms of maximising profitability while also ensuring the production of gas with a low carbon intensity.

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9 Chapter 9: Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times

Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times

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Abstract

Four feedstocks were assessed for use in a demand driven biogas system. Biomethane potential (BMP) assays were conducted for grass silage, household food waste, *Laminaria digitata* and dairy cow slurry. Semi-continuous trials were undertaken for all feedstocks, assessing biogas and biomethane production. Three kinetic models of the semi-continuous trials were compared. A first order model most accurately represented gas production in the pulse fed semi-continuous system. This model was developed for production of electricity on demand, and biomethane upgrading. The model examined a theoretical grass silage digester that would produce 435 kW_e in a continuously fed system. Adaptation to demand driven biogas required 187 minutes to produce sufficient methane to run a 2MW_e combined heat and power (CHP) unit for 60 minutes. The upgrading system was dispatched 289 minutes following CHP shutdown. Of the biogas produced 21% was used in the CHP unit and 79% was used in the upgrading system.

Keywords: Demand driven biogas; biomethane; grass silage; food waste; renewable energy

9.1 Introduction

In Ireland, 16% of gross final consumption (GFC), estimated to be 90.69PJ, needs to be from renewable sources by 2020 (The European Parliament and the Council of the European Union 2009) (Clancy et al. 2011); the specific targets are 40% renewable electricity (45.22PJ), 10% renewable transport (16.41PJ), and 12% renewable heat (19.97PJ) (Clancy et al. 2011). Renewable electricity generation from wind turbines provided approximately 83% of renewable electricity in Ireland in 2015 (Howley & Holland 2016).

Of issue with wind turbines for renewable electricity generation is that they only generate electricity when there is sufficient wind available, and as such are not fully dispatchable causing a mismatch between supply and demand of electricity. In periods of low wind and high demand, fossil fuelled generation units are dispatched to meet the required electrical load. This increases the CO_2 intensity of electricity during these periods as can be seen for the month of January 2016 in Figure 9-1, the correlation coefficient (computed using Excel 2013) between wind generation and CO_2 intensity of electricity for the period assessed was -0.88, showing a strong relationship. The CO_2 intensity of electricity was from 300-600 $gCO_2.kWh_e$ depending on the quantity of electricity generated by wind turbines. This is a significant variation and highlights the dependence of the supply of renewable, low carbon electricity in Ireland on wind turbines.

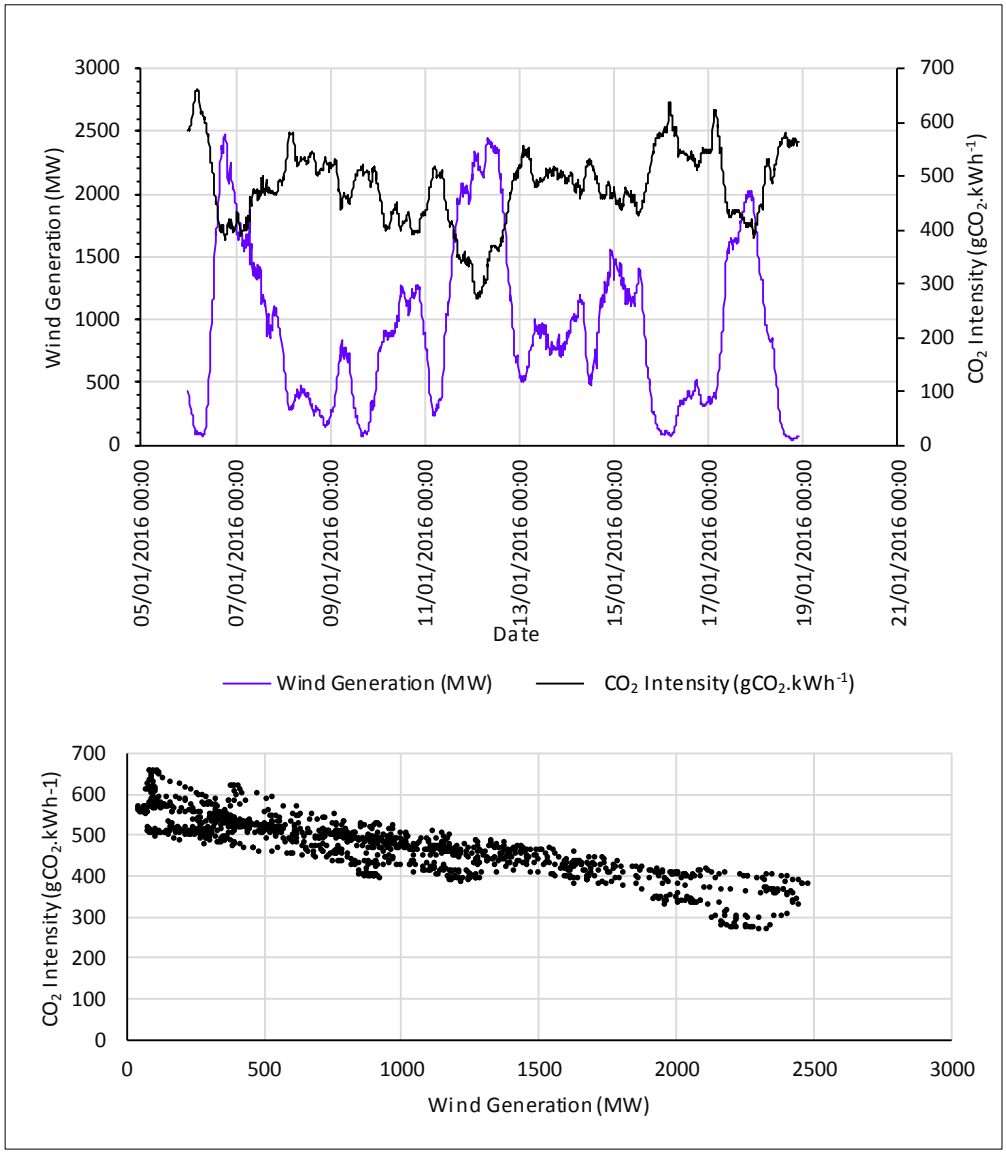


Figure 9-1Wind generation and CO_2 intensity of electricity for January 2016

Alternative sources of renewable electricity, which can be dispatched on demand are required to provide low carbon electricity generation in times of low wind if CO_2 emissions are to be minimised. Generating electricity on demand during periods of high demand can also be financially beneficial by availing of premiums or higher market prices (Hahn, Krautkremer, et al. 2014). However the output of electricity from wind turbines is not fully controllable, wind turbines cannot generate electricity on demand, this can be seen in Figure 9-2 which shows the mismatch between system demand and generation from wind turbines.

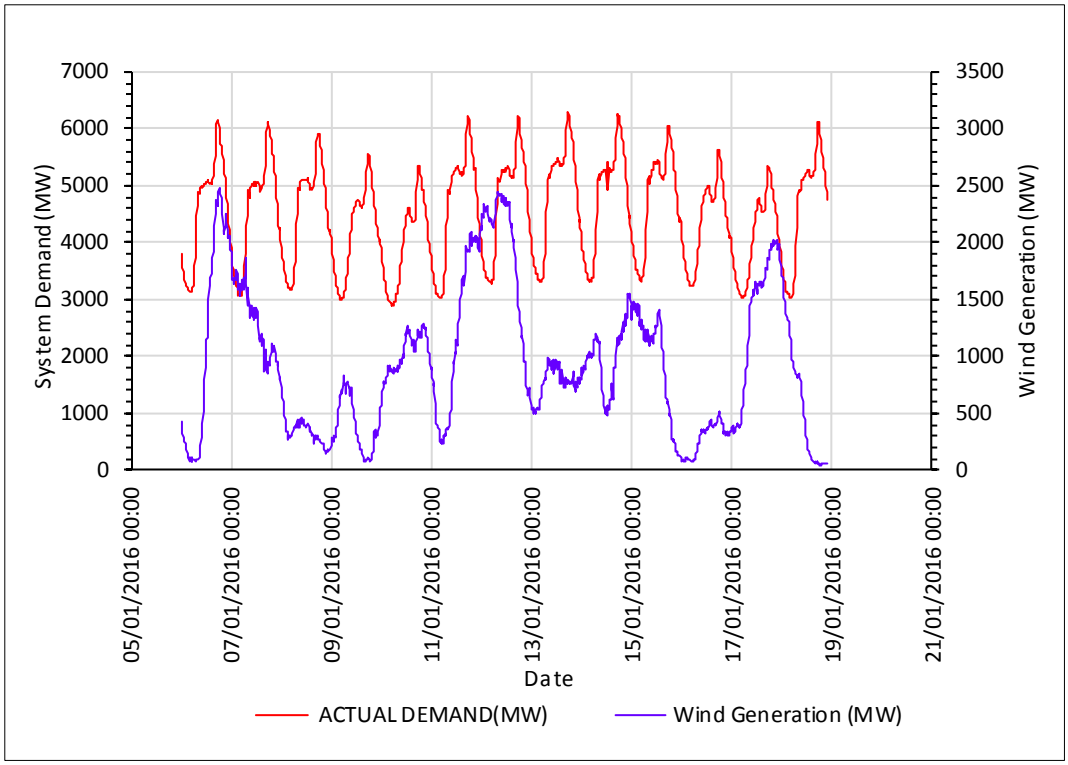


Figure 9-2 System demand and electricity generation from wind

From Figure 9-2 it can be seen that there is no clear relationship between the electrical output from wind turbines and overall system demand. Periods of high system demand do not coincide with periods of high electricity output from wind turbines. Predictions of system demand and electricity generation from wind turbines allow for conventional fossil fuel fired power stations to be dispatched at optimal times in order to meet demand, subject to system constraints. The result of this is that the supply renewable electricity from wind turbines cannot be guaranteed to available at times of high demand or at times of increasing system demand. If a fully renewable electricity supply is desired, controllable sources of renewable electricity are required to ensure that demand can be met at all times.

Biogas sourced from anaerobic digestion (AD) is a potential source of renewable electricity, which can be dispatched on demand. Biogas can be stored in gas storage membranes onsite until required for electricity production in a CHP system (Hahn, Ganagin, et al. 2014; Hahn, Krautkremer, et al. 2014; Mauky et al. 2015; Szarka et al. 2013). This requires an increased volume of gas storage at the site, with added capital expense (Hahn, Ganagin, et al. 2014). Alternatively, the feeding regime can

be altered to ensure sufficient biogas is produced by the time the CHP plant is to be dispatched (Hahn, Ganagin, et al. 2014; Hahn, Krautkremer, et al. 2014; Mauky et al. 2015; Szarka et al. 2013). This mode of operation is atypical for traditional AD plants which operate continuously (Szarka et al. 2013).

Previous studies proposed the use of anaerobic digestion plants to produce electricity in a demand driven system (Ahern et al. 2015), additional works assessed the feasibility of adding various feedstocks to laboratory scale AD reactors in a varied schedule to match the rate of biogas production (energy output) to periods of maximum electricity demand (Mauky et al. 2015). Results demonstrated that the rate of biogas production could match electricity demand, indicating the feasibility of demand driven biogas systems. Pulse feeding of AD reactors has been assessed with no difference reported in gas volume regardless of whether the reactor was fed once or twice a day (Lv et al. 2014).

Pulse feeding of AD reactors results in a variable rate of gas production, necessitating assessment of the gas production profiles of different feedstocks to enable scheduled feeding of AD systems. This ensures that a sufficient volume of biogas is available at the time of CHP unit dispatch (Szarka et al. 2013), while minimising the required storage volume. Outside the operational period of the CHP plant biogas could be sent to a biogas upgrading system for the production of biomethane. This topology was proposed in literature (Ahern et al. 2015; Persson, Murphy, Liebetrau, Trommler, Toyama, et al. 2014) however development of an operational schedule based on data from pulse fed laboratory trials has yet to be undertaken.

Feedstocks which could have a high resource potential in Ireland include; grass silage (2.2-48.2PJ), source separated household food waste (2.65PJ), the seaweed *Laminaria digitata* (potential resource of 3 million wet tonnes), and cattle slurry (7.73PJ) as outlined in the literature (Allen et al. 2015; Browne & Murphy 2013; Bruton et al. 2009; Wall et al. 2013). Assessment of the biogas or biomethane production profiles of these feedstocks in pulse fed semi-continuous trials has not been conducted to date. No prior work has been conducted using the gas production profiles of these feedstocks to develop a simplified operational schedule

for a combined system of demand driven electricity generation and biomethane production. This work aims to address this knowledge gap.

The objectives of this work are to:

1) Characterise the biomethane production of source separated household food waste, grass silage, dairy slurry, and *Laminaria digitata* in BMP assays.
2) Characterise the biogas and biomethane production of these feedstocks in semi-continuous reactors.
3) Develop a model to determine the time at which an AD plant should be fed in order to ensure adequate gas supply for a demand driven CHP system, and to determine the dispatch time of an upgrading system to reduce the biogas storage volume required.

9.2 Materials and Methods

9.2.1 Inoculum and feedstocks

Inoculum for biochemical methane potential (BMP) assays was sourced from laboratory scale semi-continuous reactors processing a combination of grass silage and dairy cow slurry. The inoculum for semi-continuous trials was sourced from an operational mesophilic AD facility processing a combination of dairy slurry and grease trap waste. The inoculum was sieved through a 500µm sieve to remove larger particles and was de-gassed for 7 days prior to experimental start-up to remove any un-degraded residual organic matter.

The grass silage (GS) used was a perennial ryegrass (*Lolium perenne*) sourced from the Animal and Grassland Research and Innovation Centre, Teagasc Grange, in Co. Meath Ireland. A full description of the harvesting, preparation, ensiling, and storage of the silage can be found in (Wall et al. 2015). The GS was shredded to a maximum particle size of 8mm using an industrial food mincer (cutting to a smaller particle size resulted in failure of the cutting device), placed in plastic bags, and stored at -20°C until experimental use as per (Wall et al. 2014).

The source separated household food waste (FW) used in this work was collected in November 2014 from a facility in which only source separated household food waste and bio-wastes were deposited. Approximately 20 kg of food waste was taken from various points in the waste collection bay. Samples were combined and mixed thoroughly by repeated quartering and re-mixing (Browne & Murphy 2013; Browne et al. 2014a). The combined sample was manually screened to remove bones, large fruit seeds and residual plastic. The screened sample was chopped manually to a particle size of less than 12 mm and thoroughly re-mixed. The waste was then reduced to a particle size of less than 4mm using an industrial food mincer, and was bagged and stored at -20°C until required.

Laminaria digitata (LD) is a large brown macroalgae (seaweed), which is common in Irish coastal waters. Samples of LD were collected from Oysterhaven, Co. Cork in July 2014; approximately 20 kg of samples were collected in total. The samples were transported to the laboratory at ambient temperature, and then stored overnight at 4°C. The following day, the seaweed was washed in fresh water to remove sand and salt. The stipe of each specimen was removed as in practice the thali are the only portion of the seaweed harvested from wild stock; stipes are left to ensure that new growth can occur allowing for a sustainable harvest. The cleaned and processed LD was reduced to a particle size of less than 4mm using an industrial grade food mincer. Samples were bagged and stored at -20°C for further use.

Dairy cow slurry (DCS) was sourced from a local dairy farm in November 2014. Samples of DCS were collected in 30L drums which were transported to the laboratory and stored at 4°C. Approximately 180L of sample was collected, a 30L subsample was used. The contents of the drum were thoroughly mixed and samples were taken for proximate and ultimate analysis. The DCS was stored at -20°C until further use.

The dry solids (DS) and volatile solids (VS) of the inoculum and feedstocks for the BMP assays are shown in Table 9-1 as well as an ultimate analysis of each feedstock. The proximate analysis of feedstocks used in the semi-continuous trials is shown in Table 9-1 along with inoculum parameters at the start of the continuous trials.

Table 9-1 Feedstock and inoculum properties for BMP and semi-continuous trials, mean values are given with ± standard deviation. wwt: wet weight, BMP: biomethane potential, DS: dry solids, VS: volatile solids

BMP	**Dry Solids (DS)**	**Volatile Solids (VS)**	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Ash**	**Ratio of carbon to nitrogen**
Feedstock	%wwt	%wwt	%DS	%DS	%DS	%DS	%DS	C:N
Grass Silage (GS)	19.5 (0.41)	17.7 (0.44)	42.5 (0.23)	6.0 (0.03)	40.9 (0.22)	1.6 (0.05	9.0 (0.36)	26.6
Source separated household food waste (FW)	21.4 (0.15)	19.6 (0.29)	43.9 (0.23)	5.7 (0.08)	39.4 (0.23)	2.6 (0.07	8.4 (0.80)	16.9
L. digitata (LD)	13.5 (0.18)	10.4 (0.14)	34.9 (0.03)	5.0 (0.01)	35.0 (0.08)	1.8 (0.06	23.3 (0.10)	19.4
Dairy cow slurry (DCS)	6.3 (0.02)	4.9 (0.02)	42.9 (0.13)	5.8 (0.04)	26.7 (0.30)	2.8 (0.14	21.9 (0.21)	15.3
Inoculum		2.9						
Semi-continuous trials	**Dry Solids (DS)**	**Volatile Solids (VS)**	**pH**	**FOS/TAC**				
Feedstock	%wwt	%wwt						
GS	18.9 (0.96)	17.0 (0.96)						
FW	21.0 (0.64)	18.7 (1.06)						
LD	15.7(1.95)	11.9 (1.29)						
DCS	7.0 (0.78)	5.3 (0.41)						
Inoculum	6.7	2.7	7.7	0.6				

9.2.2 BMP Assay

The BMP of each substrate was determined using the automated methane potential test system (AMPTS) manufactured by Bioprocess™ Control. The assays (run in triplicate) consisted of 15 bottles, each with a total volume of 500mL (working volume of 400mL) immersed in a water bath at 37°C (mesophilic range). The inoculum to substrate ratio (volatile solids basis) used was 2:1 to avoid inhibition in the BMP test (Angelidaki et al. 2009; Strömberg et al. 2014). Each bottle was stirred individually every other minute for one minute. Bottles were connected to an individual gas scrubbing system (3M NaOH), which removed CO_2 and other trace gases from the biogas produced. The volume of the biomethane produced was measured using a gas-tipping device in 10mL increments. Cumulative methane production was recorded online with the gas volumes automatically converted to dry gas volumes at standard temperature and pressure (STP) of 0°C and 101.325kPa. The BMP assays were run for 30 days.

9.2.3 Semi-continuous trials

Semi-continuous trials were conducted at an organic loading rate (OLR) of 2 $kgVS.m^{-3}.day^{-1}$ for all feedstocks to ensure stable operation. Reactors had a total volume of 5L with a working volume of 4L, and were stirred continuously at 40rpm, biogas production was measured using wet tip gas meters connected to an automated data acquisition system. A detailed description of the reactor configuration can be found in (Allen et al. 2014). The reactors were maintained at a temperature of 37°C. Digesters were fed once per day, 5 days per week as was done previously in literature, (Allen et al. 2014; Tampio et al. 2014; Wall et al. 2014), in which the discontinuous feeding showed no detrimental impact on the performance of digesters. The hydraulic retention time (HRT) and solid retention time (SRT) were equal and maintained at 36 days (the HRT for dairy cow slurry) by mixing the other feedstocks with water. By keeping the HRT and OLR equal for all reactors, any variation in biogas or biomethane production should only be as a result of the different feedstock types. Reactors were fed at an OLR of $2kgVS.m^{-3}.day^{-1}$ for one

HRT (36 days) before experimental data was collected to ensure a stable process was in place.

The semi-continuous trials were carried out in two experiments. In the first experiment, biogas production in terms of specific biogas yield (SBY), specific methane yield (SMY), and gas production kinetics were assessed. Final reported data was obtained from the second HRT (days 37-72) when stability had occurred. In the second experiment, biomethane production in terms of SMY and gas production kinetics were assessed by attaching NaOH scrubbers to the reactors to remove CO_2 from the biogas. These data were obtained from the third HRT (day 73-108) and allowed for the comparison of biomethane production to that of biogas production.

9.2.4 Analytical Methods

DS and VS content were analysed according to Standard Methods 2540 G (American Public Health Association et al. 1999). Ultimate analysis (carbon, hydrogen, oxygen, and nitrogen content) of feedstocks was carried out in triplicate using an EAC CE 4500 elemental analyser with samples prepared by drying at 105°C for 24 hours and milled to less than 500µm. Digester pH was monitored daily using a Jenway 3510 pH meter. The ratio of volatile organic acids to total alkalinity (FOS/TAC) was measured weekly using a two point titration according to the Nordmann method with end points of pH 5 and pH 4.4 using 0.1N H_2SO_4 (Drosg 2013) and a Titronic Universal Automatic Titrator. Total ammonium nitrogen (NH_4-N) was measured using Hach Lange LCK 303 cuvettes and a Hach Lange DR 3900 spectrophotometer. Free ammonia nitrogen ($NH_{3(aq)}$), the inhibitory form of ammonia, was calculated according to Equation 9-1 taking into account digester temperature and pH (Drosg 2013).

Equation 9-1 Free ammonia calculation

$$\left[NH_{3(aq)}\right] = \frac{[NH_4 - N]}{1 + \frac{10^{-pH}}{10^{-(0.09018+\left(\frac{2729.92}{T}\right)}}}$$

Gas production was measured online using tipping gas meters as described in (Allen et al. 2014). Gas composition was determined once weekly. Gas produced in 24 hours between two feedings was collected in 10L SKC Flex Foil® gas sample bags once per week on day 5 of feeding. Gas composition was measured using a gas chromatograph (HP Agilent 6890 series) equipped with a Hayesep R packed GC column (3m x 2mm, mesh range of 80-100) and a thermal conductivity detector with Argon as the carrier gas. Samples of digestate were taken weekly from each reactor to measure volatile fatty acid (VFA) concentrations. VFA composition was measured using a HP Agilent 6890 gas chromatograph equipped with a Nukol polyethylene glycol column (250µm diameter, 30m length, 0.25µm film thickness) with hydrogen as the carrier gas and a flame ionisation detector.

9.2.5 Theoretical methane yield, biodegradability index, efficiency, specific biogas yield, and specific methane yield

The maximum theoretical methane yield of a substance was calculated using the Buswell equation (Buswell & Mueller 1952) Equation 9-2.

Equation 9-2 Buswell equation

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2$$

The parameters *n, a,* and *b* are obtained from the stoichiometric formula of the substrate undergoing anaerobic digestion. The biodegradability index was calculated as the BMP yield divided by the theoretical methane yield (Allen et al. 2014).

SBY and SMY were calculated using daily gas production from last three weeks at the end of each experiment (to ensure stable operation), divided by the total mass of VS added in each day respectively. Efficiency in the semi-continuous trials was calculated as the ratio of the SMY to the BMP. The dataset of SMY of each feedstock was compared between the two experiments using Minitab. Data was checked for

normality using the Anderson Darling test, variance was checked using the F-test and Levene's test. A two sample t-test with the null hypothesis defined as there being no significant difference between the average SMY of feedstocks between the two experiments was conducted (t-test type was dependent on the result of the variance tests). The significance level (α) used in all of the above tests was 0.05.

9.2.6 Kinetics

9.2.6.1 BMP assay

Biomethane production in the BMP assays was modelled using a first order kinetic model (Strömberg et al. 2014) as per Equation 9-3 and a second order model, the modified Gompertz equation (Strömberg et al. 2015) as per Equation 9-4.

Equation 9-3 First order kinetics

$$v(t) = V_{max} * \left(1 - \mathrm{e}^{(-k*t)}\right)$$

Equation 9-4 Modified Gompertz equation

$$v(t) = V_{max} * e^{\left(-e^{\left(\left(\frac{R_m e}{V_{max}}\right)(\lambda - t)+1\right)}\right)}$$

In Equation 9-3 *v(t)* is the cumulative specific methane production ($mLCH_4.gVS_{added}^{-1}$) at time *t* (days), V_{max} is the final specific methane produced ($mLCH_4.gVS_{added}^{-1}$) at the end of the assay, and *k* is the first order decay constant (day^{-1}). Equation 9-4 allowed for R_m (maximum specific biomethane production rate ($mL\ CH_4.gVS_{added}.^{-1}day.^{-1}$)), and λ the lag phase (days) to be calculated. Parameters for the kinetic models were determined in Microsoft Excel using the built-in solver function to minimise the sum of the squared errors between the model output and the experimental data. The half-life (T50) was also calculated in Excel as the time required to achieve 50% of the final gas volume.

9.2.6.2 Semi-continuous trials

Gas production in the pulse fed, semi-continuous reactor trials was modelled using three different gas production models; a first order kinetic model Equation 9-3, a second order kinetic model (the modified Gompertz model) Equation 9-4, and a combination of two first order models as per Equation 9-5 (Strömberg et al. 2014).

Equation 9-5 Combined first order model

$$v(t) = V_{max} * \left(1 - x * \mathrm{e}^{-k_1 * t} - (1 - x) * \mathrm{e}^{-k_2 * t}\right)$$

In Equation 9-5 *v(t)* is the cumulative gas production per unit volume of reactor ($L_{gas}.L_{reactor}^{-1}$), V_{max} is the final specific gas production ($L_{gas}.L_{reactor}^{-1}$) 24 hours after feeding, k_1 and k_2 are decay constants, and *x* is the fraction of readily degradable material in the feedstock.

The cumulative specific biogas production ($L_{biogas}.L_{reactor}^{-1}$) for the first experiment, and the cumulative specific methane production ($L_{CH4}.L_{reactor}^{-1}$) for the second experiment, at each minute following feeding was averaged for each day of feeding (from the final three weeks of each experiment) to find the average cumulative gas production in a 24 hour period after feeding. This average gas production (be it biogas or biomethane) was then modelled using the aforementioned equations.

9.2.7 Development of a simplified feeding schedule for a demand driven biogas plant with both electricity generation and biogas upgrading

A biogas plant with electricity and biomethane production similar to proposals in the literature (Ahern et al. 2015; Persson, Murphy, Liebetrau, Trommler & Toyama 2014; Szarka et al. 2013) was modelled. The plant consumed biogas in a CHP plant to generate electricity on demand. Outside of this period biogas was sent to an upgrading system to produce biomethane for transport or heating. The time of reactor feeding and upgrading plant dispatch could be calculated to ensure an adequate gas supply to the CHP unit while minimising the biogas storage volume

between the AD plant, the CHP plant, and the upgrading plant. This was done using the first order model of biogas and biomethane production for pulse fed AD reactors.

The anaerobic digester had an organic loading rate of 2kgVS.m^{-3}.day^{-1}, a digester volume of 4,000m^3, and was fed grass silage in a daily single pulse. The feed time and upgrading dispatch time were calculated using the following equations.

Equation 9-6 Total volume of methane required by the CHP plant.

$$V_{CH_4}^{required} = \frac{kW_e^{CHP} * (t_{CHP}^{Off} - t_{CHP}^{On})}{\eta_e * 10.49}$$

$V_{CH4}^{required}$ is the volume of methane required by the CHP plant, $t_{CHP}^{on(off)}$ is the dispatch (shutdown) time of CHP plant, η_e is the electrical efficiency, kWh_e^{CHP} is the electrical capacity, and "*10.49*" is the energy content of methane ($kWh_{th}.Nm^{-3}CH_4$) (Murphy & McCarthy 2005).

Equation 9-7 Maximal methane production volume

$$V_{CH_4}^{max} = v_{CH_4} * V_{reactor}$$

Equation 9-8 Maximal biogas production volume

$$V_{biogas}^{max} = v_{biogas} * V_{reactor}$$

V_{CH4}^{max} and V_{biogas}^{max} are the maximum daily production of methane and biogas of the reactor ($L_{CH4}.day^{-1}$ or $L_{Biogas}.day^{-1}$), v_{CH4}^{max} and v_{biogas}^{max} are the production of methane or biogas per unit volume of reactor ($m^3_{gas}.m^{-3}_{reactor}$), and $V_{reactor}$ is the reactor volume (m^3).

Equation 9-9 First order model of methane production

$$V_{CH_4}(t) = V_{CH_4}^{max} * \left(1 - e^{-k_{CH_4} * t}\right)$$

$V_{CH4}(t)$ is the volume of methane produced at time t (minute), and k_{CH4} is the first order decay constant (minute^{-1}).

The time required to produce the necessary volume of CH_4 to fuel the CHP unit ($t^{required}_{CH4}$) was calculated as;

Equation 9-10 Calculation of time required to produced required volume of methane

$$t_{CH_4}^{required} = -\frac{\ln\left(1 - \frac{V_{CH_4}^{required}}{V_{CH_4}^{max}}\right)}{k_{CH_4}}$$

The volume of biogas at each point in time ($V_{biogas}(t)$) was found using the first order decay constant for biogas production (k_{Biogas}) in Equation 9-11:

Equation 9-11 First order model of biogas production

$$V_{biogas}(t) = V_{biogas}^{max} * \left(1 - e^{-k_{biogas} * t}\right)$$

The volume of biogas required to fuel the CHP unit ($V_{biogas}^{required}$) was then found using Equation 9-12:

Equation 9-12 Calculation of the volume of biogas required

$$V_{biogas}^{required} = V_{biogas}^{max} * \left(1 - e^{-k_{biogas} * t_{CH_4}^{required}}\right)$$

The maximum volume of biogas to be stored (V_{biogas}^{store}) occurs just prior to the dispatch of the CHP unit and can be found using Equation 9-13:

Equation 9-13 Maximum volume of biogas to be stored prior to CHP dispatch

$$V_{biogas}^{Store} = V_{biogas}^{max} * \left(1 - e^{-k_{biogas} * t_{on}^{CHP}}\right)$$

Following shutdown of the CHP unit at time t_{CHP}^{off} the volume of biogas produced by the anaerobic digester ($V_{biogas}^{\#}(t)$) was found using Equation 9-14:

Equation 9-14 Remaining biogas production following CHP shut down

$$V_{biogas}^{\#}(t) = V_{biogas}^{max} * \left(1 - e^{-k_{biogas} * t}\right) - V_{biogas}^{required} \quad for\ t \geq t_{CHP}^{Off}$$

Once the CHP unit has shutdown, biogas flows once more to the biogas storage device, biogas can then flow from the store to the biogas upgrading system to be upgraded to biomethane. The flow rate of biogas to the upgrading unit is assumed to be a constant value once the upgrading system is turned on at time t_{up}^{on}. The slope of the line defining the flow of biogas to the upgrading system is shown in Equation 9-15.

Equation 9-15 Slope of the line describing the volume of biogas sent to the upgrading system

$$m_{up} = \frac{\left(V_{biogas}^{1440} - V_{biogas}^{max} * e^{-k_{biogas} * t} - V_{biogas}^{required}\right)}{1440 - t_{up}^{On}}$$

m_{up} is the slope of the line describing the biogas sent to the upgrading system, V_{biogas}^{1440} is the final volume of biogas produced 24 hours post initial feeding (m^3), t_{up}^{on} is the dispatch time of the upgrading system (minutes), and 1440 is the number of minutes in a day.

The total volume of biogas sent to the upgrading system once it has been turned on is defined according to Equation 9-16.

Equation 9-16 Cumulative volume of biogas sent to the upgrading system

$$V_{up}(t) = m_{up} * t - 1440 * m_{up} + V_{biogas}^{1440} - V_{biogas}^{max} * e^{-k_{biogas} * t} - V_{biogas}^{required}$$

$V_{up}(t)$ is the volume of biogas sent to the upgrading system at time t.

The volume of biogas in the biogas store between the upgrading system and the anaerobic digester, *D(t)*, is governed by Equation 9-17.

Equation 9-17 Storage volume at a time t between the biogas plant and upgrading facility

$$D(t) = V_{biogas}^{\#}(t) - m_{up} * t + 1440 * m_{up} - V_{biogas}^{1440} + V_{biogas}^{max} * e^{-k_{biogas}*1440} + V_{biogas}^{required}$$

It is desirable to ensure that the maximum volume of biogas to be stored between the digester and the upgrading system is the same as the existing biogas storage volume in place for the CHP unit. This maximises the flowrate of biogas to the upgrading system without exceeding the existing biogas storage volume in place. The maximum volume of biogas to be stored between the digester and the upgrading unit occurs when the first derivative of *D(t)* (Equation 9-18) is equal to zero.

Equation 9-18 First derivative of storage volume between biogas plant and upgrading facility

$$\frac{d}{dt}\big(D(t)\big) = k * V_{biogas}^{max} * e^{-k_{biogas}*t_D^{max}} - m_{up}$$

The time at which this maximum storage volume occurs is given by t_D^{max} and can be found in terms of m_{up} according to Equation 9-19.

Equation 9-19 Time of maximum storage volume between biogas plant and upgrading facility

$$t_D^{max} = -\frac{\ln\left(\frac{m_{up}}{k_{biogas} * V_{biogas}^{max}}\right)}{k_{biogas}}$$

Substituting the value of t_D^{Max} into Equation 9-17 gives the maximum volume of biogas to be stored between the digester and the upgrading system, see Equation 9-20.

Equation 9-20 Maximum volume of biogas stored between biogas plant and upgrading facility

$$D^{max} = V_{biogas}^{max} * e^{-1440*k_{biogas}} - V_{biogas}^{max} * e^{k_{biogas}*\frac{\ln\left(\frac{m_{up}}{k_{biogas}*V_{biogas}^{max}}\right)}{k_{biogas}}} + m_{up} * \frac{\ln\left(\frac{m_{up}}{k_{biogas} * V_{biogas}^{max}}\right)}{k_{biogas}} + 1440 * m_{up}$$

D^{max} is the maximum storage volume (m^3) between the biogas plant and the upgrading system. The goal is to ensure that D^{max} is as close to V_{biogas}^{store} as possible. The value of m_{up} was found using the solver toolbox in Microsoft Excel. Once the value of m_{up} was found, the dispatch time for the upgrading system, t_{up}^{on}, can be found according to Equation 9-21.

Equation 9-21 Dispatch time of upgrading facility

$$t_{up}^{On} = 1440 - \frac{V_{biogas}^{max} - V_{biogas}^{max} * e^{-1440*k_{biogas}} - V_{biogas}^{required}}{m_{up}}$$

9.3 Results and discussion

9.3.1 Feedstock properties, Buswell yield, and BMP yield

The stoichiometric formula, theoretical methane yield, BMP, and biodegradability index of each feedstock can be seen in Table 9-2.

Table 9-2 Results of first and second order biomethane potential (BMP) kinetics

Feedstock	**Stoichiometric formula**	**Theoretical methane yield**	**BMP**	**Biodegradability index**	**First Order**				**Second Order**				
	$C_aH_bO_cN_d$	$LCH_4.kgVS^{-1}$	$LCH_4.kgVS_{added}^{-1}$	%	V_{max}	Percentage difference to BMP	k	*Adjusted* R^2	V_{max}	R_m	Lag (λ)	*Adjusted* R^2	Half-life (*T50*)
					$mLCH_4.gVS_{added}^{-1}$	%	$days^{-1}$		$mLCH_4.gVS_{added}^{-1}$	$mLCH_4.gVS_{added}^{-1}.day^{-1}$	days		days
Grass silage	$C_{31}H_{53}O_{22}N$	479.5	331.9 (12.36)	69.2	360.9 (13.6)	8.7	0.114 (0.001)	0.930	324.1 (11.90)	45.6 (0.75)	2.5 (0.07)	0.992	6.1 (0.04)
Source separated household food waste	$C_{23}H_{30}O_{13}N$	492.3	365.3 (20.25)	74.2	400.1 (25.11)	9.5	0.112 (0.004)	0.921	359.2 (20.10)	48.5 (2.49)	2.5 (0.11)	0.983	6.3 (0.13)
L. digitata	$C_{22}H_{39}O_{17}N$	453.1	262.9 (11.64)	58.0	283.1 (12.72)	7.7	0.127 (0.004)	0.916	261.4 (10.58)	36.1 (1.11)	2.2 (0.10)	0.977	5.9 (0.10)
Dairy cow slurry	$C_{18}H_{29}O_8N$	638.4	176.3 (6.01)	27.6	181.0 (5.74)	2.7	0.135 (0.007)	0.976	168.7 (4.10)	19.6 (0.54)	0.9 (0.09)	0.995	5.4 (0.23)

Mean values are given with standard deviation in parenthesis.

VS: Volatile solids,

Large differences in the theoretical methane yield and the actual BMP yield of a feedstock are typical, as exemplified by DCS and LD. The Buswell equation gives the maximum theoretical methane yield, not accounting for metabolic energy consumption of microbes in the AD system, or whether the various elemental compounds were biologically available (Labatut et al. 2011). The feedstock with the highest biodegradability index was FW, this feedstock also had the highest BMP value, followed by GS and LD. In comparison to past literature, the BMP of FW was similar to that of urban household food waste 344 $LCH_4.kgVS^{-1}$ (Browne et al. 2014b) and the BMP of GS was lower than values reported of 400 $LCH_4.kgVS^{-1}$ (Wall et al. 2013). The high biodegradability indices of FW and GS implied that these feedstocks could be readily converted to methane in the AD process. The BMP of LD and DCS were similar to that obtained in prior works of 218 $LCH_4.kgVS^{-1}$ and 136$LCH_4.kgVS^{-1}$ respectively (Allen et al. 2014; Allen et al. 2015).

9.3.2 BMP kinetics

Figure 9-3 illustrates the cumulative methane production for each of the four substrates in the BMP assay, and the first and second order models of biogas production for each feedstock.

In the case of GS, FW, and LD, a steep increase in the gas production initiated earlier than day 5, with the rate of gas production then declining after days 9-10.

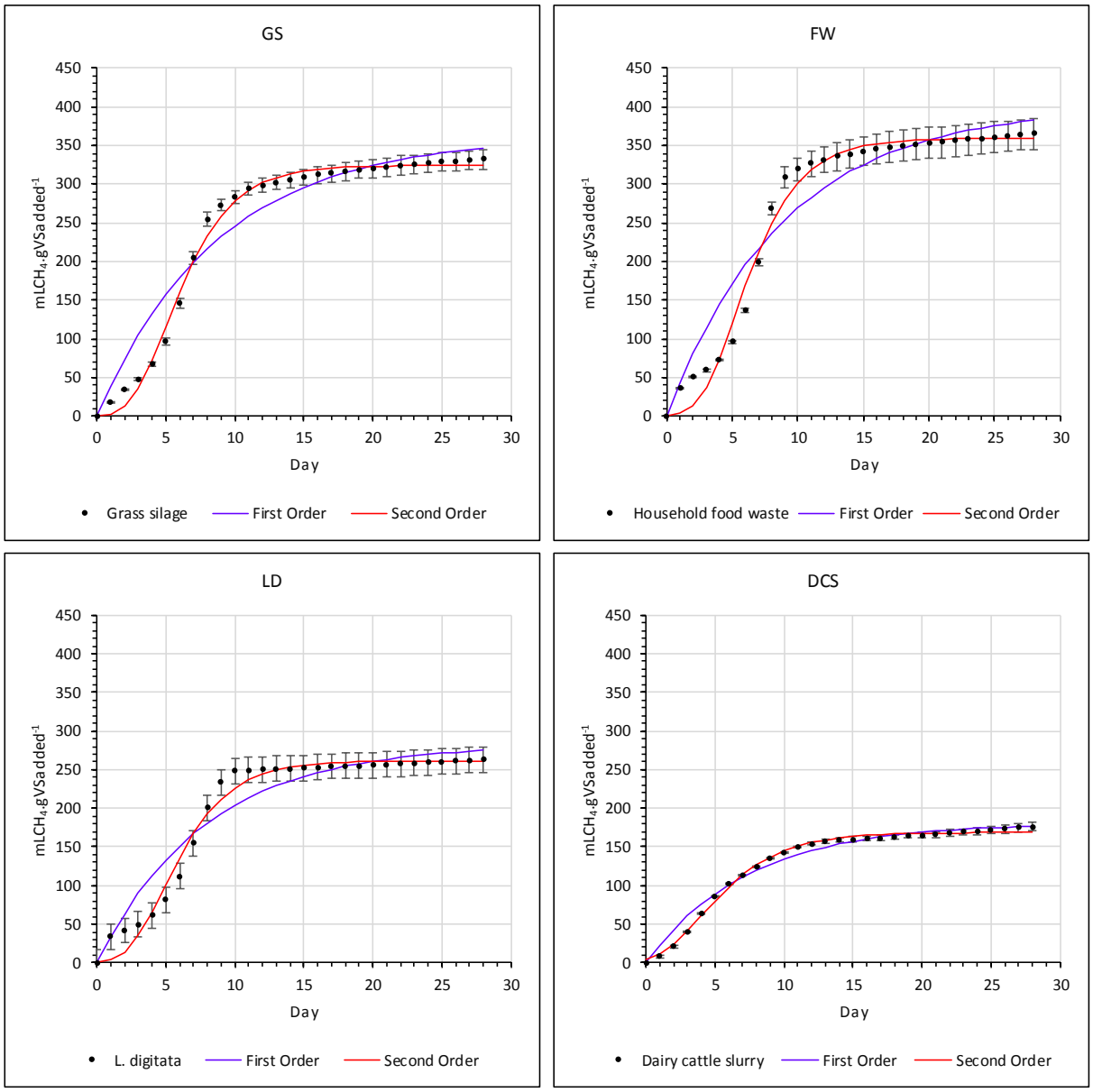


Figure 9-3 BMP methane production for GS; Grass silage, FW; Food waste, LD; Laminaria digitata, DCS; Dairy cow slurry with first and second order models

The results of the first and second order kinetic models can be seen in Table 9-2. Both the first order and second order models achieved an average *Adjusted* R^2 value (goodness of fit) in excess of 0.9 implying a good level of accuracy in modelling gas production from the BMP assays. The first order model overestimated final biomethane production (V_{max}) for all feedstocks assessed; ranging from 3% for DCS to 10% for FW. The Gompertz model showed a higher degree of accuracy than the first order model (higher *Adjusted* R^2 values) in predicting the total biomethane

production of each substrate. The maximum deviation from the experimentally obtained BMP was an underestimation of 4% for DCS.

