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Title	The impact of sustainability assessment of renewable gas systems on policy implications and optimum end use
Authors	Long, Aoife
Publication date	2021
Original Citation	Long, A. 2021. The impact of sustainability assessment of renewable gas systems on policy implications and optimum end use. PhD Thesis, University College Cork.
Type of publication	Doctoral thesis
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Download date	2026-11-03 13:52:29
Item downloaded from	https://hdl.handle.net/10468/13244

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The impact of sustainability assessment of renewable gas systems on policy implications and optimum end use

Thesis presented by

Aoife Long, BEng, MSc

for the degree of

Doctor of Philosophy

University College Cork

School of Engineering

Head of School: Dr. Jorge C. Oliveira

Supervisors: Professor Jerry Murphy & Professor Brian Ó'Gallachóir

2021

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Declaration

"This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property."



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Aoife Long

Acknowledgements

I would like to thank the following, who have supported and encouraged me throughout my research:

My supervisor, Professor Jerry Murphy for his guidance, encouragement, and technical insight. I would also like to thank him for building a strong culture of collaboration and support in our research group.

My second supervisor, Professor Brian Ó'Gallachóir has also provided support and encouragement during my research and provided insight into the mechanics of academia as I developed my own EPE skills.

The research group managers during my time, Dr. David Wall and Dr. Richard O'Shea, for reviewing my work, providing technical guidance where necessary and collaboration on research papers.

My collaborators; Archishman Bose, Dr. Richard O'Shea, Dr. Rory Monaghan, Dr. David Wall, Dr. Beatrice Smyth, Dr. Maeve O'Connell, Dr. Kian Mintz-Woo and Dr. Hannah Daly, for their technical insight and contribution to my research goals.

The Bioenergy research group that I joined is now the Circular Economy Energy and Environmental Systems group. I have learned so much from conversations and discussions with colleagues, as well as discussing my own research with new students. It has been a privilege to be a part of this group of talented academics.

Science Foundation Ireland, who have funded my research and the MaREI Institute that I am a part of.

The science communication community at UCC and beyond, who I have learned so much from as I attempted to share my own knowledge.

My family and friends, in particular those who provided childcare during Covid-19 and while I was in the final write-up stages.

Abstract

Ireland has a significant potential resource to decarbonise natural gas through producing green gas for renewable heat and transport. Key resources for anaerobic digestion include food waste, slurry from farming, and grass silage. Gasification and methanation of willow are potential future resources. The 2018 recast European Renewable Energy Directive (RED recast) sets emissions savings criteria for renewable fuels. The criteria are more stringent for use of the fuel as heat, with both a higher specified emissions savings criteria (80% versus 65% for transport) and a lower Fossil Fuel Comparator (80g CO_2 MJ^{-1} versus 94 CO_2 MJ^{-1} for transport). This research aims to determine if Irish feedstocks and conversion pathways can meet the emissions savings criteria of the RED recast. Mono-digestion of grass was initially tested and demonstrated to achieve a greenhouse gas emissions saving of 73% for transport, meeting the 65% emissions saving criteria. For use as heat, the saving achieved is 65% against criteria of 80%. Gasification and methanation of willow were then tested to determine if heat would be a viable end use from a sustainability perspective. Previous land use was shown to have a significant impact on the results of the analysis. Converting land from grassland for cultivation of willow results in greater emissions when compared to conversion from arable land as grassland has a higher rate of carbon sequestration. The gasification methanation pathway was found to meet emissions savings criteria for transport in most cases, and for heat when converting from arable land only. In Ireland, over 90% of agricultural land is grassland. The highest emission saving of 97% was achieved through conversion from arable land for the transport end use. Considering EU and national emissions policies, a transport end use for renewable gas will achieve a greater emission saving towards targets as compared to a heat end use and will contribute (with a weighting of two) to the RED recast 14% renewable energy in transport target. Using biomethane in the Emissions Trading System (ETS) sector will not contribute to national non-ETS targets set by the EU. While the analysis

demonstrates a clear policy preference for a transport end use renewable gas has been proposed as a solution to decarbonise industrial processes in Ireland, specifically heat demand (which is part of the ETS sector). As part of this effort, the breast-milk substitutes industry is proposing to use renewable gas as a substitute for fossil natural gas. However, decarbonising the industrial processing of breast-milk substitutes can have potential ethical implications that have not previously been analysed in literature. World Health Organisation nutrition targets aim to increase exclusive breastfeeding to at least 50% globally by 2025 to improve maternal, infant, and young child health and nutrition, a target that will have implications for the energy transition. The analysis in this thesis compares the emissions saved in Ireland from decarbonising the industrial processing of breast-milk substitutes with renewable gas with the emissions saved by an increase in exclusive breastfeeding to 50% in both Ireland and a key export market, China. The emissions saved from achieving the minimum global breastfeeding target are greater than when renewable gas is used to displace natural gas in the production of breast-milk substitutes in Ireland. The decarbonisation of breast-milk substitutes with renewable gas is discussed in relation to the principle of justice as non-maleficence, a principle based on the commitment to avoid harm, a novel application of a principle of justice. Considering this principle it is concluded that breastfeeding support can be considered a demand-side measure for mitigating climate change by reducing the demand for energy services to produce breast-milk substitutes.

Thesis output

Chapters which have been published as papers or are currently under review in peer-reviewed journals:

Chapter 3: Long, A., Murphy, J.D., 2019 Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range or sources for renewable heat and transport? Renewable and Sustainable Energy Reviews Volume 115, November 2019, 109347

Chapter 4: Long, A., Bose, A., O'Shea, R., Monaghan, R., Murphy, J.D. Implications of European Union recast Renewable Energy Directive sustainability criteria for renewable heat and transport: Case study of willow biomethane in Ireland. Renewable and Sustainable Energy Reviews Volume 150, October 2019, 109347

Chapter 5: Long, A., O'Shea, R., Murphy, J.D. Evaluating the best end use for agricultural biomethane from an EU energy and emissions policy perspective (complete and submitted to Applied Energy)

Chapter 6: Long, A., Mintz-Woo, K., Daly, H., O'Connell,. M., Smyth, B., Murphy,. J.D. Infant feeding and the energy transition: A comparison between decarbonising breastmilk substitutes with renewable gas and achieving the global nutrition target for breastfeeding. Under review for The Journal of Cleaner Production

Contribution to the papers

Chapter 3: I was the first author of the paper and responsible for the research and data analysis.

Chapter 4: I was the first author of the paper and responsible for the study design, research and data analysis.

Chapter 5: I was the first author of the paper and responsible for the study design, research and data analysis.

Chapter 6: I was the first author of the paper and responsible for decision making in the approach to the study, leading the collaboration and integrating contributions from co-authors. I carried out the study design, research and data analysis for emissions calculations.

Nomenclature

List of Abbreviations

AD	Anaerobic Digestion
AWMS	Animal Waste Management System
Biogas	Produced using anaerobic digestion, this gas contains carbon dioxide and methane
Biomethane	Produced by upgrading biogas to remove the carbon dioxide, this gas is normally 97% methane
BMS	Breast-milk substitutes - Any food being marketed or otherwise presented as a partial or total replacement for breast milk, whether or not suitable for that purpose (World Health Organisation, 1981)
CNG	Compressed natural Gas
Combination feeding	Infant is breastfed and also receives formula
DM	Dry Matter
EBF	Exclusive breastfeeding – Infant is only breastfed; this refers to an individual infant
FFC	Fossil Fuel Comparator, the emissions from a fossil fuel to be compared with a renewable alternative
FW	Fresh Weight
EF	Emissions Factor
F_{SN}	Annual amount of synthetic fertiliser applied to soils kg N yr^{-1} – (IPCC Nomenclature)
GNI	Gas Networks Ireland
GS:Sl	Grass Silage: Slurry
GWh	Gigawatt hour

GWP	Global Warming Potential
HGV	Heavy Goods Vehicle
HHV	Higher Heating Value
IPCC	Intergovernmental Panel on Climate Change
LHV	Lower Heating Value
Mc	Moisture content
MCF	Methane Conversion Factor
NGV	Natural Gas Vehicle
N_{cows}	Number of cows in country
Renewable Gas	This term can apply to both biogas and biomethane, it is also commonly called green gas
RED Recast	Renewable Energy Directive (recast)
RES-H	Renewable Energy Supply - Heat
RES-T	Renewable Energy Supply in Transport
SEAI	Sustainable Energy Authority of Ireland
VS	Volatile Solids
VSR	Volatile Solids Ratio
WHO	World Health Organisation
WW	Wet Weight

Units

g $CO_{2\text{-eq}}$ MJ^{-1}	grams Carbon dioxide equivalent per mega joule
GJ t^{-1}	Giga joules per tonne
GJ ha^{-1} y^{-1}	Giga joules per hectare per year
GWh	Gigawatt hour
ha	Hectare
kg t^{-1} FW_{mix}	Kilograms per tonne of fresh weight of grass and slurry mix
kWh t^{-1} FW_{mix}	Kilo watt hour per tonne of fresh weight of grass and slurry mix
kg $CO_{2\text{-eq}}$ t^{-1} FW	Kilograms of Carbon dioxide equivalent per tonne of fresh weight
kJ kg^{-1} $°C^{-1}$	Kilo joules per kilogram per degree celsius
kWh	Kilowatt hour
m^3_{biogas}	meter cubed of biogas
m^3 CH_4 t^{-1} FW	Meters cubed of methane per tonne of fresh weight
MJ m_n^{-3}	Mega joules per meter cubed
$MJ_{biomethane}$ t^{-1} FW_{mix}	Mega joules of biomethane per tonne of fresh weight of grass and slurry mix
MW_{SNG}	Mega watts of Synthetic Natural Gas

1 Introduction

1.1 Background

This thesis is concerned with the production of renewable gas in Ireland, in particular with modelling of renewable gas systems, assessment of sustainability of the systems and policy implications to assess optimum end use. Renewable gas is also known as green gas, biogas, or biomethane; when produced from thermal processes such as gasification systems it is often termed as synthetic gas or syn-gas. When we examine anaerobic digestion of wet organic materials, the gas produced contains both carbon dioxide and methane and is typically referred to as biogas, whereas biomethane is the upgraded biogas with the carbon dioxide removed. Biogas can be upgraded to natural gas standard and injected into the existing gas network. When we consider thermal gasification processes the syn-gas can undergo methanation and this gas may also be termed biomethane. Biomethane is a renewable energy vector that can be used for electricity, heat and transport.

In Ireland, approximately 60 % of national greenhouse gas (GHG) emissions reported to the IPCC are from the energy sector [1], which is currently dominated by fossil fuels [2,3]. Natural gas in particular plays a dominant role in the energy sector in Ireland, comprising 29% of Ireland's primary energy use [3]. Renewable gas, can potentially be produced at scale from Irish feedstocks and displace natural gas use [4]. Industrial heat is a particular interest, with industry users seeing it as a way to improve production from an environmental perspective, without changing any processes [5]. Use as industrial heat however, has the potential to divert the limited resource from heavy transport, which has limited options for decarbonisation [6].

In Ireland, the initial sources of biogas which should be considered include for wastes and residues such as animal slurry and food waste; such systems serve a function in treating waste products, reducing fugitive emissions

(such as from open slurry tanks) and improving water quality. Over time, energy crops such as grass, willow and seaweed may be introduced [7] to improve the resource. In Europe, traditionally biogas has mainly been used for electricity generation or Combined Heat and Power (CHP). Since 2013 there has been a significant increase in facilities which upgrade biogas for grid injection and for use as a transport fuel. In the EU in 2015, biogas production was equivalent to 4.4% of natural gas use [8]. In Denmark, 10% of the gas in the natural gas grid was considered green [9]. In The Netherlands, 3.24 PJ per annum of biomethane is injected into the grid [10]. Six EU gas grids (Belgium, Denmark, France, Germany, the Netherlands, Sweden and Switzerland) have signed up to have 100% renewable gas by 2050 under the Green Gas Initiative [11]. In order to develop a market for green gas in Ireland, certification is necessary to demonstrate compliance with EU GHG emissions savings criteria [12] and to avail of potential national subsidy schemes such as the Support Scheme for Renewable Heat (SSRH) [13].

1.2 Rationale for the thesis

Biomethane has a role to play in the energy transition. The resource for the fuel however will be limited as once we proceed beyond wastes to energy crops larger resources will require larger tracts of land for cultivation. While it is a very versatile form of renewable energy, with applications in electricity, heat or transport, the limit on the resource demands that it is applied and used in the most advantageous way, to maximise emissions saved, to complement other renewable energy sources or climate mitigation options and to serve the hard to abate sectors with few alternatives for decarbonisation. This thesis is concerned with determining an appropriate end use for biomethane, with cognisance of current EU energy and emissions policy.

1.3 Aims and objectives

During the timeframe of this research, the EU Renewable Energy Directive was under revision [14], with the final version adopted in 2018 [12]. An

initial research question was to determine if the proposed end use of a green gas pathway would have an impact on the ability of the pathway to meet the EU emissions savings criteria to be considered renewable energy within the EU (Chapter 3). This led to a further research question to determine if biomethane could meet the sustainability criteria for renewable heat, using gasification of willow followed by a methanation step as an example of a future fuel production system (Chapter 4). With a clear preference in the EU recast Renewable Energy Directive (RED recast) for transport as an end use for renewable gas established by the research in Chapters 3 and 4, Chapter 5 had an ambition to investigate how biomethane can contribute to key EU energy and emissions policies, and to demonstrate how these policies interact with each other to influence the development of national policies for biomethane. Chapter 6 documents the investigation of the wider implications of deployment of biomethane using the example of decarbonising breast-milk substitutes (BMS) to consider the previously unstudied moral implications of an engineering intervention to improve production from an environmental perspective. The key methods employed were life cycle analysis according to EU RED recast criteria and national emissions according to IPCC methodology. The principle of justice as non-maleficence was employed to consider the moral implications of decarbonising BMS.