Compared to past studies, the *k* value of the GS in this work was slightly higher than that previously found of 0.107day^{-1} (Wall et al. 2013); the FW *k* value was lower than food waste *k* values found previously of 0.14day^{-1} (Browne et al. 2014b); the LD yielded a lower *k* value than that reported previously of 0.19 day^{-1} (Allen et al. 2015); while the *k* value of DCS was higher than that obtained in prior work of 0.082day^{-1} (Wall et al. 2013) but similar to values obtained in other works of 0.13 days^{-1} (Allen et al. 2016). Caution should be taken in comparison of *k* values between trials owing to the differing nature of inoculum used.

The *k* values and half-life values (*T50*) obtained in this work were negatively correlated. Substrates with a high *k* value and short *T50* can be thought of as easily biodegraded, substrates with a decreased *k* value and increased *T50* require a longer time to degrade (Wall et al. 2013). The *k* values of GS and FW were the lowest obtained in this work, potentially due to; the lignocellulosic nature of GS which can reduce the rate of biodegradation (Allen et al. 2016), and the presence of lipids (which can be inhibitory) and cellulosic material (slow to degrade) in the FW. LD had a higher *k* value and lower *T50* than GS and FW owing to the negligible concentrations of lignin in its structure (Jard et al. 2013) and the presence of easily degraded storage polysaccharides (laminarin and mannitol) (Adams et al. 2009; Adams et al. 2011). DCS had the highest *k* value and shortest half-life of all feedstocks assessed with the lowest biodegradability index. This indicates that the portion, which was readily degradable, degraded fast, but that a significant portion of the volatile material was not readily degradable.

The maximum specific biomethane production rate of feedstocks was positively correlated with the BMP. FW had the highest BMP and the highest maximum specific biomethane production rate, followed by GS, LD, and DCS. The lag phase calculated using the modified Gompertz equation followed the opposite trend as the first order *k* value, feedstocks with a lower *k* value had a longer lag phase. DCS exhibited the shortest lag phase, followed by LD, GS, and FW. The lag phase of GS was longer than that obtained previously of 1.94 days (Wall et al. 2013) for a first

cut grass silage, but was within the range of lag times reported for a range of Irish grass silages (Allen et al. 2016). The lag phase of FW was similar to values obtained in prior work of 2.2 days (Browne et al. 2014a), while the lag phase of LD was longer than values obtained of 0.79 days (Allen et al. 2015) potentially due to the biomass being sourced from different locations at different times. The lag phase of DCS was within the range of lag phases reported for cow slurry (Allen et al. 2016). Caution should be taken in the interpretation of lag values for feedstocks in different studies owing to potentially different inoculum efficiencies.

9.3.3 Biogas production in semi-continuous trials

9.3.3.1 AD parameters

The average of daily pH values, weekly FOS/TAC ratios, weekly free ammonia (NH_3(aq)) concentrations, and weekly CH_4 concentrations, measured for the biogas production trial (during the second HRT), along with the SMY are reported in Table 9-3.

Table 9-3 Biogas and biomethane production in semi-continuous trials

Feedstock	pH	FOS/TAC	NH_3(aq)	CH_4	CO_2	SMY	SMY/BMP	Total VFA
	na	na	$mg.L^{-1}$	%vol*	%vol	$Nm^3CH_4.kgVS_{added}{}^{-1}$	%***	$mg.L^{-1}$
Biogas Trial								
Grass silage	7.2(0.03)	0.2 (0.05)	6.0	56.5	43.5	325.5 (26.13)[a]	98.1 (7.87)	86
Food waste	7.0(0.07)	0.3 (0.08)	1.5	57.4	42.3	398.8 (39.51)[b]	109.2 (10.82)	135
L. digitata	7.2 (0.04)	0.2 (0.01)	6.3	53.5	46.5	221.2 (25.18)[c]	81.1 (9.58)	76
Dairy Cow Slurry	7.3 (0.04)	0.3 (0.03)	3.8	65.9	34.1	132.0 (17.42)[d]	74.9 (9.88)	133
Biomethane Trial								
Grass silage	7.3 (0.05)	0.2 (0.07)	6.3	99.1	0.9	307.5 (34)[a]	92.6 (10.24)	127
Food waste	6.9 (0.04)	0.3 (0.08)	0.6	99.7	0.3	372.3 (43.41)[b]	101.9 (11.88)	110
L. digitata	7.2 (0.05)	0.2 (0.06)	1.5	99.3	0.7	239.0 (24.39)[c]	90.0 (9.28)	71
Dairy Cow Slurry	7.3 (0.05)	0.3 (0.03)	6.9	99.5	0.5	132.2 (12.59)[d]	75.0 (7.14)	118

Mean values are given with standard deviation in parenthesis.

SMY: Specific methane yield,

BMP: biomethane potential. VFA: Volatile fatty acids

*CH_4 concentration was found as the volume of CH_4 divided by the total volume of biogas produced, assuming that the produced biogas consisted of only CH_4 and CO_2.

**Superscripts a,b,c,d indicate if the average SMY of each feedstock was not significantly different ($p>0.05$) between the biogas trial and the biomethane trial, letters only refer to the same feedstocks between trials. All feedstocks showed no significant difference in average SMY between each trial.

***The SMY of feedstock may exceed the BMP, this can occur as a result of microbial adaptation in continuous trials

The pH values were within the range of values in which methanogenesis occurs (Drosg 2013; Fantozzi & Buratti 2011). The FOS/TAC ratio for all reactors did not increase above the stability limit of 0.3 (Drosg 2013). The concentration of NH_3(aq) was below the safe limit for stable anaerobic digestion of 3,000 $mg.L^{-1}$ (Wellinger et al. 2013). The average CH_4 concentration of biogas was typical of values expected from AD systems and similar to values obtained previously for GS, while DCS values obtained were higher (Wall et al. 2014). Values for FW were marginally lower than that reported previously (Browne et al. 2014b). The SMY/BMP ratio for GS, FW, and LD indicated an efficient AD process with the SMY close to the BMP value and

sometimes surpassing it indicating acclimatisation of the microbial community to the specific feedstock. The low SMY of DCS agreed with previous findings in which a low SMY/BMP ratio was also obtained for DCS at an OLR of 2kgVS.m^{-3}.day^{-1} (Wall et al. 2014). The total concentration of VFAs in the reactors were all below the stable operational limit of 1,000mg.L^{-1} (Drosg 2013). All reactors were deemed to be in stable operation for the biogas production trials.

9.3.3.2 Biogas production and kinetics in semi continuous trials

The average daily biogas production curves for all substrates are shown in Figure 9-4. The data plotted is the average cumulative biogas production per litre of reactor working volume ($L_{biogas}.L_{reactor}^{-1}$) at each minute over 24 hours for the last three weeks during the biogas production experiment (second HRT), a total of 15 separate days of data.

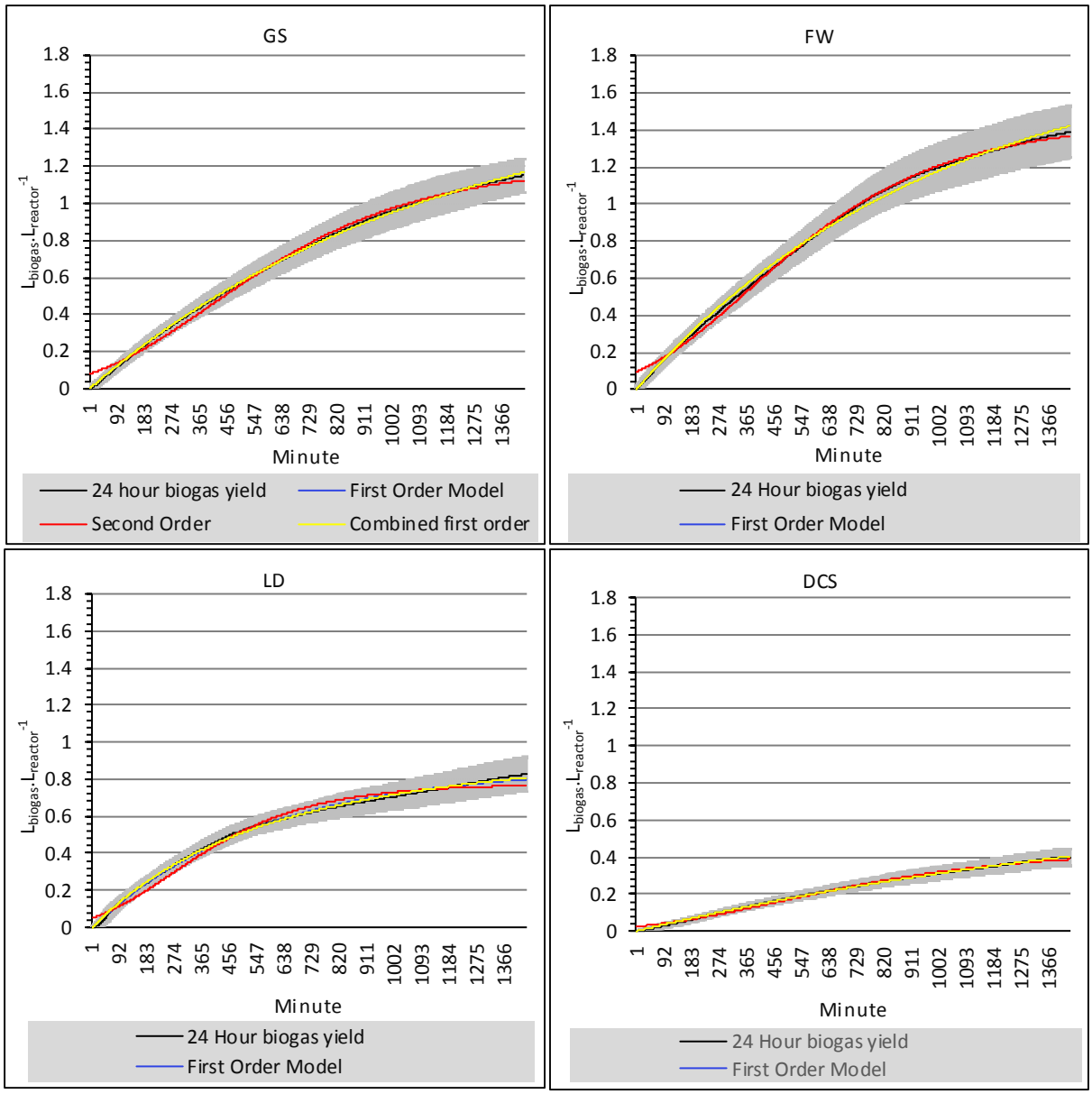


Figure 9-4 Cumulative specific biogas production for GS; Grass silage, FW; Food waste, LD; Laminaria digitata, DCS; Dairy cow slurry, with first order model, second order model, and combined first order model. Grey shaded areas represent ±one standard deviation

The total 24 hour biogas production of each feedstock ($L_{biogas}.L_{reactor}.day^{-1}$) can be seen in Table 9-4 along with the parameters of the three kinetic models assessed.

Table 9-4 Semi-continuous biogas and biomethane trial kinetics

Feedstock	**Experimental data**	**First order model**			**Gompertz model**				**Combined first order model**				
Biogas Trial	**24hr Dry biogas yield**	***V_{max}***	***k***	***Adjusted R^2***	***V_{max}***	***R_m***	***λ***	***Adjusted R^2***	***V_{max}***	***x***	***k1***	***k2***	***Adjusted R^2***
	$L_{biogas}.L_{reactor}^{-1}$	$L_{biogas}.L_{reactor}^{-1}$ .day^{-1}	$minute^{-1}$		$L_{biogas}.L_{reactor}^{-1}$ .day^{-1}	L_{biogas} .$L_{reactor}^{-1}$.$minute^{-1}$	minute		$L_{biogas}.L_{reactor}^{-1}$ .day^{-1}	%	$minute^{-1}$	$minute^{-1}$	
Grass silage	1.15	1.64	$0.9x10^{-3}$	0.999	1.21	$1.12x10^{-3}$	0	0.996	1.64	23.76	$0.9x10^{-3}$	$0.8x10^{-3}$	0.999
Food waste	1.39	1.87	$1.0x10^{-3}$	0.998	1.44	$1.44x10^{-3}$	0	0.998	1.87	20.12	$1.0x10^{-3}$	$1.0x10^{-3}$	0.998
L. digitata	0.83	0.87	$1.8x10^{-3}$	0.998	0.77	$1.10x10^{-3}$	0	0.981	1.00	51.23	$2.5x10^{-3}$	$0.7x10^{-3}$	0.998
Dairy cow slurry	0.40	0.77	$0.5x10^{-3}$	0.999	0.44	$0.35x10^{-3}$	25.66	0.999	0.77	4.66	$0.5x10^{-3}$	$0.52x10^{-3}$	0.999
Feedstock	**Experimental data**	**First order model**			**Gompertz model**				**Combined first order model**				
Biomethane Trial	**24hr CH_4 yield**	***V_{max}***	***K***	***Adjusted R^2***	***V_{max}***	***R_m***	***λ***	***Adjusted R^2***	***V_{max}***	***x***	***k1***	***k2***	***Adjusted R^2***
	$LCH_4.L_{reactor}^{-1}$	$LCH_4.L_{reactor}^{-1}$. day^{-1}	$minute^{-1}$		$LCH_4.L_{reactor}^{-1}$ .day^{-1}	LCH_4. $L_{reactor}^{-1}$. $minute^{-1}$	minute		$LCH_4.L_{reactor}^{-1}$. day^{-1}	%	$minute^{-1}$	$minute^{-1}$	
Grass silage	0.61	1.00	$0.7x10^{-3}$	0.999	0.67	$0.6x10^{-3}$	0	0.995	1.00	100	$0.7x10^{-3}$	$0.2x10^{-3}$	0.999
Food waste	0.74	0.94	$0.1x10^{-3}$	0.999	0.75	$0.8x10^{-3}$	0	0.999	0.94	94.60	$1.1x10^{-3}$	$1.1x10^{-3}$	0.999
L. digitata	0.48	0.50	$1.7x10^{-3}$	0.994	0.45	$0.6x10^{-3}$	0	0.970	0.60	18.11	$5.8x10^{-3}$	$0.9x10^{-3}$	0.999
Dairy cow slurry	0.26	0.52	$0.5x10^{-3}$	0.999	0.29	$0.2x10^{-3}$	28.28	0.999	0.52	0	$11.47x10^{-3}$	$0.5x10^{-3}$	0.999

The cumulative 24 hour biogas production ($L_{biogas}.L_{reactor}.day^{-1}$) followed the same trend as the BMP for each feedstock, FW had the highest average daily biogas production, followed by GS, LD, and DCS. All of the models assessed described the cumulative production of biogas from a pulse fed CSTR accurately, with high *Adjusted* R^2 values (>0.98) for each of the feedstocks.

Comparing *k* values, LD had the highest *k* value implying a rapid onset of biogas production. This was followed by FW, GS, and DCS. A potential reason for this was the availability of easily degradable substrate in the LD such as laminarin and mannitol (the main storage carbohydrates in macroalgae), which could be easily metabolised by microbes. The lower *k* values obtained for FW, GS, and DCS in the semi-continuous trials implied a decreasing fraction of readily degradable substrates. This does not agree with the order of *k* values obtained in the BMP assay for which DCS had the highest *k* value. This highlights a potential shortcoming of the BMP assay in predicting the profile of gas production in semi-continuous trials, and the need to conduct semi-continuous trials to assess this.

The maximum rate of biogas production obtained in the Gompertz model for the semi continuous trials was highest for FW, followed by GS, LD, and DCS. This was in agreement with the trend in R_m values obtained during the BMP assay. Little or no lag was evident between the time of feeding and the onset of biogas production for GS, FW, and LD. In the case of DCS there was a lag of 26 minutes.

All models assessed had high *Adjusted* R^2 values for each of the feedstocks and would be deemed suitable for modelling biogas production. Owing to the simplicity of the single term first order model, this model was used to predict biogas production from a theoretical plant.

9.3.4 Semi-continuous biomethane production trials

9.3.4.1 AD parameters

The average of daily pH values, weekly FOS/TAC ratios, weekly free ammonia (NH_3(aq)) concentrations and weekly CH_4 concentrations during the biomethane production trial, along with the SMY is also shown in Table 9-3. The average values of pH, FOS/TAC, NH_3(aq), and total VFA concentration were again within safe limits for the biomethane production trials. The low concentration of CO_2 in the generated gas indicated that the NaOH scrubbers were working effectively, and thus the remaining gas consisted of CH_4, N_2, O_2, and H_2O. The SMY of each feedstock obtained in the semi continuous biomethane trials did not show a statistically significant difference to the SMY of the same feedstock in the continuous biogas production trials (p values >0.05), see Table 9-3. Thus, it was evident that the AD process remained comparable and stable between the biomethane production trials and the biogas production trials.

9.3.4.2 Biomethane production and kinetics

The daily biomethane production of each reactor ($L_{biomethane}.L_{reactor}^{-1}$) can be seen in Figure 9-5. The data plotted is the average cumulative biomethane production at each minute over 24 hours for the last three weeks during the biomethane production experiment (third HRT), a total of 15 separate days of data. The figure also includes the first order, Gompertz, and combined first order gas production models for each feedstock.

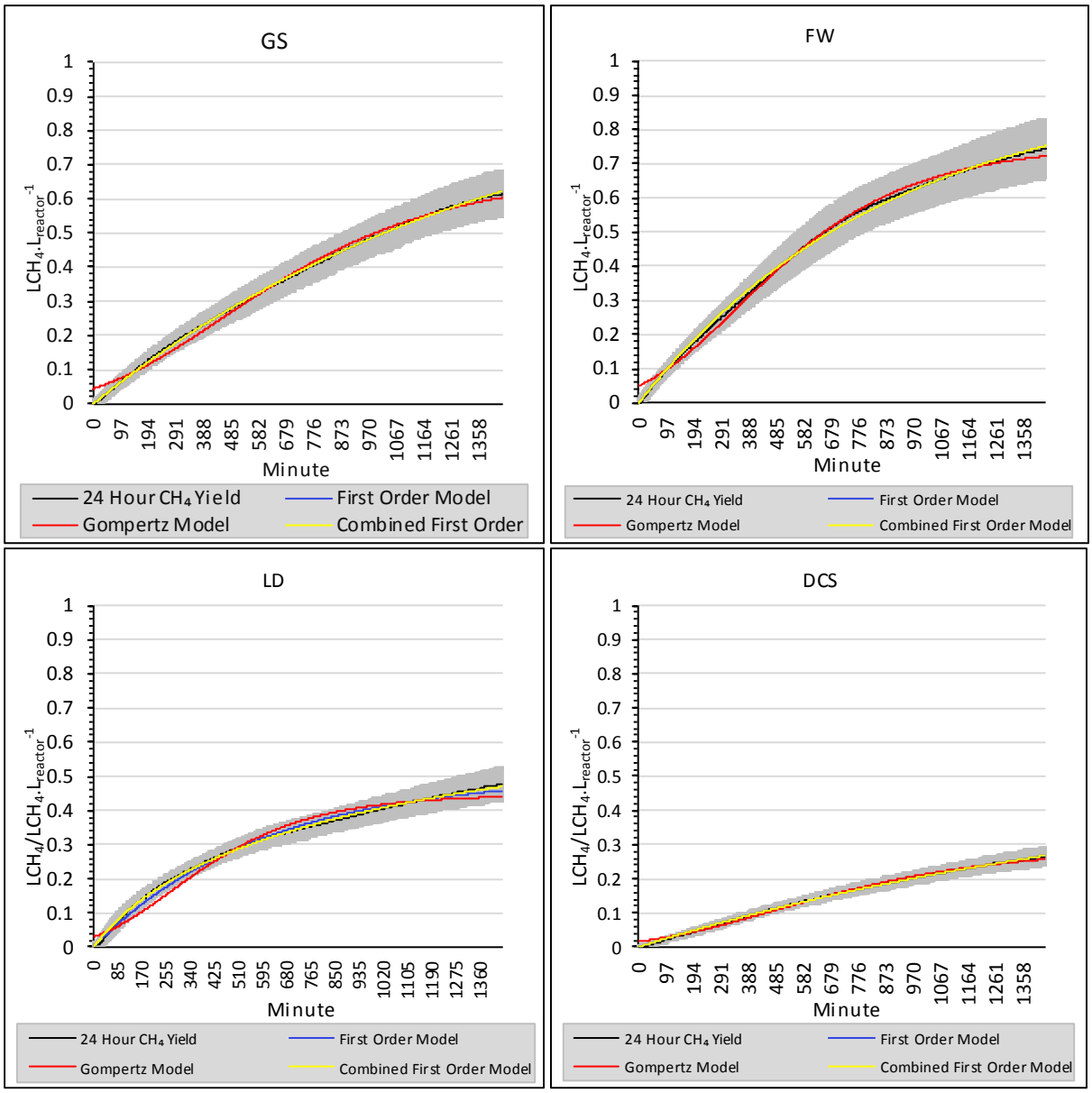


Figure 9-5 Cumulative specific methane production GS; Grass silage, FW; Food waste, LD; Laminaria digitata, DCS; Dairy cow slurry, with first order model, second order model, and combined first order model. Grey shaded areas represent ±one standard deviation of the collected experimental data over 15day period of data collection.

The 24 hour biomethane production ($L_{biomethane}.L_{reactor}^{-1}.day^{-1}$) and results of the three models are reported in Table 9-4.

The cumulative 24 hour biomethane production ($L_{biomethane}.L_{reactor}.day^{-1}$) of all feedstocks followed the same trend as the BMP yields. FW had the highest biomethane production, followed by GS, LD, and DCS.

The three models assessed in this work described the production of biomethane in the semi-continuous trials to a high level of accuracy; all models achieved an *Adjusted* R^2 value in excess of 0.90. The first order decay constants of feedstocks followed the same trend as those obtained in the biogas production trials, with LD having the highest decay constant, followed by FW, GS, and DCS.

This analysis indicates that the decay constants obtained in the semi continuous biomethane production trials differ from those obtained in the BMP assay. In the BMP assay, DCS had the highest decay constant, followed by LD, GS, and FW. While the *k* values from the BMP assay give an insight into the biodegradability of feedstock and the profile of biomethane production in a batch system, they do not give a full indication of the decay rates and biomethane production profiles for each feedstock in semi-continuous operation. If a pulse fed AD reactor operating as a demand driven system is to be used, semi continuous laboratory trials should be carried out to give an indication of the gas production profiles of specific feedstocks.

The maximum rate (R_m) of biomethane production from the Gompertz model for each feedstock followed the same trend as R_m values obtained in the biogas production trials. FW had the highest rate of methane production, followed by GS, LD, and DCS. The R_m values obtained for the production of biomethane were on average 58% of those obtained for biogas production; this would account for the volume of methane in biogas being typically 50-60%. The ranking of feedstock based on maximum rate of biomethane production obtained in a BMP assay showed some applicability to that of the semi-continuous reactors. R_m values obtained in the semi-continuous biomethane production trial followed the same trend as R_m values obtained in the BMP assay. No lag phase was evident in methane production for GS, FW, and LD according to the Gompertz equation, a lag time of 24 minutes was calculated for methane production from DCS as opposed to a lag time of 26 minutes in the biogas production trial. In terms of accurately modelling the production of biomethane from each feedstock, all three of the models assessed were adequate, giving *Adjusted* R^2 values in excess of 0.9.

The first order model was used to determine the cumulative production of methane from a theoretical plant in the following sections owing to the simplicity of the model. Kinetic parameters obtained in this work were for an OLR of 2kgVS.m^{-3}.day^{-1}, increasing the OLR could result in a change in the kinetic parameters. As the OLR increases, the production of gas per unit volume of reactor per day ($L_{biogas}.L_{reactor}^{-1}.day^{-1}$) would increase, however a perfect correlation between OLR and gas production per unit volume of reactor may not exist. The remaining parameters (k, R_m, λ) may or may not change, depending on the stability of the process. Kinetic parameters obtained for a given OLR should not be applied for other OLRs, for which additional trials should be conducted.

9.3.5 Dispatch model output

Calculation of the energy production and schedule are contained in Box 9-1. A plant was chosen which would be a typical size; a CHP capacity of 435kW_e (40% electrical efficiency, 24 hour operation). The gross daily energy production of the plant was 26,131kWh_{th} (2490Nm^3CH_4 at 37.78$MJ.Nm^{-3}$). Demand driven electricity production was taken to be 2MW_e. Operation of the CHP was between 18:30 and 19:30. The theoretical plant was fed grass silage.

Graphical results of calculations in Box 9-1 can be seen in Figure 9-6 showing the volume of biogas sent to each element of the system (primary y-axis) and the volume of biogas in the storage membrane (secondary y-axis).

Box 9-1 Calculation of feeding time for theoretical plant using grass silage

Feedstock: Grass silage, 18.9%DS, 17%VS, **OLR:** 2kgVSm^{-3}.day^{-1}, **Reactor Volume:** 4,000m^3
$v_{CH4:}$ 1m^3CH_4.$m^{-3}_{reactor}$, k_{CH4}: 0.0007, v_{biogas}: 1.64m^3_{biogas}.$m^{-3}_{reactor}$, k_{biogas}: 0.0009
Feed mass: 8,000kgVS.day^{-1}→47twwt of silage.day^{-1}
CHP capacity: 2,000kWe CHP run time: 1 hour (60 minutes)
Electricity generation: 2,000kWh_e
CHP electrical efficiency: 40%
Energy input required: 5,000kWh_{th}
Energy content of 1m^3 methane: 37.78MJ/(3.6MJ.kWh_{th}^{-1})=10.49kWh_{th}
Required volume of methane, Equation 9-6: $V_{CH4}^{Required}$= 5,000/10.49=476nm^3CH_4
First order model of methane production, Equation 9-9: $V_{CH4}(t)=(1*4,000)*(1-exp(-(0.0007)*t))$
Time to produce required methane, Equation 9-10: $t_{CH4}^{Required}$=-ln(1-119.2/(1*4,000))/0.0007 = 187 minutes (3 hours, 7 minutes)
The total volume of biomethane required (476nm^3) will be consumed by the time the CHP plant turns off (19:30). The time to produce the required volume of biomethane is 3 hours and 7 minutes. The reactor must be fed 3 hours and 7 minutes prior to the CHP turning off i.e. 16:23
Reactor feed time: 19:30-3:07=16:23
First order model of biogas production, Equation 9-11: $V_{Biogas}(t)=(1.64*4,000)*(1-exp(-0.0009*t))$
Volume of biogas required for CHP: 979m^3
The total time to produce the required volume of biogas is 187minutes from feeding to CHP shutdown. Maximum biogas storage occurs when CHP turns on, CHP is operational for 60 minutes, therefore the time at which maximum biogas storage occurs is 127 minutes after feeding
Maximum storage of biogas between AD and CHP,Equation 9-13: V_{Biogas}^{Store}= (1.64*4,000)*(1-exp(-0.0009*127))=682m^3
CHP dispatch time: 18:30
CHP shut down time: 19:30
Remaining biogas production after CHP shutdown from Equation 9-14, only applies for t>=187 i.e. the period after CHP shut down: $V^{\#}_{Biogas}(t)=(1.64*4,000)*(1-exp(-0.0009*t))-979$
It is desired that the total volume of biogas sent to biogas storage is as close to the storage volume required for the CHP i.e. 682m^3
Using equations Equation 9-15 to Equation 9-21 one can determine the dispatch time of the upgrading plant to achieve this
Upgrading dispatch time: 289 minutes post initial feeding, 21:11
Time of maximum gas accumulation in gas storage during upgrading: 660 minutes post initial feeding (03:22)

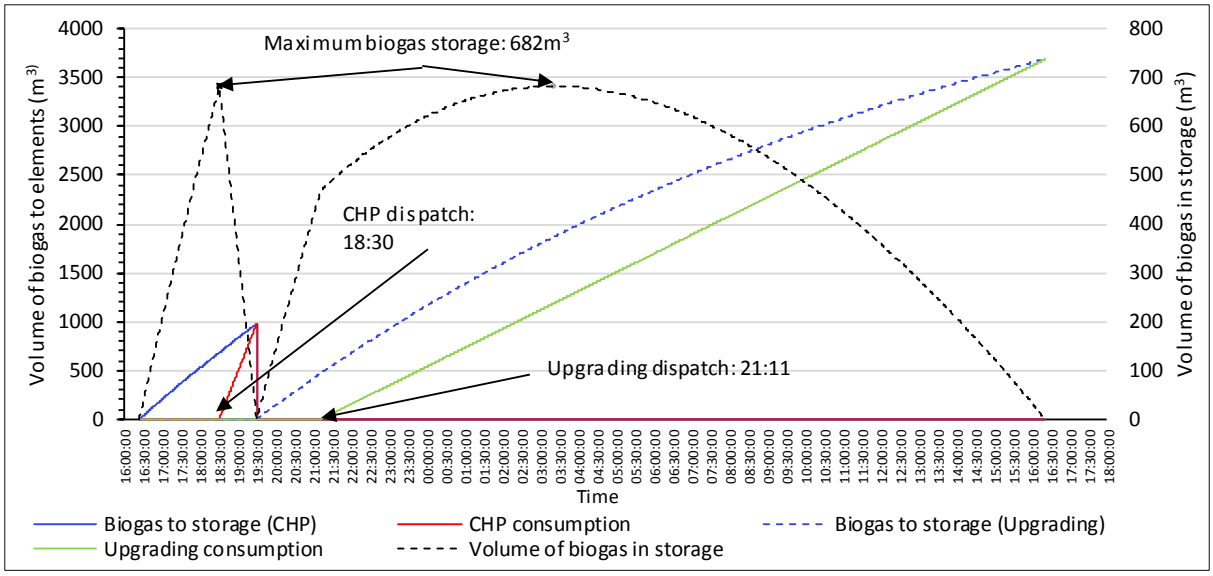


Figure 9-6 Example of biogas flows in pulse fed reactor. Feedstock is grass silage, organic loading rate of 2kgVS.m^{-3}.day^{-1}, reactor volume of 4,000m^3

The biogas consumption of the CHP was 979m^3 producing 2MWh$_e$ of electricity. Biogas consumption of the upgrading facility was 3,689m^3, producing 21,136kWh$_{th}$ of biomethane. The CHP plant consumed 21% of the biogas while the upgrading system consumed 79% of the biogas.

If the plant were to produce electricity continuously, daily electricity production would be 10,452kWh$_e$ yielding a revenue of €1,687 per day. This was calculated as follows: actual price of electricity on 7th Dec 2015 from 18:30 to 19.30 was 0.25€.kWh$_e^{-1}$ (Single Electricity Market Operator 2016) for the remainder of the day biogas electricity generates 0.15€.kWh$_e^{-1}$ (Department of Communications Energy and Natural Resources 2013). Demand driven electricity can yield €498 from 18:30-19:30 and €2,074 from biomethane production (1.03€.Nm^{-3} methane as a transport fuel (Ahern et al. 2015)). The energy return can rise from €1,687 to €2,572 per day.

Results of similar calculations carried out for the remaining feedstocks are shown in Table 9-5.

Table 9-5 Feeding time, biogas production, biomethane production

Feedstock	CHP (kW_e)	CHP dispatch time	CHP shut down time	Electricity production ($kWh_e.day^{-1}$)	Time to produce required biomethane (minutes)	Feed time	Total biogas sent to CHP ($m^3.day^{-1}$)	Upgrading dispatch time	Total biogas sent to upgrading system ($m^3.day^{-1}$)	Operation of upgrading system (minutes)	Upgrading system flow rate ($m^3CH_4.hour^{-1}$)	Biomethane production ($kWh_t.day^{-1}$)	Percentage of biogas used in CHP (%)	Percentage of biogas used in upgrading (%)
Grass silage	2,000	18:30	19:30	2,000	187	16:23	979	21:11	3,689	1,151	105	21,136	21	79
Food waste	2,000	18:30	19:30	2,000	121	17:29	846	19:30	4,844	1,319	115	26,603	15	85
L. digitata	2,000	18:30	19:30	2,000	160	16:50	861	19:30	2,336	1,280	64	14,241	27	73
Dairy cow slurry	2,000	18:30	19:30	2,000	518	10:52	721	05:42	893	310	116	6,244	45	55

Food wastes required the shortest time to produce the required volume of biogas and methane to operate the demand driven CHP plant (121 minutes) and also used the smallest share of overall biogas production in the CHP (15%). Dairy cow slurry required the longest time to produce the volume of gas needed for operation of the CHP (518 minutes) and used the largest share of overall biogas production in the CHP system (45%). All feedstocks assessed used a majority of biogas (thus energy) in the upgrading system, this could allow for a combined demand driven electricity production and upgrading system to benefit from increased revenue from higher value transportation fuels.

9.4 Conclusion

Biogas and biomethane production in pulse fed semi-continuous trials were accurately modelled using a first order model. Using these models a simplified feeding schedule was developed for a plant with combined demand driven electricity production and biomethane upgrading. For a theoretical plant pulse fed grass silage, 187 minutes was required to produce sufficient methane to run a $2MW_e$ CHP for 1 hour (yielding $2,000kWh_e$), resulting in a maximum storage volume of $682m^3$. Dispatch of the upgrading system occurred 289 minutes after CHP shutdown to give the same maximum storage volume, resulting in the production of $21,136kWh_{th}$ of biomethane. The use of demand driven biogas systems to provide renewable electricity on demand could enable further reductions of CO_2 emissions from electricity generation. Demand driven biogas plants could complement existing variable source of renewable electricity. Production of biomethane for use as a transport fuel outside of time periods of maximum electricity demand is also possible.

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10 Chapter 10: Conclusion and recommendations

10.1 Chapter overview

A recap of the aims of the thesis are presented. The conclusions of the thesis with respect to the initial objectives outlined in Chapter 1 is given. An overall conclusion synthesising this thesis is developed. Recommendations based on these conclusions will also be proposed.

10.2 Summary of thesis aims

The aim of this thesis was to determine the resource of renewable gas in Ireland from a range of sources. The total theoretical renewable gas resource associated with differing feedstocks was determined in several resource assessments. Initially, the biomethane resource of waste streams was calculated as this was seen to be a readily available source of renewable gas, with a high technology readiness level. Following this, the biomethane resource associated with anaerobic digestion of grass silage (a land based energy crop) was found; this is a feedstock that is readily available in Ireland. Subsequent to this, the potential resource of renewable gas from more advanced and therefore less technologically mature feedstocks was assessed. The biomethane resource arising from the anaerobic digestion of microalgae that could be cultivated using CO_2 from fossil fuel fired power stations was quantified. The resource of renewable gas associated with power to gas systems using existing sources of CO_2 in Ireland was also assessed. Knowing the total theoretical resource of biomethane allows for high-level conclusions to be drawn as to which potential sources of renewable gas should be prioritised and enables the overall scale of the potential resource in relation to current energy consumption in Ireland to be illustrated.

Knowing the total theoretical resource of renewable gas that could be available in Ireland does not allow for accurate estimates of how much of this potential resource could be developed. Assumptions that all of the theoretical resources identified could be used may be erroneous. A methodology to determine the quantity of renewable gas that could be utilised was developed and implemented in the utilisation plans. The utilisation plans developed for waste streams and grass silage (as these are seen to be the most technological mature sources of renewable gas) enable more informed conclusions to be drawn as to the total amount of renewable gas, in this case biomethane, that could be produced under differing scenarios. These utilisation plans allow for more a more informed estimate of potential renewable gas production and the scale of this potential production compared to current energy consumption in Ireland. Additionally, the influence of plant scale, inventive value per unit of biomethane produced, and feedstock price

or gate fees can be ascertained to further increase knowledge of their influence on potential biomethane production. Estimates of the total amount of biomethane that can be produced at a given levelized cost of energy can inform the development of incentives aimed at promoting the production of biomethane.

Comparison of the most common utilisation plan for biomethane production (centralised anaerobic digestion) to an alternative utilisation plan (decentralised anaerobic digestion) allows for potential benefits of the alternative solution to be highlighted. An alternative utilisation scenario, decentralised anaerobic digestion, could allow for either the use of feedstock that remains after the development of centralised anaerobic digestion facilities, or for an increase in the greenhouse gas (GHG) savings associated with the produced biogas owing to reduced GHG emissions in biogas production. Increased GHG savings would also allow for the produced biogas to meet the future minimum requirement for GHG emission savings in the production of renewable heat and renewable transport fuel.

Renewable gas can be used as a source of renewable heat, or as a renewable transport fuel, while this was the main focus of this thesis renewable gas can also be used as a controllable source of renewable electricity. The inability of current variable renewable electricity generation technology to provide on demand renewable electricity is a substantial challenge in decarbonising the electricity supply. The use of renewable gas, specifically biogas, as a source of controllable renewable electricity could aid this decarbonisation. Outside of hours of peak electricity demand, surplus biogas could be upgraded to biomethane for use as a source of renewable heat or as a renewable transport fuel. The development of a proposed feeding regime for an anaerobic digester involved in such a system based on laboratory trials can aid in the realisation of this concept.

10.3 Thesis conclusions with respect to the initial thesis objectives

10.3.1 Quantification of the spatially explicit resource of biomethane than can be generated from waste streams available in Ireland via anaerobic digestion.

The total theoretical biomethane resource associated with waste streams in Ireland was found to be 12.47PJ this is equivalent to 6.23% of energy consumption in transportation, application of a double weighting to this contribution raises the share to 12.45% of energy use in transportation. This is greater than the target for 10% of energy in transportation to be sourced from renewable sources by 2020. The total theoretical resource of biomethane from waste streams is sufficient to provide 47.62% of the energy consumption of heavy goods vehicles in Ireland. The theoretical resource of biomethane could meet 96% of the upper goal of CNG supply, or 1.9 times the lower goal of CNG supply outlined by Gas Networks Ireland (GNI) for use as a fuel in commercial vehicles in 2025.

The total theoretical resource of biomethane from waste streams could meet the GNI goal to supply 5.2PJ of renewable gas by 2025 approximately 2.4 times over. Use of this biomethane as a source of renewable heat by industry could displace 22% of current natural gas demand by industry. The total theoretical resource of biomethane from waste streams is equivalent to 6.97% of total thermal energy consumption in 2015 and could contribute to the target of 12% of thermal energy to be sourced from renewable sources by 2020.