1.4 Thesis structure and overview of the chapters

The thesis is divided into seven chapters. This chapter (Introduction) introduces the thesis topic and the aims and objectives of the work.

Chapter 2 is a brief literature review which outlines the state of the art in terms of renewable gas pathways for Ireland, typical end uses for biomethane and alternative options for decarbonisation for these end uses, EU policy influences and ethical issues associated with the energy transition.

Chapter 3 provides a more detailed overview of the potential for a biomethane industry in Ireland, considering key feedstocks, energy security and sample sustainability calculation considering a mono-digestion of grass silage pathway.

Chapter 4 considers the emissions savings from the full supply chain of willow for gasification/methanation using life cycle analysis methodology set out in the RED recast.

Chapter 5 focuses on the potential for biomethane from anaerobic digestion of grass silage and slurry to meet both energy and emissions targets for Ireland that have been set by the EU.

Chapter 6 considers the moral implications of using biomethane as renewable heat to decarbonise breast-milk substitutes.

Chapter 7 outlines the overall conclusions for the work and provides a potential direction for further research related to this thesis.

As this is a thesis by publication, the primary research chapters (Chapters 3-6) have been submitted to peer-reviewed journals in the field of engineering. At the time of submission, Chapters 3 & 4 have been published, Chapter 6 is under review following a response to reviewer comments, and Chapter 5 is submitted. These chapters appear in the thesis largely as published, with some modifications. Chapters 3 – 6 are summarised below:

Chapter 3: Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and or transport?

Ireland has a significant potential resource to decarbonise natural gas through producing green gas for renewable heat and transport. Key resources for anaerobic digestion include food waste, slurry from farming, and grass silage. This chapter establishes production pathways for consideration in a certification scheme. Certification is required to ensure

guarantee of origin and sustainability. This chapter also identifies potential challenges relating to sustainability and end use. Analysis in the chapter shows that biomethane must effect 12 g $CO_{2\text{-eq}}$/MJ for renewable heat and 28 g $CO_{2\text{-eq}}$/MJ for transport fuel to be deemed sustainable according to the recast Renewable Energy Directive. A sample calculation for grass biomethane shows that the emissions criteria for renewable transport are significantly easier to satisfy compared to renewable heat. Grass biomethane can achieve a greenhouse gas emissions saving of 77% for transport, meeting the 65% emissions saving criteria. For use as heat, the saving achieved is 66% against criteria of 80%. As such, these criteria push renewable gas production towards transport as an end use rather than heat which will have implications for the development of the industry in Ireland.

Chapter 4: Implications of European union recast Renewable Energy Directive sustainability criteria for renewable heat and transport: Case study of willow biomethane in Ireland

The 2018 recast European Renewable Energy Directive (RED recast) sets emissions savings criteria for renewable fuels. This chapter assesses the life-cycle emissions from gasification methanation of willow to produce renewable biomethane in order to compare the heat and transport 2026 sustainability criteria in the RED recast. The criteria are more stringent for use of the fuel as heat, with both a higher specified emissions savings criteria (80% versus 65% for transport) and a lower Fossil Fuel Comparator (80g CO_2 MJ^{-1} versus 94 CO_2 MJ^{-1} for transport). Scenarios tested were based on both the RED recast and the IPCC (Intergovernmental Panel on Climate Change) Global Warming Potential (GWP) values. Agro-chemical input data from Teagasc (the Irish Agriculture and Food Development Authority) was used for both mineral and organic fertilisers. Previous land use was shown to have a significant impact on the results of the analysis. Overall, 24 scenarios were tested. Converting land from grassland for cultivation of willow results in greater emissions when compared to

conversion from arable land. The gasification methanation pathway was found to meet emissions savings criteria for transport in most cases, and for heat when converting from arable land only. The highest emission saving of 97% was achieved through conversion from arable land for the transport end use.

Chapter 5: Evaluating the best end use for agricultural biomethane from an EU energy and emissions policy perspective

Biomethane produced via anaerobic digestion (AD) can be used as a means of displacing natural gas in the industrial sector (part of the EU Emissions Trading System (ETS)) or alternatively can be used as a transport biofuel. The transport sector is not part of the ETS but contributes instead to national emissions reduction targets under the EU effort sharing greenhouse gas (GHG) emissions reduction targets. As a circular economy system biomethane systems can simultaneously reduce GHG emissions in agriculture (also non ETS and part of national emissions). The Irish dairy sector is chosen as a case study as the number of cows in the country has increased leading to increased GHG emissions and increased slurry output which is a feedstock for AD. It is proposed that the slurry is co-digested with grass to achieve a greater energy yield than from digestion of slurry alone. The biomethane can be used in dairy processing in a circular economy approach, in residential heat or as a fuel for heavy goods transport. The Renewable Energy Directive (RED) recast sets life cycle GHG emissions criteria that must be met for the fuel to be considered sustainable. These are set lower for transport when compared to heat, with the effect that transport appears as the more advantageous end use. This chapter shows that a transport end use will achieve a greater emission saving for EU and national emissions savings targets as compared to heat and will contribute to the RED recast 14% renewable energy in transport target. Using biomethane in the ETS sector will not contribute to national non-ETS targets set by the EU.

Chapter 6: Infant feeding and the energy transition: A comparison between decarbonising breastmilk substitutes with renewable gas and achieving the global nutrition target for breastfeeding.

Renewable gas has been proposed as a solution to decarbonise industrial processes, specifically heat demand. As part of this effort, the breast-milk substitutes industry is proposing to use renewable gas as a substitute for fossil natural gas. However, decarbonising the industrial processing of breast-milk substitutes can increase social license for these products, potentially undermining breastfeeding. World Health Organisation nutrition targets aim to increase exclusive breastfeeding to at least 50% globally by 2025 to improve maternal, infant, and young child health and nutrition. This target will have implications for the energy transition. A weakness of existing energy models is that demands for end-use products such as breast-milk substitutes are typically not considered explicitly. This chapter develops an analytical framework for explicitly representing infant feeding methods in energy systems models. The emissions saved in Ireland from decarbonising the industrial processing of breast-milk substitutes with renewable gas are compared with the emissions saved by an increase in exclusive breastfeeding to 50% in both Ireland and a key export market, China. The chapter demonstrates that the emissions saved from achieving the minimum global breastfeeding target are greater than when renewable gas is used to displace natural gas in the production of breast-milk substitutes in Ireland. The decarbonisation of breast-milk substitutes is discussed in relation to the principle of justice as non-maleficence, a principle based on the commitment to avoid harm, a novel application of a principle of justice. The chapter concludes that breastfeeding support can be considered a demand-side measure for mitigating climate change by reducing the demand for energy services to produce breast-milk substitutes. A key recommendation is to position breastfeeding support as both a public health and a climate justice issue that is relevant for a just transition. The framework developed for this paper could be applied to

support the inclusion of a wider range of mitigation options with social justice outcomes in energy system models.

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2 Literature Review

2.1 Policy influences

As Ireland is an EU member state, EU policies and directives will have a significant influence on the development of a renewable gas industry in Ireland. The EU has set targets for both renewable energy shares and emissions reductions. When member states do not meet energy and greenhouse gas emissions targets fines can be imposed. There is also a reputational risk associated with not meeting targets.

2.1.1 EU Renewable Energy Directives

The initial Renewable Energy Directive (RED) [1] and the Renewable Energy Directive recast (RED recast) [2] have aimed to increase the share of renewable energy in the EU. In the initial RED target shares of renewable energy for overall energy and for the heat, electricity and transport sectors were set for each member state to reach by 2020. For Ireland the overall national target was 16% renewable energy, with individual targets of 10%, 12% and 40% for transport, heating and cooling, and electricity respectively. Data from 2017 published in 2019 showed the most progress towards the electricity target with 30.1% renewable energy share. The shares of renewable energy in transport and heat were 7.4% and 6.9% [3].

The RED recast sets an overall target of at least 27% renewable energy share for all EU countries by 2030 combined with an individual target for each member state of at least 14% renewable energy supply in transport. Some feedstocks can contribute twice their energy content towards meeting this transport target. These are listed in Annex IX of the RED recast and include lignocellulosic material such as grass and willow.

2.1.2 EU Emissions Trading System

The EU Emissions Trading System (ETS) [4] aims to reduce emissions associated with electricity production and large energy users. It is a ‘cap and trade’ system, where each installation is allowed a certain amount of

emissions, known as the ‘cap’. If an installation exceeds this cap, then then allowance must be bought to compensate for the additional emissions produced. Installations that do not produce emissions to the level of their cap are allowed to sell their emissions saved, to users who need them to reduce their emissions to their capped amount. The system aims to incentivise emissions reductions and create a market value for carbon dioxide (CO_2) emissions.

2.1.3 EU Effort Sharing Regulation

Emissions from sources that are not part of the ETS are covered by the Effort Sharing Regulation [5]. This aims to reduce non-ETS emissions and responsibility lies with EU member states. Each member state has targets of emissions reductions to achieve compared with a 2005 baseline. In Ireland, the emissions reduction to be achieved by 2030 is 30% compared to 2005 emissions. Ireland is expected to exceed it compliance obligations for 2020 by up to 17 Mt $CO_{2\text{-eq}}$ [6]. Emissions data is normally published two years after the year reported [7]. Teagasc have estimated that anaerobic digestion of bioenergy crops could account for a reduction of 1.37 Mt $CO_{2\text{-eq}}$ per annum from 2021 – 2030, noting that this much of this reduction would be attributed to the fuel consuming sectors [8] as opposed to the agriculture sector.

2.2 EU Sustainability criteria

Sustainability criteria in the RED [1] and RED recast [2] refer to the emissions savings associated with renewable energy use when compared with a fossil fuel comparator (FFC). The fossil fuel comparator is the incumbent fossil fuel to be replaced with a renewable energy source. For diesel this was set at a value of 83.8 g $CO_{2\text{-eq}}$. The emissions saving required has been getting increasingly more stringent from the introduction of the initial RED, starting with a saving of at least 35% and increasing to at least 50% for installations from 2017 and 60% from 2018. This trend continued with the introduction of the RED recast [2] which requires a saving of at least 65% for a transport end use from 2021, at least 70% for electricity,

heating and cooling from 2021 until 2025, and at least 80 % for electricity, heating and cooling from 2026. A major difference with the introduction of the RED recast is the different sustainability criteria for different end uses of renewable energy. Fossil fuel comparators are set for the different end uses as opposed to being based on the energy value of the fuel displaced. The purpose of the sustainability criteria is to measure compliance with the requirements of the directive for national targets, measure compliance with renewable energy obligations, and eligibility for financial support for the consumptions of fuels [2]. While it is possible to produce fuels that are not compliant with sustainability criteria, these fuels will not contribute towards national renewable energy targets and will not be eligible for any financial support.

2.3 Resource of biomethane in Ireland

2.3.1 Food waste

Food waste is a potentially profitable feedstock for biomethane as a gate fee can be charged for the waste [9]. In Ireland, producers of food waste must segregate the waste for treatment, while local authorities are required to provide brown bins for waste segregation at domestic level [10]. The RED recast treats food waste as a residue, with zero emissions up to the point of collection [2]. The energy resource from anaerobic digestion of food waste in Ireland could be up to 2.65 PJ y^{-1}, or 1.06 % of energy in transport in 2015 [11]. While this is a potentially valuable source of energy, anaerobic digestion of food waste can also be seen as a way to turn a waste product into a resource of energy and fertiliser, whereas composting food waste produces fertiliser (or soil amendment only).

2.3.2 Grass silage

Grass silage is potentially the largest and most viable feedstock for production of biomethane in Ireland [12]. There is no land use conversion required and the energy yield is relatively high. Wall et al., 2014 obtained a specific methane yield of 404 L CH_4 kg^{-1} Volatile Solids (VS) from grass silage [13]. The emissions associated with cultivation of the feedstock will

need to be considered for sustainability calculations [2], however, an emissions credit may also be available due to soil carbon accumulation associated with grassland [14]. In Ireland, it is expected that grass silage will be co-digested with slurry [15].

2.3.3 Slurry

Similar to food waste, treating slurry using anaerobic digestion has the potential to turn a waste product into a resource of renewable energy and biofertiliser. Manure is currently spread by farmers as a crude fertiliser [16]. By digesting slurry and adopting low emissions slurry spreading (LESS) techniques [17], the methane emissions associated with slurry spreading can be reduced, whilst enhancing the nutrient availability in the fertiliser. The enhanced nutrient availability could potentially improve water quality as a lower nutrient amount can be applied as long as best practices are used to minimise environmental impacts. The RED recast considers slurry as a residue, with zero emissions up to the point of collection. It also has a default emissions credit of 45 g CO_2 MJ^{-1} which reflects the emissions saved from improved agricultural management of the slurry [2].

2.3.4 Willow

Willow is considered a potential future resource for biomethane [12], and conversion to energy is via gasification rather than anaerobic digestion [18]. Gasification of woody crops is established technology; commercial viability however remains a challenge [19]. In Ireland, the potential resource of Willow is constrained by land use conversion limits associated with EU cross-compliance rules (91% of Irish agriculture land is under pasture or grassland) as there is no current large-scale resource that is considered available for energy production [20]. From an energy balance perspective, gasification of willow has a similar energy yield per hectare as sugarcane ethanol from Brazil [21].

2.4 Potential end uses

The advantage of biomethane is that it is a potentially versatile renewable vector, with applications in the heat, electricity, or transport sectors. Of the 15 countries participating in the International Energy Agency Bioenergy: Task 37 “Energy from Biogas” in 2017, most used renewable gas for heat, electricity or combined heat and power (GHP) generation. Some countries are in the process of building capacity to use the fuel for transport. Thus far, where countries do use renewable gas for transport, the share is in the region of 0.5 % to 3 % of available gas. Only Sweden is an exception with 55 % of their biogas used as vehicle fuel [22]. In Ireland, biomethane is not seen as a necessary means of decarbonising the electricity sector, due to the large-scale deployment of wind energy [3]. It will be more valuable in the heat or transport sectors, where Ireland will struggle to meet EU renewable energy share targets [23]. While there are potential alternatives to decarbonising heat, transport is seen as the most difficult to decarbonise sector, as options are limited, and deployment of renewables such as electricity has been slow [24]. Bio-methane has emerged as a lucrative alternative for conventional transportation fuel with all the advantages of natural gas including a dense distribution, trade and supply network [25]. These advantages are also present for bio-methane as a renewable heat source.

2.5 Alternative options for decarbonising heat

Natural gas and oil are the leading sources of heat in Ireland, with natural gas for heat use accounting for 12.8 % of energy consumption in Ireland [26]. Any renewable options will likely be replacing these incumbent fuels. Biomass boilers have been the dominant source of renewable heat in the UK since the introduction of their Renewable Heat Incentive (RHI), providing 91 % of installed capacity in the non-domestic scheme. In the domestic scheme, biomass boilers accounted for just over half of the heat generated, with air-source and ground source heat pumps making up the rest. Most of the take-up in the domestic scheme was off-gas grid homes at

72%. In addition to this 72% of take-up was associated with detached houses and bungalows, which may reflect the requirement for space for the boiler and storage of the biomass [27]. In addition to cultivated biomass, forestry thinnings and residues, a by-product of the managed forestry industry, are often used in biomass boilers. This ensures that the forestry resource is used in the most efficient way. Most of the 6.8% RES-H in Ireland has been met through solid biomass, almost half of which (46%) is wood wastes and wood residues consumed for heat in the wood processing sector [23]. In New Zealand, biomass boilers have been used as a solution to decarbonising infant formula production for the Danone brand [28].

Biofuel co-generation is often referred to as a Combined Heat and Power (CHP) system, where both electricity and heat is produced. Waste heat from industrial processes can be used for a district heating system. In Ireland, uptake of district heating has been very low, with district heating systems providing less than 1% of the heat market [29]. Heat pumps use refrigeration technology to provide renewable heat. The two main types are Air Source and Ground Source. These are identified as a source of renewable heat given their efficiency and also the added advantage that they can use renewable electricity as a heat source [27]. They are seen as a suitable means of renewable heat for homes that are not on the gas grid [30]. Given the intermittent nature of renewables such as wind and solar on the grid that are complemented with electricity from coal and gas, the heat provided from electricity cannot be considered fully renewable [31].

The interchangeability of systems is a major consideration of decarbonising heat and is why displacing natural gas with a biomass fuel version appears attractive. The required temperature level can determine the technology and fuel options available. For example, “low-temperature heat from a heat pump cannot be substituted for high-temperature heat from a gas boiler.” [31a] Renewable gas is a more appropriate technology for some high-temperature heat uses such as steel and cement production where

there are less alternatives for decarbonisation as it can achieve the same high temperature heat (>400°C) as fossil fuels [31b].

2.6 Alternative options for decarbonising transport

Oil is currently the dominant fuel in transport in Ireland [26]. Electrification of transport requires users to change both their vehicle and installing a charging point at their home. Uptake of electric vehicles in Ireland has initially been low but is gradually improving from a low base. There are now 41,000 electric vehicles and plug-in hybrids on Irish roads [32], out of a total 2,860,984 vehicles under current licence [32a]. Even if there is an increasing uptake in electric vehicles, heavier forms of transport are often not suitable for electrification [24]. Most of Ireland's renewable energy in transport is from biofuel blending [3], where biofuels have been blended with fossil fuels, and no decision making is required of the end user. A shift to more sustainable forms of transport has the potential to reduce emissions, whether moving from solo travel in passenger cars to public transport [33], or an increase in walking or cycling. It has also been suggested that cycling and walking have a much lower social cost compared to automobility in the EU due to positive health benefits [34]. While mode shift can be encouraged for passenger transport, there will be a substantial remaining transport demand for which low carbon fuels will be required.

2.7 Social justice and the energy transition

As discussed in previous sections, the end use of biogas or any renewable fuel is an important aspect of discussion for the energy transition. When specific end uses are discussed for decarbonisation, there is a risk that the wide context of alternatives is not fully considered or supported. Within the heat end-use sector, decarbonising the production of infant formula, which is also referred to as breast-milk substitute, along with products such as toddler and follow-on milks, is one of the proposed end-uses of renewable gas. While the 'greening' of breast-milk substitutes could reduce carbon emissions, the public health impacts of continued widespread use

of breast-milk substitutes are problematic. The World Health Organisation recommends exclusive breastfeeding (EBF), where an infant is only breastfed for the first 6 months, and continuing for a duration of two years for optimal infant health [35]. The World Health Organisation (WHO) Global Nutrition Target no. 5 aims to increase the rate of exclusive breastfeeding in the first 6 months to at least 50% globally by 2025 [36]. An increased rate of breastfeeding with a corresponding decrease in the use of breast-milk substitutes (BMS) could have important implications for the energy services demand to produce breast-milk substitutes, given the interdependency between the agriculture, processing and socio-cultural systems that influence infant feeding.

Some work has been done to analyse the carbon footprint of breast-milk substitutes. It has been established that breast-milk substitutes have a larger carbon footprint in comparison with breastfeeding for four countries, while noting that breastfeeding and breast-milk substitutes are functionally different [37]. Reasons for low breastfeeding rates are multi-faceted since breastfeeding is a complex behaviour dependent on mother and infant individual characteristics, public health systems, family, community and professional support and wider cultural values. Some of these factors are non-modifiable such as maternal age and socioeconomic status, but other factors may be modifiable such as self-efficacy, mode of birth, social and professional support. Promotion of breast-milk substitutes is recognised as one of the factors undermining breastfeeding [36,38]. In relation to the agri-food sector, price and ‘greenness’ are factors in consumer decisions that can influence supply chain design to optimize both profits and sustainability [39]. In addition, companies in the food and beverage industry and other sectors that address sustainability challenges either directly or indirectly can significantly outperform business-as-usual scenarios in terms of reputation and social licence [40].

2.8 Conclusion

Renewable gas can potentially be applied to the electricity, heating and cooling, or transport sectors as a means of decarbonisation. In Ireland, wind generation has been successful in generating large amounts of renewable electricity, therefore renewable gas would be better deployed in the heat or transport sectors. While alternatives to decarbonisation exist in both sectors, there will remain a demand that will require the flexibility of renewable gas. Policy in Ireland will be driven by EU energy and emissions targets, where fines will be imposed for not meeting national targets.

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3 Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and/or transport?

Aoife Long [a,b], Jerry D. Murphy[a,b,*]

[a] *MaREI Centre, Environmental Research Institute, University College Cork, Cork, Ireland*

[b] *School of Engineering, University College Cork, Cork, Ireland*

Keywords

Green gas; Biomethane; Sustainability; Policy; Life Cycle Analysis; Energy auditing

Abstract

Ireland has a significant potential resource to decarbonise natural gas through producing green gas for renewable heat and transport. Key resources for anaerobic digestion include food waste, slurry from farming, and grass silage. This paper establishes production pathways for consideration in a certification scheme. Certification is required to ensure guarantee of origin and sustainability. This paper also identifies potential challenges relating to sustainability and end use. Analysis in this paper shows that biomethane must effect 14.4 g $CO_{2\text{-eq}}$/MJ for renewable heat and 32.9 g $CO_{2\text{-eq}}$/MJ for transport fuel to be deemed sustainable according to the recast Renewable Energy Directive. A sample calculation for grass biomethane shows that the emissions criteria for renewable transport are significantly easier to satisfy compared to renewable heat. Grass biomethane can achieve an emissions saving of 77% for transport, meeting the 65% emissions saving criteria. For use as heat, the saving achieved is 66% against criteria of 80%. As such, these criteria push renewable gas production towards transport as an end use rather than heat. This will have implications for the development of the industry in Ireland.

Keywords: Green gas; biomethane; sustainability; policy; life cycle analysis; energy auditing.

*corresponding author: Prof Jerry D Murphy, MaREI centre, Environmental Research Institute, University College Cork, Ireland. E-mail: jerry.murphy@ucc.ie

3.1 Introduction

3.1.1 Rationale for renewable gas

The EU Renewable Energy Directive 2009 (RED) was introduced to increase the share of renewable energy in the EU energy system. Renewable Energy Supply Targets were set for the EU28, individual member states, and for energy type [1]. In 2015, the overall share of renewable energy in Europe was 16.4% and considered on track to meet the target of 20% of energy from renewable sources at Community level by 2020. In the EU, the greatest share of renewable heat is solid biomass. For renewable electricity, the greatest increase in renewables is attributed to increased deployment of onshore wind energy. In transport, biodiesel contributes most to meeting the target. Biogas does contribute to all three energy vector targets, albeit in a smaller share [2].

Green gas or renewable gas is gas that is produced mainly from biological material [3] and is often termed biomethane. In this paper, Biogas refers to the gas prior to upgrading, which contains approximately 55% CH_4 [4]. Biomethane refers to the upgraded gas, containing approximately 97% CH_4 [5]. It is also possible to produce gas from non-biological origins such as from electricity; this is often termed e-gas [6].

In Ireland, the initial sources of biogas should be wastes and residues such as animal slurry and food waste. Over time, energy crops such as grass, willow and seaweed may be introduced. Biogas can be upgraded to natural gas standard and injected into the existing gas network. It is a form of renewable energy that can be used for electricity, heat and transport. In Europe, traditionally biogas has mainly been used for electricity generation

or Combined Heat and Power (CHP). Since 2013 there is a significant increase in facilities which upgrade biogas for grid injection and for use as a transport fuel. In the EU in 2015, biogas production was equivalent to 4.4% of natural gas use [7]. In Denmark, 10% of the gas in the natural gas grid was considered green [8]. In The Netherlands, 3.24 PJ per annum of biomethane is injected into the grid [9]. Six EU gas grids (Belgium, Denmark, France, Germany, the Netherlands, Sweden and Switzerland) have signed up to have 100% renewable gas by 2050 under the Green Gas Initiative [10].

A green gas certification scheme is proposed for Ireland, an island economy in Northern Europe. The principal aim of the scheme is to enable a green gas market, facilitate production of biomethane and injection into the national gas grid, and trading of the gas. The certification scheme will track and verify the MWh of green gas traded and certify the greenhouse gas (GHG) emissions saved. In Europe, 6 countries now have a green gas certification scheme. These are Austria, France, Germany, Hungary, Italy and the UK. These are not all official government approved schemes. The administration is sufficient however to provide recognition and has acceptance by the relevant industry. Certification schemes are normally developed in response to an incentive to produce renewable energy. In Germany, there are three separate certification schemes to reflect the different end uses of the gas, either electricity, heat, or transport. In the UK, green gas certification is related to the Renewable Heat Incentive (RHI). The UK scheme is not formally recognised by the government, and there are therefore two separate schemes run by interested parties [11]. A secondary aim for the Irish scheme is that the certification scheme will be compatible with other schemes in the region and as such, would allow for international trading. Ireland is a small island economy, with a population of approximately 4.5 million people. A single certification scheme is therefore desirable for simplicity.

During this research, the Renewable Energy Directive has been recast. The sustainability criteria changed as new draft editions were released and again with the final version that has been adopted [12]. The analysis in this paper was initially based on emissions savings required in the 2016 Proposal for a new RED and Annexes [13][14]. The new recast EU RED was adopted as of 11 December 2018 [12]; this followed much discussion and proposals on revised sustainability criteria. In this paper, the original 2009 Renewable Energy Directive will be referred to as the RED [1]. The 2016 draft edition that part of the analysis was based on will be referred to as the draft RED [13,14], and the final adopted version will be referred to as the RED recast [12].

All EU countries are required to report their share of Renewable Energy Supply (RES) for each energy vector under the RED and RED recast [1][12]. Certifying the amount and use of renewable energy produced and used will assist Ireland in this reporting requirement. In some cases, a multiplier is applied to the energy use. For transport using advanced feedstocks listed in Annex IX of the RED recast, the RES resource is counted twice [12].

Ireland may meet or at least approach its national target for renewable electricity. Meeting heat and transport targets will be unlikely. Solid biomass is proposed to meet renewable heat targets and an increased share of biofuels is proposed for transport [15]. Both of these solutions would rely heavily on imports. While green gas can be deployed as any of the three energy vectors, in Ireland it would be more usefully deployed as renewable heat or transport, given the requirement to meet EU RED targets and avoid potential fines. A certification scheme for green gas would enable a market for selling to industry as renewable heat, or haulage and public transport companies for renewable transport. A support scheme for renewable heat (SSRH) has been introduced for Ireland. Biogas for combined heat and power installations is included in the current phase but not biomethane for grid injection. This is expected to be included in a subsequent phase. Feedstock for biomass and anaerobic digestion must

meet sustainability criteria [16]. The Emissions Trading Scheme (ETS) is already in operation in Ireland.