Cattle slurry was the single largest resource contributing 9.59PJ and was located primarily in regions with the highest dairy cow population in the south and north east of Ireland. The cattle slurry resource could be processed in 62 large centralised anaerobic digestion facilities processing 420,000$t_{wwt}.a^{-1}$ of slurry, similar to the Maabjerg biogas plant in Denmark. Co-digestion with wastes from milk processing facilities could be favourable as these were located in regions with the highest dairy cow population.

Source separated household organic waste was the second largest resource contributing 1.5 PJ of energy and was located primarily in urban and city regions (64% of the total theoretical resource). The total resource of source separated

household organic waste could be processed in 6 centralised anaerobic digestion facilities processing 120,000$t_{wwt}.a^{-1}$.

Sheep manure represented the third largest theoretical resource of biomethane (0.61 PJ) and was located primarily in western regions of the country in regions where the resource of cattle slurry was found to be low.

The biomethane resource associated with pig slurry (0.27 PJ) and chicken manure (0.12 PJ) from individual intensive farms were concentrated in specific regions within Ireland. The biomethane resource of milk processing waste (0.17 PJ) and slaughterhouse wastes (0.21 PJ) were more dispersed throughout Ireland than that of pig slurry and chicken manure but there were some noticeable patterns. Milk processing waste was located in regions with the highest dairy cow population as previously mentioned, and there was an absence of slaughterhouse waste in the west and north-west of Ireland.

The development of plans to use these feedstocks for biomethane production should take the locations of each feedstock into consideration.

10.3.2 Development of a utilisation plan for the conversion of waste streams to biomethane

The optimisation model developed in this work considered the location of feedstocks suitable for biomethane production, locations on the gas network suitable for biomethane injection, plant scale, gate fees, and incentive values. Utilisation plans for the conversion of waste streams to biomethane for grid injection were developed using this optimisation model.

The optimisation model identified suitable locations on the gas network in order of decreasing net present value. The locations of biomethane production facilities were assessed under a number of scenarios of plant scale, gate fee, and incentive value per unit of biomethane produced.

The general result of the optimisation model in all scenarios was that source separated household organic waste was the first feedstock to be utilised. Anaerobic

digesters processing this feedstock were located close to the main urban and city areas in Ireland.

Slaughterhouse wastes and milk processing wastes were the next feedstock to be utilised (along with agricultural slurries and manures). The final plants to be built processed cattle slurry almost exclusively as all other feedstocks with a high biomethane yield were already allocated to prior plants.

The optimisation model identified three potential locations which had a positive net present value in all scenarios assessed at a maximum plant scale of 50GWh. These three initial plants (Plant 10, Plant 12, and Plant 40 outlined in Figure 10-1) were in close proximity to the main urban population regions in Ireland and processed source separated household organic waste almost exclusively. The levelized cost of energy from these three plants was found to be between 60-80€.MWh^{-1} in all scenarios at a maximum plant size of 50GWh.a^{-1}.

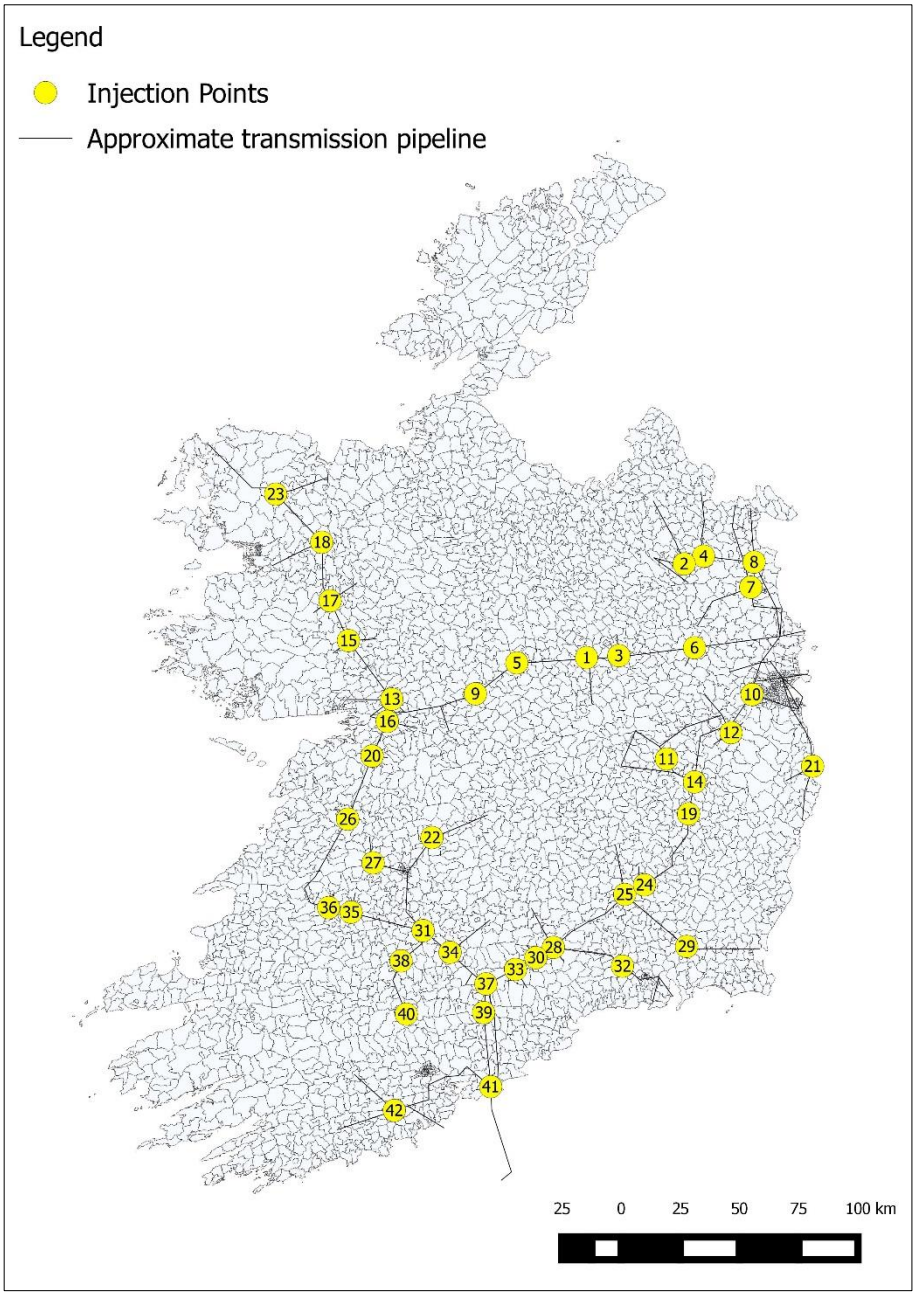


Figure 10-1 Location of potential biomethane injection points to the natural gas network

Detailed results from the most optimistic scenario at a maximum plant scale of 50GWh.a^{-1} showed that the first 5 plants to be built (Plant 10, Plant 12, and Plant 40 and two additional plants) processed source separated household organic waste almost exclusively, with each plant processing ca. 100-130kt$_{wwt}$ of feedstock per year. Following the construction of these initial facilities, subsequent facilities processed a mixture of feedstocks including milk processing waste, slaughterhouse waste, and animal manures and slurries in order to maximise their net present

value. Subsequent plants were located in regions, which were more rural than initial plants and were thus closer to the main sources of other feedstocks used.

When maximum allowable plant scale was increased to 200GWh.a^{-1} the optimal plant locations changed considerably. Two plants achieved a positive net present value in all scenarios at a maximum plant size of 200GWh.a^{-1}, Plant 10 and Plant 38. Only Plant 10, located near the major urban area of Ireland and processed a significant quantity of source separated household organic waste was able to achieve the maximum allowable scale of 200GWh.a^{-1}. Plant 38 was the second plant to be constructed in scenarios when maximum plant scale was 200 GWh.a^{-1}, this is in contrast to the scenarios when the maximum plant scale was 50GWh.a^{-1} in which Plant 38 was the 15th plant to be constructed and only achieved a positive net present value in the most optimistic scenarios of gate fee and incentive per unit of biomethane produced.

10.3.3 The impact of gate fees, incentive values, and plant scale on the resource of biomethane derived from waste streams that can be produced in a financially viable manner

An assessment of the impact of gate fee, incentive value per unit of biomethane produced, and plant scale on the resource of biomethane that could be produced from plants with a positive net present value was conducted with the optimisation model developed in this work.

At a maximum allowable plant scale of 50GWh.a^{-1} the number of financially viable biomethane facilities ranged from 6 to 22 depending on the value of the gate fee associated with source separated household organic waste, and the value of the incentive per unit of biomethane produced.

Variation in the incentive value per unit of biomethane produced had a larger impact on the number of viable biomethane plants, and therefore on the total production of biomethane than the value of the gate fee associated with household organic waste. At the maximum gate fee assessed (75€.t_{wwt}^{-1}), variation of the

incentive value per unit of biomethane produced from 38€.MWh^{-1} to 106€.MWh^{-1} resulted in biomethane production increasing from 1 PJ to 3.4 PJ.

Increasing the incentive value per unit of biomethane produced had the largest impact on the quantity of biomethane produced from cattle slurry. At a gate fee of 75 €.t_{wwt}^{-1} for source separated household organic waste, increasing the incentive value per unit of biomethane produced from 38€.MWh^{-1} to 106€.MWh^{-1} increased the total production of biomethane from cattle slurry from 0.005PJ to 1.83PJ.

In order for waste streams that do not attract a gate fee to be effectively utilised as a feedstock for the production of biomethane, the incentive value per unit of biomethane produced is important. Increased incentive value per unit of biomethane produced will increase the utilisation of waste streams that do not accrue a gate fee.

In an Irish context, the main waste stream in terms of theoretical biomethane resource is cattle slurry, utilisation of this waste stream greatly depends on the incentive value per unit of biomethane produced, designs of such incentives should be cognizant of this.

The total production of biomethane from plants processing waste streams was found to be 3.4 PJ in the most optimistic scenario at a maximum plant size of 50GWh.a^{-1}, and 3.8 PJ in the most optimistic scenario at a maximum plant size of 200GWh.a^{-1}. This resource of biomethane was approximately 27-30% of the total theoretical resource of biomethane arising from waste streams in Ireland. The levelized cost of energy (LCOE) ranged from 59.4-132.1€.MWh^{-1} at a maximum plant size of 50GWh.a^{-1}, while at a maximum plant size of 200GWh.a^{-1} LCOE ranged from 81.5-132.7€.MWh^{-1}. In general, the LCOE was lowest for initial plants to be built according to the optimisation model. The increase in LCOE for the larger plant size of 200GWh.a^{-1} was due to the increase in transportation distance required to source sufficient feedstock for the plant.

Utilisation of the biomethane resource associated with source separated household organic waste ranged from 87.5-93% of total resource; almost all of the biomethane resource associated with this feedstock was utilised by biomethane plants in the

optimisation model. The utilisation of cattle slurry was significantly lower and ranged from 0.1% to 34% of the total theoretical resource identified. Alternative uses for the remaining cattle slurry should be assessed.

The total production of biomethane from waste streams in the most optimistic scenarios (3.4-3.8 PJ) was equivalent to 1.7-1.9% of total final energy consumption in transportation in 2015, application of double weightings to this resource increased the contribution to 3.4-3.8% of energy use in transportation.

The biomethane resource from waste streams produced is also equivalent to 13-14.5% of the final energy consumption of heavy goods vehicles in Ireland in 2015. Biomethane production from plants processing waste streams was equivalent to 26-56% of the planned supply of CNG for use as a transport fuel in 2025.

The resource of biomethane from plants processing waste streams was found to be 66-73% of the GNI goal to supply 5.2PJ of renewable gas by 2025. If the biomethane were to be used as a source of renewable heat by industry it would be equivalent to 6-6.7% of natural gas consumed by industry and 1.9-2% of total thermal demand in 2015.

The analysis conducted allows for more insight into the potential utilisation of waste streams for biomethane production in Ireland than prior works.

10.3.4 Investigation of the spatially explicit resource of biomethane associated with grass silage and compare this to the location and resource of cattle slurry in Ireland

The total theoretical biomethane resource associated with grass silage in excess of livestock requirements was found to be 128.4 PJ, this is equivalent to 64% of energy consumption in transport in 2015 and 4.9 times the total energy consumption of heavy goods vehicles in Ireland in 2015. The potential resource of biomethane from grass silage was found to be 10-19 times the projected supply of CNG as a transport fuel in 2025 outlined by GNI. The theoretical resource of biomethane was equivalent to 72% of thermal energy consumption in 2015. The potential resource of biomethane from grass silage was 25 times the projected supply of renewable

gas in 2025 outlined by GNI. The potential resource of biomethane arising from grass silage in excess of livestock requirements is substantial.

Much of the resource of grass silage was located in western regions of the country where the total theoretical resource of cattle slurry was low. Regions with a large biomethane resource associated with cattle slurry show little potential for biomethane associated with grass silage owing to the use of silage in these regions as fodder for livestock. Consideration must be given to this use of grass silage as a fodder for livestock in assessing potential regions for the development of anaerobic digesters processing grass silage. The development of an anaerobic digester in a region should not impact the current and future availability of grass silage as a feedstock for livestock. Regions in which a surplus of silage can be grown should be prioritised for biomethane production. The Teagasc GRASS10 campaign (Teagasc 2017)can facilitate significantly increased production of grass per hectare to allow for feed and for biogas production without land use change.

Development of a plan to co-digest grass silage and cattle slurry in centralised anaerobic digesters to produce biomethane must consider the location of these two feedstocks, the optimal location for such facilities may not be in regions with the absolute highest resource of either feedstock.

10.3.5 Development of a utilisation plan to produce biomethane from grass silage and cattle slurry

The optimisation mode developed produced a potential build order of biomethane plants processing grass silage and cattle slurry in order of decreasing net present value. The location of each plant, and the feedstock sources suppling each plant were identified in the optimisation model. The utilisation plans proposed by the optimisation model enable the locations of the most profitable plants to be identified under a number of scenarios.

Results from the median scenario of plant scale (75,000$t_{wwt}.a^{-1}$), incentive value per unit of biomethane produced (60€.MWh^{-1}), silage price (33€.t_{wwt}^{-1}), and feedstock mixture (volatile solids ratio of grass silage to cattle slurry of 4:1) show that the

most profitable plants (those initially built) are located in regions where the neither the resource of grass silage or the location of cattle slurry is maximal. The levelized cost of energy from these plants ranged from 65.0-69.8 €.MWh^{-1} in the median scenario, for plants to achieve a positive net present value the value of biomethane produced by each plant must be greater than this. The initial plants are located in typically rural regions where there are sufficient quantities of both feedstocks, identification of these locations from inspection of maps outlining the spatially explicit resource of biomethane from grass silage and cattle slurry respectively is not intuitive.

Source locations of feedstock supplying each potential biomethane plant were also identified in the median scenario. The average transportation distance for grass silage was ca. 10.5km, the average transportation distance for cattle slurry was 6.4km owing to the lower energy yield per tonne of slurry transported.

10.3.6 Assessing the impact of silage price, plant size, feedstock mixture, and incentive value on the production of biomethane from grass silage and cattle slurry

The total biomethane production from plants processing grass silage and cattle slurry ranged from 3.51PJ to 12.19PJ depending on the scenario assessed. The most optimistic resource of biomethane production by anaerobic digesters processing grass silage and cattle slurry (12.19PJ) was equivalent to 6% of energy consumption in transportation in 2015. Total biomethane was also equivalent to 45.6% of the total final consumption of energy by heavy goods vehicles in Ireland. The potential biomethane production from plants processing grass silage and cattle slurry could meet 94-188% of the GNI goal to supply 6.5-13PJ of CNG as a transport fuel to commercial vehicles in 2025.

Biomethane production from plants processing grass silage and cattle slurry could meet the GNI goal of supplying 5.2PJ of renewable gas by 2025 approximately 2.4 times over. Use of this biomethane for the production of renewable heat by industrial natural gas users could offset 22% of natural gas demand in 2015/16. The

production of biomethane from plants processing grass silage and cattle slurry is significant and could aid Ireland in increasing the supply of indigenously sourced renewable energy.

The total production of biomethane by plants processing grass silage and cattle slurry was approximately 2.5-8.8% of the combined total theoretical resource of biomethane associated with grass silage and cattle slurry respectively. A considerable portion of the theoretical resource of grass silage and cattle slurry was not utilised. Use of the remaining resource for the production of biomethane to be injected to the natural as network would require additional injection points to be identified on the gas network, or would require a novel solution such as decentralised anaerobic digestion with biogas transportation to a central user via biogas pipelines.

An increase in plant scale increased the total production of biomethane, this would be expected. As plant scale was increased, the levelized cost of energy of energy of the biomethane produced decreased owing to economies of scale associated with the CAPEX of the anaerobic digestion plant and the upgrading plant. Larger plants could be seen to be more financially viable in the case of biomethane production from grass silage and cattle slurry, this was not the case in anaerobic digesters processing waste streams owing to the increase in transportation cost incurred in sourcing feedstock for the larger waste stream plants.

Total biomethane production generally increased with increased incentive value per unit of biomethane, this would be expected. The greatest increase in biomethane production (1.963 TWh) occurred when the incentive value was increased from 60€.MWh^{-1} of biomethane to 100€.MWh^{-1} of biomethane for plants processing 100,000$t_{wwt}.a^{-1}$, at a silage price of 47€.t_{wwt}^{-1}, and a volatile solids ratio (feedstock mixture) of 2:1 (grass silage : cattle slurry). At any value of incentive below 100€.MWh^{-1} for this combination of plant scale, silage price, and feedstock mixture, no plants were capable of producing biomethane whilst achieving a positive net present value.

The impact of increasing incentive value was not equal for all scenarios assessed. In scenarios with a volatile solids ratio of 4 and 6 (more grass silage in the feedstock

mixture) increasing the incentive value per unit of biomethane from 60€.MWh^{-1} to 100€.MWh^{-1} did not markedly increase the production of biomethane. This was a result of all plants achieving the maximum size allowable at an incentive of 60€.MWh^{-1}. Increasing the incentive value beyond 60€.MWh^{-1} in these instances would not increase total biomethane production, it would only increase the profitability of each biomethane plant

The quantity of biomethane produced increased as silage prices decreased, the converse was also true as was expected. The influence of silage price on the levelized cost of energy was significant, an increase in silage price for a given combination of plant size, incentive value per unit of biomethane produced, and feedstock mixture (volatile solids ratio) led to increases in the levelized cost of energy and vice a versa. Knowledge of the influence of silage price on the levelized cost of energy from biomethane plants is useful to determine the total quantity of biomethane that can be produced at a given value per unit of biomethane produced (which can be comprised of the market price of gas and an incentive per unit of biomethane produced).

Feedstock mixture exhibited a strong influence on the total quantity of biomethane produced. As the volatile solids ratio of grass silage to cattle slurry in the feed mixture increased (i.e. plants processed more grass silage) the total quantity of biomethane produced increased. Increasing the volatile solids ratio from 2 to 4 increased biomethane production by an average of 56% for all scenarios of plant size, grass silage price, and incentive value per unit of biomethane produced. Increasing the volatile solids ratio from 4 to 6 resulted in an average increase of 13% for total biomethane production in all scenarios of plant scale, grass silage price, and incentive value per unit of biomethane produced. This was expected as grass silage has a greater methane yield in anaerobic digestion than cattle slurry, processing more grass silage at a plant will increase biomethane production.

Of interest is that as the volatile solids ratio was increased, the levelized cost of energy reduced, as more grass silage was processed by plants producing biomethane, the cost of production per unit of biomethane decreased. This was somewhat counter intuitive as increasing the quantity of grass silage processed by a

biomethane plant will increase annual cashflow spent purchasing grass silage. However, the increase in biomethane production outweighed the increase in annual expense and resulted in a lower levelized cost of energy.

Utilisation plans for biomethane production from grass silage and cattle slurry proposed by the optimisation model developed in this work allowed for a greater level of understanding to be achieved in relation to the total production of biomethane from plants. The influence of various parameters on the quantity of biomethane produced could be assessed. Locations suitable for the development of these plants were also determined, this is a significant improvement on existing utilisation plans for biomethane production from grass silage and cattle slurry in Ireland.

These criteria are essential in setting an incentive for the production of biomethane and highlight the inefficiency and inadequacy of setting one incentive level for all forms of biomethane. There are clear and significant differences in the LCOE of biomethane produced from waste streams or grass silage and cattle slurry. Additionally, the operational nature of biomethane plants, namely the scale, feedstock prices, and volatile solids ratio (feedstock mixture) also impact the financial viability of plants. The use of a single incentive level for all biomethane plants is ill-advised and myopic, currently in Ireland there are 4 different incentive levels available for electricity production from biogas, none are available for biomethane production. The design of the current incentives for electricity production from biogas does not consider the feedstock used by the plant, the specific scale of the plant, or the feedstock mixture of the plant. Replication of such a system for biomethane production would not capture the intricate interactions of plant scale, feedstock type, feedstock mixture, and feedstock price outlined previously. A tiered approach in which these factors are considered would be more complex, but would enable the promotion of multiple sources of biomethane in Ireland. Use of a single incentive level could either discourage the development of certain resources in Ireland, or could result in the over compensation of some biomethane projects.

10.3.7 Comparing centralised and decentralised biogas production with respect to the greenhouse gas balance of biogas in a rural townland.

The production of biogas using pig slurry as a feedstock at a centralised anaerobic digester located at the biogas user (a milk processing plant in a rural townland in Ireland) resulted in the highest CO_2eq emissions in the biogas production and delivery process, the CO_2eq intensity of the produced biogas was $9.05gCO_2eq.MJ_{Biogas}^{-1}$. This figure includes for the emissions of CO_2eq in transportation of slurry to the digester, the biogas production process, and the transportation of the resulting digestate to land for use as a fertiliser. The avoided emissions of CO_2eq from storage of slurry in uncovered slurry pits are not accounted for in this figure.

Road haulage of pig slurry to a centralised anaerobic digestion plant located away from the biogas user (at a location to minimise the energy consumed in pig slurry transportation) with the delivery of biogas to the biogas user in a low-pressure pipeline reduced total CO_2eq emissions in the biogas production and delivery process by 8% compared to the previous scenario. The CO_2eq intensity of biogas in this second scenario was $8.34gCO_2eq.MJ_{Biogas}^{-1}$.

Decentralised biogas production using anaerobic digesters at each source of pig slurry, with the delivery of biogas to the biogas user in dedicated low-pressure pipelines from each pig farm to the biogas user reduced CO_2eq emissions in the biogas production and delivery process by 19% compared to the first scenario of centralised digestion of pig slurry at the biogas user. The CO_2eq intensity of biogas in this scenario was $7.36gCO_2eq.MJ_{Biogas}^{-1}$.

Decentralised anaerobic digestion of pig slurry at each farm coupled with biogas transportation to the biogas user in a pipe network of minimal length reduced the emissions of CO_2eq in the biogas production and delivery process by 18% compared to centralised anaerobic digestion of pig slurry at the biogas user. The CO_2eq intensity of biogas in this scenario was $7.43gCO_2eq.MJ_{Biogas}^{-1}$, this is higher than the CO_2eq intensity of the prior decentralised biogas production scenario, however, the total length of pipe required in this scenario is 34% lower than in the previous

decentralised biogas production scenario. This could result in a potential cost saving in the development and maintenance of such a system.

Decentralised biogas production can be a viable method to reduce the emission of greenhouse gases associated with the haulage of feedstock to centralised anaerobic digestion plants. This would allow for biogas produced in decentralised systems to achieve a greater emissions reduction in comparison to the standardised fossil fuels and sources of heat. This is of importance as it would allow for more biogas to be classified as a sustainable source of transport energy (an emission saving of 70% compared to the standardised fossil fuel comparator is required), or as a sustainable source of heat (a proposed emission saving of 85% compared to the standardised fossil fuel comparator is proposed from 2026 onward).

The use of decentralised anaerobic digestion for biogas production reduces the energy consumption and associated CO_2eq emissions arising from feedstock transportation. This is of importance for feedstocks with lower methane yields per wet tonne such as livestock slurries and could allow for an increase in their sustainable use in biogas facilities.

10.3.8 An initial assessment of the resource of biomethane from microalgae that could be cultivated using exhaust gases from fossil fuel fired power stations in Ireland

The potential biomethane resource associated with the anaerobic digestion of microalgae grown at fossil fuel fired power stations in Ireland was determined in a rudimentary resource assessment to be 9.76PJ. This theoretical resource is equivalent to 4.87% of final energy consumption in transport in 2015, application of double weighting to this resource increases the contribution to 9.8% of energy consumption in transport. If used as source of fuel by CNG fuelled vehicles it could offset 37% of the energy consumption of heavy goods vehicles in 2015. If the theoretical resource of biomethane was used as a source of renewable heat by industrial natural gas consumers, 17% of industrial natural gas demand could be

met, this would allow for up to 5.5% of thermal energy in Ireland to be generated from a renewable source.

Following the rudimentary analysis an in-depth assessment of the potential biomethane resource associated with microalgae grown using CO_2 from fossil fuel fired power stations in Ireland was conducted. The in-depth assessment considered the influence of weather and solar radiation levels on the hourly growth rate of microalgae at each power station, as well as the availability of CO_2 from each power station. The constant growth rate of microalgae assumed in the rudimentary assessment was found to be untrue, the hourly growth rate of microalgae in the in-depth assessment varied throughout the year with maximum growth rates during summer months.

Prior assessments of the resource of microalgae in regions assumed that CO_2 would be constantly available to the microalgae cultivation system. The in-depth assessment highlighted the risks of this assumption, CO_2 was not always available from power stations owing to their varying operational schedules. Only one power station assessed in this work could constantly supply CO_2 to the microalgae cultivation system. The remaining power stations exhibited hours with no CO_2 availability owing to either maintenance work or due to the power stations being shut down and then brought online again in order to satisfy variations in time specific electricity demand.

When the CO_2 availability to microalgae cultivation systems was considered, the reduction in the annual microalgae yield from a single raceways pond ranged from 0% to 99% compared to the assumption of constant CO_2 availability.

The in-depth assessment of the potential biomethane resource associated with microalgae grown at fossil fuel fired power stations indicated that 1.75PJ of biomethane could potentially be produced. This potential resource is equivalent to 0.87% of final energy consumption in transportation in 2015, application of double weighting increases this contribution to 1.74% of final energy consumption in transportation. If used as a fuel for heavy good vehicles, the potential biomethane resource could replace 7% of the energy consumed by heavy good vehicles. If the potential biomethane resource is used by industrial natural gas consumers for the

production of renewable heat it could offset 3% of industrial natural gas demand and supply 1% of thermal energy demand in Ireland.

Assessments which aim to quantify the resource of microalgae associated with CO_2 from fossil fuel fired power stations should consider the impact of weather conditions, solar radiation levels, and the availability of CO_2 from power stations. Failure to consider the influence of weather or CO_2 availability on the growth of microalgae resulted in a potential resource of microalgae which was 6 times larger than the resource identified when these parameters were considered.

10.3.9 Estimation of the current resource of renewable gas that could be generated using existing sources of CO_2 in Ireland in power to gas systems.

The most suitable sources of CO_2 currently available in Ireland for use in power to gas systems were identified as large distilleries, and wastewater treatment plants which produce biogas from the anaerobic digestion of sludges generated in the sewage treatment process. The total potential resource of methane that could be produced by using the most suitable existing sources of CO_2 in power to gas systems was 1.43PJ, equivalent to 5.5% of the energy consumed by heavy goods vehicles in Ireland. In relation to the GNI goal to supply CNG as a transport fuel, the potential methane resource from CO_2 sources identified could meet 11-22% of the 2025 goal. If the methane produced from these CO_2 sources were to be used by industrial natural gas consumers it could offset 2.6% of industrial natural gas demand in 2015. In relation to the GNI goal of supplying 5.2PJ of renewable gas by 2025, the potential resource of methane that could be produced using the most suitable CO_2 sources identified in power to gas systems could meet 28% of this goal.

Overall, the electricity requirement for the production of methane from the identified CO_2 sources was greater than the total amount of electricity from renewable sources that was dispatched down in 2015. The existing CO_2 source identified present a significant mechanism for the storage of excess renewable electricity that would otherwise have been wasted in the form of methane which

can then be used as a source of renewable transport fuel or a source of renewable heat.

The most suitable source of CO_2 identified was a large distillery in the south of Ireland. The potential resource of methane that could be produced using CO_2 from this distillery was 0.93 PJ, and would require 132.6% of the total quantity of electricity from renewable sources that was dispatched down in 2015. This distillery has significant potential in terms of its ability to store excess renewable electricity, and in terms of the resource of methane that could be produced. The potential methane resource that could be produced using CO_2 from this distillery could be used to fuel the main bus fleet of the nearest city bus fleet of 88 buses if used in CNG fuelled buses.

The existing resource of CO_2 available in Ireland is significant with regard to its use in power to gas systems for the production of methane from excess renewable electricity. Further investigation of the optimal methods of integrating power to gas facilities at the CO_2 sources identified should be conducted.

10.3.10 Evaluation of a potential feeding regime for use in a demand driven biogas system

Potential feeding regimes for an anaerobic digester producing biogas on demand for use in a combined heat and power (CHP) unit were determined for four feedstocks; grass silage, source separated household food waste, *Laminaria digitata* (common kelp), and dairy cow slurry. Data was obtained from experimental trials using 5L continuously stirred tank reactors. Feeding was conducted in a pulse. First order kinetic models of biogas and biomethane production were found to accurately model biogas and biomethane production from the lab scale anaerobic digesters.

The time at which a notional anaerobic digester operating in a demand driven regime was to be fed, and the time at which and upgrading system should be switched on to process the remaining biogas into biomethane for use as a transport

fuel, was determined using first order kinetic models of biogas and biomethane production from each feedstock.

For the case of a 4,000m^3 anaerobic digester processing grass silage, if a 2MWe CHP unit is required to generate electricity for one hour at a time of peak electricity demand, the anaerobic digester should be fed grass silage approximately three hours before the time at which the CHP unit is to be dispatched. The maximum storage volume for biogas between the anaerobic digester and the CHP unit was 682m^3.

Following the shutdown of the CHP unit, the remaining biogas can be sent to an upgrading system for the production of biomethane. To maximise the use of the existing biogas storage volume in place, the upgrading unit should be turned on 289 minutes following the shutdown of the CHP unit. Of the total biogas produced by the anaerobic digester, 21% was used for electricity generation in the CHP unit, the remaining 79% was used for the production of biomethane.

Operating the same biogas plant continuously for the production of electricity only would result in a daily income of €1,687 from the sale of electricity. Operation of the biogas plant on a demand driven basis to generate electricity during the period of maximum price for one hour, and for the production of biomethane as a transport fuel outside of this time period yielded a daily income of €2,572.

Demand driven biogas plants could complement existing sources of renewable electricity generation such as onshore wind turbines by suppling renewable electricity during times of peak electricity demand. Outside of these periods, biogas can be upgraded to biomethane for use as a sustainable fuel in transportation.

10.4 Overall conclusion

The total theoretical resource of renewable gas from each of the sources assessed in this thesis can be seen in Figure 10-2. The total theoretical resource of waste streams is dominated by cattle slurry, reflective of the main farming practice in Ireland. The next largest waste resource is that of source separated household organic waste. The remaining waste streams (comprised of animal slurries and manures excluding cattle, and food processing wastes) contribute a minor share of the total theoretical biomethane potential from wastes. Based on the scale of the potential resources alone it can be argued that the use of cattle slurry and source separated household organic waste for the production of biomethane should be prioritised. The geographical variation in feedstock showed that cattle slurry was concentrated in the south and north east of the country and source separated household organic wastes were mainly found in high population regions. A simple conclusion is that biomethane plants processing these wastes should locate in these regions respectively, the remaining waste streams assessed should also be considered in deciding upon the location of such biomethane plants.

The total theoretical resource of biomethane from grass silage is significant (Figure 10-2), it is the single largest potential resource of biomethane in Ireland. The use of grass silage as a potential source of biomethane should therefore be prioritised following the use of waste streams. The majority of the biomethane resource associated with grass silage is in the western regions of Ireland, a simplified policy would be to prioritise the development of anaerobic digestion plants to produce biomethane in this region.

The total theoretical resource of biomethane from microalgae that could be grown at fossil fuel fired power stations in Ireland varies considerably based on the methodology used. The rudimentary assessment results indicated a potential resource ca. 6 times that of the in-depth assessment. Use of the in-depth assessment results should be made, as these are more realistic. The scale of the potential biomethane resource from microalgae is comparable to that of source separated household organic waste, development of this potential resource could be valuable, however the scale of the resource is minor in comparison to the

potential resource of biomethane associated with readily available feedstocks such as waste streams and grass silage. As such, the development of biomethane production systems using microalgae grown at fossil fuel fired power stations should be considered once the existing resources of biomethane have been developed.

The total theoretical resource of renewable gas that could be produced using the most suitable sources of CO_2 in power to gas systems is comparable to the total theoretical resource of source separated household organic waste. As is the case for microalgae, this resource is minor in comparison to the total theoretical resource of waste streams and grass silage. However, the development of power to gas systems would allow for the conversion of surplus renewable electricity into a valuable and easily storable energy vector. The potential resource of renewable gas from power to gas systems using the most suitable sources of CO_2 identified in this work would allow for linking of the electricity and gas network in a manner that could allow for large scale energy storage in the form of renewable gas. Increased development of variable renewable electricity generation systems in Ireland, namely onshore wind turbines, offshore wind turbines, and solar P.V. systems should be cognizant of the potential synergies that could exists with this power to gas resource.

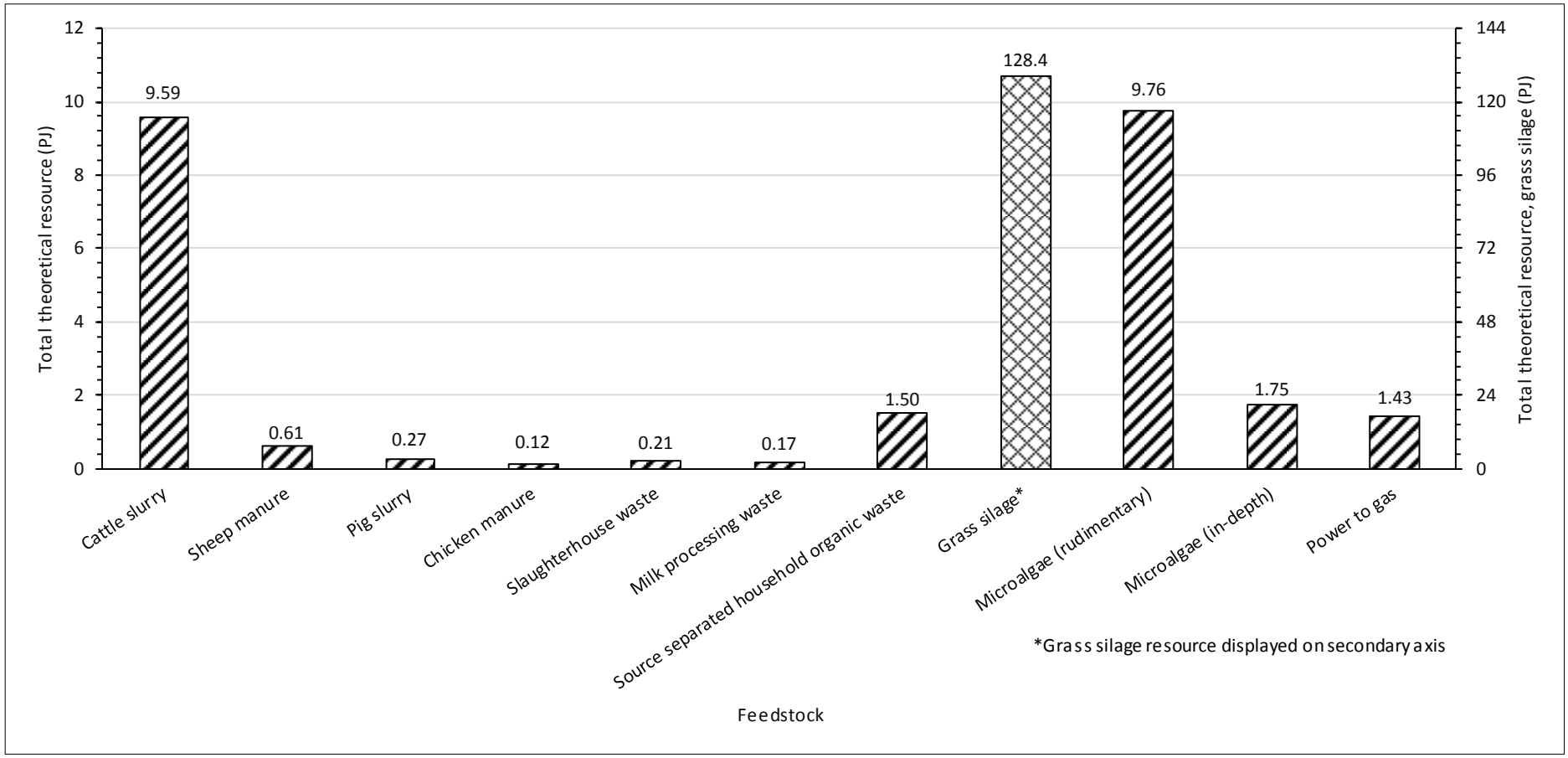


Figure 10-2 Total theoretical resource of renewable gas in Ireland, the scale for grass silage is on the secondary Y-axis to allow for ease of interpretation

The scale of the total theoretical renewable gas resource in Ireland compared to thermal energy consumption and energy consumption in transport can be seen in Figure 10-3. Comparison of the scale of the total theoretical renewable gas resource to natural gas consumption and diesel consumption can be seen in Figure 10-4.

The total theoretical resource of renewable gas in Ireland is equivalent to 86% of thermal energy demand in Ireland, this is significant as currently thermal energy production from renewable sources in Ireland is only at a scale of 6.5-6.7% (Howley & Holland 2016) with the majority of renewable heat consumption occurring in the wood and wood products industry through the use of waste timber. Currently, 40% of total thermal energy demand is met using natural gas, renewable gas could in theory allow for the replacement of this natural gas with a renewable energy source. The total theoretical resource of renewable gas in Ireland is equivalent to 85% of total natural gas consumption in Ireland, as such, the use of natural gas as a source of thermal energy could be almost completely replaced by the total theoretical resource of renewable gas in Ireland identified in this work. The total theoretical resource of renewable gas is equivalent to 2.7 times the natural gas demand of industry, and 6 times the natural gas demand of the residential sector. The use of renewable gas to provide a source of renewable thermal energy could immediately increase renewable energy consumption in these sectors with minimal alterations to end user equipment required. This would aid Ireland in meeting the goal of supply 16% of final energy consumption from renewable energy sources by 2020, additionally the use of renewable gas would increase energy security in the Irish gas system.

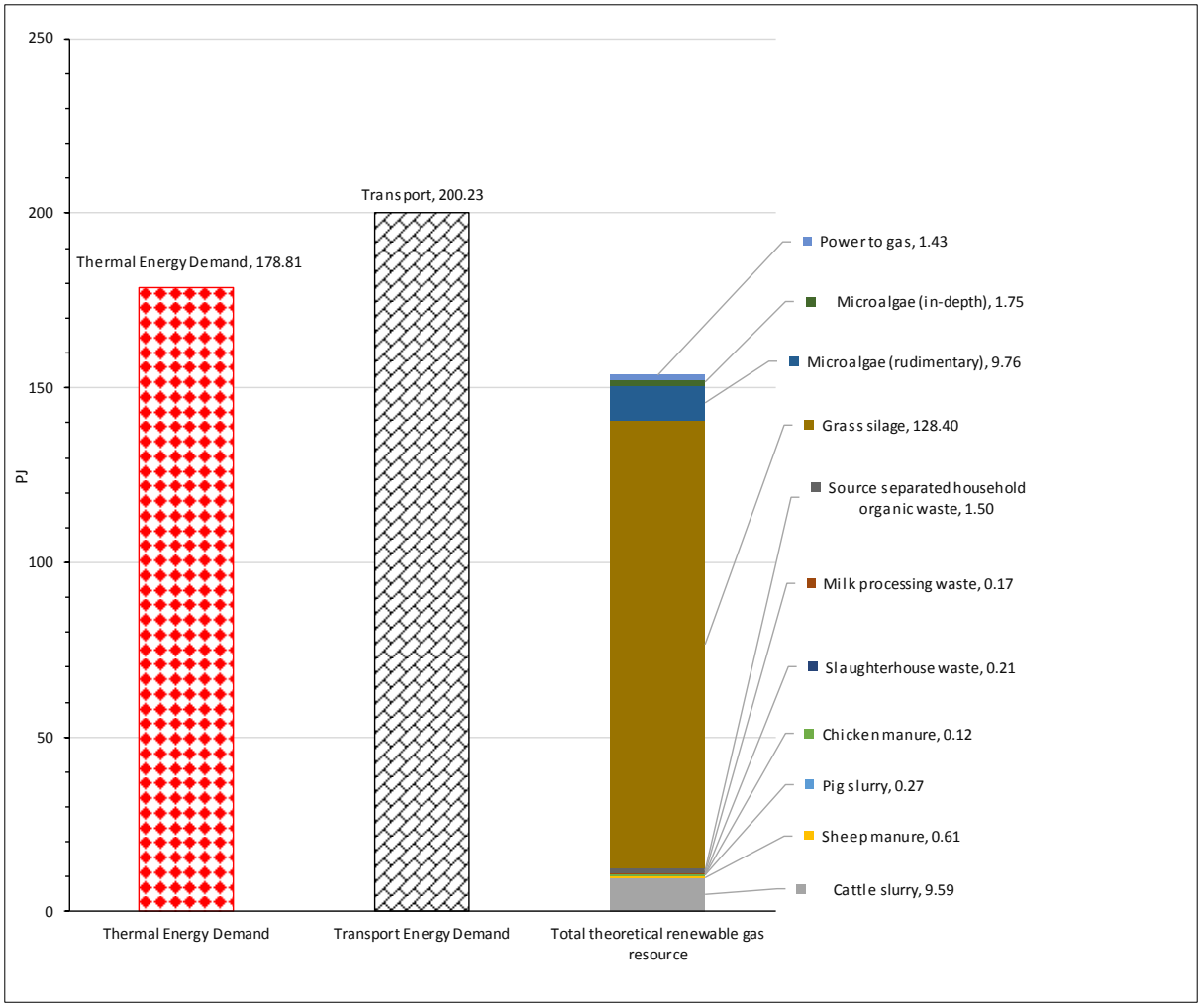


Figure 10-3 Scale of the total theoretical renewable gas resource in Ireland compared to thermal energy demand and transport energy demand. Data on thermal energy and transport energy demand adapted from (Howley & Holland 2016).

In relation to energy consumption in transportation, the total theoretical resource of renewable gas in Ireland is equivalent to 77% of energy consumption. Current biofuel consumption accounts for 3.3% of energy consumption in transport. The potential resource of renewable gas in Ireland could significantly improve renewable energy consumption in transport, and energy security in the Irish transportation sector. Currently 97.2% of all energy consumed in transportation is in the form of petroleum oil derived products all of which is imported and 83.6% of renewable transport fuel currently used in Ireland is imported. Renewable gas is a substantial resource if it were to be used in compressed natural gas (CNG) fuelled vehicles. The total theoretical resource of renewable gas in Ireland is 5.9 times the energy consumption of heavy goods vehicles in Ireland; the use of compressed

natural gas, and compressed biomethane as a transport fuel by heavy goods vehicles is being promoted by Gas Networks Ireland. The total theoretical resource of renewable gas in Ireland could meet the goal for CNG use in transport 12 times over. The use of renewable gas as a transport fuel would reduce GHG emissions and increase the energy security of the Irish transportation sector markedly. This could aid Ireland in meeting the goal of supplying 10% of energy in transport from renewable sources in 2020.

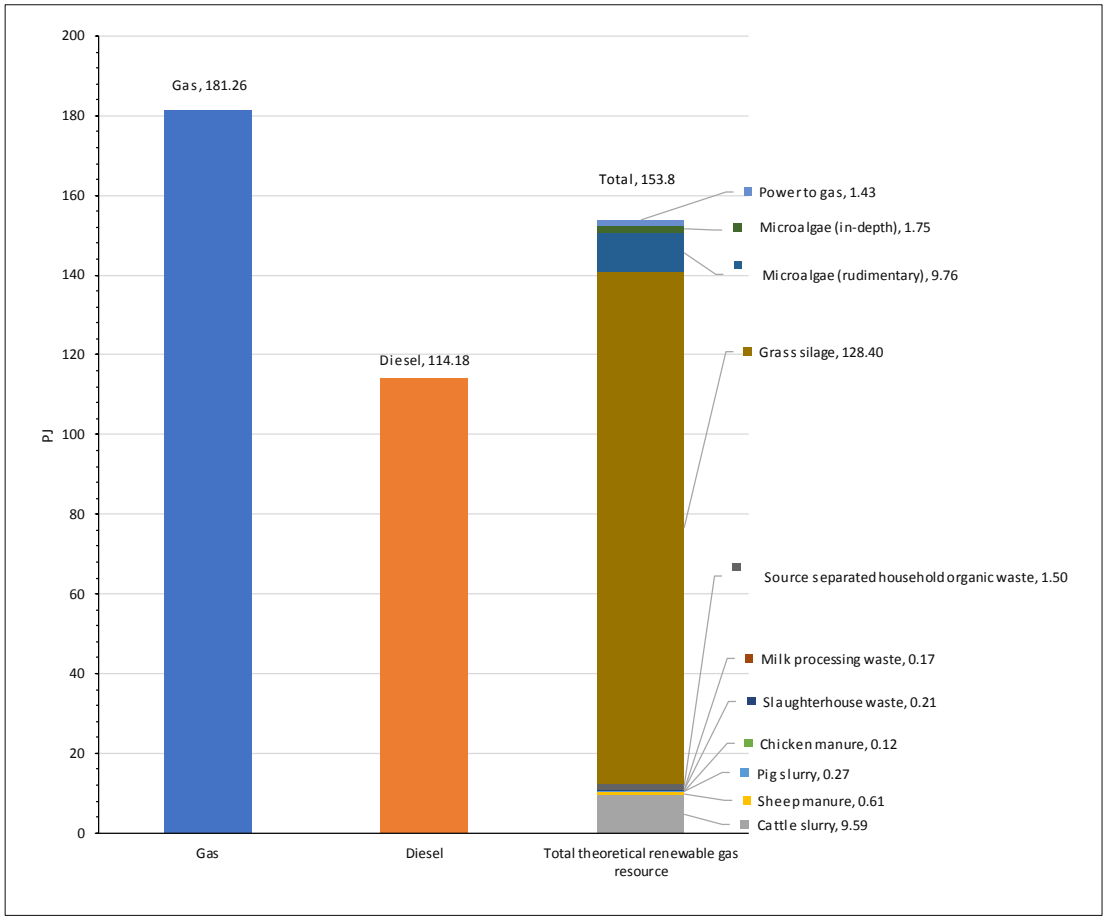


Figure 10-4 Scale of total theoretical renewable gas resource in Ireland compared to natural gas consumption and diesel consumption. Data on gas and diesel demand adapted from (Howley & Holland 2016) *and* (Gas Networks Ireland 2016)

The scale of the total theoretical resource of renewable gas in Ireland is significant both in terms of thermal energy demand and in terms of energy consumption in transportation. However, the prior contribution towards various goals and targets assumed that the entire total theoretical resource could be utilised. While this assumption can lend gravity to the potential benefits of developing a renewable gas industry in Ireland, it is not entirely correct. The optimisation models used to develop utilisation plans in this thesis allow for an estimation of the financially viable resource of renewable gas (in this case biomethane) that can be produced from waste streams in several scenarios and that could be produced from grass silage and cattle slurry in a number of scenarios. The utilisation plans were developed for waste streams and grass silage as these feedstocks are the most abundant in Ireland, and are also the most technologically mature in terms of deployment in other regions.

The total production of biomethane from plants processing waste streams, at a given levelized cost of energy, can be seen in Figure 10-5 for a maximum plant scale of 50GWh.a^{-1} and for a maximum plant scale of 200GWh.a^{-1} in Figure 10-6. Additionally, the scale of the contribution of this biomethane toward various targets and goals is shown on the additional axes. Both Figure 10-5 and Figure 10-6 illustrate that the total production of biomethane from plants processing waste streams is decidedly less than the total theoretical resource of biomethane. The contribution of biomethane derived from wastes streams to total thermal energy consumption, and total energy consumption in transportation ranged from 1.89-2.13% and 1.69-1.9% respectively (depending on maximum plant scale). The complete substitution of thermal energy demand, and energy demand in transport with biomethane derived from waste streams is unrealistic based on the assumptions made in the utilisation plans. The same can be said for replacing total natural gas consumption and diesel consumption with biomethane derived from wastes. However, the targeted use of biomethane derived from waste streams in certain sectors could allow biomethane to play a significant role increasing renewable energy consumption in these sectors.

Biomethane produced from waste streams could provide 6-6.7% of natural gas demand in industry. As noted in Chapter 1 the use of renewable gas, such as biomethane, would allow for industries to reduce their GHG emissions in line with ETS targets if the installation is in the ETS, or the use of renewable gas could allow for a reduction in non-ETS emissions if the installation is not in the ETS. The use of natural gas in industry is ubiquitous; replacement of this natural gas with renewable gas would allow certain industries to reduce their GHG emissions without needing to alter their equipment. Alternatively, industries could change from natural gas to other sources of renewable thermal energy such as wood chips, this would require a retooling of energy production equipment, and would also pose logistical issues in the sourcing, transportation, and storage of the wood chips at installations which use them. These issues may not be of major concern for some installations, but for others, the use of wood chips for the production of renewable heat is not viable. A possible example of this is the St James' Gate Brewery in Dublin city centre. Land is at a premium in this location, and the transportation of large masses of woodchips to this facility would be a logistical challenge owing to heavy traffic flow in its vicinity. In relation to industrial energy consumption, the use of biomethane derived from waste streams should be prioritised for installations for which the use of alternative sources of renewable thermal energy is not viable.

As noted in Chapter 1, the largest energy related source of GHG emissions in Ireland is transportation. Within transportation, private cars are the largest emitter of GHG, followed by light duty trucks and heavy-duty trucks. Current policy in Ireland is aimed at promoting the use of electric vehicles to reduce GHG emissions from private cars, and the use of biofuel blending with petrol and diesel to reduce GHG emissions from liquid fuelled vehicles. There are no major policies in place to reduce GHG emissions from trucks in Ireland. The use of biomethane derived from wastes in Ireland could replace 13-14.5% of energy consumed by heavy goods vehicles; limited alternatives are available to reduce GHG emissions from these vehicles. As such, biomethane used in compressed natural gas fuelled heavy goods vehicles could aid in reducing GHG emissions in transportation and in increasing the share of renewable energy in transport. The use of compressed natural gas as a transport

fuel in commercial vehicles is being promoted by GNI, and the production of biomethane from waste streams could meet 65-73% of their projected supply of compressed natural gas by 2025. The use of biomethane as a fuel for heavy goods vehicles is a mature technology; therefore, if biomethane is to be used as a transport fuel, use in heavy goods vehicles should be prioritised.

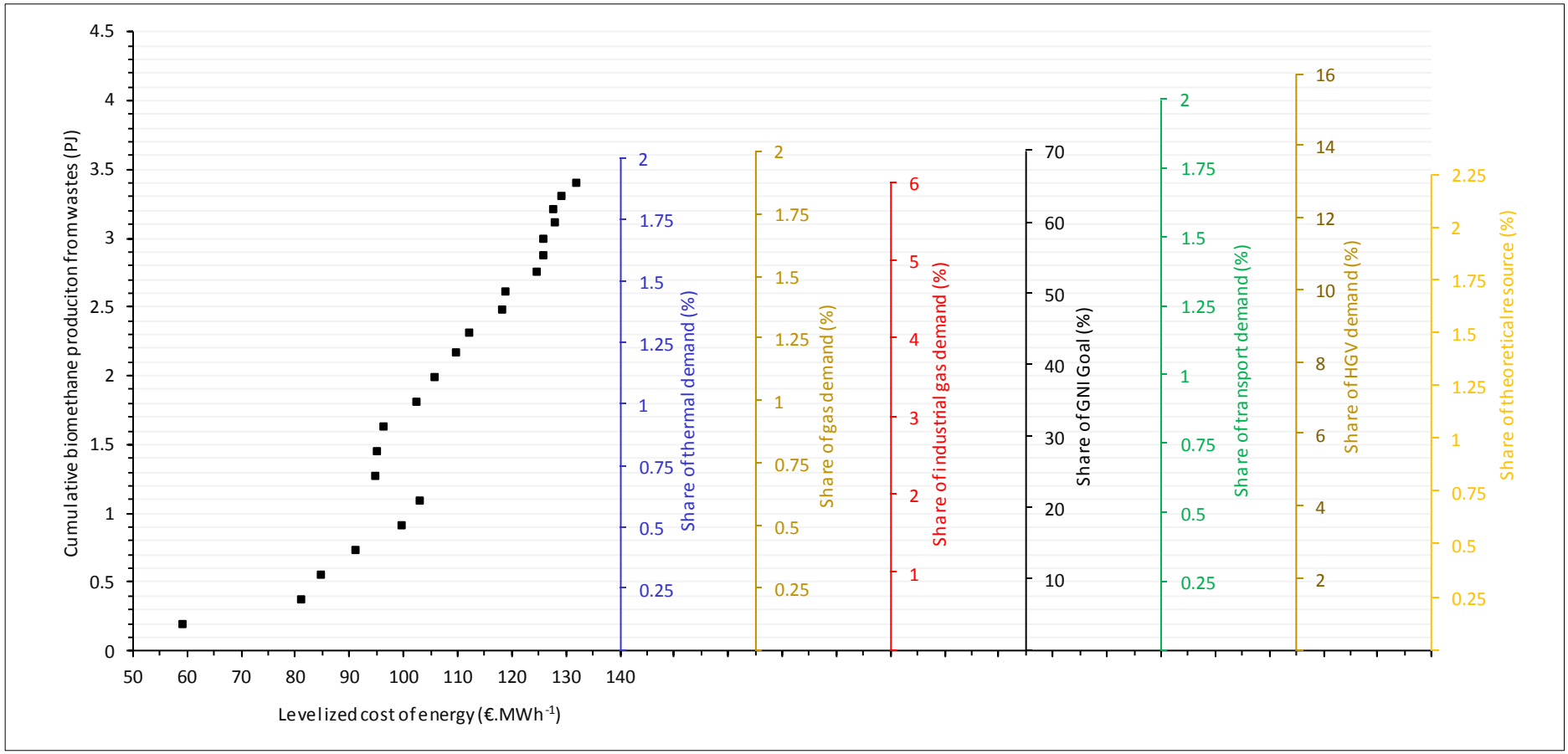


Figure 10-5 Total production of biomethane from wastes at a given levelized cost of energy and the scale of the contribution towards various targets and goals. Data displayed is for plants processing waste feedstocks at a maximum plant scale of 50GWh.a^{-1}, an incentive per unit of biomethane produced of 106€.MWh^{-1}, and a gate fee of 75€.t_{wwt}^{-1} of household organic waste (scenario 9a in Chapter 4). GNI Goal: 5.2PJ of renewable gas by 2025.

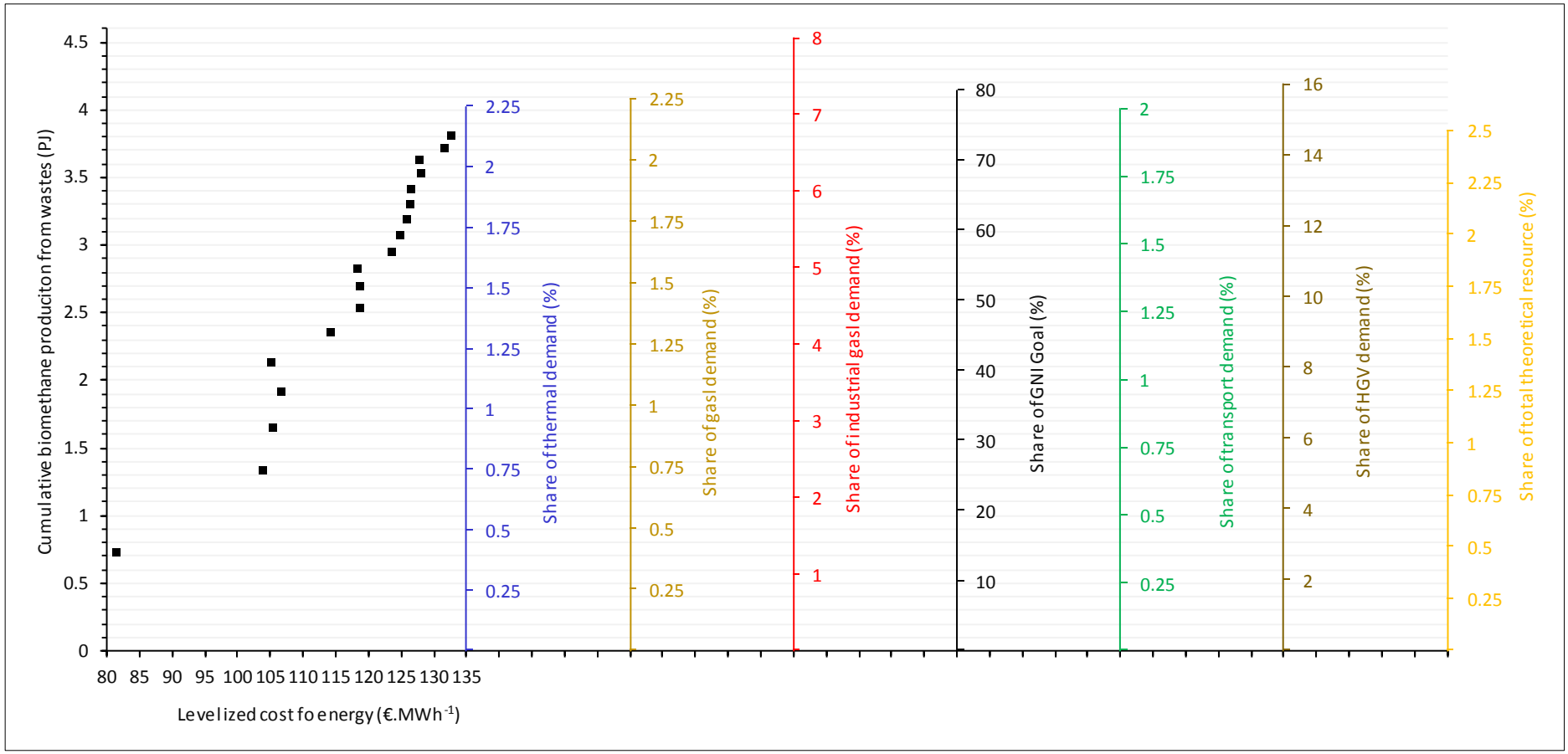


Figure 10-6 Total production of biomethane from wastes at a given levelized cost of energy and the scale of the contribution towards various targets and goals. Data displayed is for plants processing waste feedstocks at a maximum plant scale of 200GWh.a^{-1}, an incentive per unit of biomethane produced of 106€.MWh^{-1}, and a gate fee of 75€.t_{wwt}^{-1} of household organic waste (scenario 9b in Chapter 4). GNI Goal: 5.2PJ of renewable gas by 2025.

The second utilisation plan developed in this work assessed the production of biomethane from grass silage and cattle slurry under a total of 81 different scenarios. The cumulative production of biomethane from the plants assessed at a given levelized cost of energy can be seen in Figure 10-7 for the most optimistic scenario (100,000$t_{wwt}.a^{-1}$,19€.t_{wwt}^{-1} of silage, volatile solids ratio of 6:1, incentive value of 100€.MWh^{-1}). The scale of the contribution of this biomethane production to a range of goals and targets can be seen on additional axes to the right of the chart area.

Once again it can be seen that the total production of biomethane from grass silage and cattle slurry according to the utilisation plan developed is markedly lower than the total theoretical biomethane resource. The contribution towards total thermal energy consumption and energy consumption in transport are ca. 7% and ca. 6% respectively, therefore the full replacement of energy consumption in these sectors with biomethane derived from grass silage and cattle slurry is improbable. The total production of biomethane from grass silage and cattle slurry is larger than the total production of biomethane from waste streams and the contribution of the biomethane produced from grass silage toward energy consumption in various sectors is proportionally greater.

A significant portion (ca. 22%) of industrial natural gas demand could be met using biomethane derived from grass silage and cattle slurry. As previously noted this would require minimal alterations to end user equipment of existing industrial natural gas users. The use of biomethane could also be the most viable option for industrial energy consumers to increase renewable energy consumption if alternative sources of renewable energy such as wood chips are unsuitable.

The portion of energy consumed by heavy goods vehicles that could be replaced by biomethane derived from grass silage and cattle slurry (ca. 47%) is considerable. The use of this biomethane derived from grass silage and cattle slurry as a fuel for heavy goods vehicles could increase renewable energy consumption in transport. In a similar manner to biomethane derived from wastes, biomethane derived from grass silage and cattle slurry when used as a transport fuel should be prioritised in the heavy goods vehicle sector.

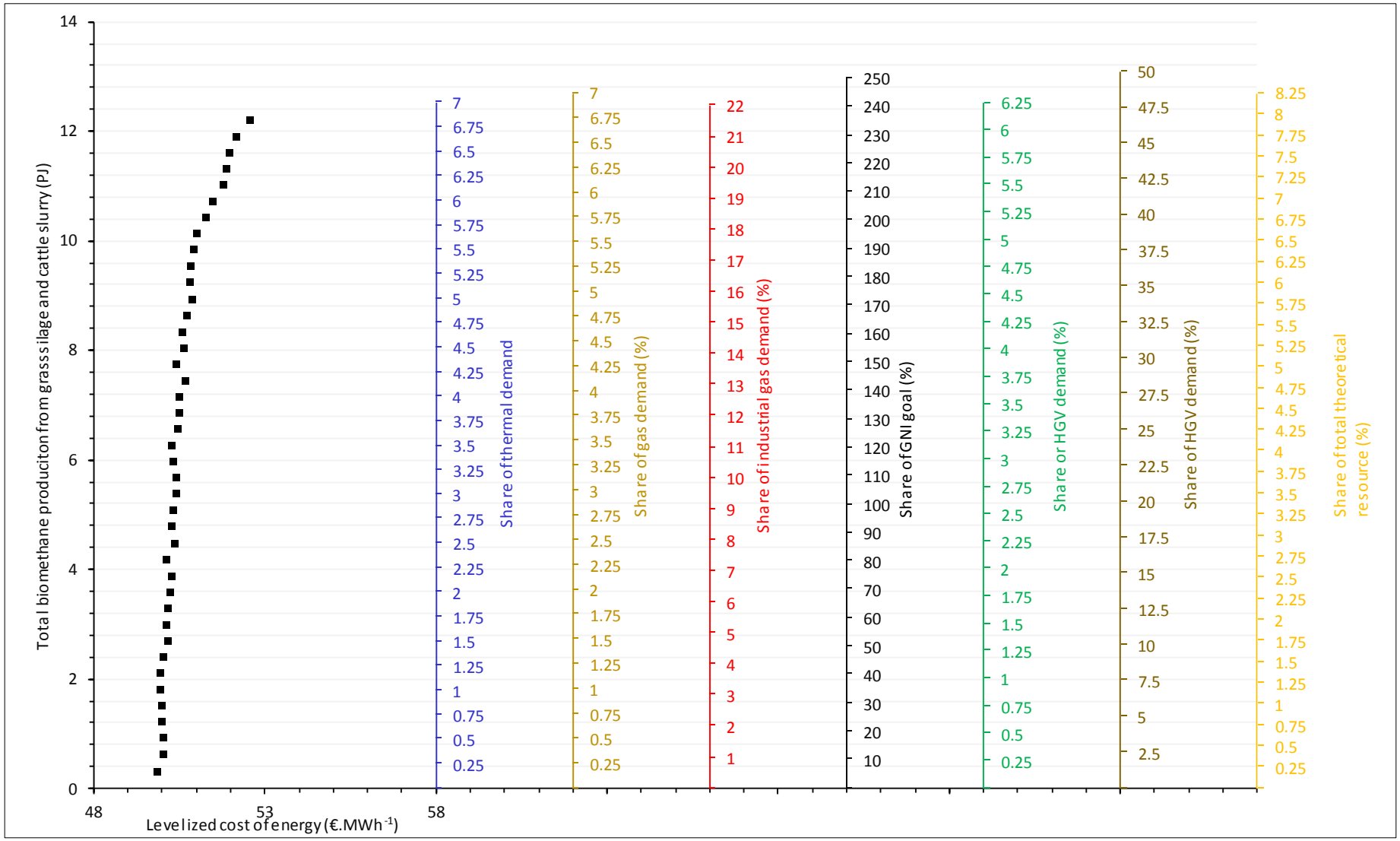


Figure 10-7 Total production of biomethane from grass silage and cattle slurry at a given levelized cost of energy and the scale of the contribution towards various targets and goals. Data displayed is for plants processing 100,000$t_{wwt}.a^{-1}$ of feedstock at a volatile solids ratio of 6:1 (Grass silage : Cattle slurry), silage price of 19€.t_{wwt}^{-1}, and an incentive value of 100€.MWh^{-1} of biomethane produced. GNI Goal: 5.2PJ of renewable gas by 2025.

An important conclusion that can be drawn from the results of the utilisation plans is that trying to determine how much renewable gas (in this case biomethane) can be produced in Ireland, how much of current natural gas demand this can replace, or how much of energy used in transport can be replaced, is an open-ended question with no simple answer. The answer depends on multiple factors; it depends on what feedstock is used, what gate fee or feedstock price is considered, what feedstock mixture is used, and what incentive is in place to promote the production of biomethane.

The results shown in Figure 10-5, Figure 10-6, and Figure 10-7 illustrate the total cumulative biomethane production in relation to the levelized cost of energy of the biomethane produced. A number of conclusions can be drawn:

Firstly, as the desired production of biomethane increases, the levelized cost of energy associated with the marginal plant increases for both biomethane derived from wastes streams and grass silage. The levelized cost of energy is indicative of the sale price of energy required to ensure that the plant in question can achieve a net present value of zero. Thus, the total quantity of biomethane that can be produced in Ireland depends on the sale price of the biomethane, or a combination of the sale price and any potential incentive value per unit of biomethane produced. The design of any potential incentives will have a direct impact on the total quantity of biomethane that can be produced. The design of such incentives should be cognisant of this impact. If an incentive is proposed which is too low, the potential resource of biomethane in Ireland will be underutilised, if an incentive is proposed that is too high, some plants will be over compensated. The decision regarding the value of any future incentive for biomethane production should aim to find the optimal trade-off between the cost of the incentive to either the exchequer or energy users, and the total production of biomethane that this incentive could stimulate.

Secondly, the levelized cost of energy is noticeably different for plants processing waste streams, and for plant processing grass silage and cattle slurry. In addition to this, there is a variation in the levelized cost of energy between plants processing waste streams depending on which waste streams they use, and between plants

processing grass silage and cattle slurry depending on the relative proportions of these feedstock used by plants (See Chapter 5, Figure 5-9). The design of an incentive to promote biomethane production should be aware of these intricacies. If an incentive is introduced which is too simplistic the result could be the development of certain biomethane resources, while others remain underutilised. A tiered incentive structure, which considers plant scale, feedstock used, feedstock mixture, and projected feedstock price should be implemented. While this is more complicated than a single incentive level, the tiered system would be able to take into account the intricacies of the different biomethane sources and would avoid potential underutilisation of resources in comparison to a more basic incentive structure.

Thirdly, the scale of biomethane proposed by the utilisation plans developed is significantly lower than the total theoretical resource of the resources identified in this work. Alternative proposals for the use of the remaining resource of each feedstock that is not used in the utilisation plans should be developed to increase the production of renewable gases in Ireland.

Comparison of potential alternative biogas production systems namely; centralised anaerobic digestion adjacent to a biogas end user (CAD1) centralised anaerobic digestion at remote from a biogas user with biogas transport in a low pressure pipeline (CAD2), decentralised anaerobic digestion with biogas transport to a biogas user in dedicated pipelines from each decentralised digester (DAD1), and decentralised anaerobic digestion with biogas transport to a biogas user in a pipeline of minimum length (DAD2) can be seen in Figure 10-8. The CO_2eq emission per MJ of biogas delivered to the biogas user along with the energy consumption per MJ of biogas delivered to the biogas user are shown. The use of alternative biogas production pathways can reduce the CO_2eq emissions and the specific energy consumption per MJ of biogas delivered to a biogas end user.

The reduction in CO_2eq emissions and specific energy consumption for scenario CAD2 highlights that centralised anaerobic digestion facilities can be improved upon by considering the location of the biogas user, and the location of the feedstock to be used. In the case assessed in this work it was found that locating the centralised

anaerobic digestion facility away from the biogas user and transporting the biogas to the end user via a pipeline was beneficial in comparison to co-location of the centralised anaerobic digester and the biogas end user. The main implication of this result is that improvements in the GHG balance of biogas from centralised anaerobic digestion plants can be made by decoupling the digester location and the end user location, provided that the case in question allows for this.

The use of decentralised anaerobic digestion systems with biogas transportation in pipelines resulted in a reduction in CO_2eq emissions and a reduction in energy consumption per unit of biogas delivered to the biogas end user. This biogas production and transportation method can enable the use of feedstock that either have a high moisture content which inhibits road transportation (such as pig slurry which was assessed in this work) or feedstocks which struggle to meet the required GHG saving criteria to be classified as a source of renewable transport or thermal energy. The implications of decentralised anaerobic digestion with biogas transportation in pipelines to a biogas end user are significant. The savings in CO_2eq emissions and energy consumption in comparison to centralised systems are beneficial, especially in an Irish context in which a substantial resource of renewable gas is located in rural regions. The case assessed in this work considered a large milk processing plant and several pig farms in the vicinity of the plant. Identification of similar situations for large consumers of thermal energy such as other milk processing plants, slaughterhouses, or distilleries should be conducted. The use of a decentralised biogas production system would increase the sustainability of the produced biogas and ensure that the decentralised biogas production systems would have a large and relatively consistent user of the produced biogas. Use of similar decentralised systems to produce and transport biogas to centralised upgrading facilities for compression and injection to the gas network, or compression and injection to CNG cylinders for distribution to end users is also possible.

The distributed nature of feedstock suitable for renewable gas production in Ireland may in certain instances lend itself for use in a distributed biogas production system. In the assessment of potential routes for the use of feedstock for

renewable gas production, utilisation plans should consider both centralised and decentralised anaerobic digestion in order to ensure that the optimal system (in terms of maximum GHG saving per unit of biogas) is developed.

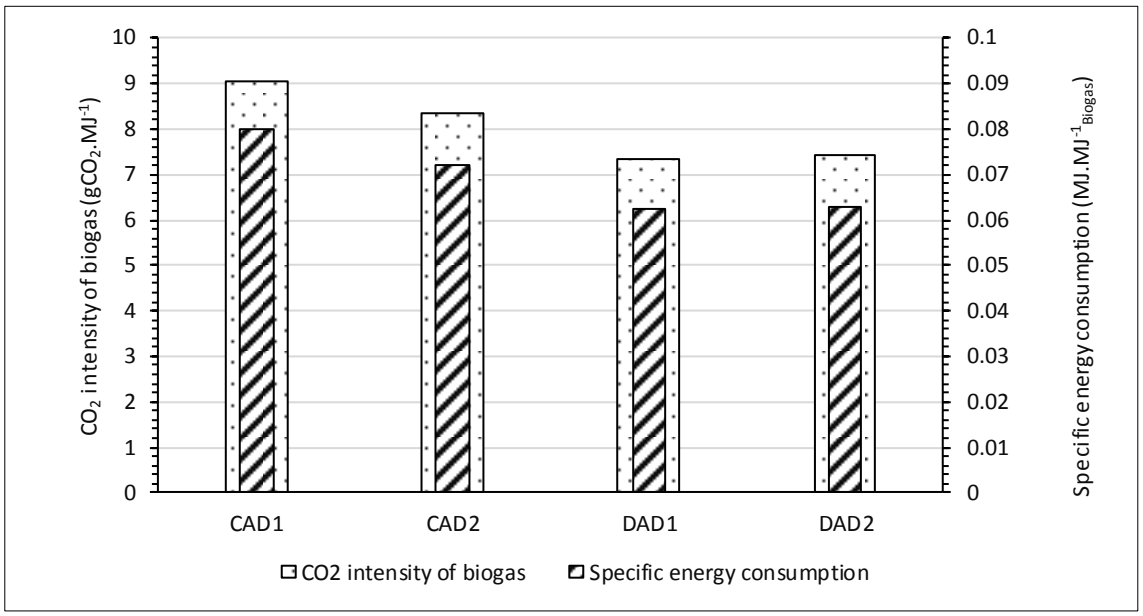


Figure 10-8 Comparison of CO_2eq intensity and specific energy consumption per MJ of biogas delivered to a biogas user from various biogas production pathways. CAD1: centralised anaerobic digestion adjacent to a biogas end user. CAD2: centralised anaerobic digestion at remote from a biogas user with biogas transport in a low-pressure pipeline. DAD1: Decentralised anaerobic digestion with biogas transport to a biogas user in dedicated pipelines from each decentralised digester. DAD2: decentralised anaerobic digestion with biogas transport to a biogas user in a pipeline of minimum length.

The ability of renewable gas to produce on demand renewable electricity at times of increased electricity demand can aid in the decarbonisation of the electricity supply. The development of a proposed feeding regime to achieve this was carried out in this thesis. The results of this feeding regime can be seen in Figure 10-9. The time at which this system is fed to ensure that there is sufficient biogas available to produce electricity at the period of maximum electricity demand from January 6th 2016 to January 18th 2016 was determined. Biogas is used for electricity production between 17:30 and 18:30, which coincides with the period of maximum electricity demand. Outside of this period the biogas is upgraded to biomethane for used as a source of renewable thermal energy or renewable transport fuel. This combined system topology is atypical of current biogas production plants, however, use of this

system would allow for the on-demand production of renewable electricity along with renewable gas for further uses. The lack of controllable sources of renewable electricity in Ireland means that there is a potential niche for such systems. The development of demand driven biogas systems for the combined production of electricity and biomethane should also be considered along with that of plants, which only produce biomethane for use as a source of renewable thermal energy or renewable transport fuel.

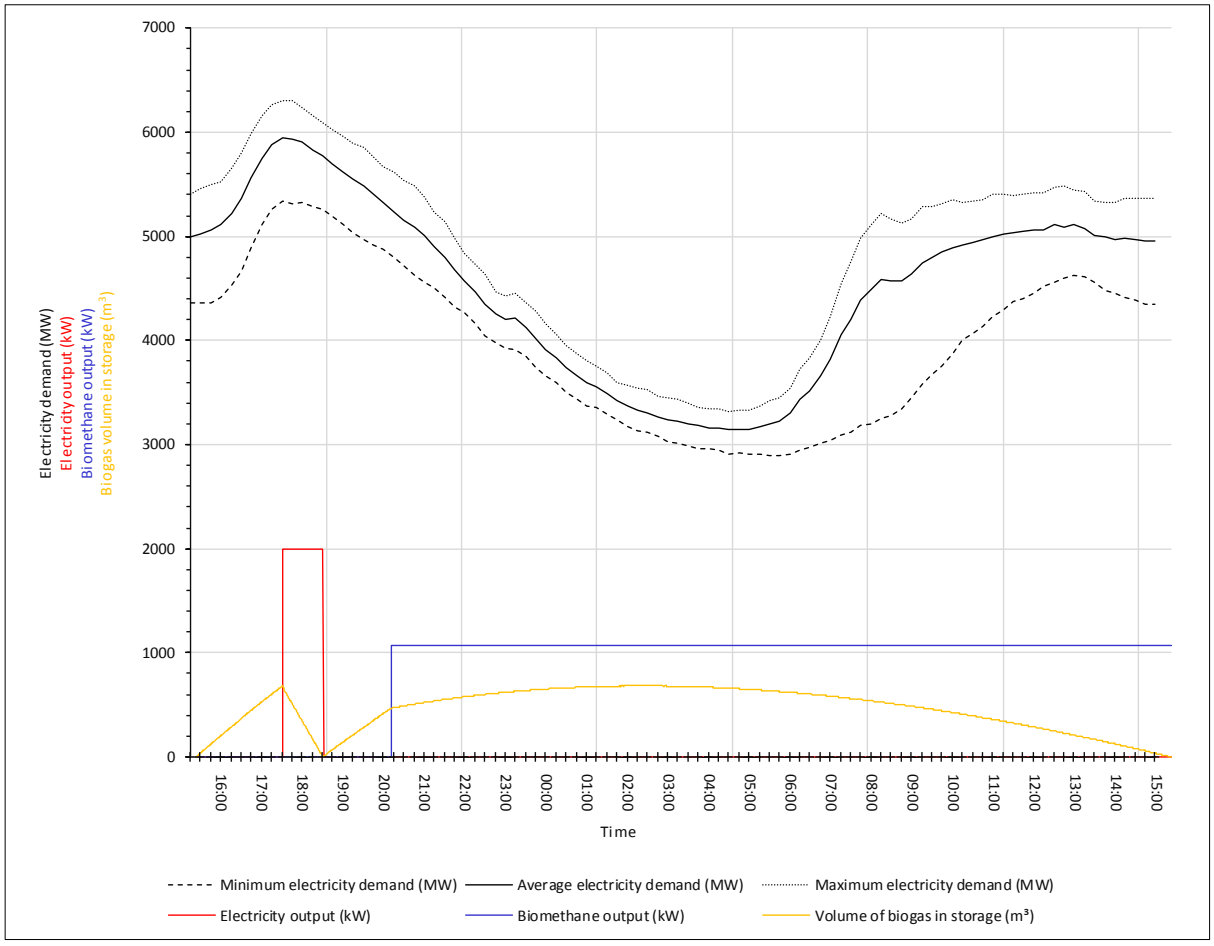


Figure 10-9 Minimum, average, and maximum electricity demand from January 6th 2016 to January 18th 2016, along with renewable electricity production, biomethane production, and the total volume of biogas in the storage system at the biogas plant from a 2MWe demand driven biogas system processing grass silage.

10.5 Recommendations based on work conducted

The following recommendations are made based on the research conducted in this thesis:

1. Assessments of the total theoretical resource of biomethane from waste streams in a country allow for the identification of regions in which a significant biomethane resource is present and can aid in informing the development of biomethane industries in a region or country.
2. Plans for the utilisation of waste streams for biomethane production and injection to the gas network should consider feedstock locations, potential sites suitable for biomethane injection, plant scale, incentives per unit of biomethane produced, and potential gate fees associated with feedstocks used. This can allow for a more informed development of a biomethane industry in a region, as well as assessing the impact of varying plant scale, incentive value per unit of biomethane, and gate fees for feedstock on the quantity of biomethane that can be produced by plants using waste feedstocks.
3. Initial biomethane production plants in Ireland should be near urban areas to make use of large resource of source separated household organic waste arising in these regions. Subsequent biomethane production plants utilise milk processing wastes, slaughterhouse wastes, and livestock manures and slurries. A significant quantity of cattle slurry remains unutilised by biomethane production plants assessed in this work, alternative pathways for biomethane production from this remaining cattle slurry resource should be investigated.
4. The total theoretical resource of biomethane associated with grass silage in excess of livestock requirements is significant. The majority of this resource is located in the western regions of Ireland. Regions with a lower resource of biomethane from grass silage are typically located in areas with substantial dairy cow populations, development of a biomethane industry using grass silage in these regions should be aware of potential impacts on fodder supply.