3.1.2 State of the art in renewable gas

A large body of research has been carried out to assess the theoretical resource of various feedstocks for Anaerobic Digestion (AD) in Ireland. Browne and Murphy, 2013 have identified the potential resource for food waste as 2.8% of energy in transport [17]; Smyth et al [5,18] and Wall et al., 2014 [19] have examined grass biomethane. Considering renewable fuels produced from electricity, anaerobic digestion of wastes/residues and grass, and gasification of woody crops, these resources were assessed at 19% of energy in transport in Ireland. Applying factors in the RED the resources would be equivalent to 40% RES-T (Renewable Energy Supply – Transport) [20]. This demonstrates that the resource is sufficient to introduce a green gas industry to this economy. The potential resource could be used for renewable transport [20] or heat [21]. More recently O'Shea et al. have assessed the practical resource and potential build order of biomethane plants in proximity to the national gas grid [22,23]. The profitable resource found adjacent to the gas grid from anaerobic digestion systems only was estimated as 12 PJ of biomethane (equivalent to 5.6% of transport fuel).

Emissions from bioenergy systems can be higher when compared with other non-combustion renewable technologies (such as wind and PV). Biogas and biomethane systems however, can be part of the circular economy system, and as such have benefits outside the energy system, such as in waste treatment [24], production of biofertilizer, improvement of water quality and reduced smells in the environment [25–27]. Anaerobic Digestion is considered mature technology. Current research is focused on optimising methane yields through pre-treatment of the biomass [28][29], Direct Interspecies Electron Transfer (DIET) [30] or the addition of trace elements [19] [31].

The primary commercially available resource of green gas is from wastes, residues and grass silage. These feedstocks were included in an “Increased biomethane scenario” in a report produced by the Sustainable Energy Authority of Ireland (SEAI). This scenario assumes that food waste, slurry waste streams, and grass silage will the main feedstocks for Ireland. The biomethane produced from this resource would then be injected into the grid at 42 above ground installations [32]. The “Increased biomethane scenario” would supply approximately 8.5 PJ of energy by 2030 and 13.3 PJ by 2050. This is approximately 4% and 6.2% respectively of projected 2020 energy demand in Transport [33]. Additionally, an ‘All AD feedstocks’ scenario assumes maximum use of grass silage and other resources with additional injection points, and an ‘Exploratory’ scenario included gasification technology. The ‘Increased Biomethane’ scenario of 12.5 PJ of renewable energy by 2050, is considered the most likely biomethane scenario for Ireland by the authors. This scenario makes maximum use of food wastes and slurries and some of Ireland’s large grass silage resource.

Seaweed has been proposed as a feedstock for AD in Ireland [34][35], however this is unlikely to be developed to an industrial level in the short term and as such need not be part of a certification scheme prior to 2020. Gasification of woody biomass has also been proposed [21] but there are very few plants producing biomethane from gasification globally, due to the high cost and low technology readiness level [TRL] of the technology [36]. Again, this would not be considered for a certification scheme prior to 2020.

Gas generation through Power to Gas technologies, has been found to be potentially an extremely important means of storing renewable electricity in the form of green gas [37]. Combining Power to Gas technology with anaerobic digestion has the potential to increase the methane output by a factor of close to two and to have circular economy benefits [38]. This technology is not deemed to be at a sufficiently high Technology Readiness Level (TRL), however there are numerous demonstration facilities in place,

with a facility in Wertle, Germany, operated by Audi integrating a 6MW electrolysis system producing hydrogen from wind electricity with the CO2 from a food waste digester to produce renewable methane for use as a transport fuel in natural gas vehicles (NGVs). Including sustainability criteria in the certification scheme is relevant to ensure the long-term viability of the industry. The RED recast has sustainability criteria of up to 65% greenhouse gas emissions savings by 2030 for transport and 80% for heat [12]. Thus, it is plausible that a particular green gas system may provide a sustainable renewable fuel for use as a propellant (in transport) but not as a source of renewable heat. For example, Korres et al., 2010 [39] demonstrated that a grass biomethane system for transport can have a range of potential emissions savings. If carbon sequestration is not included the GHG savings were assessed as 54.2%; allowing for carbon sequestration of 0.6 t Soil C ha^{-1} $annum^{-1}$ the GHG savings were assessed as 75%; sequestration of 2.8 t Soil C ha^{-1} $annum^{-1}$ can lead to GHG savings of 150%, [39]. An assessment of a pre-commercial seaweed biomethane system associated with fish-farming demonstrated up to 61% GHG savings when compared with compressed natural gas as a transport fuel and 70% when compared with gasoline [40].

3.1.3 Gap in the state of the art and innovation in paper

The criteria for sustainability is different for heat and transport, and differs in the future from what is proposed for now. The criteria that have been adopted differ from what was proposed in previous draft versions of the Directive. The fossil fuel comparators (FFC) in the Directive are different for electricity, heat and transport. As such, there is no definitive research that considers how biomethane systems can meet the new sustainability criteria for different end uses. There is no literature that addresses how sustainability criteria for different sources and uses of renewable gas can be met within a single certification scheme. As an example, Korres et al., 2010 [39] carried out extensive work on Life Cycle Analysis for grass biomethane as a biofuel for transport. This would need to be updated to reflect the latest recommended GWP100 values, and the fossil fuel

comparators and emissions savings criteria for different end uses. The innovation in this paper is to consider the practical implications of a green gas certification scheme for different energy uses, with an emphasis on sustainability criteria and EU reporting mechanisms for national energy use. While there is substantial literature available on the resource potential, in the search undertaken by the authors there is no paper that combines resource, production process, sustainability and use of said resource into a single document that could be included in a certification scheme.

3.1.4 Objectives

The objectives of this paper are to:

- Establish a range of viable biomethane pathways that would be suitable for certification in the short term:
- Establish the key production processes that would need to be considered in the certification scheme;
- Evaluate the ability of the biomethane systems to achieve the EU emissions savings targets for heat and transport in the RED recast;
- Consider alternative pathways that would meet heat sustainability criteria;
- Highlight the challenges relating to the interaction between policy, reporting and national infrastructure.

3.2 Establishing the main AD pathways for Ireland

This section introduces the main AD pathways for Ireland, identifying the resources that are most viable for Ireland and the key considerations in the production process. Understanding the production process is important to identify where GHG emissions will occur, and the potential energy yield from the anaerobic digestion system. These can then be quantified for certification.

3.2.1 Food Waste

Food waste has a potential to provide 2.65 PJ/a in Ireland, approximately 1.4% of expected energy in transport in 2020 [17]. Implementation of the Landfill Directive [41] has led to more biodegradable waste diverted to energy recovery. However, in 2016, approximately 64% of biodegradable waste disposed to landfill was from household and commercial brown bin systems. It is recognised that treatment infrastructure is required in the state to manage this waste [42].

There are two waste-to-energy facilities in Ireland based on incineration. This is not considered the best way of processing organic waste. The high water content of waste reduces the Lower Heating Value [LHV] of the biomass and can negatively affect the incineration process whilst minimising the energy return. Based on life cycle assessment methodology, *the waste treatment technologies are recommended in proper sequence from anaerobic digestion, heat-moisture reaction technology, composting, incineration and finally landfill* [43].

Household organic waste is an important resource for Ireland. The associated gate fee allows sustainable financial sustainability without the requirement of large subsidies [22]. Some biogas plants using a similar resource are already in operation using waste from industrial food processing. This potentially profitable resource could therefore encourage and stimulate the green gas industry in Ireland.

Food waste digesters will most likely be based in urban areas, where the resource availability will be higher than rural areas. Even with this, the distance travelled by the waste is likely to be higher compared to on-farm digestion of agricultural products. This is possible because transport costs are assumed to be borne by the waste collector for this resource. This would result in higher emissions due to transport in the certification process and lower transport costs. Food waste and municipal organic waste is already collected and transported significant distances to

treatment/disposal systems: as such transport is not the critical parameter in the viability of such biogas systems [22].

3.2.1.1 Collection and processing

Realising the potential for food waste depends on the effective source segregation of waste. Contamination of waste with other household waste materials is a commonly cited as a challenge in the waste management industry [44]. These contaminants can have a negative impact on the digestion process. If we fail to develop systems that are more effective than the current ones, then this would rule out some streams of food waste as a feedstock for anaerobic digestion and composting may be a more appropriate means of processing the waste.

Irish legislation requires that food waste producers segregate food waste for collection or treatment to ensure the waste does not contain potentially polluting wastes, products, materials or packaging [45]. At domestic level, local authorities must provide a brown bin collection service for food waste. At household level, waste must be either segregated, composted or brought to an authorised facility. Segregated collection services were required to be available in all population agglomerations greater than 500 people by July 1st 2016. These have been established in most, but not all counties in Ireland [46].

Catering waste is considered Category 3 material under the Irish conditions for Approval and operation of biogas plants transforming animal by-products and derived products in Ireland. This waste must be processed according to this standard by heating, mixing and minimising particle size to 400mm. The digestate can only be supplied for use in the Republic of Ireland [47]. Heat and processing energy demand within the system should be a standard element of the certification for this pathway. There are no transformation requirements for domestic food waste.

3.2.1.2 Sustainability

From a greenhouse gas perspective, digesting food waste or more broadly the organic faction of municipal solid waste (OFMSW) has a net benefit.

This is related to the circular economy nature of the treatment of OFMSW and the mitigation of fugitive methane emissions that would have resulted from landfill of OFMSW. The typical and default GHG savings for biogas from municipal organic waste as compressed natural gas in the RED are 80% and 73% respectively [1]. The typical value is an estimate of the greenhouse gas emissions for a particular pathway; the default value is where factors are applied to parts of the pathway with relatively low emissions. Where the pathway is available in the RED, the default values can be used in lieu of a detailed assessment. This can reduce the administrative requirements of a certification scheme. Otherwise, the actual emissions value based on the formula provided in Annex C Part V are used. The default value would meet the emissions saving requirement of 65% for Transport in the RED recast, but not the heat requirement of 80% by 2026 [12].

3.2.1.3 Potential yield

The composition of OFMSW has an impact on biomethane yield. For example, samples of OFMSW without garden waste gave higher biomethane yields per unit of volatile solid (VS) than samples which included garden waste [43]. This could inform whether a default value is used for certification or the full pathway. Catering waste samples were also found to have a higher methane yield compared to household waste streams [48]. The biomethane yield of food waste from a university canteen tested in Cork, Ireland was assessed using small batch Biomethane Potential (BMP) tests and larger scale continuously stirred tank reactors (CSTRs). The small scale test used the automatic methane potential test system (AMPTS^{TM}), which consisted of 15 number 500mL glass bottles. The larger scale tests were carried out in CSTRs with a working volume of 5L. The stoichiometric equation of a sample used was $C_{16.4}H_{29}O_{9.8}N$, which had a theoretical maximum yield of 549 m^3 CH_4/tVS. The BMP assays for a range of food waste samples yielded results in the range 314-529 $m_n^3CH_4$/tVS food waste [17]. These values compare well with a large scale commercial digester in Shropshire, U.K. processing mainly domestic food

waste, which generated 642 m^3 biogas t^{-1} VS and a specific methane yield of 402 m^3 CH_4/tVS at a methane content of the biogas of approximately 62% [49]. Both countries have a similar diet so a similar methane yield can be expected in Ireland. Table summarises the potential food waste yield for Ireland [17]. The biomethane production of 70 million m^3_n yr^{-1} is equivalent to 2.65 PJ yr^{-1}, or 1.06% of energy in Transport in 2015 [15].

Table 3-1 Bioresource of OFMSW beyond 2016 – adapted from Browne and Murphy, 2013 [17]

Food waste in Ireland (4.8 million people * 110 kg food waste /head)	530,000 t/a
Quantity of VS (29.4% DS of which 95.3% VS)	148,500 t VS yr^{-1}
BMP range 467–520m^3_n CH4/tVS	470 m^3_n CH_4 tVS^{-1}
Biomethane production	70 million m^3_n yr^{-1}
Energy yield at 37 MJ/mn^3	2.6PJ/a

3.2.1.4 Energy balance and processing

The digester in Shropshire included for a 900m^3 tank mixed by continuous gas recirculation and maintained at 42 °C by external heat exchangers. During the study period of 426 days, 3,372 t/a of waste were processed, 95% of which was source-segregated domestic food waste. The average organic loading rate was 2.7 kg VS m^{-3} day^{-1}, based on the average volume of the digester contents. The biogas output was 156 m^3 $tonne^{-1}$ wet weight. The waste was first shredded and then macerated to mix the waste and reduce the particle size to less than 12mm, which is in line with the EU pasteurisation standard. The associated Combined Heat and Power (CHP) Unit was a 195 kW MAN unit with assumed electrical conversion efficiency of 32% at full load and a potential of 53% recovery of heat. The overall

energy balance has been adapted to allow for comparison with other systems [49].

3.2.1.5 Food waste digestate

Digestate from source segregated food waste can be used on tillage land as a soil improver (after pasteurisation) or made into garden compost [50]. The digestate from the Shropshire plant had an average nutrient content of 5.6, 0.4 and 2.3 kg/tonne wet weight for Total Kjeldhal Nitrogen (TKN), Phosphorous (P) and Potassium (K) respectively. A nutrient mass balance taking into account water additions showed outputs equal to 86.1%, 32.8% and 96.4% of the input values of TKN, P and K [49]. Data from Table 2 suggests a net yield of 1.25 GJ of energy from 1 tonne of food waste. In an Irish context with 530,000 t yr^{-1}; this can supply a net energy yield of 662,500 GJ yr^{-1} in the form of electricity and heat. The differentiation between gross energy yield from wastes (2.6 PJ/a from Table) and net energy yield post treatment of waste (0.663PJ/a based on Table 3-1) is explained by the energy required to treat waste, the optimum use of the energy produced in the energy market and the differentiation between primary energy and final energy. Without biogas production in a "do-nothing" scenario, energy is required to treat waste. Biogas production satisfies this energy demand in treating waste and leaves surplus energy for other uses which displace fossil fuel use. If as in the case of the Shropshire a 32% electrical efficiency is obtained and if only electricity is sold and no heat, then final energy will be 32% of the primary energy in the biogas. This highlights the need to maximise the use of biogas in particular exploitation of the heat market. The more final energy produced from the biogas the more the carbon footprint is diluted per unit of energy; this is essential from a certification perspective.