5. Development of a utilisation plan to co-digest grass silage and cattle slurry for the production of biomethane needs to take the location of each feedstock into account, along with potential sites on the gas network suitable for biomethane injection. The influence of plant scale, grass silage price, feedstock mixture, and incentive value per unit of biomethane produced should be considered in the development of a utilisation plan.
6. Optimal plants processing grass silage and cattle slurry are typically located in rural regions in which the resource of both grass silage and cattle slurry is sufficient, identification of these regions from visual inspection of resource maps is not trivial.
7. The quantity of biomethane that can be produced by plants processing waste streams, and by plants processing grass silage and cattle slurry depends on a number of factors. The design of incentives to promote the production of biomethane from these feedstocks should consider the implications of the incentive amount on the total production of biomethane that it enables.
8. The design of an incentive to promote the production of biomethane should incorporate flexibility with regards to the feedstock used by plants, plant scale, feedstock mixture, and gate fees or feedstock prices. Application of a single simplified incentive should be discouraged as it could potentially result in the underutilization of certain feedstocks.
9. The use of decentralised anaerobic digestion for the production of biogas, with biogas transportation to an end user via low pressure pipelines can reduce the total quantity of greenhouse gases emitted in biogas production and delivery when compared to centralised anaerobic digestion. The use of decentralised anaerobic digestion in conjunction with biogas pipelines should be further assessed in terms of using the residual biomethane resource from wastes and grass silage remaining after the initial development of centralised anaerobic digesters for biomethane production and grid injection.
10. Assessments conducted within any region which aim to quantify the potential resource of microalgae that could be grown using CO_2 from power

stations should consider the availability of the CO_2 and the influence of weather on microalgae growth. Failure to do so could lead to an overestimation of the potential microalgal resource.

11. The resource of biomethane associated with microalgae which could be grown using CO_2 from power stations in Ireland is substantial. However, microalgae represent a significantly smaller resource of biomethane than that associated with waste streams and grass silage. The development of a biomethane industry using waste streams and grass silage should be prioritised.
12. The most suitable sources of CO_2 for use in power to gas systems in Ireland were identified as distilleries, and waste water treatment plants with anaerobic digesters. The potential resource of methane that could be produced using the existing sources of CO_2 in a power to gas system in Ireland is significant. The ability of such power to gas system to store surplus renewable electricity from variable renewable electricity generators is attractive in Ireland owing to the large installed capacity of onshore wind turbines. Further work to assess the optimal integration of power to gas systems with the CO_2 sources identified should be conducted.
13. Laboratory trials of a pulse fed demand driven biogas system can be used to determine an operational regime to allow for on demand electricity production at times of high electricity demand, and biomethane production outside of these time periods. Demand driven biogas production for electricity generation and biomethane production could be more profitable than electricity production alone. Further assessments of the economics of such systems should be conducted.
14. The total theoretical resource of renewable gas in Ireland is significant, however, the quantity of renewable gas (in this case biomethane) that can be produced is substantially smaller. Optimal use of this biomethane needs to be determined, potential high priority users of this resource could be industrial users of natural as who have limited options to source renewable thermal energy, or heavy goods vehicles through the use of compressed biomethane as a transport fuel. The optimal use of renewable gas, or

biomethane, along with what defines “optimal”, should be assessed in future work.

15. Alternative applications of renewable gas for linking the electricity and gas networks, such as a in power to gas systems to act as a form of energy storage, or in demand driven biogas systems for on demand renewable electricity consumption need to be further assessed. The implications of such technologies on the electricity and gas networks should be elucidated, along with an assessment of how such technologies can be optimally deployed.

10.6 Future research questions following on from this work

Pursuant to the work conducted herein, a number of research questions have been identified within each chapter which require further research:

1. Inclusion of technological learning rates in the resource utilisation studies conducted for biomethane production from waste streams as well as from the co-digestion of grass silage and cattle slurry.
2. Assessment of the potential resource of biomethane considering potential advances in the technology associated with the anaerobic digestion process. Potential advancements include but are not limited to the use of enzymes to aid in the digestion process, multi-stage digestion, and the application of high pressure anaerobic digestion to increase methane concentration in the resulting biogas thus lowering downstream upgrading costs.
3. A full greenhouse gas life cycle assessment of biomethane production from grass silage and cattle slurry accounting for potential emissions savings associated with improved slurry management and reduced fertiliser use (through replacement with digestate) as well as potential carbon sequestration in grassland should be conducted using the most up to date information available.
4. The influence of societal acceptance for large anaerobic digestion plants producing biomethane should also be ascertained in future work either in the form of increased costs or lead in times. Additional work should also be conducted to identify regions on the gas network which are suitable from a technical aspect (in terms of ease of grid connection) as well as in terms of a societal aspect (such as in regions with sufficient transport infrastructure while maintaining distance from high population regions) in order to minimise objections to such facilities from the members of the public.
5. The optimal use of the potential resource of grass silage should be assessed in greater detail. This work suggested the conversion of grass silage to biomethane which in turn can be used as a renewable and sustainable source of energy however there are alternative uses which also offer benefit. Processing of grass in biorefineries to produce protein rich compounds (for use in animal feed), lactic acid (for use in bioplastic

production) and fibres for use as insulative materials offer an alternative route to use the potential resource of grass in Ireland. Both pathways have benefits in terms of the production of renewable energy and renewable bio-products. The optimal use of grass silage, or the optimal share of grass silage to be used in either pathway should be assessed in future works.

6. Further assessments need to be conducted which can quantify the net energy ratio of biomethane production from microalgae cultivation systems in Ireland based on the resource assessments conducted in this thesis. In addition to this, economic analysis of microalgae cultivation systems for the production of biomethane are required to ascertain whether the concept is financially viable and if not, what improvements are required to make them so. The impact of utilising potential waste heat sources to maintain correct culture temperature should also be investigated.
7. Refinement of the methodology developed for the in-depth analysis of microalgae resource can also be realised through the incorporation of species specific growth responses to temperature and light intensity within the calculation process. This would increase the accuracy of the methodology developed.
8. A full life cycle assessment of power to gas facilities utilising existing sources of CO_2 and surplus renewable electricity for the production of renewable methane gas should be conducted to ensure that the resulting gaseous energy source is in fact renewable and sustainable.
9. The optimal operational mode of a power to gas system, integrated with either a distillery or a waste water treatment plant, must be elucidated in terms of when the system should operate, what price it should pay for electricity, whether the system should run continuously or not and what size the system should be in order to maximise profitability. Such an analysis would also allow the process improvements required to make power to gas systems economically viable to be identified.

10.7 References

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Howley, M. & Holland, M., 2016. *Energy in Ireland 1990 – 2015*, Dublin. Available at: http://www.seai.ie/Publications/Statistics_Publications/Energy_in_Ireland/Energy-in-Ireland-1990-2015.pdf.

Teagasc, 2017. Grass10 - Teagasc | Agriculture and Food Development Authority. Available at: https://www.teagasc.ie/crops/grassland/grass10/ [Accessed August 29, 2017].

Appendix A

MATLAB code for optimisation model in Chapter 4

The code developed for the optimisation model in Chapter 4 is shown below.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Start of Code%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
clc
home=cd; % get current directory i.e. home directory
cd C:\gurobi604\win64\matlab % change directory to Gurobi
run('gurobi_setup') % run Gurobi solver
cd(home)% change directory to home


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Initial setup %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Load waste data %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
load('household_bmw_distance_meters'); % distance to household organic waste
load('household_bmw_tonnage'); % tonnage of household organic waste at each ED
load('household_bmw_methane_yields'); % methane yield of household organic waste
n_household_bmw=length(BMW_tonnes); % number of EDs for household organic waste

load('slaughterhouse_tonnage'); % tonnage of slaughterhouse waste at each plant
load('slaughterhouse_methane_yield'); % methane yield of slaughterhouse waste
load('slaughterhouse_distance'); % distance to slaughterhouse waste
n_slaughter=length(slaughterhouse_tonnage); % number of slaughterhouses

load('milk_processing_tonnage'); % tonnage of milk processing waste at each plant
load('milk_processing_methane_yield'); % methane yield of milk processing waste
load('milk_processing_distance'); % distance to milk processing waste
n_milk_processing=length(milk_processing_tonnage); % number of milk processing plants

load('cattle_slurry_tonnage'); % tonnage of cattle slurry at each ED
load('cattle_slurry_methane_yield'); % methane yield of cattle slurry
n_cattle_slurry=length(cattle_slurry_tonnage); % number of EDs for cattle slurry

load('sheep_manure_tonnage'); % tonnage of sheep manure at each ED
load('sheep_manure_methane_yield'); % methane yield of sheep manure
n_sheep_manure=length(sheep_manure_tonnage); % number of EDs for sheep manure

load('chicken_manure_tonnage'); % tonnage of chicken manure
load('chicken_manure_methane_yield'); % methane yield of chicken manure
load('chicken_manure_distance'); % distance to chicken manure
n_chicken_manure=length(chicken_manure_tonnage); % number of chicken farms

load('pig_slurry_tonnage'); % tonnage of pig slurry
load('pig_slurry_methane_yield'); % pig slurry methane yield
load('pig_slurry_distance'); % distance to pig slurry
n_pig_slurry=length(pig_slurry_tonnage); % number of pig farms
```

```
%% Specify gate fee for household organic waste and incentive value %%%%%%%%%%%%%
gate_fee_value=75;  % gate fee value  to be assessed, €/t
incentive=60;     % incentive value to be assessed, €/MWh

%% Specify output file name%%%%%%%%%%%%%%%%%%%%%%%%%%%
gate_text=num2str(gate_fee_value);  % text for file name
incentive_text=num2str(incentive);  % text for file name
file_to_save=strcat('plant_removal_gate_fee',gate_text,'_Incentive_',incentive_text,'.xlsx');  %
filename for output Excel file

%% Combine data for input to model %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
feedstock_tonnes=[BMW_tonnes;slaughterhouse_tonnage;milk_processing_tonnage;cattle_slurry_t
onnage;sheep_manure_tonnage;chicken_manure_tonnage;pig_slurry_tonnage];
% combined feedstock tonnage vector

tonnage_at_site=feedstock_tonnes'; % combined tonnage row vector

methane_yields=[household_bmw_methane_yields',slaughterhouse_methanee_yield',milk_processi
ng_methane_yield',cattle_slurry_methane_yield',sheep_manure_methane_yield',chicken_manure_
methane_yield',pig_slurry_methane_yield'];
%combined methane yield row vector

distance=[household_bmw_distance;slaughterhouse_distance;milk_processing_distance;household
_bmw_distance;household_bmw_distance;chicken_manure_distance;pig_slurry_distance];
% combined distance matrix

n=length(tonnage_at_site); % total number of feedstock locations


%% Financial Assumptions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 specific_transport_cost=0.111655891; %cost per tonne kilometre, unit: €/km
G=gate_fee_value; %Gate Fee for waste accepted at site, unit: €/T
FC=0; %Feedstock Cost, unit: €/T
natural_gas_price=28; %market price of natural gas €/MWh
additional_gas_revenue=incentive; %additional revenue from gas sales €/MWh
R=natural_gas_price+additional_gas_revenue; %Revenue from sale of gas, unit: €/MWh
E=0.01017961111; %Energy content of unit m3 of gas, unit: MWh/m3
Sc=277.75730616038600000000; %slope of capex cost curve, unit: €/MWh
Cc=7380556.807; %constant for capex cost curve, unit: €/a
So=7.318693902; %slope of opex cost curve, unit: €/MWh
Co=120189.5696; %constant for opex cost curve, unit: €/a
Y=20; %project lifetime, unit: years
dr=0.08; %discount Rate, unit: %/100
DF=((1+dr)^Y-1)/(dr*(1+dr)^Y); %Discount factor for calculating, Short et al.
Eff=0.8; %volatile solids destruction, unit: %/100
max_plant_size=50000; %maximum allowable plant size, this can be altered. unit: MWh
Load_factor=0.84; % parasitic demand, upgrading losses, and upgrading capacity factor, unit: %/100
tortuosity=sqrt(2); %tortuosity factor for rural roads
no_plants=42; %number of injection Points


%% cost multipliers to account for digestate return and empty return %%%%%%%%%%%%%
bmw_trnaport_cost_multiplier=ones(1,n_household_bmw).*1.62;
slaughter_transport_cost_multiplier=ones(1,n_slaughter).*2;
mpw_transport_cost_multiplier=ones(1,n_milk_processing).*2;
```

```
catttle_transport_cost_multiplier=ones(1,n_cattle_slurry).*2;
sheep_transport_cost_multiplier=ones(1,n_sheep_manure).*2;
chicken_transport_cost_multiplier=ones(1,n_chicken_manure).*2;
pig_transport_cost_multiplier=ones(1,n_pig_slurry).*2;

cost_multiplier=[bmw_trnaport_cost_multiplier,slaughter_transport_cost_multiplier,mpw_transport
_cost_multiplier,catttle_transport_cost_multiplier,sheep_transport_cost_multiplier,chicken_transpo
rt_cost_multiplier,pig_transport_cost_multiplier,0,0];



%% Interim Results Storage %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ED_allocation_table=zeros(n,no_plants); %Table containing the EDs allocated to Each
                                        %Injection Point
NPV_results=zeros(25,no_plants);      %Empty matrix of main results from interim
                                      %calculations
used_supply_points=zeros(n,no_plants); % empty matrix of used feedstock sources
allowed_points=ones(1,n); % initially all possible feedstock sources are allowed
dim=2;
dead_supply_points=zeros(n,1); % initially no sources of feedstock are dead or used


%% Final Results %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
final_results=zeros(25,no_plants);
final_supply=zeros(n,no_plants);
dead_plants=zeros(1,no_plants).*100;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculations %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

sites=0;

for k=1:no_plants
% Outer "for loop". For each iteration, the injection point with the highest NPV is found from the
possible injection points remaining that have not been "built"

for iteration=1:no_plants;
% Inner "for loop". Determine the NPV of possible injection points that have not %been "built" one at
a time, store the results and fins the injection point with %the highest NPV

lia=ismember(iteration,dead_plants); % Is current injection point already built?
                                     % 1=Yes 0=No

if lia==0 %if potential injection point has not been built

d=distance(:,iteration); % distance from current injection point to feedstock
dd=(d./1000).*tortuosity; % convert distance to km and account for tortuosity
D=dd';


%% Transport Cost%%%%%%%%%%

tonnage_at_site_plus_dummy=[tonnage_at_site,[1,1]]; %row vector of tonnage at site plus 2 dummy
variables set to1 for capex and opex constants, unit: T
distance_to_site=[D];
```

```
distance_to_site_plus_dummy=[distance_to_site,[0,0]]; %row vector of distance to site plus 2
dummy variables set to 0 for capex and opex constants, unit: km

transport_cost_vector=(tonnage_at_site_plus_dummy.*distance_to_site_plus_dummy).*cost_multi
plier.*specific_transport_cost; %row vector of transport costs, unit: €/a,


%% Feedstock Cost%%%%%%%%
feedstock_cost_vector=tonnage_at_site_plus_dummy.*([ones(1,n).*FC,[0,0]]);
%row vector of feedstock costs, unit: €/a


%% CAPEX cost %%%%%%%%%%%
energy_yield_at_site_first=((tonnage_at_site.*methane_yields.*E).*Eff).*Load_factor;
% energy yield of feedstock at each source of feedstock accounting for plant efficiency and load
factor
energy_yield_at_site=[energy_yield_at_site_first,[1,1]];
%row vector of energy yield at site plus 2 dummy variables at end equal to 1, unit: MWh
capex_cost_curve_slope=[ones(1,n).*Sc,[Cc,0]];
%row vector of capex curve slope (€/MWh), and curve constant (€)
capex_cost_vector=energy_yield_at_site.*capex_cost_curve_slope;
%Contribution of feedstock energy yield at each site to overall CAPEX


%% OPEX cost %%%%%%%%%%%
energy_yield_at_site_first=((tonnage_at_site.*methane_yields.*E).*Eff).*Load_factor;
% energy yield of feedstock at each source of feedstock accounting for plant efficiency and load
factor
energy_yield_at_site=[energy_yield_at_site_first,[1,1]];
%row vector of energy yield at site plus 2 dummy variables at end equal to 1, unit: MWh,
opex_cost_curve_slope=[ones(1,n).*So,[0,Co]];
%row vector of slopes of opex curve (€/MWh), and opex curve constant (€)
opex_cost_vector=energy_yield_at_site.*opex_cost_curve_slope;
%Contribution of feedstock energy yield at each site to overall CAPEX


%% Revenue %%%%%%%%%%%%
revenue=energy_yield_at_site.*([ones(1,n).*R,[0,0]]);
%row vector of revenue from gas sourced from each site, unit: €


%% Gate Fee %%%%%%%%%%%%
gate_fee=tonnage_at_site_plus_dummy.*([ones(1,n_household_bmw).*G,zeros(1,+n_slaughter+n_
milk_processing+n_cattle_slurry+n_sheep_manure+n_chicken_manure+n_pig_slurry+2)]);
%row vector of revenue from tonnage sourced from each site, only applies to household organic
waste, unit: €


%% Annual Cashflow %%%%%
annual_cashflow=(revenue)+(gate_fee)-(transport_cost_vector)-(feedstock_cost_vector)-
(opex_cost_vector); %Vector of annual cashflows, unit:€


%% Present Value of Annual Cashflows %%%%%%
PV_cashflow=annual_cashflow.*DF; % determine present value of future cash flows
NPV=capex_cost_vector.*-1+PV_cashflow; %NPV of cashflows, CAPEX + PV of future cash flows
```

```
%% integer constraint %%%%%%%%%%%%%%%%%%%%%%%%
intcon=[1:n+2]; % set decision variables to integer values
lb=[zeros(1,n),[1,1]];  %lower bound on decision variables is 0, except for dummy variables, lower bound is 1 for these
ub=[ones(1,n).*allowed_points,[1,1]];  %upper bound on decision variables is 1 for all allowed feedstock sources


%% Inequality Constraints %%%%%%%%%%%%%%%%%%%%%%%%%%%
A=[energy_yield_at_site_first,[0,0]];
b=max_plant_size;


%% Turn minimisation into "maximisation"
f=NPV.*-1;
Aeq=[];
beq=[];
selectsites=intlinprog(f, intcon, A, b,Aeq,beq, lb, ub); % determine feedstock sources to maximise NPV


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Interim Results Calculation %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ED_allocation_table(:,iteration)=selectsites(1:n);
plant_transport_cost=dot(selectsites',transport_cost_vector); % annual feedstock transportation cost for current injection point
plant_feedstock_cost=dot(selectsites',feedstock_cost_vector); % annual feedstock cost for current injection point
plant_capex_cost=dot(selectsites',capex_cost_vector); % CAPEX for current injection point
plant_opex_cost=dot(selectsites',opex_cost_vector); % annual OPEX for current injection point
plant_revenue=dot(selectsites',revenue); % annual revenue for current injection point
plant_gate_fee=dot(selectsites',gate_fee); % annual gatefee for current injection point
plant_lcoe=(plant_capex_cost+(plant_opex_cost+plant_transport_cost+plant_feedstock_cost)*DF)/((dot(selectsites(1:n)',energy_yield_at_site_first))*DF); % levelized cost of energy from current injection point
plant_MWh=dot(selectsites(1:n)',energy_yield_at_site_first); % annual energy production of injection point in question
plant_npv=(-1*plant_capex_cost)+(plant_revenue+plant_gate_fee-plant_feedstock_cost-plant_transport_cost-plant_opex_cost)*DF; % NPV of current injection point
plant_payback=log(1/(1-(plant_capex_cost*dr/plant_revenue)))/log(1+dr); % time to reach NPV of 0, not used in this analysis
plant_tonnage_BMW=dot(selectsites(1:n_household_bmw)',tonnage_at_site(1:n_household_bmw))
;
% tonnage of household organic waste used at current injection point
plant_energy_bmw=dot(selectsites(1:n_household_bmw)',energy_yield_at_site_first(1:n_household_bmw)); % energy produced from household organic waste at current injection point
sites=n_household_bmw;
plant_tonnage_slaughter=dot(selectsites(sites+1:sites+n_slaughter)',tonnage_at_site(sites+1:sites+n_slaughter)); % tonnage of slaughterhouse waste used at current injection point
plant_energy_slaughter=dot(selectsites(sites+1:sites+n_slaughter)',energy_yield_at_site_first(sites+1:sites+n_slaughter)); % energy produced from slaughterhouse waste at current injection point
sites=sites+n_slaughter;
```

```
plant_toannage_milk_processing=dot(selectsites(sites+1:sites+n_milk_processing)',tonnage_at_site(sites+1:sites+n_milk_processing)); % tonnage of milk processing waste accepted at current injection point

plant_energy_milk_processing=dot(selectsites(sites+1:sites+n_milk_processing)',energy_yield_at_site_first(sites+1:sites+n_milk_processing)); % energy produced from milk processing waste at current injection point
sites=sites+n_milk_processing;
plant_tonnage_cattle_slurry=dot(selectsites(sites+1:sites+n_cattle_slurry)',tonnage_at_site(sites+1:sites+n_cattle_slurry)); % tonnage of cattle slurry accepted at current injection point
plant_energy_cattle_slurry=dot(selectsites(sites+1:sites+n_cattle_slurry)',energy_yield_at_site_first(sites+1:sites+n_cattle_slurry)); % energy produced from cattle slurry at current injection point
sites=sites+n_cattle_slurry;
plant_tonnage_sheep_manure=dot(selectsites(sites+1:sites+n_sheep_manure)',tonnage_at_site(sites+1:sites+n_sheep_manure)); % tonnage of sheep manure accepted at current injection point
plant_energy_sheep_manure=dot(selectsites(sites+1:sites+n_sheep_manure)',energy_yield_at_site_first(sites+1:sites+n_sheep_manure)); % energy production from sheep manure at current injection point
sites=sites+n_sheep_manure;
plant_tonnage_chicken_manure=dot(selectsites(sites+1:sites+n_chicken_manure)',tonnage_at_site(sites+1:sites+n_chicken_manure)); % tonnage of chicken manure accepted at current injection point
plant_energy_chicken_manure=dot(selectsites(sites+1:sites+n_chicken_manure)',energy_yield_at_site_first(sites+1:sites+n_chicken_manure)); % energy production from chicken manure at current injection point
sites=sites+n_chicken_manure;
plant_tonnage_pig_slurry=dot(selectsites(sites+1:sites+n_pig_slurry)',tonnage_at_site(sites+1:sites+n_pig_slurry)); % tonnage of pig slurry accepted at current injection point
plant_energy_pig_slurry=dot(selectsites(sites+1:sites+n_pig_slurry)',energy_yield_at_site_first(sites+1:sites+n_pig_slurry));% energy production from pig slurry at current injection point
sites=0;

%% store interim results %%%%%%%
NPV_results(1,iteration)=plant_capex_cost;
NPV_results(2,iteration)=plant_transport_cost;
NPV_results(3,iteration)=plant_feedstock_cost;
NPV_results(4,iteration)=plant_opex_cost;
NPV_results(5,iteration)=plant_gate_fee;
NPV_results(6,iteration)=plant_revenue;
NPV_results(7,iteration)=plant_lcoe;
NPV_results(8,iteration)=plant_MWh;
NPV_results(9,iteration)=plant_tonnage_BMW;
NPV_results(10,iteration)=plant_tonnage_slaughter;
NPV_results(11,iteration)=plant_toannage_milk_processing;
NPV_results(12,iteration)=plant_tonnage_cattle_slurry;
NPV_results(13,iteration)=plant_tonnage_sheep_manure;
NPV_results(14,iteration)=plant_tonnage_chicken_manure;
NPV_results(15,iteration)=plant_tonnage_pig_slurry;
NPV_results(16,iteration)=plant_energy_bmw;
NPV_results(17,iteration)=plant_energy_slaughter;
NPV_results(18,iteration)=plant_energy_milk_processing;
NPV_results(19,iteration)=plant_energy_cattle_slurry;
NPV_results(20,iteration)=plant_energy_sheep_manure;
NPV_results(21,iteration)=plant_energy_chicken_manure;
NPV_results(22,iteration)=plant_energy_pig_slurry;
NPV_results(23,iteration)=plant_payback;
NPV_results(24,iteration)=plant_npv;
NPV_results(25,iteration)=iteration;
```

```
used_supply_points(:,iteration)=selectsites(1:n);%used supply points for current injection point


for j=1:n
   if selectsites(j)==1
      dead_supply_points(j,iteration)=0; %supply points used become dead supply points
   elseif selectsites(j)==0
      dead_supply_points(j,iteration)=1;
   end
end


clear selectsites %clear selected sites, allows for recalculation for next injection point


elseif lia==1    % if current injection point is already built
NPV_results(1,iteration)=0;
NPV_results(2,iteration)=0;
NPV_results(3,iteration)=0;
NPV_results(4,iteration)=0;
NPV_results(5,iteration)=0;
NPV_results(6,iteration)=0;
NPV_results(7,iteration)=0;
NPV_results(8,iteration)=0;
NPV_results(9,iteration)=0;
NPV_results(10,iteration)=0;
NPV_results(11,iteration)=0;
NPV_results(12,iteration)=0;
NPV_results(13,iteration)=0;
NPV_results(14,iteration)=0;
NPV_results(15,iteration)=0;
NPV_results(16,iteration)=0;
NPV_results(17,iteration)=0;
NPV_results(18,iteration)=0;
NPV_results(19,iteration)=0;
NPV_results(20,iteration)=0;
NPV_results(21,iteration)=0;
NPV_results(22,iteration)=0;
NPV_results(23,iteration)=0;
NPV_results(24,iteration)=-1000000000000; %set NPV to extremely low value
NPV_results(25,iteration)=iteration;

dead_supply_points(1:n,iteration)=ones(n,1);

end

end
% end   of inner "for loop" assessing the NPV of possible injection points that have % yet to be built
npv_vals=NPV_results(24,:); % extract NPV vales of injection points assessed
[max_plant_npv,plant_index]=max(npv_vals); % find maximum NVP and associated injection point
allowed_points=allowed_points.*(dead_supply_points(:,plant_index)');
% multiply allowed supply points row vector by dead supply points for the injection point with the
largest NPV in this instance. This is a multiplication of 1 by 0 and results in the upper bound of the
allowed points which have already been assigned to an injection point being set to 0. This ensures
that supply points are not assigned to more than one injection point.
```

```
dead_plants(k)=NPV_results(25,plant_index);  % extract the plant number of the injection point with the highest NPV in this instance. This will be built and added to the "dead plant" vector to ensure that it is not re-assessed in future iterations.


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Store final results %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
final_results(1:24,k)=NPV_results(1:24,plant_index); % add the results for the injection point with the highest NPV for this instance to the final results matrix
final_results(25,k)=NPV_results(25,plant_index);
final_supply(:,k)=used_supply_points(:,plant_index); % add the supply points assigned to the injection plant with the highest NPV in this instance to the final results matrix
end
% end of outer "for loop"


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Results to save to Excel file %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
plant_metrics_and_supply=[final_results;sum(final_supply);final_supply]; % final metrics of each injection point that has been built
input_assumptions={'Transport Cost (€/Tkm)','Gate Fee(€/T)', 'Feedstock Cost(€/T)', 'Natural Gas Price(€/MWh)', 'Additional Gas Revenue (€/MWh)','Energy Content of Methane (MWh/m3)','Project Lifetime (Years)', 'Discount Rate','Volatile Solids Destruction (%)','Maximum Plant Size (MWh/a)','Load Factor'}; % input assumptions for the calculations conducted, to be saved in Excel file
input_assumption_values=[specific_transport_cost,G,FC,natural_gas_price,additional_gas_revenue, E,Y,dr,Eff,max_plant_size,Load_factor];
input_data_to_write={input_assumptions;input_assumption_values};% input assumptions for the calculations conducted, to be saved in Excel file
result_names={'CAPEX (€)';'Transport Cost (€)';'Feedsotck Cost (€)';'OPEX (€)';'Gate Fee (€)';'Revenue (€)';'LCOE (€/MWh)';'Plant Size (MWh)';'Plant Tonnage BMW (T)';'Plant Tonnage Slaughterhouse (T)';'Plant Tonnage Milk Processing (T)';'Plant Tonnage Cattle Slurry (T)';'Plant Tonnage Sheep Manure (T)';'Plant Tonnage Chicken Manure (T)';'Plant Tonnage Pig Slurry (T)';'Plant Energy BMW (MWh)';'Plant Energy Slaughter (MWh)';'Plant Energy Milk Processing (MWh)';'Plant Energy Cattle Slurry (MWh)';'Plant Energy Sheep Manure (MWh)';'Plant Energy Chicken Manure (MWh)';'Plant Energy Pig Slurry (MWh)';'Discounted Payback (Years)';'NPV';'Plant Number';'Total Supply Points Used'}; % Names of final results to be saved in Excel file

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Save results to Excel file %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cd('plant_allocation_with_removal_results 5') % change directory to fold in which results are to be saved
file_name=file_to_save; % file name
xlswrite(file_name,input_assumptions,1,'C3'); % write data to Excel file
xlswrite(file_name,input_assumption_values,1,'C4'); % write data to Excel file
xlswrite(file_name,result_names,1,'C6'); % write data to Excel file
xlswrite(file_name,plant_metrics_and_supply,1,'D6'); % write data to Excel file
cd(home); % change directory to home directory

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% End of Code%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix B

Matlab Code for optimisation model in Chapter 5

The optimisation model was implemented in Matlab using the Gurobi solver engine. The Code developed for this model can be seen below.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Start of Code%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
clc
home=cd; % get current directory i.e. home directory
cd C:\gurobi604\win64\matlab % change directory to Gurobi
run('gurobi_setup') % run Gurobi solver
cd(home)% change directory to home


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Initial Setup %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%% Load Variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
load('excess_silage_highN_NFS_distance_meters'); % Load distance to silage supply sites
load('excess_silage_highN_NFS_tonnage_wet'); % Load tonnage of silage at each supply site
n_silage=length(excess_silage_highN_NFS_tonnage_wet); % number of silage supply sites
load('cattle_slurry_tonnage'); % Load tonnage of cattle slurry at each supply site
n_cattle_slurry=length(cattle_slurry_tonnage); % number of slurry supply sites

%% Specify Ranges for plant size, premium value, grass silage price, and volatile solids ratio %%%
for Tplant=50000:25000:100000 % for the given range of maximum plant tonnage
for premium=20:40:100 % for the given range of incentive or premium value
   for grass_price=19:14:47 % for the given range of grass silage prices
      for VSgs_VSds_ratio=2:2:6 % for the given volatile solids ratio of grass silage to cattle slurry

% Tplant=75000; % for single plant size assessment
% premium=60; % for single incentive or premium value assessment
% grass_price=33; % for a single grass silage price
% VSgs_VSds_ratio=4; % for a single ratio of silage VS to slurry VS

%% Plant Metrics %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
TM=Tplant; %maximum plant size twwt/a
TM_accuracy=5; %accuracy on total plant tonnage i.e. +/- %
VSdest=1; %volatile solids destruction, unit: %/100
CH4slip=0.005; %CH4 losses in Amine upgrading, unit: %
hours=8585; %operational hours of upgrading system, hrs/annum,98% available
Emethane=37.78; %energy content of methane, MJ/m3
MCds=0.9165; %moisture content of slurry, %wwt
MCgs=0.707; %moisture content of silage, %wwt
VSds=0.06234; %VS content of slurry, %wwt
VSgs=0.268; %VS content of silage, % wwt
T_AD=70; %AD pasteurisation temperature, Celsius
T_feed=10; %feedstock temperature, Celsius
TM_min=TM*(1-TM_accuracy/100); %minimum plant tonnage, twwt/a
TM_max=TM*(1+TM_accuracy/100); %maximum plant tonnage, twwt/a
```

```
Mds_min=TM_min*VSgs/(VSgs_VSds_ratio*VSds+VSgs); %minimum allowable mass of slurry,
twwt/a
Mgs_min=TM_min-Mds_min; %minimum allowable mass of silage, twwt/a
Mds_max=TM_max*VSgs/(VSgs_VSds_ratio*VSds+VSgs); %maximum allowable mass of slurry,
twwt/a
Mgs_max=TM_max-Mds_max; %maximum allowable mass of silage, twwt/a

%% Specific Methane Yields from Wall et al %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if VSgs_VSds_ratio >=0 && VSgs_VSds_ratio<0.25 % VS ratio check
   SMY=(VSgs_VSds_ratio-0)/(0.25-0)*(220-143)+143; % specific methane yield, m3CH4/tVS
   concCH4=0.54; %Concentration of CH4 in biogas, Unit: %

end

if VSgs_VSds_ratio>=0.25 && VSgs_VSds_ratio<0.666 % VS ratio check
   SMY=(VSgs_VSds_ratio-0.25)/(0.666-0.25)*(266-220)+220; %specific methane yield, m3CH4/tVS
   concCH4=0.55; %Concentration of CH4 in biogas, Unit: %
end

if VSgs_VSds_ratio >=0.666 && VSgs_VSds_ratio<1.5 % VS ratio check
   SMY=(VSgs_VSds_ratio-0.666)/(1.5-0.666)*(328-266)+266; % specific methane yield, m3CH4/tVS
    concCH4=0.55; %Concentration of CH4 in biogas, Unit: %
end

if VSgs_VSds_ratio >=1.5 && VSgs_VSds_ratio <4 % VS ratio check
   SMY=(VSgs_VSds_ratio-1.5)/(4-1.5)*(366-328)+328; % specific methane yield, m3CH4/tVS
    concCH4=0.55; %Concentration of CH4 in biogas, Unit: %
end

if VSgs_VSds_ratio>=4 % VS ratio check
   SMY=414; % specific methane yiled, m3/tVS
   concCH4=0.53; %Concentration of CH4 in biogas, Unit: %
end

%% Grid connection cost %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
grid_connection=1892000; %cost of connection to gas grid, based on Urban et al., €

%% AD CAPEX Curve Linearization, based on cost curve in Browne et al.%%%%%%%%%
AD1=554.89*(TM_min^0.841); %Point one on cost curve, unit is €/twwt accepted on site
AD2=554.89*(TM_max^0.841); %Point two on cost curve, unit is €/twwt accepted on site
M_AD_CAPEX=(AD2-AD1)/(TM_max-TM_min); %Slope of line between points 1 and 2
C_AD_CAPEX=AD1-TM_min*M_AD_CAPEX+grid_connection; %Intersection of line for AD CAPEX

%% AD OPEX, from Browne et al. %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
AD_OPEX=5; %OPEX of 5€/twwt/a accepted onsite, based on Browne et al.
AD_elec=10; %electricity consumption of AD system, kWhe/twwt/a, from Murphy and Mc Carthy
boiler_efficiency=0.9; %efficiency of boiler based on Browne et al.

%% Upgrading CAPEX linearisation based on SGC for amine system %%%%%%%%%%%%
minVS=Mds_min*VSds+Mgs_min*VSgs; %minimum mass of VS accepted at the plant, tVS/a
maxVS=Mds_max*VSds+Mgs_max*VSgs; %maximum mass of VS accepted at the plant, tVS/a
Vbiog_min=(minVS*SMY*VSdest)/concCH4; %gross production of biogas, m3/a
Vbiog_min_rate=Vbiog_min/hours; %hourly gross biogas production
UP1=181613*(Vbiog_min_rate^0.373); %Upgrading CAPEX for point 1 from SGC upgrading report,
unit: €/m3/hr
Vbiog_max=(maxVS*SMY*VSdest)/concCH4; %gross production of biogas, m3/a
Vbiog_max_rate=Vbiog_max/hours; %hourly gross biogas production
```

```
UP2=181613*(Vbiog_max_rate^0.373); %Upgrading CAPEX for point 2 from SGC upgrading report, unit: €/m3/hr

M_UP_CAPEX=(UP2-UP1)/(Vbiog_max_rate-Vbiog_min_rate); %slope of upgrading CAPEX Curve
C_UP_CAPEX=UP1-Vbiog_min_rate*M_UP_CAPEX; %intersection of upgrading CAPEX curve


%% Upgrading OPEX %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
UP_elec=0.11; %electricity consumption of upgrading system, kWhe/m3Biog
UP_heat=0.1; %net heat consumption of upgrading system, kWhth/m3Biog as per puregas quote
UP_maintenance=101293; % based on maintenance quote from Puregas to GNI, converted to euro from sterling at rate of 0.726 for 2015

%% Compression cost %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Compression_elec=0.12; %electrical energy from compression to 16bar gauge, per m3 of biomethane

%% Financial Assumptions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
specific_transport_cost=0.111655891; %cost per tonne kilometre, unit: €/km
feed_cost_value=grass_price; %feedstock cost price €/twwt
FC=feed_cost_value; %Feedstock Cost, unit: €/twwt
tortuosity=sqrt(2); %tortuosity factor for rural roads
max_collection_radius=40; %maximum collection radius from the plant for each feedstock
no_plants=42; %number of injection Points
digestate_return=2; %double transport cost as same mass digestate returned to source of silage/slurry
elec_cost=0.16; %cost of electricity, unit: €/kWhe
heat_cost=0.04/boiler_efficiency; %cost of heat delivered to the system, takes into account the boiler efficiency, unit: €/kWhth
gas_price=20; %gas market price, unit: €/MWh
incentive=premium; %incentive on gas production, unit: €/MWh
dr=0.08; %discount Rate, unit: %/100
Y=20; %life time
DF=((1+dr)^Y-1)/(dr*(1+dr)^Y); %Discount factor for calculating, Short et al.

%% combined tonnage vector %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tonnage=[cattle_slurry_tonnage;excess_silage_highN_NFS_tonnage_wet]; %combined tonnage of feedstock
tonnage=[tonnage',1,1]; %turn into row vector, Appended with ones to account for CAPEX intersection for AD and Upgrading
N=length(tonnage); %total number of slurry supply points and silage supply points

%% combined distances matrix %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
distance=[excess_silage_highN_NFS_distsance_meters;excess_silage_highN_NFS_distsance_meters]
;%distances to each ED for slurry and silage

%% Interim Results Storage %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ED_allocation_table=zeros(N-2,no_plants); %Table containing the EDs allocated to Each Injection Point
results=zeros(9,no_plants); %interim results table
used_supply_points=zeros(N-2,no_plants); % interim used supply points
allowed_points=ones(1,N-2); %interim allowable supply points, not used
dim=2;
dead_supply_points=zeros(N-2,1); %used or dear supply points


%% Final Results%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
final_results=zeros(30,no_plants); % final results table
```

```
final_supply=zeros(N-2,no_plants); % final supply points to each injection point
dead_plants=zeros(1,no_plants).*100; % final dead or built plants
 count=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculations %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

sites=0;
for k=1:no_plants % outer loop

for iteration=1:no_plants; %inner loop

lia=ismember(iteration,dead_plants); %check is current plant being assessed already built
if lia==0 % if current plant being assessed is not built

%% distance
d=distance(:,iteration); %distance from EDs to plant number in question, meters, Euclidian
dd=(d./1000).*tortuosity; %Distance from EDs to plant in question accounting for tortuosity, km
for distance_check=1:length(dd)
   if dd(distance_check,1)>max_collection_radius
% if the supply point is greater than the maximum allowable supply distance
      dd(distance_check,1)=1000000;
%set the distance to the supply point to a large number, will prevent the model from choosing sites
that are %far from the plant being assessed
   end
end

D=dd'; %turn dd into row vector
distance_to_site=[D,0,0]; % appended zeros are for the CAPEX intersections for AD and Upgrading

%% Transport Cost
transport_cost_vector=tonnage.*distance_to_site.*digestate_return.*specific_transport_cost;
%row vector of transport costs, unit: €/a, multiplied by 2 in order to take into account digestate
return to %source of feedstock


%% Feedstock Cost
feedstock_cost=[zeros(1,n_cattle_slurry),ones(1,n_silage),0,0].*FC;
% row vector of feedstock cost, appended with zeros to account for CAPEX of AD and Upgrading
feedstock_cost_vector=tonnage.*feedstock_cost;
%row vector of feedstock costs if feed selected from each ED, unit: €/a

%% AD CAPEX
AD_CAPEX_slope_vector=[ones(1,n_cattle_slurry),ones(1,n_silage),0,0].*M_AD_CAPEX;
% row vector of AD CAPEX slopes for each ED
AD_CAPEX_vector=(AD_CAPEX_slope_vector.*tonnage)+[zeros(1,(n_cattle_slurry+n_silage)),C_AD_C
APEX,0]; % row vector of CAPEX for each ED

%% AD OPEX
AD_OPEX_Vector=tonnage.*[ones(1,n_cattle_slurry+n_silage).*AD_OPEX,0,0];
%row vector of OPEX for each ED

%% AD Elec
AD_elec_vector=tonnage.*[ones(1,n_cattle_slurry+n_silage).*(AD_elec*elec_cost),0,0];
 %row vector for electricity for each ED

%% AD Heat
```

```
moisture_vector=[ones(1,n_cattle_slurry).*MCds, zeros(1,n_silage).*MCgs, 0,0];
%moisture content of cattle slurry
AD_heat_vector=(moisture_vector.*tonnage.*(1000*4180*(T_AD-
T_feed)/(1000000*3.6))).*heat_cost;
%cost of thermal energy to heat cattle slurry from each site


%% Upgrading CAPEX
ED_VS=[ones(1,n_cattle_slurry).*VSds,ones(1,n_silage).*VSgs,0,0];
%volatile solids at each supply site from cattle slurry and grass silage
gross_methane=tonnage.*ED_VS.*VSdest.*SMY; %gross methane yield
gross_biog_yield=gross_methane./concCH4; %gross biogas yield per ED, unit: m3Biog
gross_biog_rate=gross_biog_yield./hours; %gross biogas rate per ED unit: m3biog/hr
UP_CAPEX_slope_vector=[ones(1,n_cattle_slurry+n_silage).*M_UP_CAPEX,0,0];
%row vector of upgrading CAPEX slope for each supply site
UP_CAPEX_vector=[gross_biog_rate.*UP_CAPEX_slope_vector]+[zeros(1,n_cattle_slurry+n_silage),0,
C_UP_CAPEX]; % row vector of upgrading CAPEX for each supply site

%% Upgrading opex
UP_elec_vector=gross_biog_yield.*(UP_elec*elec_cost); %row vector of upgrading OPEX
UP_maintenance_vector=[zeros(1,n_cattle_slurry+n_silage),0,UP_maintenance];
%row vector of upgrading maintenance
UP_heat_vector=gross_biog_yield.*(UP_heat*heat_cost); %row vector of upgrading thermal cost

%% net methane production
net_methane=[gross_methane.*(1-CH4slip)];
%net biomethane production from each supply site for each feedstock
net_MWh=net_methane.*(Emethane/(3.6*1000));
%net energy production from each supply site for each feedstock
gas_sale_revenue=net_MWh.*gas_price;
% row vector of revenue from each supply site from the sale of biomethane for each feedstock
gas_incentive=net_MWh.*incentive;
% row vector of incentive or premium income from gas at each supply site for each feedstock


%% Compression elec
Compression_elec_vector=net_methane./(1-CH4slip).*Compression_elec.*elec_cost;
%gas compression electricity cost

%% annual cashflow
annual_cash_vector=gas_sale_revenue+gas_incentive-transport_cost_vector-
feedstock_cost_vector-AD_OPEX_Vector-AD_elec_vector-AD_heat_vector-UP_elec_vector-
UP_heat_vector-UP_maintenance_vector-Compression_elec_vector; %annual cash flow
pv_annual_cash_vector=annual_cash_vector.*DF; %present value of annual cash flow
NPV=(AD_CAPEX_vector+UP_CAPEX_vector).*-1+pv_annual_cash_vector; % net present value


%% Value to maximisee
f=NPV.*-1; % Turn maximisation into minimisation

%% integer constraint
intcon=[1:N]; % integer constaints on decision variables
lb=[zeros(1,(n_cattle_slurry+n_silage)),1,1]; %lower bound on decision variables is zero
ub=[ones(1,N-2).*allowed_points,1,1];
%upper bound on decision variables, can be 1 if supply site is available, is zero if supply site is not
available
```

```
%% Equality Constraints
Aeq=[];
beq=[];

%% Inequality constraints
A=[tonnage;-tonnage;[cattle_slurry_tonnage',zeros(1,n_silage),0,0];-
[cattle_slurry_tonnage',zeros(1,n_silage),0,0];[zeros(1,n_cattle_slurry),excess_silage_highN_NFS_to
nnage_wet',0,0];-[zeros(1,n_cattle_slurry),excess_silage_highN_NFS_tonnage_wet',0,0];];
%constraints on total plant tonnage and individual feedstock tonnage
b=[TM_max;-TM_min;Mds_max;-Mds_min;Mgs_max;-Mgs_min;];

%% Run Optimisation
selectsites=intlinprog(f, intcon, A, b,Aeq,beq, lb, ub);
%determine supply sites for maximum NPV for plant being assessed

ED_allocation_table(:,iteration)=selectsites(1:N-2);
%add selected supply points to interim storage for current plant being assessed


plant_transport_cost_slurry=dot(selectsites(1:n_cattle_slurry)',transport_cost_vector(1:n_cattle_slu
rry));
 % slurry transport cost for current plant being assessed
plant_feedstock_cost_slurry=dot(selectsites(1:n_cattle_slurry)',feedstock_cost_vector(1:n_cattle_sl
urry)); %slurry feedstock cost for current plant being assessed
plant_tonnage_slurry=dot(selectsites(1:n_cattle_slurry)',tonnage(1:n_cattle_slurry));
% tonnage of slurry accepted at plant being assessed
sites=n_cattle_slurry;

plant_transport_cost_silage=dot(selectsites(sites+1:sites+n_silage)',transport_cost_vector(sites+1:sit
es+n_silage));
% silage transport cost for current plant being assessed
plant_feedstock_cost_silage=dot(selectsites(sites+1:sites+n_silage)',feedstock_cost_vector(sites+1:si
tes+n_silage));
% silage cost for current plant being assessed
plant_tonnage_silage=dot(selectsites(sites+1:sites+n_silage)',tonnage(sites+1:sites+n_silage));
% tonnage of silage accepted at plant being assessed
sites=sites+n_silage;
VS_ratio=(plant_tonnage_silage*VSgs)/(plant_tonnage_slurry*VSds); %calculate plant VS Ratio
plant_feedstock_cost=dot(selectsites',feedstock_cost_vector); %total feedstock cost at plant being
assessed
plant_transport_cost=dot(selectsites',transport_cost_vector);
% total feedstock transport cost for plant being assessed
plant_AD_capex=dot(selectsites',AD_CAPEX_vector); % AD system CAPEX for plant being assessed
plant_AD_opex=dot(selectsites',AD_OPEX_Vector); % AD system OPEX for plant being assessed
plant_AD_elec=dot(selectsites',AD_elec_vector); % AD system electricity cost for plant being
assessed
plant_AD_heat=dot(selectsites',AD_heat_vector); % AD system gas cost for plant being assessed
plant_UP_capex=dot(selectsites',UP_CAPEX_vector); %Upgrading system CAPEX for plant being
assessed
plant_UP_elec=dot(selectsites',UP_elec_vector); % Upgrading system electricity cost for plant being
assessed
plant_UP_heat=dot(selectsites',UP_heat_vector); % Upgrading system heat cost for plant being
assessed
plant_UP_maintenance=dot(selectsites',UP_maintenance_vector);
% Upgrading system maintenance cost for plant being assessed
```

```
plant_Compression_elec=dot(selectsites',Compression_elec_vector);
% Compression electricity cost for plant being assessed
plant_gas_revenue=dot(selectsites',gas_sale_revenue);
% Revenue from sale of biomethane for plant being assessed
plant_incentive_revenue=dot(selectsites',gas_incentive);
% Revenue from incentive for biomethane for plant being assessed

plant_methane=dot(selectsites',net_MWh); % total engegy production for plant being assessed
plant_LCOE=(plant_AD_capex+plant_UP_capex+(plant_feedstock_cost+plant_transport_cost+plant_
AD_opex+plant_AD_elec+plant_AD_heat+plant_UP_elec+plant_UP_heat+plant_UP_maintenance+pl
ant_Compression_elec)*DF)/(plant_methane*DF); %LCOE for plant being assessed

plantNPV=(plant_AD_capex+plant_UP_capex)*-1+(plant_gas_revenue+plant_incentive_revenue-
plant_feedstock_cost-plant_transport_cost-plant_AD_opex-plant_AD_elec-plant_AD_heat-
plant_UP_elec-plant_UP_heat-plant_UP_maintenance-plant_Compression_elec)*DF; %NPV for plant
being assessed


NPV_results(1,iteration)=plant_tonnage_silage; % store interim results
NPV_results(2,iteration)=plant_feedstock_cost_silage;
NPV_results(3,iteration)=plant_transport_cost_silage;
NPV_results(4,iteration)=plant_tonnage_silage*VSgs;

NPV_results(5,iteration)=plant_tonnage_slurry;
NPV_results(6,iteration)=plant_feedstock_cost_slurry;
NPV_results(7,iteration)=plant_transport_cost_slurry;
NPV_results(8,iteration)=plant_tonnage_slurry*VSds;

NPV_results(9,iteration)=(plant_tonnage_silage*VSgs)/(plant_tonnage_slurry*VSds);
NPV_results(10,iteration)=SMY;
NPV_results(11,iteration)=plant_methane;
NPV_results(12,iteration)=0;

NPV_results(13,iteration)=plantNPV;
NPV_results(14,iteration)=plant_feedstock_cost_silage;
NPV_results(15,iteration)=plant_feedstock_cost_slurry;
NPV_results(16,iteration)=plant_transport_cost_silage;
NPV_results(17,iteration)=plant_transport_cost_slurry;
NPV_results(18,iteration)=plant_AD_capex;
NPV_results(19,iteration)=plant_UP_capex;
NPV_results(20,iteration)=plant_AD_opex;
NPV_results(21,iteration)=plant_AD_elec;
NPV_results(22,iteration)=plant_AD_heat;
NPV_results(23,iteration)=plant_UP_elec;
NPV_results(24,iteration)=plant_UP_heat;
NPV_results(25,iteration)=plant_UP_maintenance;
NPV_results(26,iteration)=plant_Compression_elec;
NPV_results(27,iteration)=plant_gas_revenue;
NPV_results(28,iteration)=plant_incentive_revenue;

NPV_results(29,iteration)=plant_tonnage_silage+plant_tonnage_slurry;
NPV_results(30,iteration)=plant_LCOE;
NPV_results(31,iteration)=iteration;


used_supply_points(:,iteration)=selectsites(1:N-2);
% add supply points used for the current plant being assessed to the used supply points table
```

```
for j=1:N-2
   if selectsites(j)==1
      dead_supply_points(j,iteration)=0;
% determine whether or not to add supply point to the dead supply points
   elseif selectsites(j)==0
      dead_supply_points(j,iteration)=1;
   end
end




clear selectsites % clear selected sites between runs


elseif lia==1    % if current plant being assessed is already built set all interim results to arbitrary
values
NPV_results(1,iteration)=0;
NPV_results(2,iteration)=0;
NPV_results(3,iteration)=0;
NPV_results(4,iteration)=0;
NPV_results(5,iteration)=0;
NPV_results(6,iteration)=0;
NPV_results(7,iteration)=0;
NPV_results(8,iteration)=0;
NPV_results(9,iteration)=0;
NPV_results(10,iteration)=0;
NPV_results(11,iteration)=0;
NPV_results(12,iteration)=0;
NPV_results(13,iteration)=-1000000000000;
NPV_results(14,iteration)=0;
NPV_results(15,iteration)=0;
NPV_results(16,iteration)=0;
NPV_results(17,iteration)=0;
NPV_results(18,iteration)=0;
NPV_results(19,iteration)=0;
NPV_results(20,iteration)=0;
NPV_results(21,iteration)=0;
NPV_results(22,iteration)=0;
NPV_results(23,iteration)=0;
NPV_results(24,iteration)=0;
NPV_results(25,iteration)=0;
NPV_results(26,iteration)=0;
NPV_results(27,iteration)=0;
NPV_results(28,iteration)=0;
NPV_results(29,iteration)=0;
NPV_results(30,iteration)=0;
NPV_results(31,iteration)=iteration;

dead_supply_points(1:N-2,iteration)=ones(N-2,1);

count=count+1;

end
```

```
end %end of inner loop

total_cost_val=NPV_results(13,:); % for all of the plants assessed in the inner loop create a vector of NPV
[max_plant_cost,plant_index]=max(total_cost_val); % find the plant with the highest NPV
allowed_points=allowed_points.*(dead_supply_points(:,plant_index)');
% find the supply points assigned to the plant with the highest NPV


dead_plants(k)=NPV_results(31,plant_index);
% add the plant with the highest NPV to the built plant list (plant is now dead and cannot be reassessed)

final_results(1:31,k)=NPV_results(1:31,plant_index);
% for the plant that was built add results to final result table
final_supply(:,k)=used_supply_points(:,plant_index);
 % for the plant that was built add supply points to the final result table
end %end of outer loop

plant_metrics_and_supply=[final_results;sum(final_supply);final_supply];


plant_silage=plant_metrics_and_supply(1,:);
plant_slurry=plant_metrics_and_supply(5,:);




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Save Date to Excel File %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
input_assumptions={'Transport Cost (€/Tkm)', 'Feedstock Cost(€/T)','Maximum Plant Size (twwt/a)','VS Destruction','CH4 Slip','AD Elec Use (kWhe/twwt)','Upgrading Elec Use (kWhe/m3BIOG)','Compression Elec Use (kWhe/m3BioCH4)','Feed Temperature (C)','Digester Temperatrue (C)','Elec Price (€/kWhe)','Heat Cost (€/kWhth)','Desired VS Ratio','Hours','Discount Rate (%)','Lifetime','Gas Price (€/MWh)','Incentive (€/MWh)'}; % input assumptions
input_assumption_values=[specific_transport_cost,feed_cost_value,TM,VSdest,CH4slip,AD_elec,UP_elec,Compression_elec,T_feed,T_AD,elec_cost,heat_cost,VSgs_VSds_ratio,hours,dr,Y,gas_price,incentive];
% input assumption values
input_data_to_write={input_assumptions;input_assumption_values};

result_names={'Silage Tonnage (twwt)';'Silage Cost (€)';'Silage Transport Cost (€)';'Silage VS (tVS)';'Slurry Tonnage (twwt)';'Slurry Cost (€)';'Slurry Transport Cost (€)';'Slurry VS(tVS)';'VS Ratio (GS/CS)';'SMY (m3CH4/tVS)';'Methane (MWhnet)';'Blank';'NPV (€)';'Silage Cost (€/a)';'Slurry Cost (€/a)';'Silage Transport Cost (€/a)';'Slurry Tansport Cost (€/a)';'AD CAPEX (€)';'Upgrading CAPEX (€)';'AD OPEX (€/a)';'AD Elec Cost (€/a)';'AD Heat Cost (€/a)';'Upgrading Elec Cost (€/a';'Upgrading Heat Cost €/a';'Upgrading maintenance cost €/a';'Compression Elec Cost €/a';'Gas Revenue (€/a)';'Incentive Revenue (€/a)';'Total Tonnage (twwt/a)';'Plant LCOE (€/MWh)';'Plant Number';'Supply Points Used'}; %result names

file_to_save=strcat('silage_and_slurry_TM',num2str(TM),'_VSratio_',num2str(VSgs_VSds_ratio),'_Silage_Price_',num2str(feed_cost_value),'€twwt','_Incentive_',num2str(incentive),'_40km_max','.xlsx');
% name of excel file to save
cd('Silage3 NPV') % change directory to location for saving file
```

```
cd('results for resubmission 2') % go to sub-directory
file_name=file_to_save; % filename of Excel file to be saved
xlswrite(file_name,input_assumptions,'results','C3'); %save input assumptions to Excel file
xlswrite(file_name,input_assumption_values,'results','C4');

xlswrite(file_name,result_names,'results','C6'); % save results to Excel file
xlswrite(file_name,plant_metrics_and_supply,'results','D6');
xlswrite(file_name,input_assumptions,'slurry','C3'); %save input assumptions to Excel file
xlswrite(file_name,input_assumption_values,'slurry','C4');
xlswrite(file_name,'plant no.','slurry','C6');
xlswrite(file_name,'Total supply','slurry','C7');

xlswrite(file_name,plant_metrics_and_supply(31,:),'slurry','D6');% save results to Excel file
xlswrite(file_name,plant_metrics_and_supply(32:32+n_cattle_slurry,:),'slurry','D7');
xlswrite(file_name,input_assumptions,'silage','C3'); %save input assumptions to Excel file
xlswrite(file_name,input_assumption_values,'silage','C4');
xlswrite(file_name,'plant no.','silage','C6');
xlswrite(file_name,'Total supply','silage','C7');
xlswrite(file_name,plant_metrics_and_supply(31,:),'silage','D6');% save results to Excel file
xlswrite(file_name,plant_metrics_and_supply(32+n_cattle_slurry:end,:),'silage','D7');
cd(home); %return home
clc
total_iterations=count

    end %end of range of VS ratio loop
  end % end of range of silage price loop
end  %end of range of incentive or premium value loop
end  % end of range of plant size loop

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% End of code %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix C

Matlab Code to determine pressure drop in biogas pipelines, Chapter 6

```
clear all
close all
clc

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%Initial Set Up%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Farm and user coordinates
farm_x=[0, 990.6817615, 6930.399201, 1528.569273, 8101.00481]; % farm x co ordinates
farm_y=[0,3658.704371, 0, 3963.020368, 4285.103407]; % farm y coordinates
user_x=6038.394716; %user x coordinates
user_y=3134.262258; %user y coordinates

%% Biogas properties
YCH4=0.6; % volume fraction of CH4
YCO2=1-YCH4; %volume fraction of CO2
MCH4=16; %molar mass CH4
MCO2=44; %molar mass CO2
Mbiogas=YCH4*MCH4+YCO2*MCO2; %biogas molar mass
uCH4=0.000011; %dynamic viscosity of CH4
uCO2=0.0000147; %dynamic viscosity of CO
ubiogas=(uCH4*YCH4*sqrt(MCH4)+uCO2*YCO2*sqrt(MCO2))/(YCH4*sqrt(MCH4)+YCO2*sqrt(MCO2)
); %dynamic viscosity of biogas
RU=8314.41; %universal gas constant
R_biogas=(1/Mbiogas)*RU; %R for Biogas
RCH4=(1/MCH4)*RU; %R for CH4
RCO2=(1/MCO2)*RU; % R for CO2

%% AD conditions
P_AD=111325; % AD gas pressure
T_AD=288.15; % AD gas temperature
biogas_density_AD=(Mbiogas*P_AD)/(T_AD*RU); %density of biogas at AD conditions

%% Biogas Properties continued
Cp_CH4=1000*(-0.703029+108.4773*(T_AD/1000)-
42.52157*(T_AD/1000)^2+5.862788*(T_AD/1000)^3+0.678565/((T_AD/1000)^2))/MCH4; %Cp CH4

Cp_CO2=1000*(24.99735+55.48696*(T_AD/1000)-
33.69137*(T_AD/1000)^2+7.948387*(T_AD/1000)^3-0.136638/((T_AD/1000)^2))/MCO2; %Cp CO2

Cv_CH4=Cp_CH4-RCH4; %Cv CH4
Cv_CO2=Cp_CO2-RCO2; %Cv Co2

Cp_biogas=(YCH4*MCH4/Mbiogas)*Cp_CH4+(YCO2*MCO2/Mbiogas)*Cp_CO2; %Cp Biogas
Cv_biogas=(YCH4*MCH4/Mbiogas)*Cv_CH4+(YCO2*MCO2/Mbiogas)*Cv_CO2; %Cv Biogas
k=Cp_biogas/Cv_biogas; %Ratio of Cp to Cv for biogas

%% pipeline inlet assumption
P1_initial=500000; %initial guess of pipeline inlet pressure
T_1=T_AD;

%% Pipeline properties
```

```
pipe_diameter_AD=[0.1,0.1,0.1,0.1,0.1]; %AD pipe diameter m
pipe_diameter_user=0.1; %user pipe diameter
pipe_roughness=0.000003; %pipe absolute roughness m
A_AD=pi.*pipe_diameter_AD.*pipe_diameter_AD/4; %pipe area AD
A_user=pi*pipe_diameter_user*pipe_diameter_user/4; %pipe Area User
f_initial=0.02; %initial guess for Darcy friction factor
f_difference=0.00001; % minimum difference for calculations of f

%% User conditions
P_user=111325;
T_user=T_AD;
T_nexus=T_AD;

%% Standard conditions
P_st=101325;
T_st=288.15;
biogas_density_st=(Mbiogas*P_st)/(T_st*RU); %density of biogas at standard conditions

%% Farm biogas flow rate at AD conditions
farm_m=[28887, 35041, 13254, 33059, 11304]; %mass of slurry at farm
farm_Q=[0.009969153, 0.012092951, 0.00457407, 0.011408946, 0.003901108]; %flow rate of biogas
at AD conditions
user_Q=sum(farm_Q); %flow rate to user at standard conditions
farm_mass_flow=farm_Q.*(biogas_density_AD); % mass flow rate of biogas from farm
user_mass_flow=sum(farm_mass_flow); % mass flow rate of biogas to user

%% biogas fow at standard conditions
farm_Q_st=farm_mass_flow./biogas_density_st; %volumetric flow at standard conditions
user_Q_st=user_mass_flow/biogas_density_st; %volumetric flow to user at standard conditions

%% Compressor parameters
adiabatic_eff=0.8;
mech_eff=0.95;

%% Scenario
pipe_to_user=1; %build pipe to user or not, 1= yes, 0=no
AD_at_user=0; %build large AD unit at user, 1=yes, 0=no

%% Set up grid
grid_step_size=10; %grid size meters
Nexus_x=0:grid_step_size:9000;
Nexus_y=0:grid_step_size:9000;
total_x_points=9000/grid_step_size+1;
total_y_points=9000/grid_step_size+1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Road Haulage to CAD remote from user %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% specific energy consumption of slurry tranportation MJ/tkm
MJ_per_tkm=0.87588; % Haulage energy consumption
annual_MJ_transport=zeros(length(Nexus_x),length(Nexus_y));

row=1;
col=1;

for row=1:length(Nexus_x)
```

```
    for col=1:length(Nexus_y)

        tkm=((((farm_x(1)-Nexus_x(row))^2+(farm_y(1)-
Nexus_y(col))^2)^0.5)/1000)*farm_m(1)+((((farm_x(2)-Nexus_x(row))^2+(farm_y(2)-
Nexus_y(col))^2)^0.5)/1000)*farm_m(2)+((((farm_x(3)-Nexus_x(row))^2+(farm_y(3)-
Nexus_y(col))^2)^0.5)/1000)*farm_m(3)+((((farm_x(4)-Nexus_x(row))^2+(farm_y(4)-
Nexus_y(col))^2)^0.5)/1000)*farm_m(4)+((((farm_x(5)-Nexus_x(row))^2+(farm_y(5)-
Nexus_y(col))^2)^0.5)/1000)*farm_m(5);
        annual_MJ_transport(row,col)=round(tkm*MJ_per_tkm);

    end

    col=1;

end


[Min, I]=min(annual_MJ_transport(:)); %Determine location of CAD that results in minimum slurry
haulage energy consumption
[I_row,I_col]=ind2sub(size(annual_MJ_transport),I);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Plot Location of CAD%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(1)
contour(Nexus_x,Nexus_y,annual_MJ_transport',50)
axis square
grid on
hold on
plot(farm_x,farm_y,'ko','MarkerFaceColor','k','MarkerSize',10)
plot(user_x,user_y,'ks','MarkerFaceColor','k','MarkerSize',10)
plot(Nexus_x(I_row),Nexus_y(I_col),'ko','MarkerFaceColor','w')
text(Nexus_x(I_row)-200,Nexus_y(I_col)-200,'Centralised Anaerobic Digester')

xlabel('X co-ordinate')
ylabel('Y co-ordinate')

text(farm_x(1)+200,farm_y(1)+200,'A')
text(farm_x(2)-200,farm_y(2)-200,'B')
text(farm_x(3),farm_y(3)+200,'C')
text(farm_x(4)+200,farm_y(4)+200,'D')
text(farm_x(5)+200,farm_y(5)+200,'E')
text(user_x+200,user_y+200,'User')

legend('Annual Transport Energy consumption (MJ)','Pig Farms', 'Biogas User', 'Centralised Anaerobic
Digester')

plot([farm_x(1),Nexus_x(I_row)],[farm_y(1),Nexus_y(I_col)],'k-')
plot([farm_x(2),Nexus_x(I_row)],[farm_y(2),Nexus_y(I_col)],'k-')
plot([farm_x(3),Nexus_x(I_row)],[farm_y(3),Nexus_y(I_col)],'k-')
plot([farm_x(4),Nexus_x(I_row)],[farm_y(4),Nexus_y(I_col)],'k-')
plot([farm_x(5),Nexus_x(I_row)],[farm_y(5),Nexus_y(I_col)],'k-')
```

```
c1=colorbar;
ylabel(c1,'Energy required to transport slury by road (MJ/a)');
hold off
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Pipeline Pressure Drop Calculation %%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%% Incompressible flow%%%%%%%%%%%%%%%%%%%%%%%%
farm_velocity=farm_Q./A_AD; % velocity of biogas in pipe from each farm
farm_Re=farm_velocity.*biogas_density_AD.*pipe_diameter_AD./ubiogas; %Reynold's number of
biogas from each farm
farm_f=zeros(1,length(farm_x));

user_velocity=user_Q/A_user; % velocity of biogas in pipe to the user
user_Re=user_velocity*biogas_density_AD*pipe_diameter_user/ubiogas; %Reynold's number of
biogas flow to user

Re_Crit_farm=35.235.*(pipe_roughness./pipe_diameter_AD).^-1.1039; %Critical Re for pipeline from
farm
Re_Crit_user=35.235*(pipe_roughness/pipe_diameter_user).^-1.1039; %Critical Re for pipeline to
user

Nexus_x=0:grid_step_size:9000; %X coordinates for nexus
Nexus_y=0:grid_step_size:9000; % Y coordinates for nexus

for farm_count=1:length(farm_x) % Calculation of f for flow from each farm
if farm_Re(farm_count)<2100 % Laminar flow check from farm
   farm_f(farm_count)=64/farm_Re(farm_count); % Re for laminar flow

elseif farm_Re(farm_count)<Re_Crit_farm(farm_count) % Re less than Re Crit?

   f_new=(-1/(2*log10(2.825/(farm_Re(farm_count)*f_initial^0.5))))^2; % f calculation Prandtl-Von
Karmann

   while abs(f_initial-f_new)>f_difference % iterative calculation of f
     f_initial=f_new;
     f_new=(-1/(2*log10(2.825/(farm_Re(farm_count)*f_initial^0.5))))^2;
   end
     f_initial=0.02; % reset f to initial value of 0.02
     farm_f(farm_count)=f_new; % store f for farm being analysed
else
   farm_f(farm_count)=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(farm_count)))))^2; %f
calculation Nikuradse

end

end


if user_Re<2100 %Laminar flow check to user
   user_f=64/user_Re; %Re for laminar flow

elseif user_Re<Re_Crit_user %Re of flow < Re crit?
      f_new=(-1/(2*log10(2.825/(user_Re*f_initial^0.5))))^2; % f calculation Prandtl-Von Karmann
      while abs(f_initial-f_new)>f_difference % iterative calculation of f
     f_initial=f_new;
```

```
    f_new=(-1/(2*log10(2.825/(user_Re*f_initial^0.5))))^2;
  end
    f_initial=0.02;
    user_f=f_new; % store f for pipe from nexus to user
else
  user_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_user))))^2; % f calculation Nikuradse
end



annual_MJ_pipe_incompressible=zeros(901,901);
% table to store annual energy consumption associated each possible nexus location

hf1_Nexus_table=zeros(total_x_points,total_y_points); % store for hf from each farm to nexus
hf2_Nexus_table=zeros(total_x_points,total_y_points);
hf3_Nexus_table=zeros(total_x_points,total_y_points);
hf4_Nexus_table=zeros(total_x_points,total_y_points);
hf5_Nexus_table=zeros(total_x_points,total_y_points);
hfU_Nexus_table=zeros(total_x_points,total_y_points); % store for hf for nexus to user


P1_table_incompressible=zeros(total_x_points,total_y_points); % Store for pressure at farms
P2_table_incompressible=zeros(total_x_points,total_y_points);
P3_table_incompressible=zeros(total_x_points,total_y_points);
P4_table_incompressible=zeros(total_x_points,total_y_points);
P5_table_incompressible=zeros(total_x_points,total_y_points);
PNexus_table_incompressible=zeros(total_x_points,total_y_points); % Store for pressure at nexus


for row=1:length(Nexus_x)


  for col=1:length(Nexus_y) %calculation of hf from each farm to nexus


    hf1_Nexus=(biogas_density_AD)*(farm_f(1))*(farm_velocity(1)^2)*(((farm_x(1)-
Nexus_x(row))^2+((farm_y(1)-Nexus_y(col))^2))^0.5)./(2*pipe_diameter_AD(1));

    hf2_Nexus=(biogas_density_AD)*(farm_f(2))*(farm_velocity(2)^2)*(((farm_x(2)-
Nexus_x(row))^2+((farm_y(2)-Nexus_y(col))^2))^0.5)./(2*pipe_diameter_AD(2));

    hf3_Nexus=(biogas_density_AD)*(farm_f(3))*(farm_velocity(3)^2)*(((farm_x(3)-
Nexus_x(row))^2+((farm_y(3)-Nexus_y(col))^2))^0.5)./(2*pipe_diameter_AD(3));

    hf4_Nexus=(biogas_density_AD)*(farm_f(4))*(farm_velocity(4)^2)*(((farm_x(4)-
Nexus_x(row))^2+((farm_y(4)-Nexus_y(col))^2))^0.5)./(2*pipe_diameter_AD(4));

    hf5_Nexus=(biogas_density_AD)*(farm_f(5))*(farm_velocity(5)^2)*(((farm_x(5)-
Nexus_x(row))^2+((farm_y(5)-Nexus_y(col))^2))^0.5)./(2*pipe_diameter_AD(5));

   if pipe_to_user==1 % check if nexus pipe to be connected to user, 1=yes, 0=no

    hfU_Nexus=(biogas_density_AD)*(user_f)*(user_velocity^2)*(((user_x-
Nexus_x(row))^2+((user_y-Nexus_y(col))^2))^0.5)/(2*pipe_diameter_user);
%calculation of hf from nexus to user

   else
```

```
        hfU_Nexus=0;
    end

    hf1_Nexus_table(row,col)=hf1_Nexus; % store hf
    hf2_Nexus_table(row,col)=hf2_Nexus;
    hf3_Nexus_table(row,col)=hf3_Nexus;
    hf4_Nexus_table(row,col)=hf4_Nexus;
    hf5_Nexus_table(row,col)=hf5_Nexus;
    hfU_Nexus_table(row,col)=hfU_Nexus;

    P_Nexus=P_user+hfU_Nexus; %calculate nexus pressure, is user pressure plus hf from nexus to
user

    P_1=P_Nexus+hf1_Nexus; % calculate farm pressure, is nexus pressure plus hf from farm in
question to nexus
    P_2=P_Nexus+hf2_Nexus;
    P_3=P_Nexus+hf3_Nexus;
    P_4=P_Nexus+hf4_Nexus;
    P_5=P_Nexus+hf5_Nexus;

    P1_table_incompressible(row,col)=P_1; % store pressures at each farm and at the nexus
    P2_table_incompressible(row,col)=P_2;
    P3_table_incompressible(row,col)=P_3;
    P4_table_incompressible(row,col)=P_4;
    P5_table_incompressible(row,col)=P_5;
    PNexus_table_incompressible(row,col)=P_Nexus;


    %calculate energy require for compression from each farm to nexus
    E1=(k/(k-1))*R_biogas*T_AD*((P_1/P_AD)^((k-1)/k)-
1)*biogas_density_AD*farm_Q(1)*3600*8760/1000000;
    E2=(k/(k-1))*R_biogas*T_AD*((P_2/P_AD)^((k-1)/k)-
1)*biogas_density_AD*farm_Q(2)*3600*8760/1000000;
    E3=(k/(k-1))*R_biogas*T_AD*((P_3/P_AD)^((k-1)/k)-
1)*biogas_density_AD*farm_Q(3)*3600*8760/1000000;
    E4=(k/(k-1))*R_biogas*T_AD*((P_4/P_AD)^((k-1)/k)-
1)*biogas_density_AD*farm_Q(4)*3600*8760/1000000;
    E5=(k/(k-1))*R_biogas*T_AD*((P_5/P_AD)^((k-1)/k)-
1)*biogas_density_AD*farm_Q(5)*3600*8760/1000000;

    E_Tot=(E1+E2+E3+E4+E5)/(adiabatic_eff*mech_eff); % Calculate electrical energy required for
all compressors at all farms

    annual_MJ_pipe_incompressible(row,col)=E_Tot;

  end

  col=1;

end


[Min_pipe, I_pipe]=min(annual_MJ_pipe_incompressible(:)); %find minimum total electrical energy
requirement
[I_row_pipe,I_col_pipe]=ind2sub(size(annual_MJ_pipe_incompressible),I_pipe);
```

```
figure (2) %plot results
contour(Nexus_x, Nexus_y, annual_MJ_pipe_incompressible',50)
axis square
grid on

hold on
plot(farm_x,farm_y,'ko','MarkerFaceColor','k','MarkerSize',10)
plot(user_x,user_y,'ks','MarkerFaceColor','k','MarkerSize',10)
plot(Nexus_x(I_row_pipe),Nexus_y(I_col_pipe),'ko','MarkerFaceColor','w')
text(Nexus_x(I_row_pipe)-200,Nexus_y(I_col_pipe)+200,num2str(round(Min_pipe)))
text(Nexus_x(I_row_pipe)+200,Nexus_y(I_col_pipe)-200,'Nexus')
xlabel('X co-ordinate')
ylabel('Y co-ordinate')

text(farm_x(1)+200,farm_y(1)+200,'A')
text(farm_x(2)-200,farm_y(2)+-200,'B')
text(farm_x(3),farm_y(3)+200,'C')
text(farm_x(4)+200,farm_y(4)+200,'D')
text(farm_x(5)+200,farm_y(5)+200,'E')
text(user_x+200,user_y+200,'User')

legend('Annual Compressor Energy consumption (MJ)','Pig Farms', 'Biogas User', 'Nexus')

plot([farm_x(1),Nexus_x(I_row_pipe)],[farm_y(1),Nexus_y(I_col_pipe)],'k-')
plot([farm_x(2),Nexus_x(I_row_pipe)],[farm_y(2),Nexus_y(I_col_pipe)],'k-')
plot([farm_x(3),Nexus_x(I_row_pipe)],[farm_y(3),Nexus_y(I_col_pipe)],'k-')
plot([farm_x(4),Nexus_x(I_row_pipe)],[farm_y(4),Nexus_y(I_col_pipe)],'k-')
plot([farm_x(5),Nexus_x(I_row_pipe)],[farm_y(5),Nexus_y(I_col_pipe)],'k-')

if pipe_to_user==1
plot([user_x,Nexus_x(I_row_pipe)],[user_y,Nexus_y(I_col_pipe)],'k-')
end
c2=colorbar;
ylabel(c2,'Energy required to transport biogas (Incompressible Method) (MJ/a)');
hold off




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%% Compressible flow method  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
annual_MJ_pipe_compressible=zeros(total_x_points,total_y_points);

P1_table_compressible=zeros(total_x_points,total_y_points);
P2_table_compressible=zeros(total_x_points,total_y_points);
P3_table_compressible=zeros(total_x_points,total_y_points);
P4_table_compressible=zeros(total_x_points,total_y_points);
P5_table_compressible=zeros(total_x_points,total_y_points);


E1_table_compressible=zeros(total_x_points,total_y_points);
E2_table_compressible=zeros(total_x_points,total_y_points);
E3_table_compressible=zeros(total_x_points,total_y_points);
```

```
E4_table_compressible=zeros(total_x_points,total_y_points);
E5_table_compressible=zeros(total_x_points,total_y_points);

PNexus_table_compressible=zeros(total_x_points,total_y_points);


for row=1:length(Nexus_x)


   for col=1:length(Nexus_y)

      %%% pressure drop from Nexus to User %%%

      if pipe_to_user==0
          P_inlet_nexus_user=P_user;
      else

      L_nexus_user=(((user_x-Nexus_x(row))^2+((user_y-Nexus_y(col))^2))^0.5); %distance from
nexus to user

      if L_nexus_user==0
      P_inlet_nexus_user=P_user;

      else
      biogas_density_pipe_inlet_nexus=(Mbiogas*P1_initial)/(RU*T_1);
      volumetric_flow_inlet_nexus=user_mass_flow/biogas_density_pipe_inlet_nexus;
      velocity_inlet_nexus=volumetric_flow_inlet_nexus/A_user;

Re_inlet_nexus=biogas_density_pipe_inlet_nexus*velocity_inlet_nexus*pipe_diameter_user/ubioga
s;
      Re_Crit_nexus=35.235*(pipe_roughness/pipe_diameter_user)^-1.1039;

      if Re_inlet_nexus<2100 %f calculation, laminar
      nexus_f=64/Re_inlet_nexus;
      elseif Re_inlet_nexus<Re_Crit_nexus %f calculation, Prandtl-Von Karmann
      f_new=(-1/(2*log10(2.825/(Re_inlet_nexus*f_initial^0.5))))^2;
      while abs(f_initial-f_new)>f_difference
      f_initial=f_new;
      f_new=(-1/(2*log10(2.825/(Re_inlet_nexus*f_initial^0.5))))^2;
      end
      f_initial=0.02;
      nexus_f=f_new;
      else
      nexus_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_user))))^2; %f calculation Nikuradse
      end

      nexus_Q_st_calc=sqrt((pi^2*pipe_diameter_user^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_user^2))/(8*nexus_f*L_nexus_user*P_st^2*Mbiogas^2*2*RU*T_user));
%calculated value of Qst

      nexus_user_Q_st_diff=(abs(nexus_Q_st_calc-user_Q_st)/user_Q_st)*100;
%difference between Qst calculated and actual Qst

      while nexus_user_Q_st_diff>0.0001
 %iterative calculation of new P inlet value to minimise difference between Qst calculated and actual
Qst
```

```
P1_new=sqrt((RU*T_user*16*nexus_f*L_nexus_user*P_st^2*Mbiogas^2*user_Q_st^2)/(Mbiogas*pi^2*pipe_diameter_user^5*RU^2*T_st^2)+P_user^2);

    P1_initial=P1_new;

    biogas_density_pipe_inlet_nexus=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_nexus=user_mass_flow/biogas_density_pipe_inlet_nexus;
    velocity_inlet_nexus=volumetric_flow_inlet_nexus/A_user;

Re_inlet_nexus=biogas_density_pipe_inlet_nexus*velocity_inlet_nexus*pipe_diameter_user/ubiogas;
    Re_Crit_nexus=35.235*(pipe_roughness/pipe_diameter_user)^-1.1039;

    if Re_inlet_nexus<2100
    nexus_f=64/Re_inlet_nexus;
    elseif Re_inlet_nexus<Re_Crit_nexus
    f_new=(-1/(2*log10(2.825/(Re_inlet_nexus*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_nexus*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    nexus_f=f_new;
    else
    nexus_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_user))))^2;
    end

    nexus_Q_st_calc=sqrt((pi^2*pipe_diameter_user^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-P_user^2))/(8*nexus_f*L_nexus_user*P_st^2*Mbiogas^2*2*RU*T_user));
    nexus_user_Q_st_diff=(abs(nexus_Q_st_calc-user_Q_st)/user_Q_st)*100;
    end

    P1_initial=500000;

    P_inlet_nexus_user=P1_new;

    end

    end

    %%%% Pressure drop from farm 1 to nexus %%%%%%%%

    L_farm1_nexus=(((farm_x(1)-Nexus_x(row))^2+((farm_y(1)-Nexus_y(col))^2))^0.5);

    if L_farm1_nexus==0;

    P_inlet_farm1_nexus=P_inlet_nexus_user;
    biogas_density_pipe_inlet_farm1=(Mbiogas*P_AD)/(RU*T_1);
    else

    biogas_density_pipe_inlet_farm1=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm1=farm_mass_flow(1)/biogas_density_pipe_inlet_farm1;
    velocity_inlet_farm1=volumetric_flow_inlet_farm1/A_AD(1);

Re_inlet_farm1=biogas_density_pipe_inlet_farm1*velocity_inlet_farm1*pipe_diameter_AD(1)/ubiogas;
```

```
    Re_Crit_farm1=35.235*(pipe_roughness/pipe_diameter_AD(1))^-1.1039;

    if Re_inlet_farm1<2100
    farm1_f=64/Re_inlet_farm1;
    elseif Re_inlet_farm1<Re_Crit_farm1
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm1*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm1*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm1_f=f_new;
    else
    farm1_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(1)))))^2;
    end

    farm1_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(1)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm1_f*L_farm1_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));

    farm1_nexus_Q_st_diff=(abs(farm1_Q_st_calc-farm_Q_st(1))/farm_Q_st(1))*100;

    while farm1_nexus_Q_st_diff>0.0001


P1_new=sqrt((RU*T_nexus*16*farm1_f*L_farm1_nexus*P_st^2*Mbiogas^2*farm_Q_st(1)^2)/(Mbi
ogas*pi^2*pipe_diameter_AD(1)^5*RU^2*T_st^2)+P_inlet_nexus_user^2);
    P1_initial=P1_new;

    biogas_density_pipe_inlet_farm1=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm1=farm_mass_flow(1)/biogas_density_pipe_inlet_farm1;
    velocity_inlet_farm1=volumetric_flow_inlet_farm1/A_AD(1);

Re_inlet_farm1=biogas_density_pipe_inlet_farm1*velocity_inlet_farm1*pipe_diameter_AD(1)/ubio
gas;
    Re_Crit_farm1=35.235*(pipe_roughness/pipe_diameter_AD(1))^-1.1039;

    if Re_inlet_farm1<2100
    farm1_f=64/Re_inlet_farm1;
    elseif Re_inlet_farm1<Re_Crit_farm1
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm1*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm1*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm1_f=f_new;
    else
    farm1_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(1)))))^2;
    end

    farm1_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(1)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm1_f*L_farm1_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));
    farm1_nexus_Q_st_diff=(abs(farm1_Q_st_calc-farm_Q_st(1))/farm_Q_st(1))*100;

    end

    P1_initial=500000;
```

```
P_inlet_farm1_nexus=P1_new;

end



%%%% Pressure drop from farm 2 to nexus %%%%%%%%

L_farm2_nexus=(((farm_x(2)-Nexus_x(row))^2+((farm_y(2)-Nexus_y(col))^2))^0.5);

if L_farm2_nexus==0;

P_inlet_farm2_nexus=P_inlet_nexus_user;
biogas_density_pipe_inlet_farm2=(Mbiogas*P_AD)/(RU*T_1);
else

biogas_density_pipe_inlet_farm2=(Mbiogas*P1_initial)/(RU*T_1);
volumetric_flow_inlet_farm2=farm_mass_flow(2)/biogas_density_pipe_inlet_farm2;
velocity_inlet_farm2=volumetric_flow_inlet_farm2/A_AD(2);

Re_inlet_farm2=biogas_density_pipe_inlet_farm2*velocity_inlet_farm2*pipe_diameter_AD(2)/ubio
gas;
Re_Crit_farm2=35.235*(pipe_roughness/pipe_diameter_AD(2))^-1.1039;

if Re_inlet_farm2<2100
farm2_f=64/Re_inlet_farm2;
elseif Re_inlet_farm2<Re_Crit_farm2
f_new=(-1/(2*log10(2.825/(Re_inlet_farm2*f_initial^0.5))))^2;
while abs(f_initial-f_new)>f_difference
f_initial=f_new;
f_new=(-1/(2*log10(2.825/(Re_inlet_farm2*f_initial^0.5))))^2;
end
f_initial=0.02;
farm2_f=f_new;
else
farm2_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(2)))))^2;
end

farm2_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(2)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm2_f*L_farm2_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));

farm2_nexus_Q_st_diff=(abs(farm2_Q_st_calc-farm_Q_st(2))/farm_Q_st(2))*100;

while farm2_nexus_Q_st_diff>0.0001


P1_new=sqrt((RU*T_nexus*16*farm2_f*L_farm2_nexus*P_st^2*Mbiogas^2*farm_Q_st(2)^2)/(Mbi
ogas*pi^2*pipe_diameter_AD(2)^5*RU^2*T_st^2)+P_inlet_nexus_user^2);
P1_initial=P1_new;

biogas_density_pipe_inlet_farm2=(Mbiogas*P1_initial)/(RU*T_1);
volumetric_flow_inlet_farm2=farm_mass_flow(2)/biogas_density_pipe_inlet_farm2;
velocity_inlet_farm2=volumetric_flow_inlet_farm2/A_AD(2);

Re_inlet_farm2=biogas_density_pipe_inlet_farm2*velocity_inlet_farm2*pipe_diameter_AD(2)/ubio
gas;
```

```
    Re_Crit_farm2=35.235*(pipe_roughness/pipe_diameter_AD(2))^-1.1039;

    if Re_inlet_farm2<2100
    farm2_f=64/Re_inlet_farm2;
    elseif Re_inlet_farm2<Re_Crit_farm2
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm2*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm2*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm2_f=f_new;
    else
    farm2_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(2)))))^2;
    end

    farm2_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(2)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm2_f*L_farm2_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));
    farm2_nexus_Q_st_diff=(abs(farm2_Q_st_calc-farm_Q_st(2))/farm_Q_st(2))*100;

    end

    P1_initial=500000;

    P_inlet_farm2_nexus=P1_new;

    end



    %%%% Pressure drop from farm 3 to nexus %%%%%%%%%

    L_farm3_nexus=(((farm_x(3)-Nexus_x(row))^2+((farm_y(3)-Nexus_y(col))^2))^0.5);

    if L_farm3_nexus==0;

    P_inlet_farm3_nexus=P_inlet_nexus_user;
    biogas_density_pipe_inlet_farm3=(Mbiogas*P_AD)/(RU*T_1);
    else

    biogas_density_pipe_inlet_farm3=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm3=farm_mass_flow(3)/biogas_density_pipe_inlet_farm3;
    velocity_inlet_farm3=volumetric_flow_inlet_farm3/A_AD(3);

Re_inlet_farm3=biogas_density_pipe_inlet_farm3*velocity_inlet_farm3*pipe_diameter_AD(3)/ubio
gas;
    Re_Crit_farm3=35.235*(pipe_roughness/pipe_diameter_AD(3))^-1.1039;

    if Re_inlet_farm3<2100
    farm3_f=64/Re_inlet_farm3;
    elseif Re_inlet_farm3<Re_Crit_farm3
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm3*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm3*f_initial^0.5))))^2;
    end
    f_initial=0.02;
```

```
farm3_f=f_new;
else
farm3_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(3)))))^2;
end

farm3_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(3)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm3_f*L_farm3_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));

farm3_nexus_Q_st_diff=(abs(farm3_Q_st_calc-farm_Q_st(3))/farm_Q_st(3))*100;

while farm3_nexus_Q_st_diff>0.0001


P1_new=sqrt((RU*T_nexus*16*farm3_f*L_farm3_nexus*P_st^2*Mbiogas^2*farm_Q_st(3)^2)/(Mbi
ogas*pi^2*pipe_diameter_AD(3)^5*RU^2*T_st^2)+P_inlet_nexus_user^2);
P1_initial=P1_new;

biogas_density_pipe_inlet_farm3=(Mbiogas*P1_initial)/(RU*T_1);
volumetric_flow_inlet_farm3=farm_mass_flow(3)/biogas_density_pipe_inlet_farm3;
velocity_inlet_farm3=volumetric_flow_inlet_farm3/A_AD(3);

Re_inlet_farm3=biogas_density_pipe_inlet_farm3*velocity_inlet_farm3*pipe_diameter_AD(3)/ubio
gas;
Re_Crit_farm3=35.235*(pipe_roughness/pipe_diameter_AD(3))^-1.1039;

if Re_inlet_farm3<2100
farm3_f=64/Re_inlet_farm3;
elseif Re_inlet_farm3<Re_Crit_farm3
f_new=(-1/(2*log10(2.825/(Re_inlet_farm3*f_initial^0.5))))^2;
while abs(f_initial-f_new)>f_difference
f_initial=f_new;
f_new=(-1/(2*log10(2.825/(Re_inlet_farm3*f_initial^0.5))))^2;
end
f_initial=0.02;
farm3_f=f_new;
else
farm3_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(3)))))^2;
end

farm3_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(3)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm3_f*L_farm3_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));
farm3_nexus_Q_st_diff=(abs(farm3_Q_st_calc-farm_Q_st(3))/farm_Q_st(3))*100;

end

P1_initial=500000;

P_inlet_farm3_nexus=P1_new;

end


%%%% Pressure drop from farm 4 to nexus %%%%%%%%

L_farm4_nexus=(((farm_x(4)-Nexus_x(row))^2+((farm_y(4)-Nexus_y(col))^2))^0.5);

if L_farm4_nexus==0;
```

```
    P_inlet_farm4_nexus=P_inlet_nexus_user;
    biogas_density_pipe_inlet_farm4=(Mbiogas*P_AD)/(RU*T_1);
    else

    biogas_density_pipe_inlet_farm4=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm4=farm_mass_flow(4)/biogas_density_pipe_inlet_farm4;
    velocity_inlet_farm4=volumetric_flow_inlet_farm4/A_AD(4);

Re_inlet_farm4=biogas_density_pipe_inlet_farm4*velocity_inlet_farm4*pipe_diameter_AD(4)/ubio
gas;
    Re_Crit_farm4=35.235*(pipe_roughness/pipe_diameter_AD(4))^-1.1039;

    if Re_inlet_farm4<2100
    farm4_f=64/Re_inlet_farm4;
    elseif Re_inlet_farm4<Re_Crit_farm4
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm4*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm4*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm4_f=f_new;
    else
    farm4_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(4)))))^2;
    end

    farm4_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(4)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm4_f*L_farm4_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));

    farm4_nexus_Q_st_diff=(abs(farm4_Q_st_calc-farm_Q_st(4))/farm_Q_st(4))*100;

    while farm4_nexus_Q_st_diff>0.0001


P1_new=sqrt((RU*T_nexus*16*farm4_f*L_farm4_nexus*P_st^2*Mbiogas^2*farm_Q_st(4)^2)/(Mbi
ogas*pi^2*pipe_diameter_AD(4)^5*RU^2*T_st^2)+P_inlet_nexus_user^2);
    P1_initial=P1_new;

    biogas_density_pipe_inlet_farm4=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm4=farm_mass_flow(4)/biogas_density_pipe_inlet_farm4;
    velocity_inlet_farm4=volumetric_flow_inlet_farm4/A_AD(4);

Re_inlet_farm4=biogas_density_pipe_inlet_farm4*velocity_inlet_farm4*pipe_diameter_AD(4)/ubio
gas;
    Re_Crit_farm4=35.235*(pipe_roughness/pipe_diameter_AD(4))^-1.1039;

    if Re_inlet_farm4<2100
    farm4_f=64/Re_inlet_farm4;
    elseif Re_inlet_farm4<Re_Crit_farm4
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm4*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm4*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm4_f=f_new;
```

```
    else
    farm4_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(4)))))^2;
    end

    farm4_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(4)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm4_f*L_farm4_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));
    farm4_nexus_Q_st_diff=(abs(farm4_Q_st_calc-farm_Q_st(4))/farm_Q_st(4))*100;

    end

    P1_initial=500000;

    P_inlet_farm4_nexus=P1_new;

    end



    %%%% Pressure drop from farm 5 to nexus %%%%%%%%

    L_farm5_nexus=(((farm_x(5)-Nexus_x(row))^2+((farm_y(5)-Nexus_y(col))^2))^0.5);

    if L_farm5_nexus==0;

    P_inlet_farm5_nexus=P_inlet_nexus_user;
    biogas_density_pipe_inlet_farm5=(Mbiogas*P_AD)/(RU*T_1);
    else

    biogas_density_pipe_inlet_farm5=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm5=farm_mass_flow(5)/biogas_density_pipe_inlet_farm5;
    velocity_inlet_farm5=volumetric_flow_inlet_farm5/A_AD(5);

Re_inlet_farm5=biogas_density_pipe_inlet_farm5*velocity_inlet_farm5*pipe_diameter_AD(5)/ubio
gas;
    Re_Crit_farm5=35.235*(pipe_roughness/pipe_diameter_AD(5))^-1.1039;

    if Re_inlet_farm5<2100
    farm5_f=64/Re_inlet_farm5;
    elseif Re_inlet_farm5<Re_Crit_farm5
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm5*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm5*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm5_f=f_new;
    else
    farm5_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(5)))))^2;
    end

    farm5_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(5)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm5_f*L_farm5_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));

    farm5_nexus_Q_st_diff=(abs(farm5_Q_st_calc-farm_Q_st(5))/farm_Q_st(5))*100;

    while farm5_nexus_Q_st_diff>0.0001
```

```
P1_new=sqrt((RU*T_nexus*16*farm5_f*L_farm5_nexus*P_st^2*Mbiogas^2*farm_Q_st(5)^2)/(Mbi
ogas*pi^2*pipe_diameter_AD(5)^5*RU^2*T_st^2)+P_inlet_nexus_user^2);
    P1_initial=P1_new;

    biogas_density_pipe_inlet_farm5=(Mbiogas*P1_initial)/(RU*T_1);
    volumetric_flow_inlet_farm5=farm_mass_flow(5)/biogas_density_pipe_inlet_farm5;
    velocity_inlet_farm5=volumetric_flow_inlet_farm5/A_AD(5);

Re_inlet_farm5=biogas_density_pipe_inlet_farm5*velocity_inlet_farm5*pipe_diameter_AD(5)/ubio
gas;
    Re_Crit_farm5=35.235*(pipe_roughness/pipe_diameter_AD(5))^-1.1039;

    if Re_inlet_farm5<2100
    farm5_f=64/Re_inlet_farm5;
    elseif Re_inlet_farm5<Re_Crit_farm5
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm5*f_initial^0.5))))^2;
    while abs(f_initial-f_new)>f_difference
    f_initial=f_new;
    f_new=(-1/(2*log10(2.825/(Re_inlet_farm5*f_initial^0.5))))^2;
    end
    f_initial=0.02;
    farm5_f=f_new;
    else
    farm5_f=(-1/(2*log10(pipe_roughness/(3.7*pipe_diameter_AD(5)))))^2;
    end

    farm5_Q_st_calc=sqrt((pi^2*pipe_diameter_AD(5)^5*T_st^2*RU^2*Mbiogas*(P1_initial^2-
P_inlet_nexus_user^2))/(8*farm5_f*L_farm5_nexus*P_st^2*Mbiogas^2*2*RU*T_nexus));
    farm5_nexus_Q_st_diff=(abs(farm5_Q_st_calc-farm_Q_st(5))/farm_Q_st(5))*100;

    end

    P1_initial=500000;

    P_inlet_farm5_nexus=P1_new;

    end


    P1_table_compressible(row,col)=P_inlet_farm1_nexus; %storage for pressure results at each
farm
    P2_table_compressible(row,col)=P_inlet_farm2_nexus;
    P3_table_compressible(row,col)=P_inlet_farm3_nexus;
    P4_table_compressible(row,col)=P_inlet_farm4_nexus;
    P5_table_compressible(row,col)=P_inlet_farm5_nexus;
    PNexus_table_compressible(row,col)=P_inlet_nexus_user; %storage for pressure results at
Nexus


    E1_comp=(k/(k-1))*R_biogas*T_AD*((P_inlet_farm1_nexus/P_AD)^((k-1)/k)-
1)*biogas_density_pipe_inlet_farm1*farm_Q(1)*3600*8760/1000000; %energy for compression
    E2_comp=(k/(k-1))*R_biogas*T_AD*((P_inlet_farm2_nexus/P_AD)^((k-1)/k)-
1)*biogas_density_pipe_inlet_farm2*farm_Q(2)*3600*8760/1000000;
    E3_comp=(k/(k-1))*R_biogas*T_AD*((P_inlet_farm3_nexus/P_AD)^((k-1)/k)-
1)*biogas_density_pipe_inlet_farm3*farm_Q(3)*3600*8760/1000000;
```

```
        E4_comp=(k/(k-1))*R_biogas*T_AD*((P_inlet_farm4_nexus/P_AD)^((k-1)/k)-
1)*biogas_density_pipe_inlet_farm4*farm_Q(4)*3600*8760/1000000;
        E5_comp=(k/(k-1))*R_biogas*T_AD*((P_inlet_farm5_nexus/P_AD
        )^((k-1)/k)-1)*biogas_density_pipe_inlet_farm5*farm_Q(5)*3600*8760/1000000;

        E_Tot_comp=(E1_comp+E2_comp+E3_comp+E4_comp+E5_comp)/(adiabatic_eff*mech_eff);
%total electrical energy for compression


        E1_table_compressible(row,col)=E1_comp/(adiabatic_eff*mech_eff);
        E2_table_compressible(row,col)=E2_comp/(adiabatic_eff*mech_eff);
        E3_table_compressible(row,col)=E3_comp/(adiabatic_eff*mech_eff);
        E4_table_compressible(row,col)=E4_comp/(adiabatic_eff*mech_eff);
        E5_table_compressible(row,col)=E5_comp/(adiabatic_eff*mech_eff);



        annual_MJ_pipe_compressible(row,col)=E_Tot_comp;

    end

        col=1;

end


[Min_pipe_comp, I_pipe_comp]=min(annual_MJ_pipe_compressible(:)); % find nexus that minimises
energy consumption
[I_row_pipe_comp,I_col_pipe_comp]=ind2sub(size(annual_MJ_pipe_compressible),I_pipe_comp);


figure (3) %plot results
contour(Nexus_x, Nexus_y, annual_MJ_pipe_compressible',50)
axis square
grid on

hold on
plot(farm_x,farm_y,'ko','MarkerFaceColor','k','MarkerSize',10)
plot(user_x,user_y,'ks','MarkerFaceColor','k','MarkerSize',10)
plot(Nexus_x(I_row_pipe_comp),Nexus_y(I_col_pipe_comp),'ko','MarkerFaceColor','w')
text(Nexus_x(I_row_pipe_comp)-
200,Nexus_y(I_col_pipe_comp)+200,num2str(round(Min_pipe_comp)))
text(Nexus_x(I_row_pipe_comp)+200,Nexus_y(I_col_pipe_comp)-200,'Nexus')
xlabel('X co-ordinate')
ylabel('Y co-ordinate')

text(farm_x(1)+200,farm_y(1)+200,'A')
text(farm_x(2)-200,farm_y(2)+-200,'B')
text(farm_x(3),farm_y(3)+200,'C')
text(farm_x(4)+200,farm_y(4)+200,'D')
text(farm_x(5)+200,farm_y(5)+200,'E')
text(user_x+200,user_y+200,'User')

legend('Annual Compressor Energy consumption (MJ)','Pig Farms', 'Biogas User', 'Nexus')

plot([farm_x(1),Nexus_x(I_row_pipe_comp)],[farm_y(1),Nexus_y(I_col_pipe_comp)],'k-')
plot([farm_x(2),Nexus_x(I_row_pipe_comp)],[farm_y(2),Nexus_y(I_col_pipe_comp)],'k-')
```

```
plot([farm_x(3),Nexus_x(I_row_pipe_comp)],[farm_y(3),Nexus_y(I_col_pipe_comp)],'k-')
plot([farm_x(4),Nexus_x(I_row_pipe_comp)],[farm_y(4),Nexus_y(I_col_pipe_comp)],'k-')
plot([farm_x(5),Nexus_x(I_row_pipe_comp)],[farm_y(5),Nexus_y(I_col_pipe_comp)],'k-')

if pipe_to_user==1
plot([user_x,Nexus_x(I_row_pipe_comp)],[user_y,Nexus_y(I_col_pipe_comp)],'k-')
end
c3=colorbar;
ylabel(c3,'Energy required to transport biogas (Compressible Method) (MJ/a)');

hold off


%%%%%%%%%%%%%%%%%%Show results for compressible flow methodology%%%%%%%%%%

 final_Nexus_x=Nexus_x(I_row_pipe_comp)
 final_Nexus_y=Nexus_y(I_col_pipe_comp)

 P1_final=P1_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 P2_final=P2_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 P3_final=P3_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 P4_final=P4_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 P5_final=P5_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 P_Nexus_final=PNexus_table_compressible(I_row_pipe_comp,I_col_pipe_comp)

 E1_final=E1_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 E2_final=E2_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 E3_final=E3_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 E4_final=E4_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
 E5_final=E5_table_compressible(I_row_pipe_comp,I_col_pipe_comp)
```