Table 3-1 Overall Energy Balance for one year of operation of Shropshire Digester treating 3372 t/a of waste - adapted from Banks et al., 2011

Parameter	Value (GJ yr^{-1})
CHP net electrical output	2,629
Parasitic electrical requirement of process plant	718
Net energy output as electricity	1,911
Recoverable heat output from CHP	4,547
Parasitic heat requirement of plant	1,377
Net energy output as heat	3,170
CHP natural gas used	57
Energy required for digestate transport and application to land	106
Total potentially recoverable energy (heat and electricity)[a]	4,919
Total potentially recoverable energy per wet tonne of food waste	1.45

[a] Includes heat energy generated but not used at the time of the study.

3.2.2 Slurry

Slurry has a lower biomethane yield compared to other feedstocks. It is advantageous for anaerobic digestion for a number of reasons. Primarily it is abundant. Ireland, a state with a population of 4.8 million people, has a significant dairy industry with a national dairy herd of approximately 1.4 million cows [51]. Co-digestion of manure and organic feedstocks increases the biological stability of the AD process, when compared with mono-digestion due to the microbial fauna in the slurry [3]. Slurry is normally stored in open tanks releasing methane to the atmosphere. An advantage of using slurry for biogas production is that these fugitive emissions do not occur and as such biogas from slurry can be assessed as greenhouse gas negative. The Joint Research Centre (JRC), the European Commission's science and knowledge service has estimated that according to

Intergovernmental Panel on Climate Change (IPCC) guidelines, an emissions credit of 17.5% of the methane produced, can be accounted for in greenhouse gas calculations [52]. Thus, co-digestion of a substrate with slurry can be used to increase the GHG savings of the biomethane. This is an essential parameter for inclusion in a certification scheme.

Manure and digestive tract content are considered category 2 waste and can be transformed according to EU standards by heating to 70°C for 60 minutes, with a particle size less than or equal to 12mm prior to conversion to biogas. If biogas is produced from slurry, with imported amounts of slurry of less than 5,000 tonnes per annum, there is no need for pasteurisation [47].

3.2.2.1 Potential energy yield

The slurry yield can vary throughout the year depending on the diet and lactation stage of the animals. This variation should be considered when designing a biogas facility to ensure a reliable economic return [53]. For slurry collected from an Irish farm the Dry Solids (DS) content varied from 57 to 96 g/kg depending on the time of year; with a Volatile Solids (VS) content on average of 75 g/kg DS [54]. Dairy slurry tested in Ireland has been assessed as having a biomethane potential (BMP) in the range of 175 to 239 L CH_4 kg^{-1} VS [53] [55]. The higher value is equivalent to 16 m^3 CH_4 t^{-1} fresh weight (FW). For certification, the variation in composition and energy yield from the slurry should be accounted for.

3.2.2.2 Slurry Digestate

Current practice is to spread slurry on land as a biofertiliser. If slurry were to be used for anaerobic digestion it is recommended to return the same amount of digestate by mass back to the farm. Previous analysis has included the cost of sourcing manure and returning digestate to the farm in plant operation costs [22]. This ensures that farmers are not deprived of the fertiliser value from the cattle slurry they supplied to the anaerobic digestion facility [23]. If slurry (prior to AD) is compared with digestate

(post AD) the availability of nutrients is significantly increased due to mineralisation of the nutrients in the digestate [50]. A comparison of digestate with pig slurry and dairy slurry has shown that digestates have a different chemical composition to the slurries, but without posing a higher risk with respect to their impact on soil microbial activity [56]. Additionally, the results suggested that digestate may be a more suitable fertiliser for soils with high clay and carbon content, and that slurries may be more suitable for sandier soils containing less organic carbon. There will be water quality implications of using digestate as fertiliser. While it is outside the scope of this study, it would be relevant for interdisciplinary analysis of introducing anaerobic digestion in Ireland.

3.2.3 Grass silage

Grass has long been mooted as a potential feedstock for biomethane in Ireland. Farmers in Ireland are already familiar with managing grass, and there is no need for land use change due to the high availability. Compared to first generation biofuels such as ethanol, in which alcohols must be evaporated off stillage, the parasitic energy demand for grass biomethane is low. [57]. Grass is considered an advanced biofuel and the feedstock is classed as 'non-food cellulosic material' under the RED recast [12]. It has been identified as the most significant resource for Ireland for Anaerobic Digestion and could produce up to 35PJ energy supply by 2035. This is 22% of the 2015 natural gas supply [32].

3.2.3.1 Grass cultivation and yield

Grass is theoretically cultivated on an 8-year cycle with two cuts per year following the first year of cultivation. An Irish resource assessment by Smyth et al., 2009 assessed a theoretical 137.5 ha farm with a grass yield of 12 t DS ha^{-1} yr^{-1} at 90% volatile solids. The fertilisers applied [5] are annualised and summarised in Table 3-2:

Table 3-2 Annual fertilisers applied for grass cultivation

Substance	Nitrogen	Phosphorous	Potassium	Lime

Quantity (kg ha^{-1} yr^{-1})	250	38.75	308.75	1,500
Conversion to molecular form		2.3	1.2	
Quantity molecular form (kg ha^{-1} yr^{-1})	250 kg N	89.13 kg P_2O_5	370.5 kg K_2O	1,500 kg CaO

Teagasc, the Irish Agriculture and Food Development Authority is promoting a grass cultivation strategy known as Grass10. This aims to increase the number of livestock grazings per paddock to 10 and the amount of grass utilised to 10 tonnes grass dry matter per hectare. Developing a focused nutrient management plan is part of the programme, so fertiliser use will not necessarily increase, and in some cases it can be reduced [58]. Typically, the available grass for cattle in a pasture situation (allowing for trampling by cattle) is 6 tonnes grass dry matter per hectare. This strategy can also benefit farmers growing grass as a feedstock for anaerobic digestion. Farmers participating in a grassland measuring system run by Teagasc have increased average grass yields from 12.2 t DM ha^{-1} yr^{-1} in 2013 when the database started to 14.1 t DM ha^{-1} yr^{-1} in 2015 [59]. Thus, with no additional land take farmers can increase yields by between 16 % and 67% allowing for both food and fuel production. The grass silage yield per hectare is an important input for certification calculations; more efficient yield of grass silage and associated biomethane per hectare should reduce the carbon footprint per unit of biomethane.

3.2.3.2 Potential energy yield

The composition of biogas from grass is typically 55% methane [57]. This is reinforced by the stoichiometry of grass silage when assessed using the Buswell Equation. Theoretical assessments of an Irish grass-based biofuel

scenario assessed the gas production conservatively as 300 m^3 CH_4 tVS^{-1} [18]. This was based on based on a theoretical 137.5 ha farm with a grass yield of 12 t DS ha^{-1} yr^{-1} at 90% volatile solids. The gross energy per hectare was 122.41 GJ ha^{-1} yr^{-1} [5]. Subsequent testing in the lab demonstrated higher yields for grass mono-digestion of up to 400 m^3 CH_4 tVS^{-1} [55]. Further testing at a larger scale obtained a specific methane yield of 405L CH_4/kgVS [54]. This value was used by O'Shea et al., 2017 [23] to assess the total theoretical grass biomethane resource for Ireland as 128.4PJ.

It is unlikely that grass will be digested on its own. At high loading rates, the biomethane yield from mono-digestion of grass can reduce over time. This can be mitigated by co-digestion with slurry, or by adding trace elements to the mix. Wall et al., 2014 reported on the role of trace elements in negating a drop off in biomethane yield and illustrated a specific methane yield for mono-digestion of grass silage with trace element addition of up to 404 l CH_4 kg^{-1} VS at an organic loading rate of 4.0 kg VS m^{-3} day^{-1} [19]. The BMP is considered by some as a reliable estimate of the methane yield of a substrate [60], while others suggest that is unlikely that the result of a BMP assay can be achieved at full-scale production [44]. Hollinger et al recommended an extrapolation coefficient of 0.8 should be applied to avoid overestimating the methane production from a BMP [61]. In Table 3-3 a conservative factor of 0.9 is applied as the lab testing by Wall et al [19,54,55] on grass silage was undertaken in a continuous digester over long periods of time, as opposed to a BMP over a 30-day period of time.

3.2.3.3 Energy balance

The gross energy per hectare and energy balance of a grass to biomethane system, based on a theoretical 137.5 ha farm adapted from Smyth et al., 2009 [5] is presented in Table 3-3, and updated to reflect the higher methane yield as assessed in the lab [54].

Table 3-3 Energy balance of a grass to biomethane system (Smyth et al.,2009) [5] *with data from Wall et al., 2014* [54]

Energy	(Smyth et al., 2009) GJ ha^{-1} yr^{-1}	(Wall et al., 2014) GJ ha^{-1} yr^{-1}	(Wall et al., 2014) * 90% GJ ha^{-1} yr^{-1}
		SMY 404 L CH_4 kg^{-1} VS	SMY 404 L CH_4 kg^{-1} VS *0.9
Gross energy production	122.4	163.2	146.9
Parasitic demand and heat loss	17.1	17.1	17.1
Biogas for upgrading	105.3	146.1	129.8
Upgrading losses	1.56	2.19	1.95
Gross Biomethane Production	103.7	143.9	127.8

The emissions savings from using grass biomethane for transport were assessed as 75% [39], including for soil carbon sequestration of 0.6 t soil C ha^{-1} yr^{-1}. It should be borne in mind that the reactor type can result in a variation of energy production and emissions savings; variations of 15% in the emissions savings have been suggested [62]. The certification process needs to be cognisant of these variables.

3.2.4 Future energy systems

This section outlines the future resource of green gas in Ireland. This is unlikely to be realised in the short term, given lack of policy and incentivisation drivers and the required improvements in biogas systems including for enhanced cultivation methods and novel technology systems as outlined below. The certification systems need to be aware of these innovative pathways for Ireland's future energy mix.

3.2.5 Algae biomethane

Both micro and macro-algae (also known as seaweed) can be converted to biomethane. Micro-algae have been assessed as an unlikely source of biomethane in Ireland, given the extensive requirement for land for cultivation and unfavourable climatic conditions [63] . It is suggested by the authors that extensive micro-algae cultivation could be more suited to tropical climates rather than temperate oceanic climates such as Ireland.

The opposite is true for macro-algae such as kelps whose growth is optimised in temperate climates such as in waters off Ireland. Ireland has extensive sea-based kelp forests. It would not be sustainable to harvest these, as it would damage existing ecosystems. Instead, it is proposed to cultivate seaweed for anaerobic digestion along with a fish farming industry, in a system known as integrated multi-trophic aquaculture (IMTA). The seaweed would mitigate the eutrophication caused by fish farming, which would in turn-improve the yields of the seaweed; an example of a circular economy system.

In a European context Jacob et al., (2016) suggested that 1.25% of the current energy in transport demand of the EU, or 206 PJ/a, would require annual production of 168 Mt of seaweed integrated with 13 Mt of farmed salmon. This was deemed to require 2,603 number seaweed digesters each digesting 64,500 tonnes of wet weight of *S. latissma* (also known as sugar kelp) [64]. A sample Life Cycle Analysis of such a system, using renewable wind energy, has demonstrated GHG savings of 70% when compared with

gasoline fossil fuel [40]. This reduces to 60% when displacing compressed natural gas as a propellant.

3.2.5.1 Willow biomethane

Short-rotation coppice willow (SRCW) has been proposed as an alternative to importing woody biomass. It is estimated that eleven number $50MW_{th}$ gasifiers could supply a total of 10.4 PJ p/a with an area of land required of 6,800 ha per $50MW_{th}$ gasifier [21]. Willow has the advantage that it can be grown on marginal land and cultivated in the vicinity of the bioenergy facility. SRCW would be converted to biomethane using gasification followed by methanation.

It is assumed that plant cost and required scale of cultivation of willow will be a limiting factor on realising the gasification resource in 2030. The gasification resource is constrained by technology. While biomass gasification is an established technology for combined heat and power, the commercial application of syngas methanation is as yet limited [65]. The GoBiGas demonstration project in Gotenburg is an example of such a process [66]. This 20MW facility has now ceased operation.

3.2.5.2 Gaseous fuel from non-biological origin

Power to Gas (P2G) technology uses electricity to perform hydrolysis to split water into Oxygen and Hydrogen. The Hydrogen in turn can be combined with CO_2 to produce biomethane ($4H_2 + CO_2 = CH_4 + 2H_2O$). To be economically viable these systems require cheap electricity and a cheap concentrated source of CO_2 [67]. Curtailed and constrained electricity would be essential elements in the production of cheap electricity. However, systems that operate for a few hours a day to avail of cheap electricity do not optimise the capital investment of the facility. Much work is required in optimising the whole Power to Gas system. Waste CO_2 from industrial processes, CO_2 from ethanol facilities and distilleries, and CO_2 from biogas upgrading are cheap concentrated sources of CO_2. Both the hydrogen produced from electrolysis and methane produced from methanation are considered renewable gas. There is some confusion on

the naming of these gases; often they are called e-gases as they are sourced from electricity. The EU RED and RED recast uses the term gaseous fuel of non-biological origin [1,12].

Ireland due to its island status and its high portion of intermittent renewable electricity, mainly associated with wind, will have significant curtailment [67]. An optimal biogas model has been proposed by Ahern et al., 2015 [68], where the facility would utilise a model whereby both CHP and gas grid injection systems co-exist. At times of peak demand for electricity the biogas system would incorporate demand driven biogas concepts to produce enhanced levels of electricity. Conversely at times of peak production of, and low demand for, electricity, excess electricity could be converted to hydrogen and this hydrogen could be used to upgrade biogas to biomethane ($4H_2 + CO_2 = CH_4 + 2\ H_2O$) and injected to the gas grid. This model is dependent on an established biomethane industry. More recent research by McDonagh et al. posits that e-gases need not depend on curtailment [69] but rather tools such as wind forecasting and pricing can ensure use of electricity at times of low carbon intensity, thus improving the sustainability of such gaseous fuels. Plant cost may be a limiting factor on realising this technology in the near future but with maturation of the industry electrolysis and methanation systems should reduce in price. There are commercial applications of this technology, notably in Wertle, Germany where a plant is run by Audi, generating e-gas for transport fuel [6].

3.3 Environmental Sustainability

The main sources of food waste are domestic brown bin waste, canteen waste from restaurants, and waste from industrial food processing. Anaerobic digestion means that this waste resource can have a value. Biogas created from any wet organic waste product is highly sustainable; as the waste would otherwise go to landfill, and/or generate high levels of fugitive methane emissions. If landfilling is no longer available then composting becomes the main comparison point. While both are a valid

means of processing organic waste, the fuel generated from anaerobic digestion can displace fossil fuels, thus saving more emissions. In the case of slurry, it is assumed that there is a greenhouse gas emissions saving of 17.5%, associated with open storage of slurry, before any other processes are considered [52].

Considering grass, which covers 91% of Irish agricultural land, Cross Compliance rules of the Common Agricultural Policy limit the amount of land that can be converted to other uses beyond grass. Ireland already has a significant amount of grassland, which could be used for anaerobic digestion. As discussed Teagasc have a model in place (Grass10) facilitating improved cultivation techniques increasing the yield of grass by 16% to 67% [58]. This would create a significant resource in excess of feed requirements for AD that is both abundant and compliant with EU legislation.

Willow can be grown on marginal land, so that arable land is retained for food cultivation and other uses. Particularly for Willow, this marginal land includes peatland, so this crop could be grown on land that has been stripped for electricity generation from peat, thus retaining the land use of energy supply. Willow can remove heavy metals from soil. It is commonly planted next to domestic septic tanks to reduce contamination. An interesting use of this crop would be to clean toxic sites and then be used in turn to generate energy. The char and ash may be contaminated as a result. Harvesting willow on soft lands may be more expensive due to requirement for specialist machinery.

The concept of using renewable electricity that would have otherwise been curtailed or constrained and combining with captured carbon leads to extremely sustainable Power to Gas systems. Power to Gas, has the potential to almost double the output of a biogas plant, as it converts CO_2 in biogas to CH_4. Using the CO_2 from a bioenergy system such as upgraded biogas in a cascading bioenergy circular economy system especially when

the digested substrate is a slurry or residue can put P2G into GHG negative category.

Micro-algae can also be used in a cascading system capturing CO_2 from bioenergy systems [38]. Such algae biofuels can be very sustainable but are at a low technology readiness level (TRL) and are not expected to be commercialised for a number of years yet.

3.3.1 Greenhouse gas accounting and emissions reduction potential

3.3.1.1 Reference system – what to include

The definition of the system's boundaries and choice of the reference system are crucial, as the results of Life Cycle Analysis (LCA) vary according to the reference system chosen. In order to present a comprehensive understanding of the system, boundaries should be expanded to include co-products, by-products and residues [70]. Selecting the appropriate system boundary will be fundamental for compliance with any certification system. The boundary selected must also be compliant with current policy.

Co-products are not eligible for allocation under the RED [1]. The RED recast has clarified that agricultural residues are not considered co-products, and that the established method of energy allocation has worked well and should be continued [12].

3.3.1.2 Functional Unit

The Functional Unit (FU) is the key measure describing the system performance. It is recommended that the FU reflect the biofuel life cycle stages, so that for example, if the feedstock requires agricultural land, it should be reported on a per ha basis [70]. Where the biomethane is to be used for transport fuel the functional unit is often expressed as g $CO_{2\text{-eq}}$ per km vehicle travel. The RED uses g $CO_{2\text{-eq}}$ /$MJ_{biofuel}$.

3.3.1.3 Fossil Fuel Comparator

The Environmental Protection Agency (EPA) reports Irish emission factors to the United Nations Framework Convention for Climate Change

(UNFCCC). These are specific to each reporting year. In 2016 the emission factors for Natural Gas and Diesel were 56.716 t CO_2/TJ and 73.3 t CO_2/TJ respectively [71]. These are end of pipe values and do not include for whole life cycle analysis of the fossil fuel such as exploration, extraction, refining. The RED requires that country-specific values are used as the emissions factors [1].

For transport the fossil fuel comparator in the RED is diesel at 83.8 g $CO_{2\ eq}$ /MJ [1]. For biofuels in the RED recast, the fossil fuel comparator for transport is 94 g $CO_{2\ eq}$ /MJ. For useful heat the fossil fuel comparator is 80 g $CO_{2\ eq}$ /MJ [12]. These values are on a whole life cycle analysis basis. Biomass fuels require the conversion efficiency to be considered. For a certification scheme, where green gas is injected into the gas grid for use elsewhere, this would mean choosing a default value for a generic conversion process or else including the conversion efficiency as site-specific criteria. The RED recast requires a GHG emissions saving of 65% for transport and 80% for heat installations by 2026 [12].

3.3.1.4 Sustainability as renewable heat as compared to renewable transport fuel

The end use of the biomethane has a very significant impact on the sustainability. If, for example, the heating system were 90% efficient then the effective FFC for renewable heat would be 72 g $CO_{2\text{-}eq}$ /MJ. A comparison of the emissions allowed for the different end uses is presented in Table 3-5. Thus, if the developer injects green gas to the gas grid the hurdle for sustainability at the end user for renewable heat is approximately 2.3 times that for renewable transport fuel.

Table 3-5 Comparison of emissions allowed for Renewable heat and transport

End Use	Fossil Fuel Comparator (g $CO_{2\text{-}eq}$/MJ)	Conversion efficiency	Effective Fossil Fuel Comparator (g $CO_{2\text{-}eq}$/MJ)	Calculation	Emissions Allowed (g $CO_{2\text{-}eq}$/MJ)
Heat	80	90%	72	72 g $CO_{2\text{-}eq}$/MJ*(1-0.8)	14.4

Transport	94	100%	94	94 g $CO_{2\text{-eq}}$/MJ*(1-0.65)	32.9

3.3.1.5 Evidence for emissions savings in displacing synthetic fertiliser with digestate

In a grass biomethane case study Smyth et al., 2009 identified a mass of 15,695 t yr^{-1} of grass digestate [5] for land application and displacement of synthetic fertiliser and the associated fossil fuel used in production of synthetic fertilisers. The associated grass silage input was 7,500 t WW yr^{-1}. Emissions savings from displacement of synthetic fertiliser by digestate are not specifically included in the emissions calculations of the RED [1] or the RED recast [12]. The RED does allow for allocation of emissions based on energy content as described above. However, there is limited data available on the energy content of digestate related to specific feedstocks so assumptions would be required.

It must be borne in mind that anaerobic digestion is more than a renewable energy system. It cannot be compared directly with a wind turbine for example. Anaerobic digestion is usually employed as a waste treatment system or a means to improve environmental sustainability. The digestate is a sustainable fertiliser. For example, in Denmark a new organic biogas facility will be used to pipe 9 million m^3 biomethane to the gas grid but as it uses organic wastes the organic biofertiliser is a big element of the output [72]. It is quite common also that the CO_2 separated from the CH_4 has an asset value such as use in decarbonised/sustainable carbonated water. Thus, biogas facilities treat waste, produce organic biofertiliser, produce decarbonised CO_2 for the beverage industry and also produce biomethane. Attributing all the emissions to the biomethane is not in keeping with the rationale for biogas facilities. Adams et al estimated 20% allocation to digestate based on the Higher Heating Value (HHV) of the feedstock. This method was not considered ideal, but that it has some sense in application for green gas [73].

3.3.1.6 Evidence for emissions savings from carbon sequestration from grassland

Sequestration of atmospheric carbon in Irish grasslands will only be acknowledged in IPCC greenhouse gas accounting methods when Ireland can produce evidence-based Measurement, Reporting and Verification (MRV) of carbon sequestration [74]. Byrne et al demonstrated that two farms based in Cork were net sinks of the order of 2 t C ha^{-1} y^{-1}. These included farm activity such as slurry spreading and animal respiration in the calculation and the authors concluded that the C sequestration would need to be verified with soil Carbon measurements. For the grassland only the soil carbon sequestration was estimated at about 1 t $CO_{2\text{-eq}}$ ha^{-1} y^{-1} [75].

Including carbon sequestration of grass has a very significant impact on the LCA of grass-based dairy farming. However these effects are considered unreliable due to the uncertainty regarding the data available for Ireland [76] [77]. The average of values used in these studies of 1.19 tCO_2 ha^{-1} is in line with values quoted above. For grass biomethane utilised as a transport fuel, a value of 0.6 t soil C ha^{-1} yr^{-1} yields a GHG saving of 75%; varying the sequestration rate chosen can substantially affect the result, giving GHG savings of up to 150% [39].

Given the limited soil sequestration data available for Ireland, and the extensive effort that would be required to measure sequestration for individual grassland sources, it may be more appropriate to use a conservative default value, such as the lower value of 0.6 t soil C ha^{-1} yr^{-1}, for sequestration in any GHG calculation for a green gas certification system. This would ensure that the system is credible.

3.3.2 Qualifying and quantifying the potential GHG savings – focussing on AD

3.3.2.1 Parasitic energy source

GHG emissions can be reduced through the use of renewable electricity, this can be a key factor in the sustainability of a biomethane system [62][40]. In Ireland, the electricity emission factor has declining gradually as more renewable electricity has been added to the grid. For 2015 the

emission factor was 0.4675 kg CO_2/kWh_e; in 2001 it was 0.8067 kg CO_2/kWh_e [78]. Both heat and electricity are required for the biomethane process.

It is assumed that electricity will come from the grid and the biogas produced will be burned to produce heat. This however reduces the final energy produced. In Linkoping Sweden, which produces biomethane for transport biofuel, the biogas is seen as too important a product to burn to satisfy parasitic heat demand. An external fuel source is combusted [79].

3.3.2.2 Biogas upgrading technology

Upgrading technologies can be roughly assigned to four main groups; adsorption, absorption, permeation and cryogenic upgrading [4]. Cost can be the most significant criterion in selecting the upgrading type. However, CH_4 recovery is also very important, both for economic and ecological impact [80]. For certification, the methane loss of the technology chosen, along with the electricity and heat demand, will be important parameters in assessing the Life Cycle Analysis and the sustainability of the green gas system. The typical technologies being considered by Industry in Ireland are Membrane and Chemical absorption. These have efficiencies of methane loss to biomethane, according to the literature, in the range of ca. 0.1% and 1-15% respectively. It would be extremely unlikely to have slippage of 15%. Typically, either-off gas is recirculated back to the systems or at worst the off-gas is combusted or oxidised to CO_2. In practice most methane recovery systems have losses under 2% [4].

3.3.3 Quantifying greenhouse gas savings using BioGrace

BioGrace is an excel calculation tool, developed to demonstrate the calculation of greenhouse gas savings for the default renewable energy pathways in the RED. It is also used to adapt these existing pathways or to create a new biofuel pathway [81]. A greenhouse gas balance for grass was carried out using BioGrace methodology. Although Korres et al., 2010 [39] identified an emissions saving of 75%, this was based on theoretical analysis of a grass biogas system 9 years ago; the scientific literature and

policy have changed considerably in that time. The updated biomethane yield from experiments carried out by Wall et al., 2013 [55] and outlined in Section 3.2.3.3 was used to update the greenhouse gas balance. In addition, fossil fuel comparators from the RED recast were applied to calculate the emissions saving. The RED had some ambiguity regarding the $CO_{2\text{-eq}}$ Global Warming Potential (GWP) values applied to CH_4 and N_2O. Depending on the IPCC process at that particular time, the global warming potential over a 100-year time frame (GWP100) were 23 and 296 respectively, and at other times were 25 and 298. The RED recast clarifies this, using values of 25 and 298 [12].

3.3.3.1 Greenhouse gas savings for residues

In the RED recast, residues are removed from the list of default pathways [12]. The current GHG savings outlined in BioGRACE for Compressed Natural Gas from Wet Manure, Dry Manure and Municipal Solid Waste are 69%, 71% and 68% respectively, with petrol as the fossil fuel comparator at a carbon intensity of 83.8 g $CO_{2\text{-eq}}$/MJ. The RED recast gives savings of between 72% and 206% for wet manure converted to Biomethane for Transport [12]. The variation in values results from different combinations of open and closed digestate storage, and whether off-gas combustion is used or not. The high value for GHG (206%) is based on the emissions savings from displaced fugitive methane emissions in open storage of slurry [52].