Matlab Code to determine minimum biogas pipeline network length, Chapter 6

```
%%%%%%%%minimum spanning tree%%%%%%%%%%

clear all
clc
close all


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%Initial Setup %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

farm_x=[0, 990.6817615, 6930.399201, 1528.569273, 8101.00481]; % farm x co ordinates
farm_y=[0,3658.704371, 0, 3963.020368, 4285.103407]; % farm y coordinates

user_x=6038.394716; %user x coordinates
user_y=3134.262258; %user y coordinates

test_conv_hull_x=[farm_x,user_x]; %x points defining convex hull containing farms and user
test_conv_hull_y=[farm_y,user_y]; %y points defining convex hull containing farms and user

total_distance=1000000000;  %initialise the total distance variable to a high value

count=1; %counter variable


for nexus_point_1_x=0:10:9000 % 10 meter increment in x co-ordinate of potential steiner point

   for nexus_point_1_y=0:10:5000 % 10 meter increment in y co-ordinate of potential steiner point

k=convhull(test_conv_hull_x,test_conv_hull_y); %convex hull of farms and user

in=inpolygon(nexus_point_1_x, nexus_point_1_y, test_conv_hull_x(k),test_conv_hull_y(k));
%determine if potential Steiner point in convex hull

if in==1 % if potential Steiner point is in convex hull

point_x=[farm_x,nexus_point_1_x,user_x]; % x co-ordinates
point_y=[farm_y, nexus_point_1_y, user_y]; %y co-ordinates


dist_matrix=zeros(length(point_x),length(point_x)); % distance matrix between all points
size_dist_matrix=size(dist_matrix);
dist_matrix_rows=size_dist_matrix(1);
dist_matrix_cols=size_dist_matrix(2);

for i=1:dist_matrix_rows
   for j=1:dist_matrix_cols
      dist_matrix(i,j)=((point_x(i)-point_x(j))^2+(point_y(i)-point_y(j))^2)^0.5; % euclidian distance
between all points
   end
end


node_counter=1; % counter for nodes
```

```
for i=1:length(point_x)

   for j=i:length(point_x)

      s(node_counter)=i; % sources
      t(node_counter)=j; %terminators
      node_counter=node_counter+1;
   end

end

s_final=s;
t_final=t;


w=zeros(1,length(s_final)); %weighting to apply to arcs between nodes, in this case the length of the
arc


for i=1:length(s_final)
   w(i)=dist_matrix(s_final(i),t_final(i));
end


DG=sparse(s,t,w); %determine minimum spanning tree

UG=tril(DG+DG'); %graph results

[ST,pred] = graphminspantree(UG);

[receiver_run, sender_run, distance_run]=find(ST); %find receivers and senders for this potential
Steiner point

total_distance_new=sum(distance_run); % Determine total network lenght for this Steiner point


if(total_distance_new<total_distance) %is this network length less than the minimum netowrk
length found previously
[receiver, sender, distance]=find(ST); % set senders and receivers
total_distance=total_distance_new;
best_ST=ST; %set best configuration of senders and receivers

best_point_x=point_x;
best_point_y=point_y; %save Steiner point y co-ordinate

best_nexus_1_x=nexus_point_1_x; %save Steiner point x co-ordinate
best_nexus_1_y=nexus_point_1_y; %save Steiner point y co-ordinate



figure (2) %plot results of intermediate calculations

plot(farm_x,farm_y,'bo','MarkerFacecolor','b')
hold on
plot(user_x,user_y,'ks','MarkerFaceColor','k')
plot(best_nexus_1_x,best_nexus_1_y,'kp','MarkerFaceColor','r')
```

```
axis 'square'
grid on
for i=1:length(sender)

plot([best_point_x(sender(i)),best_point_x(receiver(i))],[best_point_y(sender(i)),best_point_y(receiv
er(i))])
end
xlim([0 9000])
ylim([0 9000])
hold off
end




end

count=count+1;


   end
end




view(biograph(best_ST,[],'ShowArrows','off','ShowWeights','on')) %view final minimum spanning
tree

figure (1) % plot results

plot(farm_x,farm_y,'ko','MarkerFacecolor','k')
hold on
plot(user_x,user_y,'ks','MarkerFaceColor','k')
plot(best_nexus_1_x,best_nexus_1_y,'ko')
text_x=farm_x;
text_y=farm_y+400;
text(text_x,text_y,{'A','B','C','D','E'})
legend('Pig Farms','Biogas User','Steiner Point')
axis 'square'
grid on

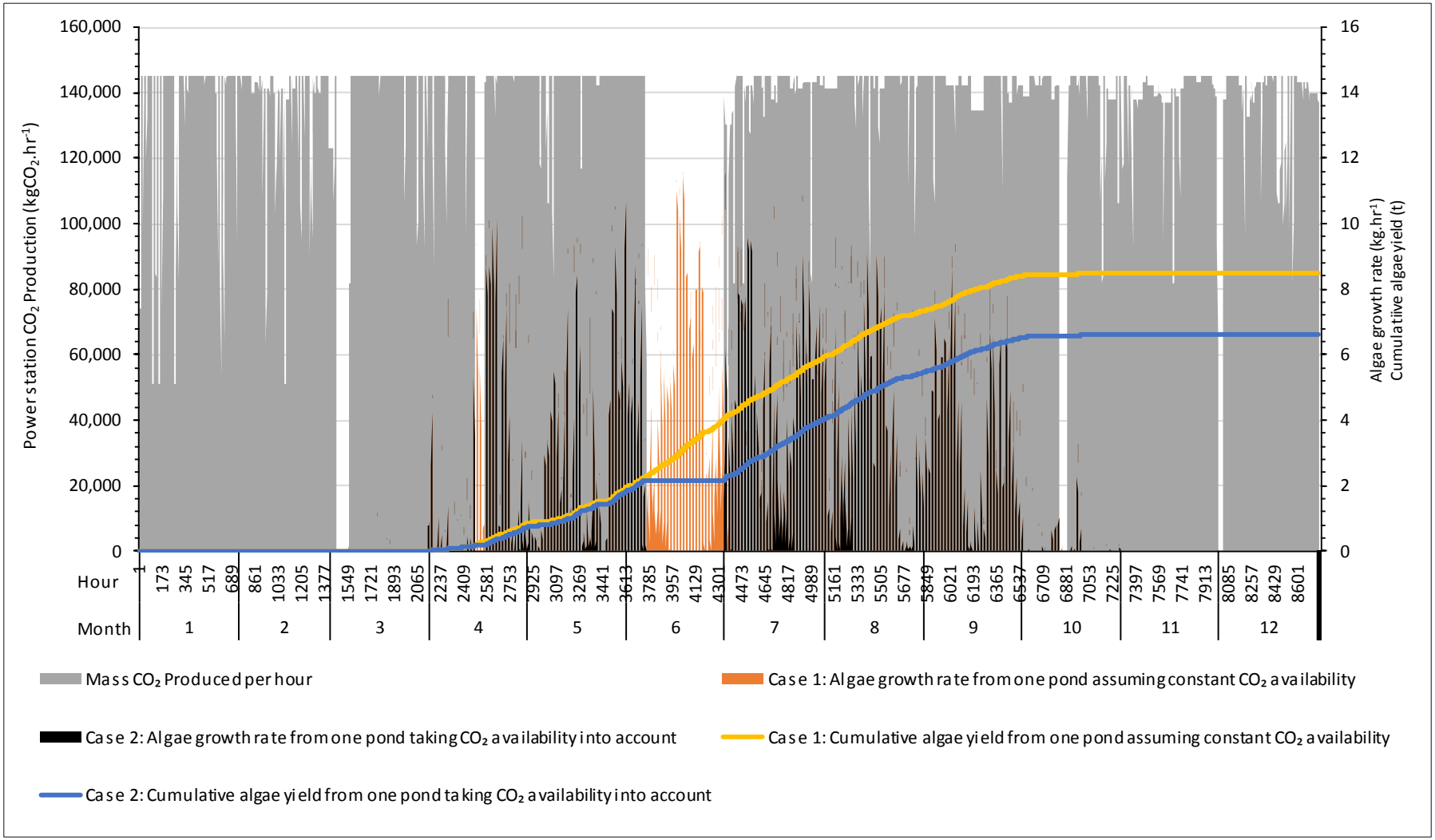
for i=1:length(sender)


plot([best_point_x(sender(i)),best_point_x(receiver(i))],[best_point_y(sender(i)),best_point_y(receiv
er(i))])

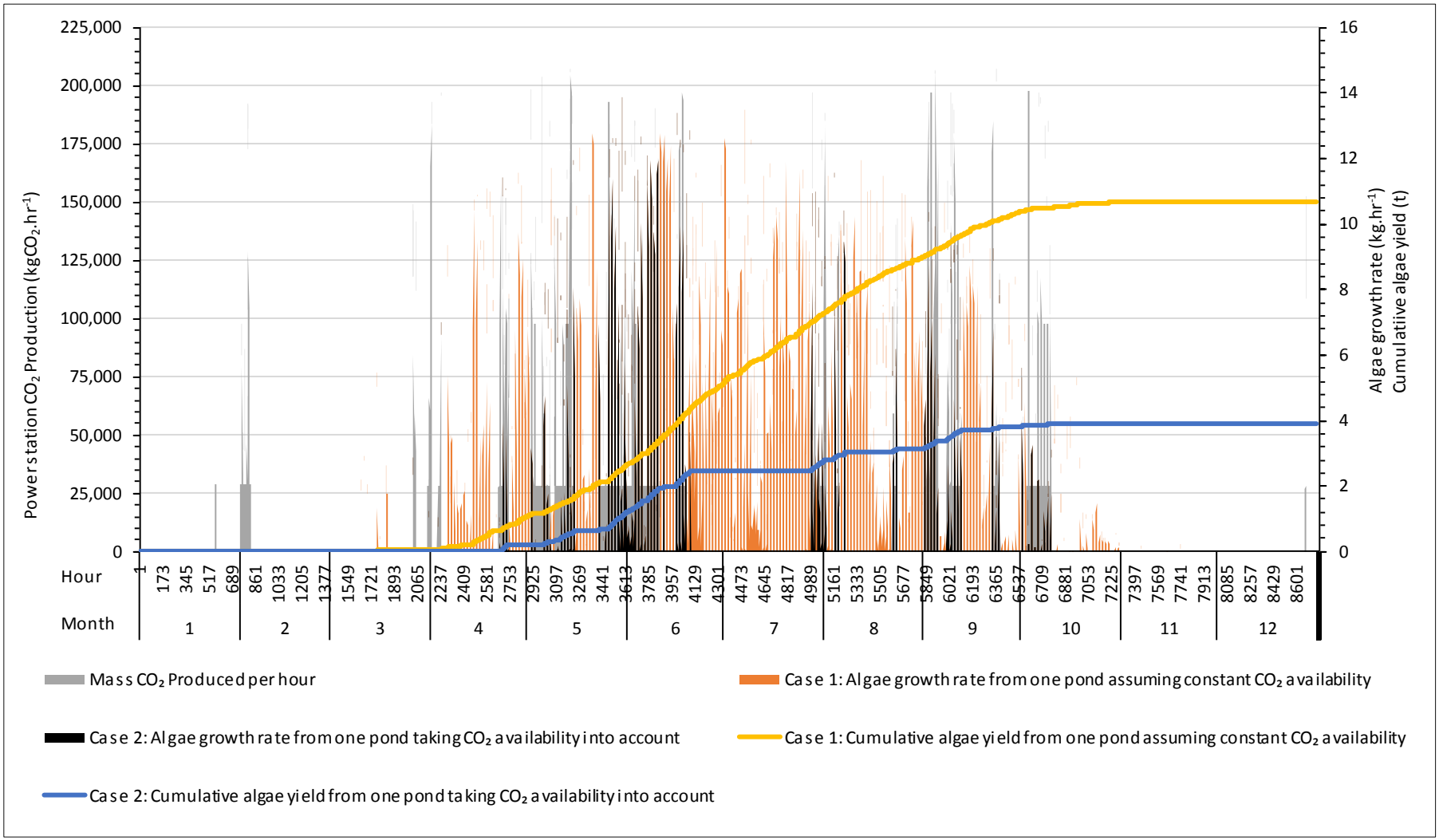
end
xlim([0 9000])
ylim([0 9000])
```

Appendix D

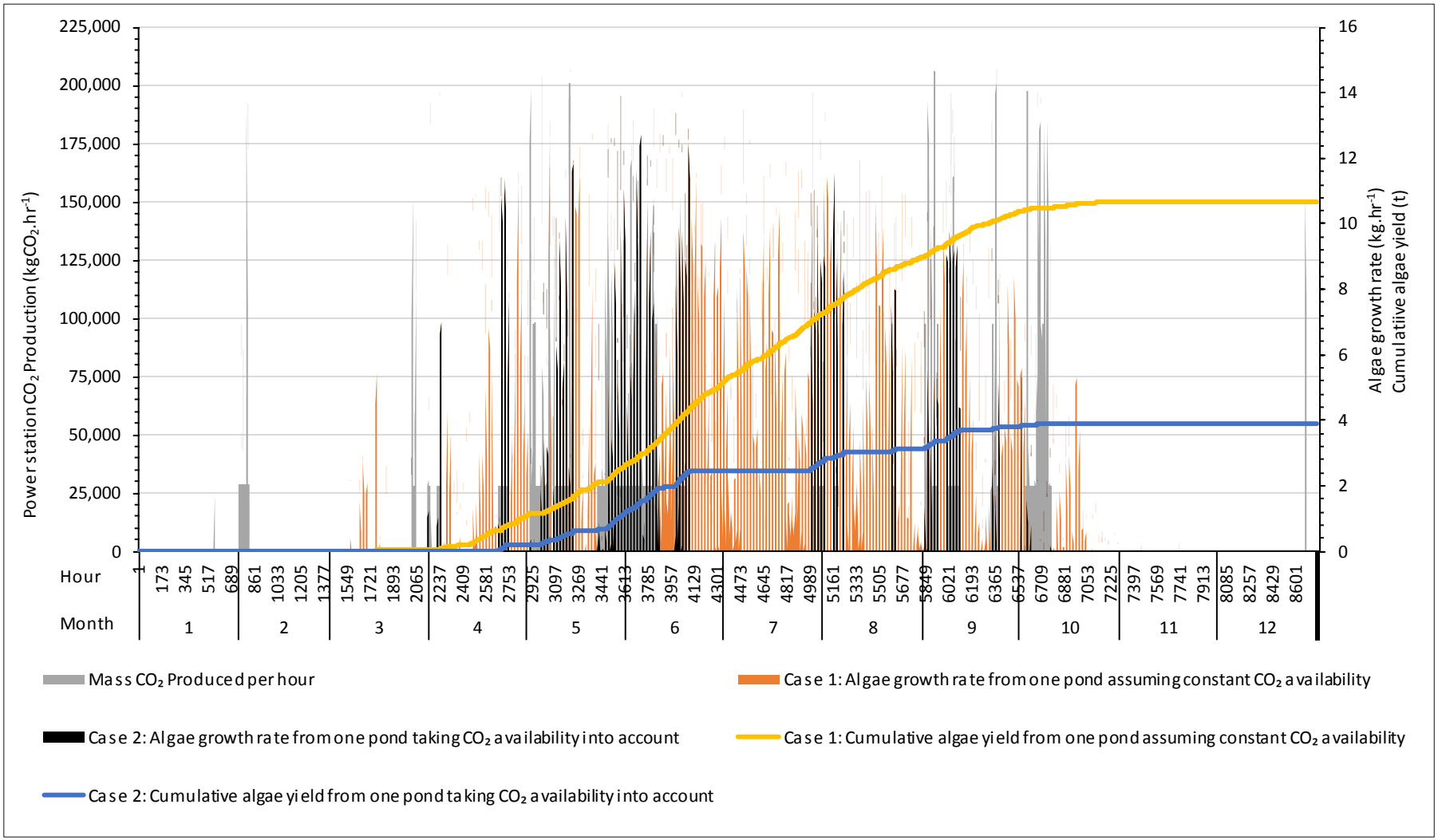
Hourly CO_2 production, hourly microalgal growth rate, and cumulative growth of microalgae at fossil fuel fired power stations in Ireland, Chapter 7



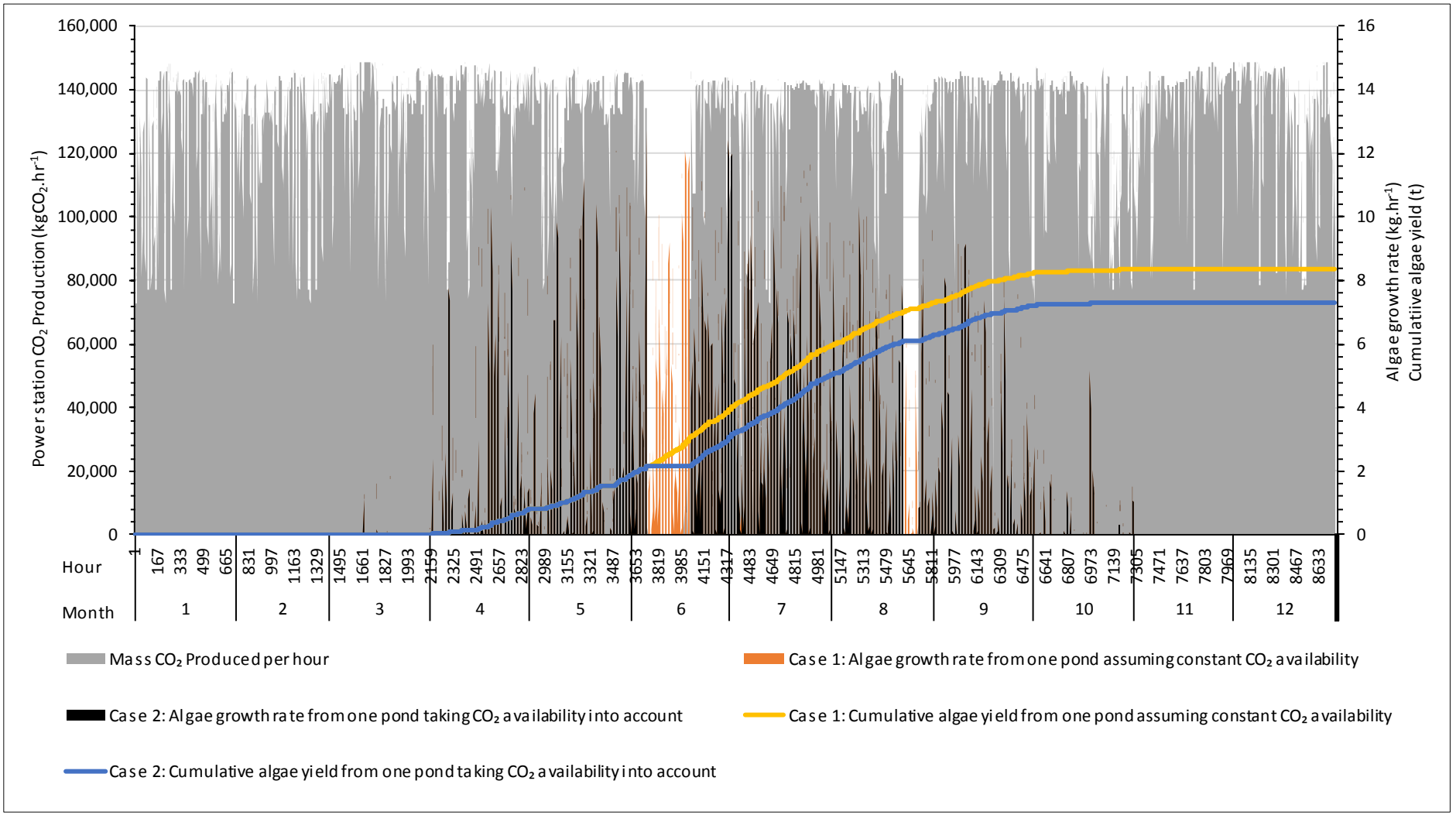
Shannon bridge


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulatiive algae yield (t)
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
16
14
12
10
8
6
4
2
0
Hour
Month
1 173 345 517 689 861 1033 1205 1377 1549 1721 1893 2065 2237 2409 2581 2753 2925 3097 3269 3441 3613 3785 3957 4129 4301 4473 4645 4817 4989 5161 5333 5505 5677 5849 6021 6193 6365 6537 6709 6881 7053 7225 7397 7569 7741 7913 8085 8257 8429 8601
1 2 3 4 5 6 7 8 9 10 11 12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