3.3.3.2 Grass biomethane greenhouse gas savings

A sample emissions pathway was calculated for grass biomethane, in order to illustrate how the key production processes effect the potential energy yield and emissions, and subsequently, the certification of the fuel pathway. The pathway is based on a 137.5 ha farm outlined in Smyth et al. 2009 and illustrated in Figure 3-1 [5].

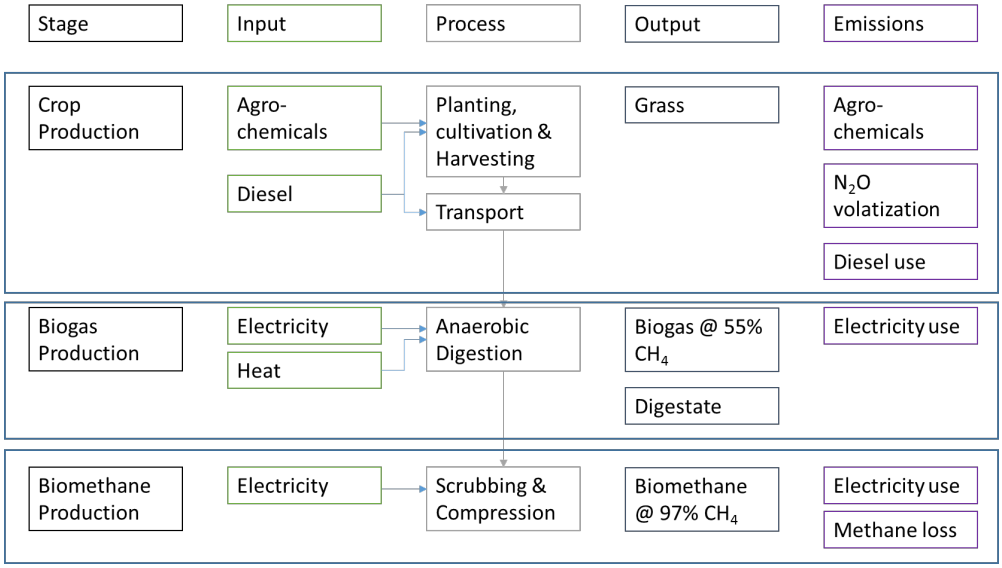


Figure 3-1 Grass biomethane system - Adapted from Smyth et all. 2009

Grass is cultivated on an 8-year cycle, with two cuts per annum. Fertilisers are applied in the establishment year and following each cut of grass. The biomass yield from Smyth et al., 2009 [5] is presented in Table 3-6.

Table 3-6 Biomass Yield for Grass – from Smyth et al 2009 [5]

Land Area	137.5 ha
Grass Silage Yield	54.55 t ha^{-1} y^{-1}
@ 22% Dry Solids	12 t ha^{-1} y^{-1}
@ 90% Volatile Solids	10.8 t ha^{-1} y^{-1}

3.3.3.3 Emissions in Agriculture

Emissions factors for fuel and for agro-chemicals are taken from BioGrace. GWP values of 1, 25 and 298 are applied for CO_2, CH_4 and N_2O respectively. The emissions associated with the agro-chemical inputs in this analysis are presented in Table 3-7.

Table 3-7 Agro-chemicals emissions – Input data from Smyth et al., 2009 [5] and emission factors adapted from BioGrace

Agro-chemicals	Input	Emissions Factors from BioGrace	Emissions

	kg ha^{-1} y^{-1}	g CO_2/kg	gCH_4/kg	gN_2O/kg	g$CO_{2\text{-eq}}$/kg	kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}
N-fertiliser	250	2,827.005	8.679	9.642	5,917.231	1,479
P_2O_5-fertiliser	89.125	964.887	1.331	0.052	1,013.509	90
K_2O-fertiliser	370.5	536.311	1.571	0.012	579.249	215
CaO-fertiliser	1,500	119.116	0.216	0.018	129.967	195
Pesticides/Herbicides	0.72	9,886.502	25.527	1.681	11,025.737	8
Total						1,987

Field N_2O emissions were initially calculated using IPCC Tier 1 methodology [82]. This is presented in Box 3-1. The tables and equations referred to in Box 3-1 are the table and equation numbers in the IPCC methodology. The value obtained using Tier 1 calculations (363 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}) is lower than the value obtained by Korres et al of 525 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}, which was itself considered within the lower range of N_2O values reported for Ireland of *between 2 to 8.4 kg N_2O ha^{-1} y^{-1}* [39]. The Tier 1 calculation only included for synthetic fertiliser, which has lower factors applied compared to organic fertilisers. For this reason the higher value of 525 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1} will be used in the emissions savings calculation.

N_2O from atmospheric deposition of N volatised from managed soils

Equation 11.9 $N_2O\text{-}N = [F_{SN} * Frac_{GASF}] * EF_4$

Where:

F_{SN} = Synthetic Nitrogen = 250 kg N ha^{-1} y^{-1}

$Frac_{GASF}$ (from Table 11.3) = N volatilisation and re-deposition = 0.1

EF_4 (from Table 11.3) = N volatilisation and re-deposition = 0.01

$N_2O\text{-}N$ = 250 kg ha^{-1} y^{-1} * 0.1 * 0.01 = 0.25 kg $N_2O\text{-}N$ ha^{-1} y^{-1}

Conversion to N_2O

$N_2O = N_2O\text{-}N * 44/28 = 0.25 * 44/28 = 0.392$ kg N_2O ha^{-1} y^{-1}

N_2O from atmospheric deposition of N volatised from managed soils

Equation 11.10 $N_2O\text{-}N = F_{SN} * Frac_{LEACH\text{-}(H)} * EF_5$

Where:

F_{SN} = Synthetic Nitrogen = 250 kg N ha^{-1} y^{-1}

EF_5 (from Table 11.3) = N volatilisation and re-deposition = 0.0075

$Frac_{LEACH\text{-}(H)} * EF_5$ (from Table 11.3) = 0.3

$N_2O\text{-}N = 250$ kg ha^{-1} $y^{-1} * 0.3 * 0.0075 = 0.5625$ kg $N_2O\text{-}N$ ha^{-1} y^{-1}

Conversion to N_2O

$N_2O = N_2O\text{-}N * 44/28 = 2.5 * 44/28 = 0.88$ kg N_2O ha^{-1} y^{-1}

Total $N_2O = 0.392 + 0.88 = 1.22$ kg N_2O ha^{-1} y^{-1}

Conversion to $CO_{2\text{-}eq}$

1.22 kg N_2O ha^{-1} $y^{-1} * 298 =$ **363 kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}**

Box 3-1 Field N_2O emissions - Tier 1 Methodology

3.3.3.4 Emissions from transport

The transport emissions are a result of transporting the biomass to the anaerobic digester and are presented in Box 3-2. For transport emissions, an average distance of 10.5km from the AD plant was assumed based on an analysis of 42 no. potentially profitable plant configurations in Ireland [23]. This gives a round trip of 21km and an emission of 94.4 kg CO_2 ha^{-1} y^{-1}.

Transport distance = 21km

Fuel efficiency for truck for dry product = 0.94 MJ/t.km

Diesel emissions = 87.64 g CO_2/MJ_{Diesel}

Dry Matter Yield = 54.55 t ha^{-1} y^{-1}

Transport emissions = 21km * 0.94 MJ_{Diesel}/t.km * 87.64 g CO_2/MJ_{Diesel} * 54.55 t ha^{-1} a^{-1}

= 94.4 kg CO_2 ha^{-1} y^{-1}

Box 3-2 Emissions from transporting the biomass

3.3.3.5 Emissions from processing

Thus far, the emissions have been calculated per unit of land area. In order to calculate the emissions per MJ for the fuel for certification, the conversion process needs to be outlined. In this case, the biomass is converted by Anaerobic Digestion to produce biogas, containing approximately 55% methane.

The energy demand assumptions for the digestion and upgrading process are based mainly on Smyth et al [5] unless otherwise stated: The assumptions used in Box 3-3, Box 3-4 and Box 3-5 are as follows:

Methane Production = 404 L CH_4 tVS^{-1} * 0.9 = 363.6 L CH_4 tVS^{-1} from Wall et al., 2014 [54]; Electricity Emissions Factor = 467 g CO_2 / kWh - Value from 2015 [78]; Parasitic Energy Demand of the Digester = 17,120 MJ ha^{-1} y^{-1}; Grid Electricity Demand = 4,870 MJ ha^{-1} y^{-1}; Grid Electricity Demand in kWh = 4,870 / 3.6 = 1352 kWh; Volumetric Energy Value of Methane = 37.78 MJ m^{-3}. The electricity demand for scrubbing and compression was 0.35 kWh m^{-3} upgraded biomethane, giving a grid electricity demand of 0.7 kWh $m^{-3}_{biomethane}$. Biomethane is assumed to contain 97% CH_4. Methane loss in upgrading was 1.5%.

Total biogas output = 363.6 L CH_4 tVS^{-1} * 10.8 tVS ha^{-1} y^{-1}/0.55 = 7,140 m^3 Biogas ha^{-1} y^{-1}

Total methane output = 363.6 L CH_4 tVS^{-1} * 10.8 tVS ha^{-1} y^{-1}= 3,927 m^3 CH_4 ha^{-1} y^{-1}

Gross Energy Output = 3,927 m^3 CH_4 ha^{-1} y^{-1} * 37.78 MJ m^{-3} = 148,362 MJ ha^{-1} y^{-1}

Parasitic Energy Demand = 17,120 MJ ha^{-1} y^{-1}

Net Energy = 148,362 – 17,120 = 131,242 MJ ha^{-1} y^{-1}

Net Methane Yield = 131,242 MJ ha^{-1} y^{-1} / 37.38 MJ m^{-3} = 3,474 m^3 CH_4 ha^{-1} y^{-1}

Biogas available for upgrading = 3,474 m^3 CH_4 ha^{-1} y^{-1} / 0.55 = 6,316 m^3 Biogas ha^{-1} y^{-1}

Box 3-3 Anaerobic Digestion Process energy requirement and methane yield

Parasitic Energy Demand = 17,120 MJ ha^{-1} y^{-1}

Emissions from burning the biogas are considered biogenic, and are therefore zero. If biogas not used then an alternative renewable source such as wood chip combustion, a heat pump or solar thermal could be used.

Emissions from electricity demand = 1,352 kWh * 467 g CO_2/kWh = **631,384 g $CO_{2\text{-eq}}$ ha^{-1} y^{-1}.**

Box 3-4 Emissions from Anaerobic Digestion

Electricity Consumption

= 0.7 kWh $m^{-3}_{biomethane}$ * 3,474 m^3 Biomethane ha^{-1} y^{-1} / 0.97 = 2,507 kWh ha^{-1} y^{-1}

Emissions from electricity consumption

= 467 g CO_2 kWh^{-1} * 2507 kWh ha^{-1} y^{-1} /1,000 = **1,170 kg CO_2 ha^{-1} y^{-1}**

Methane content

= 6,316 m^3 Biogas ha^{-1} y^{-1} * 55% = 3,474 m^3 CH_4 ha^{-1} y^{-1}

Methane losses in upgrading

= 3,474 m^3 CH_4 ha^{-1} y^{-1} * 1.5% = 52.11 m^3 CH_4 ha^{-1} y^{-1} * 37.78 MJ m^{-3} = 1,968 MJ ha^{-1} y^{-1}

Emissions from methane losses

= 52.11 m^3 CH_4 ha^{-1} y^{-1} * 0.71 kg_{CH4} m^{-3} = 37 kg CH_4 ha^{-1} y^{-1}

Converting to $CO_{2\text{-eq}}$

= 37 kg CH_4 ha^{-1} y^{-1} * 25 = **925 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}**

Methane Yield

= 3,474 m^3 CH_4 ha^{-1} y^{-1} – 52 m^3 CH_4 ha^{-1} y^{-1} = 3,422 m^3 CH_4 ha^{-1} y^{-1}

Energy Yield following upgrading

= 3,422 m^3 CH_4 ha^{-1} y^{-1} * 37.78 MJ m^{-3} = 129,283 MJ ha^{-1} y^{-1}

Total emissions from upgrading

= 1,170 kg CO_2 ha^{-1} y^{-1} + 925 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}

= 2,095 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}

Box 3-5 Emissions from upgrading

Table 3-8 Summary of emissions – 100% methane yield, no allocation, values are rounded

Stage	Emissions (g $CO_{2\text{-eq}}$ ha^1 y^{-1})	Emissions (g $CO_{2\text{-eq}}/MJ_{biomethane}$)
Cultivation	1,900,000	15.37
Field N_2O	525,000	4.06
Transport	94,400	0.73
Biogas generation	643,900	4.98
Upgrading to biomethane	2,095,000	16.2
Total excluding sequestration	5,258,300	41.34
Carbon sequestration	2,200,000	17.01
Total emissions including for sequestration	3,058,300	24.33

The total emissions for a biomethane yield of 129.3 GJ ha^{-1} y^{-1} were 24.33 g $CO_{2\text{-eq}}/MJ_{biomethane}$ (Table 3-8). This needs to be compared with the Fossil Fuel Comparator (FFC) to determine if the sustainability criteria can be met. Table 3-9 outlines this comparison.