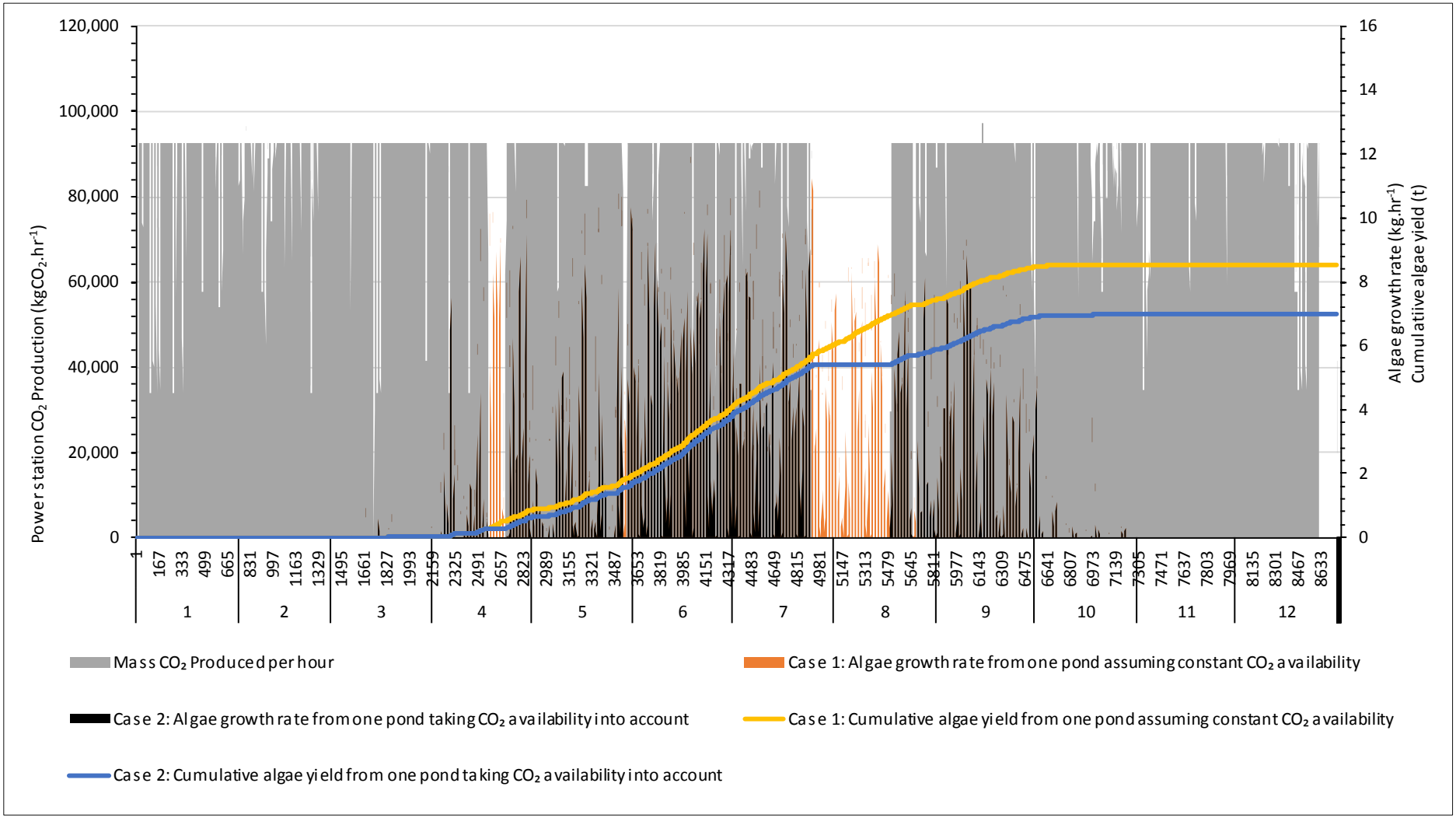
Aghada CCGT



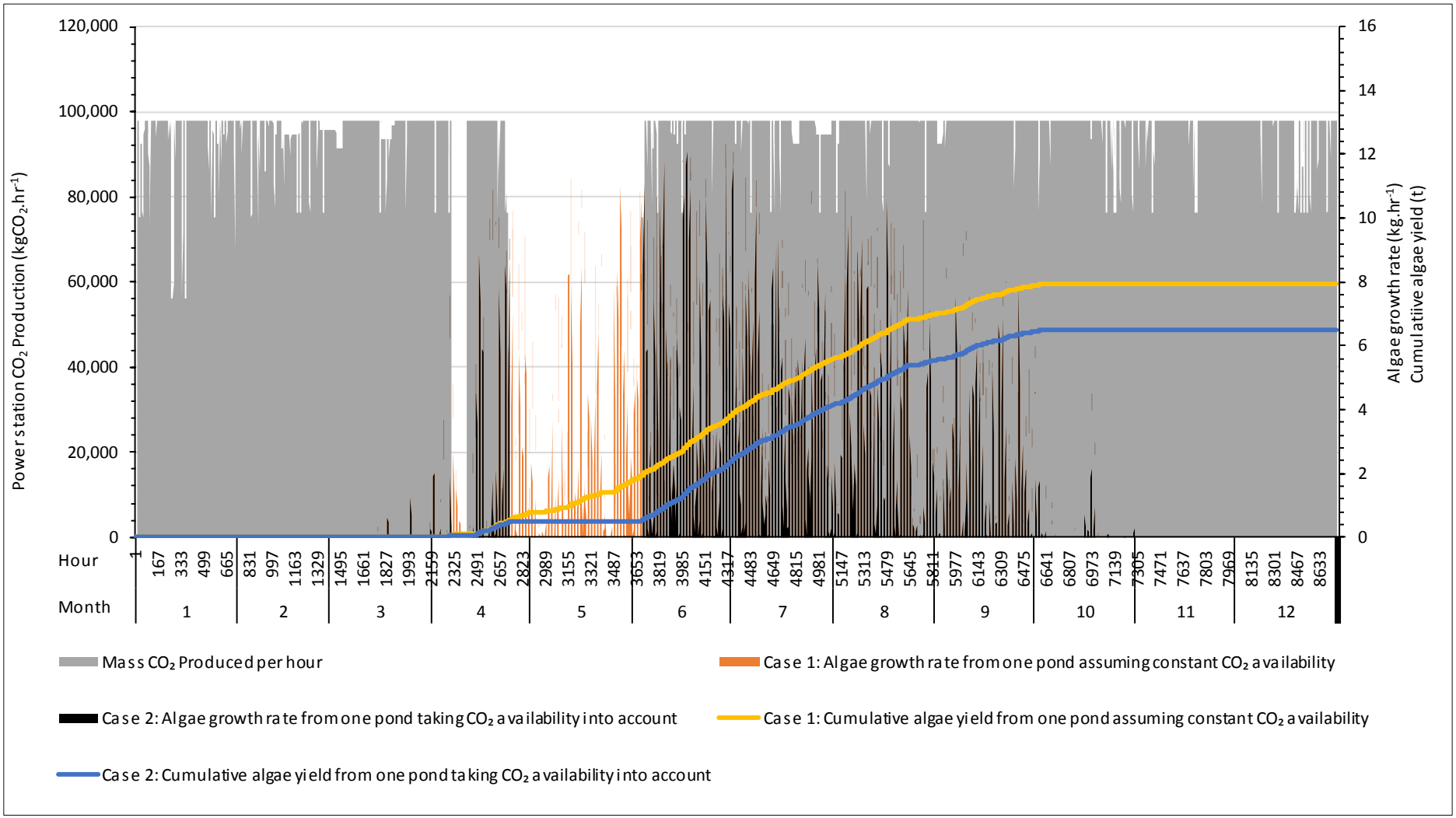
Aghada boiler


160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Power station CO_2 Production ($kgCO_2.hr^{-1}$)
16
14
12
10
8
6
4
2
0
Algae growth rate ($kg.hr^{-1}$)
Cumulative algae yield (t)
Hour
1
167
333
499
665
831
997
1163
1329
1495
1661
1827
1993
2159
2325
2491
2657
2823
2989
3155
3321
3487
3653
3819
3985
4151
4317
4483
4649
4815
4981
5147
5313
5479
5645
5811
5977
6143
6309
6475
6641
6807
6973
7139
7305
7471
7637
7803
7969
8135
8301
8467
8633
Month
1
2
3
4
5
6
7
8
9
10
11
12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

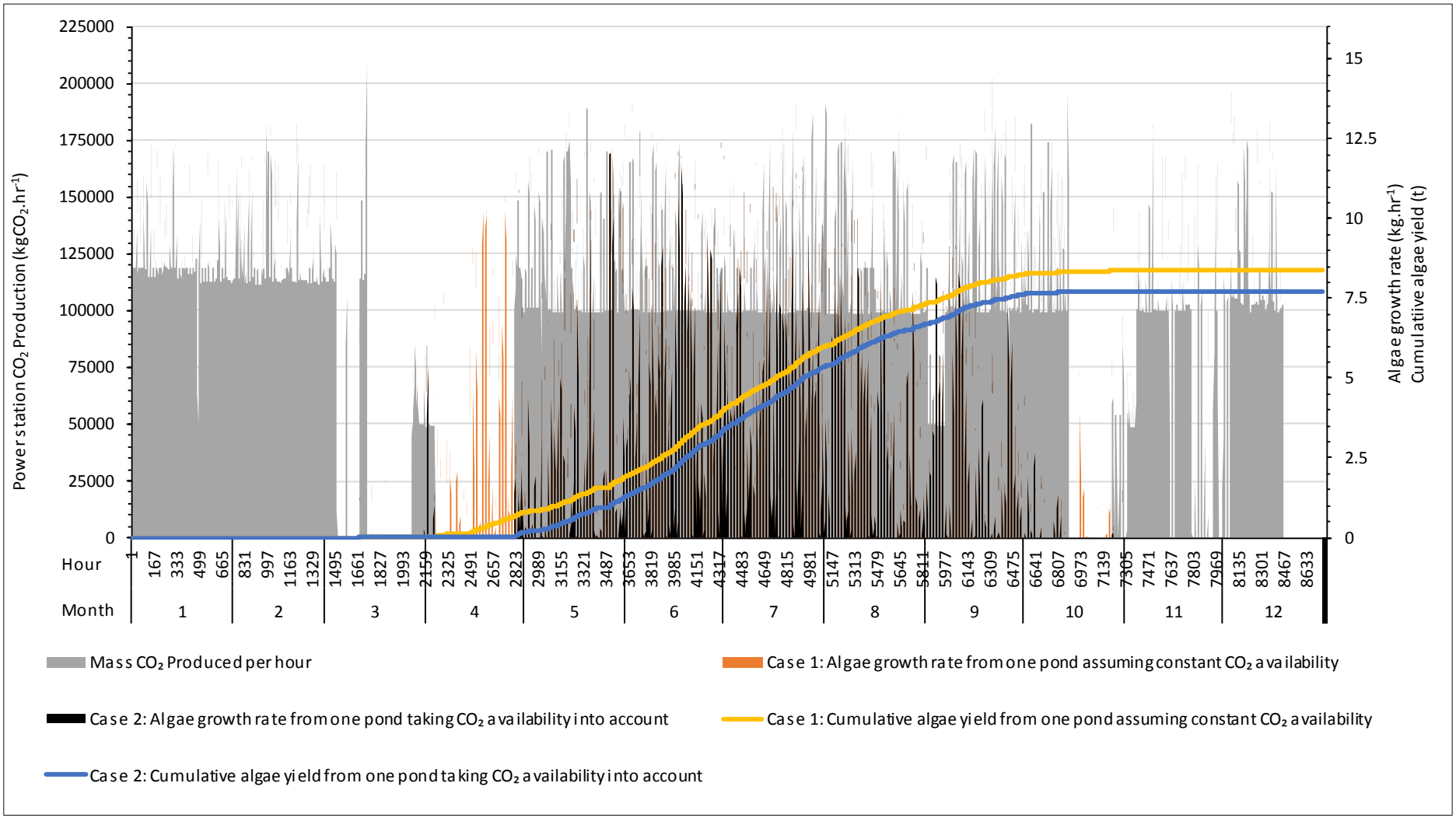
Dublin Bay


120,000
100,000
80,000
60,000
40,000
20,000
0
Power station CO_2 Production ($kgCO_2.hr^{-1}$)
16
14
12
10
8
6
4
2
0
Algae growth rate ($kg.hr^{-1}$)
Cumulatiive algae yield (t)
1
167
333
499
665
831
997
1163
1329
1495
1661
1827
1993
2159
2325
2491
2657
2823
2989
3155
3321
3487
3653
3819
3985
4151
4317
4483
4649
4815
4981
5147
5313
5479
5645
5811
5977
6143
6309
6475
6641
6807
6973
7139
7305
7471
7637
7803
7969
8135
8301
8467
8633
1
2
3
4
5
6
7
8
9
10
11
12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

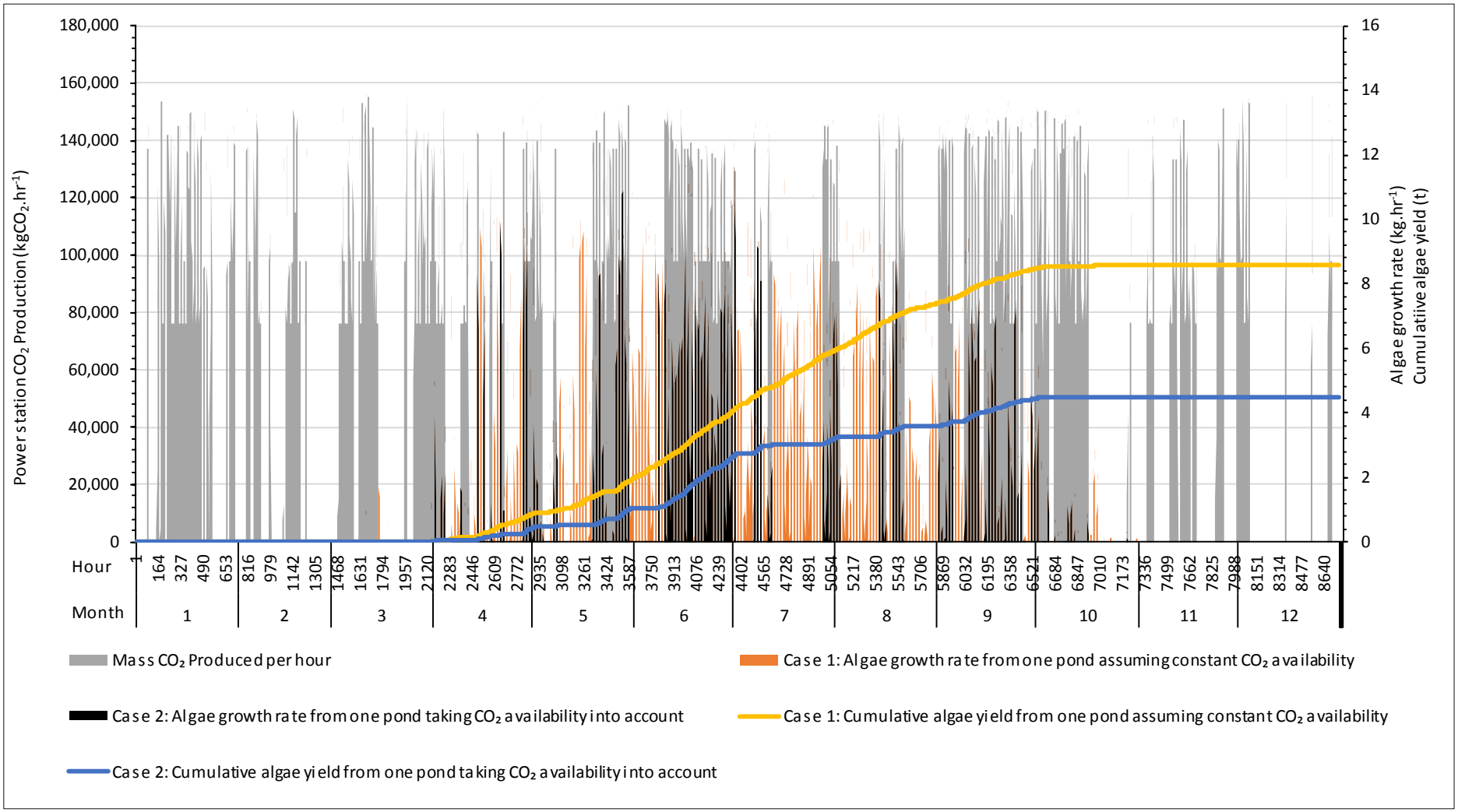
Edenderry


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulatiive algae yield (t)
120,000
100,000
80,000
60,000
40,000
20,000
0
16
14
12
10
8
6
4
2
0
Hour
1 167 333 499 665 831 997 1163 1329 1495 1661 1827 1993 2159 2325 2491 2657 2823 2989 3155 3321 3487 3653 3819 3985 4151 4317 4483 4649 4815 4981 5147 5313 5479 5645 5811 5977 6143 6309 6475 6641 6807 6973 7139 7305 7471 7637 7803 7969 8135 8301 8467 8633
Month
1 2 3 4 5 6 7 8 9 10 11 12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

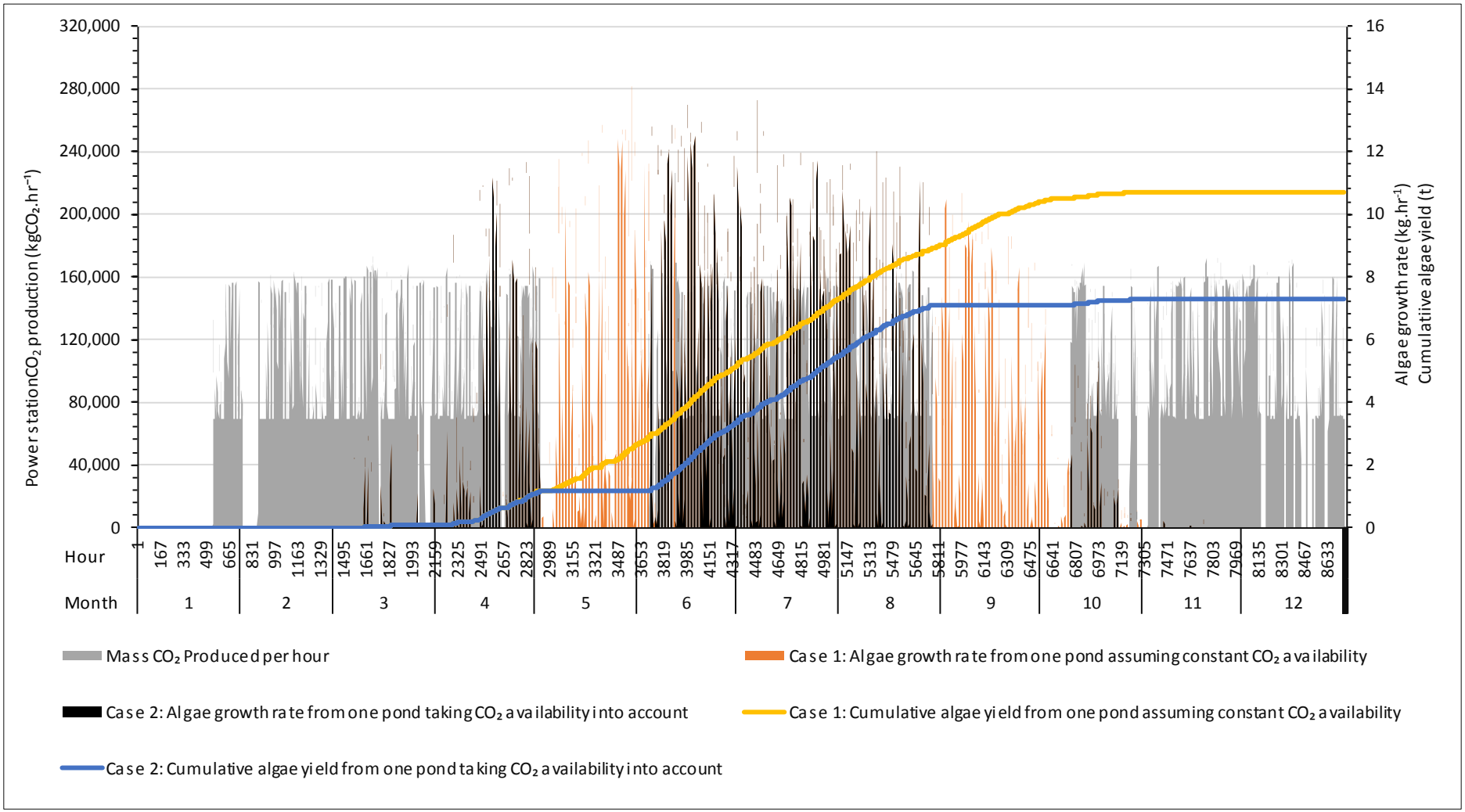
Loughree


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulatiive algae yield (t)
225000
200000
175000
150000
125000
100000
75000
50000
25000
0
15
12.5
10
7.5
5
2.5
0
Hour
1
167
333
499
665
831
997
1163
1329
1495
1661
1827
1993
2159
2325
2491
2657
2823
2989
3155
3321
3487
3653
3819
3985
4151
4317
4483
4649
4815
4981
5147
5313
5479
5645
5811
5977
6143
6309
6475
6641
6807
6973
7139
7305
7471
7637
7803
7969
8135
8301
8467
8633
Month
1
2
3
4
5
6
7
8
9
10
11
12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

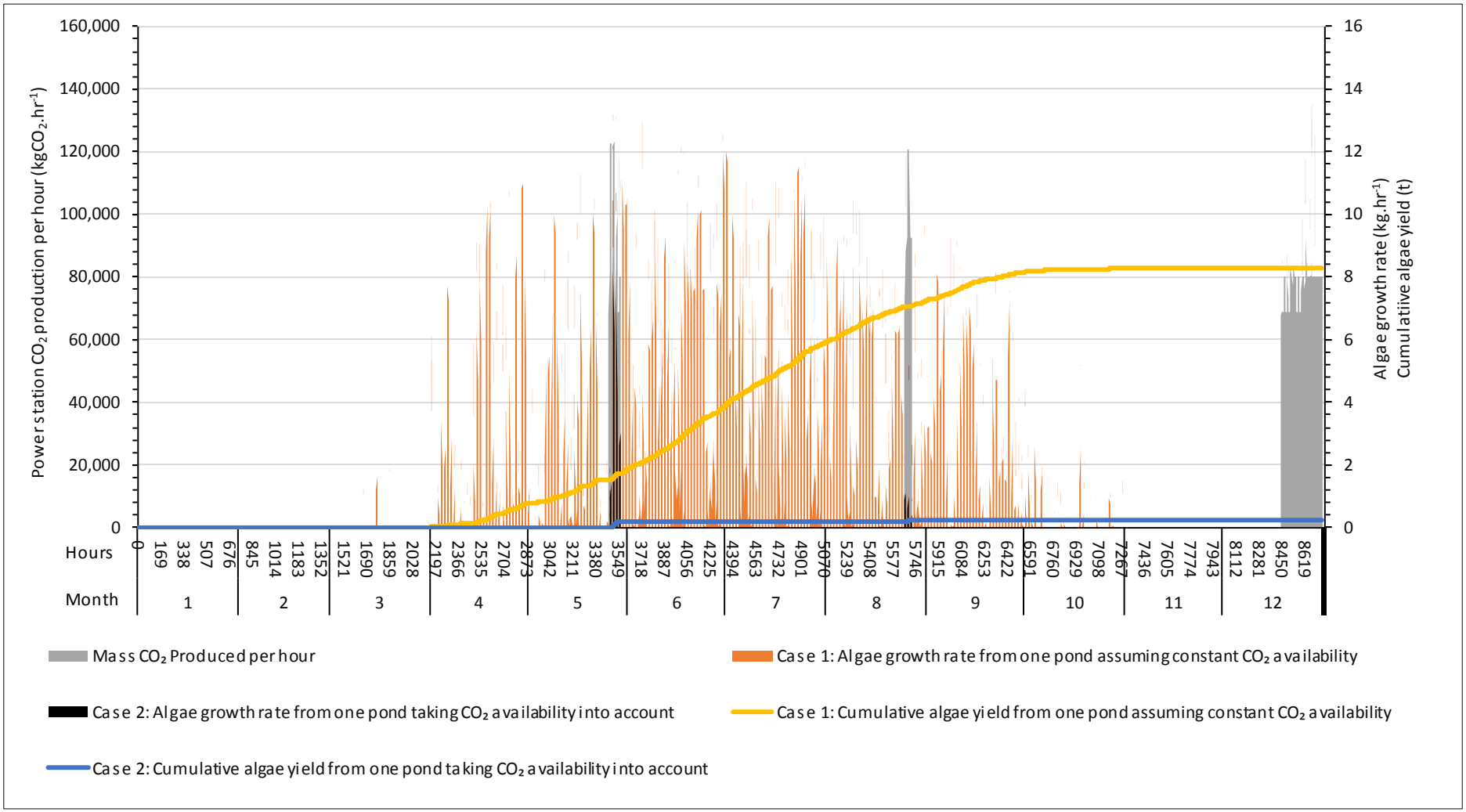
Poolbeg


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulatiive algae yield (t)
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
16
14
12
10
8
6
4
2
0
Hour
1
164
327
490
653
816
979
1142
1305
1468
1631
1794
1957
2120
2283
2446
2609
2772
2935
3098
3261
3424
3587
3750
3913
4076
4239
4402
4565
4728
4891
5054
5217
5380
5543
5706
5869
6032
6195
6358
6521
6684
6847
7010
7173
7336
7499
7662
7825
7988
8151
8314
8477
8640
Month
1
2
3
4
5
6
7
8
9
10
11
12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

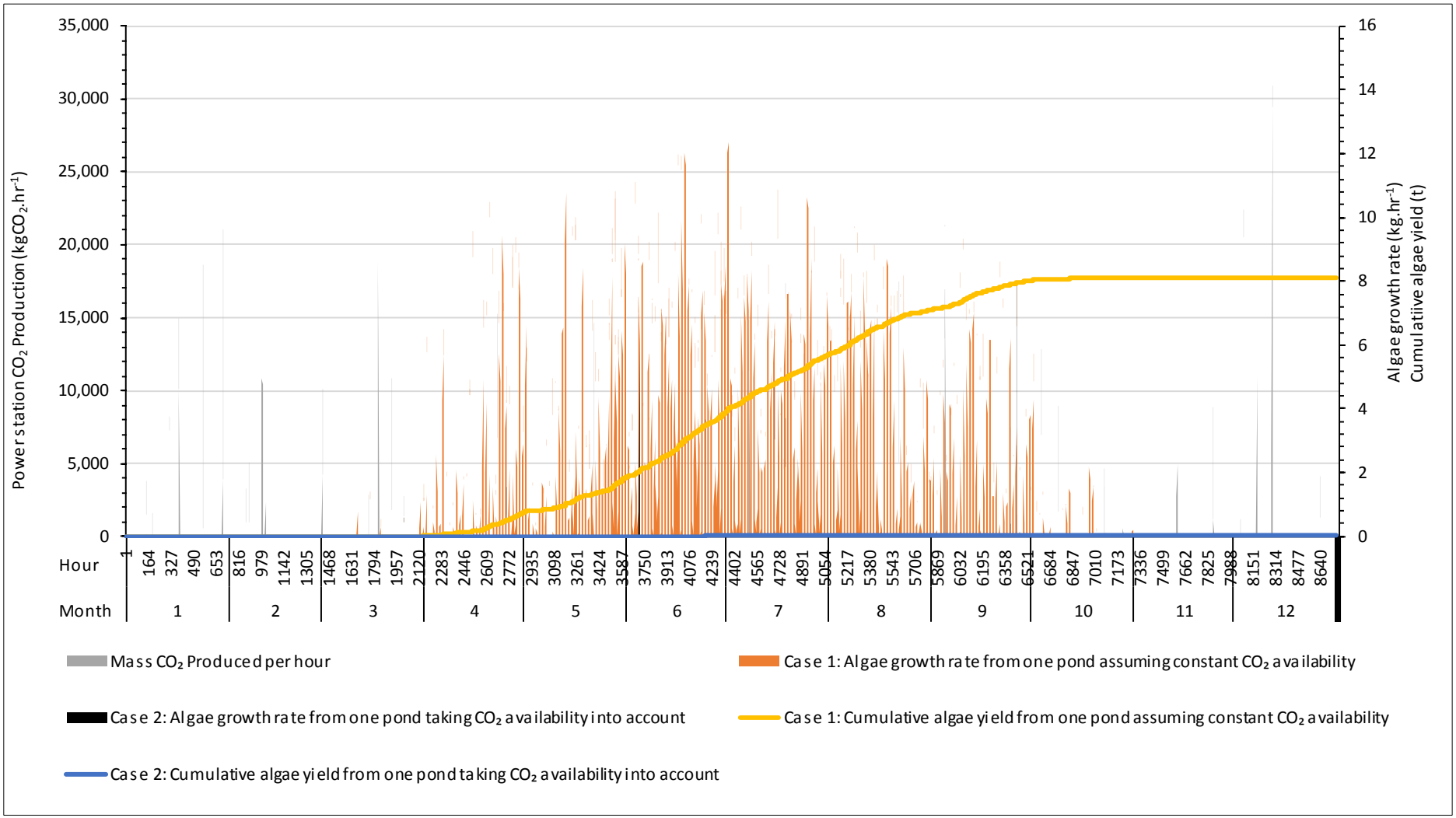
Tynagh


Power station CO_2 production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulative algae yield (t)
320,000
280,000
240,000
200,000
160,000
120,000
80,000
40,000
0
16
14
12
10
8
6
4
2
0
Hour
1 167 333 499 665 831 997 1163 1329 1495 1661 1827 1993 2159 2325 2491 2657 2823 2989 3155 3321 3487 3653 3819 3985 4151 4317 4483 4649 4815 4981 5147 5313 5479 5645 5811 5977 6143 6309 6475 6641 6807 6973 7139 7305 7471 7637 7803 7969 8135 8301 8467 8633
Month
1 2 3 4 5 6 7 8 9 10 11 12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

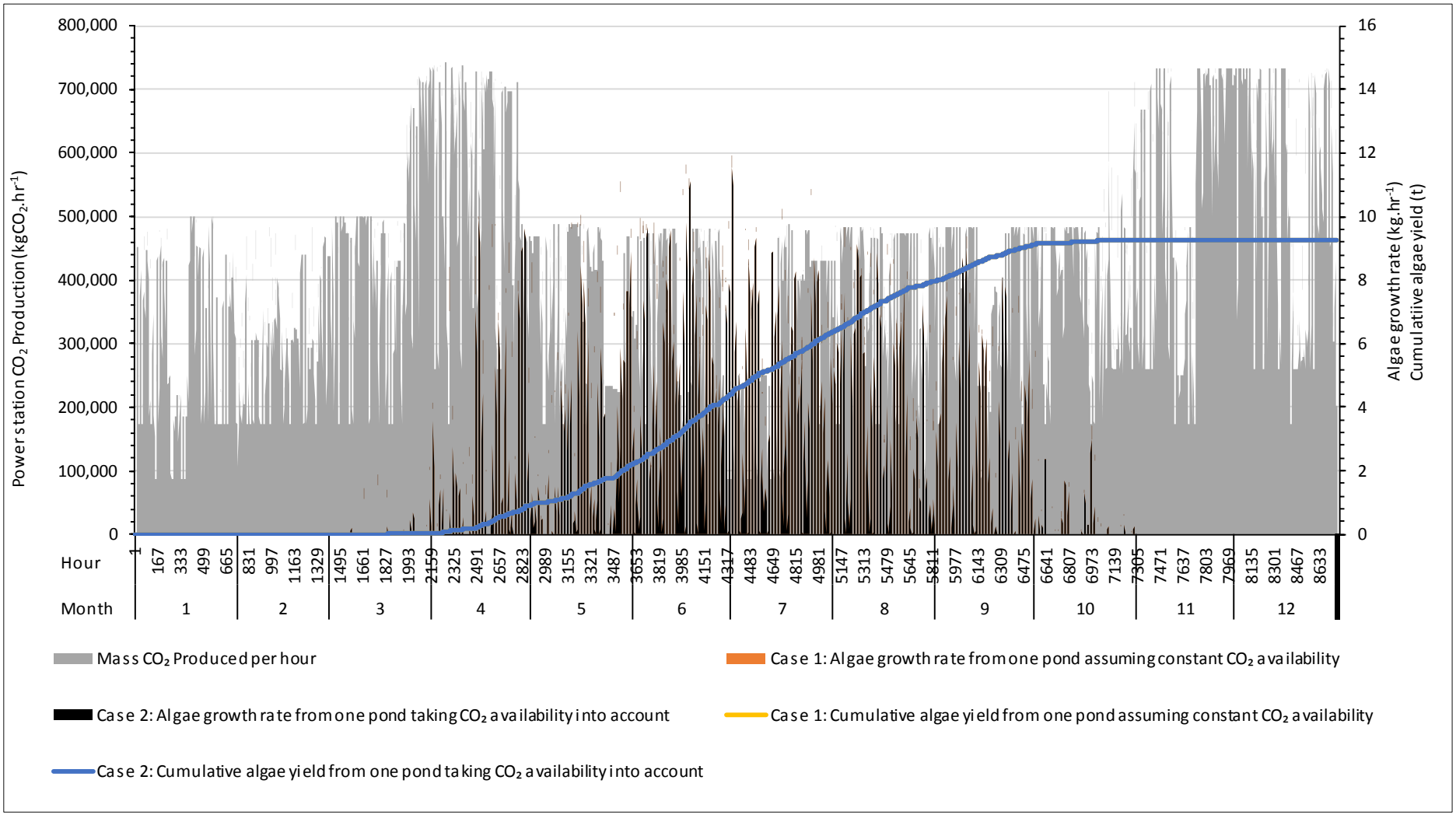
Whitegate


Power station CO_2 production per hour ($kgCO_2.hr^{-1}$)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Algae growth rate ($kg.hr^{-1}$)
Cumulative algae yield (t)
16
14
12
10
8
6
4
2
0
Hours
0 169 338 507 676 845 1014 1183 1352 1521 1690 1859 2028 2197 2366 2535 2704 2873 3042 3211 3380 3549 3718 3887 4056 4225 4394 4563 4732 4901 5070 5239 5408 5577 5746 5915 6084 6253 6422 6591 6760 6929 7098 7267 7436 7605 7774 7943 8112 8281 8450 8619
Month
1 2 3 4 5 6 7 8 9 10 11 12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

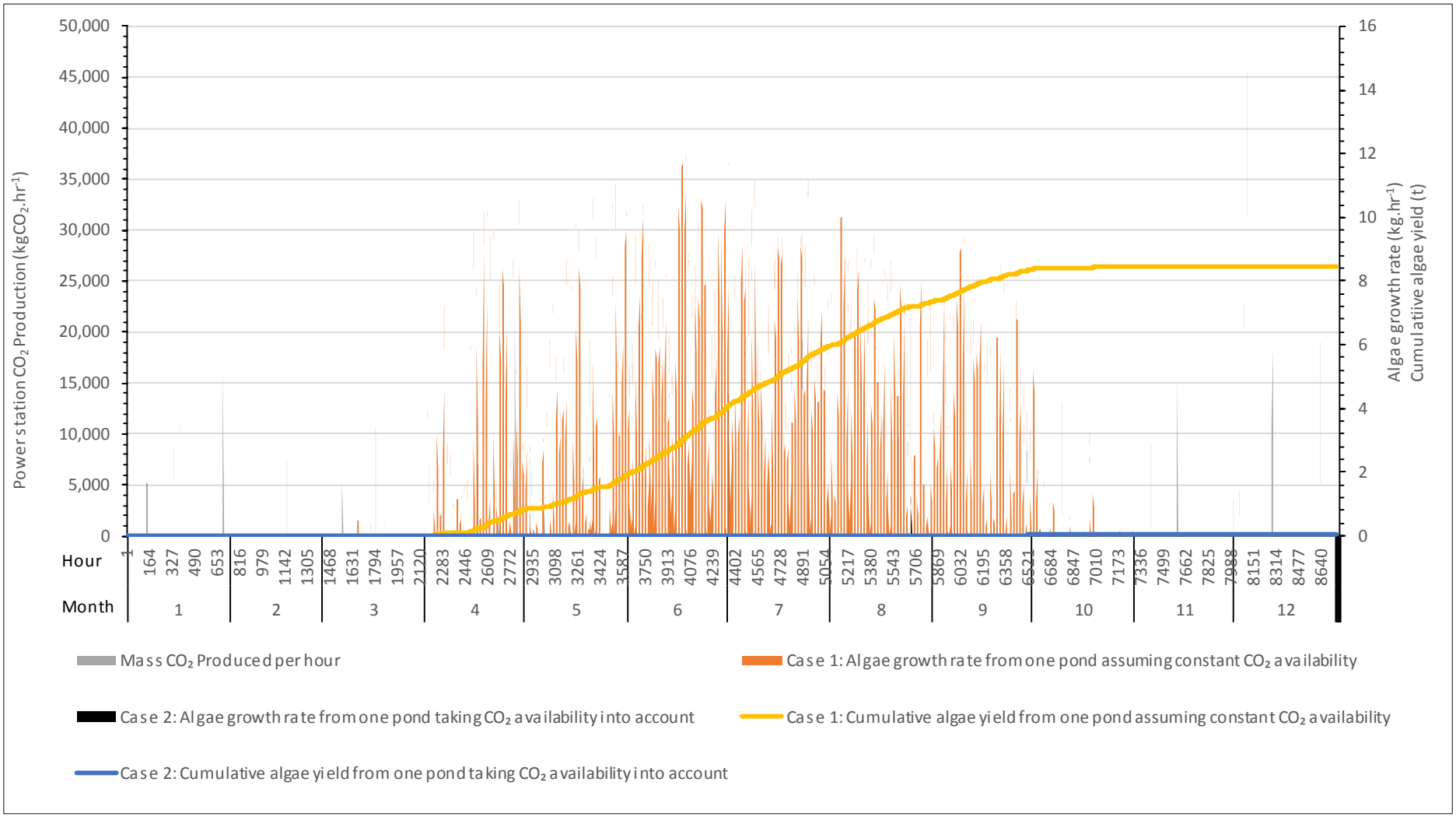
Huntstown



Tawnaghmore


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulative algae yield (t)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
16
14
12
10
8
6
4
2
0
Hour
1
167
333
499
665
831
997
1163
1329
1495
1661
1827
1993
2159
2325
2491
2657
2823
2989
3155
3321
3487
3653
3819
3985
4151
4317
4483
4649
4815
4981
5147
5313
5479
5645
5811
5977
6143
6309
6475
6641
6807
6973
7139
7305
7471
7637
7803
7969
8135
8301
8467
8633
Month
1
2
3
4
5
6
7
8
9
10
11
12
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

Moneypoint


Power station CO_2 Production ($kgCO_2.hr^{-1}$)
Algae growth rate ($kg.hr^{-1}$)
Cumulative algae yield (t)
Hour
Month
Mass CO_2 Produced per hour
Case 1: Algae growth rate from one pond assuming constant CO_2 availability
Case 2: Algae growth rate from one pond taking CO_2 availability into account
Case 1: Cumulative algae yield from one pond assuming constant CO_2 availability
Case 2: Cumulative algae yield from one pond taking CO_2 availability into account

Rhode