Table 3-9 Sustainability of Biomethane for Heat and Transport

	Heat	Transport
Emissions before conversion (g $CO_{2\text{-eq}}/MJ_{biomethane}$)	24.33	24.33
Conversion efficiency	0.9	1
Total emissions (g $CO_{2\text{-eq}}/MJ_{biomethane}$)	27	24.33
Fossil Fuel Comparator (g $CO_{2\text{-eq}}$/MJ)	80	94
Emissions Saving	66%	77%
Emissions Saving Criteria 2026	80%	65%

The emissions savings were calculated as 77% for transport and 66% for heat, with a conversion efficiency of 0.9 assumed for heat. It will be possible to comply with the emissions savings target of 65% for transport but not the 80% target for heat. Obviously, the importance of including the sequestration of 0.6 t soil C ha^{-1} yr^{-1} (2.2 t CO_2 ha^{-1} yr^{-1}) is crucial. Without this grass biomethane emissions are 41.3 g $CO_{2\text{-eq}}/MJ_{biomethane}$ which yields a 59% emissions savings for transport and as such would need to be co-digested with slurry to allow sustainable transport biofuel [83].

3.3.3.6 Grass biomethane greenhouse gas savings with allocation for digestate

When allocating emissions between co-products and the fuel, the emissions to be allocated are the emissions that arise up until the process step where a co-product is formed. Allocation takes place after the process step directly after the forming of a co-product [84]. In the case of grass biomethane, allocation takes place after the digestion process. As digestate leaves this process, it takes GHG emissions with it. Allocation of 80% of the emissions after biogas processing to the biomethane and 20% to digestate results in emissions savings of 80% for transport and 73% for heat, meeting the transport target but not the heat target.

3.3.3.7 Sensitivity Analysis

A sensitivity analysis was applied to vary some of the parameters and assess the impact on emissions. The parasitic energy requirement of the biogas was replaced with a heat pump to meet the heat requirement of the anaerobic digester. A heat pump with a coefficient of performance (COP) of 2.5 was used as the energy source for the heating demand of the digester, in place of burning the biogas generated. Heat pumps can have a COP ranging from 2.5 to 4, so 2.5 was chosen as a conservative measure [85]. This will have an impact on the overall energy yield resulting in lower emissions per output. Additional parameters varied by 10% were the methane recovery losses and carbon sequestration. Box 3-6 outlines the calculations and Table 3-10 shows the impact on overall emissions of the system with a number of sensitivity measures combined.

Parameters varied

Parasitic heat demand = heat pump

Methane recovery losses – 10%

Soil carbon sequestration + 10%

Parasitic heat demand – See box 3-3 – 3-5 for earlier parameters

Coefficient of performance (COP) = 2.5

Heat demand = 17,120 MJ ha^{-1} y^{-1} = 4,756 kWh [5]

Electricity required to meet heat demand = 4,765/2.5 = 1877 kWh ha^{-1} y^{-1}

Electricity Emissions Factor = 467 g CO_2 / kWh – Value from 2015 [78]

Emissions from electricity consumption for digester heat demand

= 467 g CO_2 kWh^{-1} * 1,877 kWh ha^{-1} y^{-1} /1,000 = **877 kg CO_2 ha^{-1} y^{-1}**

(From Box 3-4) Emissions from electricity demand = 1,352 kWh * 467 g CO_2/kWh = **631,384 g $CO_{2\text{-eq}}$ ha^{-1} y^{-1}**

The total emissions from the biogas generation stage are:

631 kg CO_2 ha^{-1} y^{-1} + 877 kg CO_2 ha^{-1} y^{-1} = **1,508 kg CO_2 ha^{-1} y^{-1}**

Using a heat pump to meet the digester heat demand results in a higher methane yield.

If a fully zero-carbon heat source is used then the emissions from the electricity demand for biogas generation are **631,384 g $CO_{2\text{-eq}}$ ha^{-1} y^{-1}**

From Box 3-3

Gross Energy Output = 3,927 m^3 CH_4 ha^{-1} y^{-1} * 37.78 MJ m^{-3} = 148,362 MJ ha^{-1} y^{-1}

Methane recovery losses – 10%

Methane loss from upgrading = 1.5% * -10% = 1.485%

3,927 m^3 CH_4 ha^{-1} y^{-1} * 1.485% = 58.3 m^3 CH_4 ha^{-1} y^{-1}

Emissions from methane losses

= 58.3 m^3 CH_4 ha^{-1} y^{-1} * 0.71 kg_{CH4} m^{-3} = 41.4 kg CH_4 ha^{-1} y^{-1}

Converting to $CO_{2\text{-eq}}$

= 41.4 kg CH_4 ha^{-1} y^{-1} * 25 = **1,035 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}**

Net energy generated = 3,927 – 58.3 = 3,869 m^3 CH_4 ha^{-1} y^{-1} = 146,160 MJ ha^{-1} y^{-1}

Electricity Consumption for upgrading

= 0.7 kWh $m^{-3}_{biomethane}$ * 3,869 m^3 Biomethane ha^{-1} y^{-1} / 0.97 = 2,972 kWh ha^{-1} y^{-1}

Emissions from electricity consumption

= 467 g CO_2 kWh^{-1} * 2,972 kWh ha^{-1} y^{-1} /1,000 = **1,304 kg CO_2 ha^{-1} y^{-1}**

The total emissions from the upgrading stage are:

1,035 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1} + 1,304 kg CO_2 ha^{-1} y^{-1} = **2,239 kg CO_2 ha^{-1} y^{-1}**

<u>Soil carbon sequestration + 10%</u>

= 2,200 * 1.1 = **2,420 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}**

Box 3-6 Parameters varied for sensitivity analysis

The summary emissions as a result of this sensitivity analysis are presented in Table 3-10. The resulting greenhouse gas emissions are 26.32 g $CO_{2\text{-eq}}$/MJ, giving an emission saving of 63%, which is lower than the required

saving of 80%. Using a fully zero-carbon heat source for biogas generation gives total emissions of 20.32 g $CO_{2\text{-}eq}$/MJ, with an emissions saving of 72%. In this analysis, removing the parasitic heat demand to increase the energy output meant a higher energy demand in the upgrading process, and increased fugitive emissions. It should be noted that this analysis is based on a generic system with EU values applied. A specific system with more detailed data could potentially be designed to meet the emissions savings criteria for certification.

Table 3-10 Summary of emissions - 100% methane yield, no allocation, values are rounded

Stage	Emissions (g $CO_{2\text{-}eq}$ ha^1 y^{-1})	Emissions (g $CO_{2\text{-}eq}$/$MJ_{biomethane}$)
Cultivation	1,900,000	13
Field N_2O	525,000	3.59
Transport	94,400	0.65
Biogas generation	1,508,000	10.32
Upgrading to biomethane	2,239,000	15.32
Total excluding sequestration	6,266,400	42.88
Carbon sequestration	2,420,000	16.56
Total emissions including for sequestration	3,846,400	26.32

3.4 Social and economic impact

3.4.1 Energy Supply and Security

3.4.1.1 Defining energy security

Energy security broadly refers to the ability to ensure an uninterrupted supply of energy at an economically viable price. Energy security has been traditionally thought of in terms of the geopolitics of fossil fuels. This is

now changing as a result of climate action and key climate meetings such as COP 21 in Paris and subsequent annual meetings. There is little consensus on a final definition of energy security in literature given the vast amount of parameters and risks [86]. Risks to security are either major external events such as disaster, conflict, political tensions and instability or major accidents. Internal risks refer to infrastructure capacity, investment uncertainty, resource variability and civil and labour disputes [87]. Various indicators of energy security therefore have their limitations due to the inherent nature of indicators and also the various interpretations of energy security that indicators can be applied to. Green gas has potential to contribute to energy security in terms of the fuel supply, source diversity and as an indigenous source of fuel.

3.4.1.2 EU Energy security and renewables

In the EU, a long-term relationship between energy security and renewables deployment has been identified based on data from 21 EU countries, including Ireland, from 1990 to 2013. This found that the main driver behind renewables deployment was energy security rather than environmental concerns and sustainability policies [88]. Analysis by Chalvatzis et al (2017) focusing on countries most affected by the financial crisis found that renewable energy sources played a significant role in reducing import dependence. Ireland had the least diverse fuel mix of the countries considered followed by Portugal, Spain, Italy and Greece [89].

3.4.1.3 Energy Security in Ireland

Ireland had an import dependency of 85% in 2014 and 95% of natural gas supply was sourced from Britain [87]. In 2016 this changed significantly to 57.8% as a new gas field (the Corrib Gas field) came on stream [90]. Natural Gas accounts for 53% of electricity generation in Ireland and 38% of heat demand. There is an interdependence between heat and electricity when gas is the source, so having a more secure gas supply will have benefits for both energy sectors. Drivers for diversity in energy supply in the countries examined by Chalvatzis, including Ireland, were reduced transport use and

an increase in renewables from 2008 to 2014 [89]. The reduced transport demand is a result of reduced economic activity so if the economy improves, as one would hope, this diversity gain may well be lost. In the Electricity sector, warnings of an over-reliance on limited sources of supply and the 1970s oil crises have led to greater diversification and reduced exposure to risk [91].

According to SEAI, a fully developed biogas industry could supply up to 30% of Ireland's gas demand by 2030 [32]. Renewable gas has the advantage of being a more regular supply instead of the peak and decline over decades that has characterised Irish supply as Irish gas fields start, peak and then run out. There may be slight variation in the supply related to harvest but this will be much less significant compared with the variation associated with a gas field over time.

3.4.1.4 The role of renewable gas

The main modern renewable energies are wind and solar which are considered inexhaustible resources. While these have the advantage of *free* fuel until the point of processing, the downside is that they are not completely dispatchable [88]. Biogas/biomethane is different from wind and solar in that the feedstock has either a cost, or in the case of food waste it may generate a revenue in the form of gate fee. The biogas/biomethane system is reliant on a successful or reliable substrate. A significant benefit of biogas is that the technology is dispatchable and is capable of meeting a variable demand. Indeed the biogas output can be ramped up or down through feeding regimes and biogas storage. O'Shea et al., 2016 have demonstrated that the timing of reactor feeding and upgrading can be optimised to meet electrical demand while minimising the storage requirement [92]. Diversification of transport fuel is a particular concern for Ireland due to the near total dependence on oil, which is unique out of all sectors of the economy [87]. Biomethane can address this and add to the diversity of supply sources for transport fuel.

3.4.1.5 Brexit

Brexit is considered a potential risk to the Irish energy market, as Ireland will (for a time) no longer have interconnection with another EU country. A policy evaluation has noted that there are bilateral agreements between Ireland and the UK that are outside of the EU [93]. In addition to this, it is impossible to cut supply to the Republic of Ireland without simultaneously cutting supply to Northern Ireland. The implications of trading with a non-EU partner can be considered relevant for the gas market but should not have a big impact on the certification scheme.

3.4.1.6 Jobs and economic growth

SEAI have estimated that over 4,000 jobs could be created in Ireland by 2050 in the biogas industry; this includes direct and indirect jobs. This is in a conservative scenario which includes for the digestion of the available wastes and grass silage resource in Ireland. According to the SEAI report these were not considered new jobs, as they are more likely to be related to upskilling from other industries [32]. However, in times of recession employment is extremely important. This report considered employment at a national level.

A sample biogas plant producing 10,200,600 Nm^3 biomethane per year can be assumed to employ seven people [94]. This includes three skilled and four semi-skilled workers. As digesters can be expected to be located outside of Ireland's main urban centres [23] the technology would be of benefit to the rural economy, where these would be considered 'new' jobs. Further jobs would be created transporting locally sourced feedstock to the digester as well as the digestate by-product.

3.4.1.7 Rural development

The countries with the most developed biogas or biomethane markets in terms of the number of plants are Germany, Italy and the UK [94]. In Germany biogas production was associated with job creation in the biomass sector and the strengthening of rural areas [96]. There were also adverse side-effects such as: competition for biomass use, a change in

maize cultivation and use, and problems of acceptance. In Ireland, the dominant feedstock for biogas should be grass, which is already in place. Grass can be used without competing with traditional agricultural systems, and could provide an alternative enterprise and income to farmers [97].

There is considerably more research on the negative effects of renewable energy compared with possible positive effects. Analysis by Guenther-Lůbbers et al found that the benefits of biogas production can vary depending on the type of farming existing in the region. CHP facilities were seen as benefiting social and public relations due to the level of cooperation required to develop a district heating system [98].

3.4.2 Competitiveness and sustainability of agriculture, manufacturing and processing sector

Agriculture is the single largest contributor to Ireland's greenhouse gas emissions [99]. The Food Harvest 2020 strategy [100] aims to increase Irish beef and dairy output by 20% and 50% respectively between 2010 and 2020 while also reducing GHG emissions. Diverting the slurry associated with this farming to energy generation can help reduce the GHG emissions by realising the 17.5% emissions saving due to capture of fugitive CH_4 emissions from open storage tanks. There is also the potential to reduce fossil mineral fertiliser application as nutrients in the slurry will be better mineralised reducing the requirement for fossil fertiliser. Improving grass yields for energy use will improve the efficiency of agriculture, and improve competitiveness as a result of diversifying grass use.

The impacts of climate change will mean more CO_2 in the atmosphere which will has a positive effect on grass production in temperate climates like Ireland in the short to medium term [101]. This can potentially be a positive effect for Ireland as there will be sufficient grass to meet the requirements of increased beef and dairy output and also produce sufficient biomass for anaerobic digestion. A more erratic climate with more frequent drought and excessive temperatures however may also

"stress the growing crop and negate the positive impact of extra CO_2 fertilisation" [102].

3.4.2.1 Safety

One of the challenges to the public perception of biofuels has been negativity, alleging that fuels produced through anaerobic digestion are not as beneficial or safe as they purport to be. The UK Environment Agency reported 12 serious pollution incidents in 2015, the latest year for which information is available in a report by the Environmental Agency [102]. An analysis of accidents in biogas production and upgrading by Moreno et al [103] found that the number of accidents is growing faster than production and that the main lessons learnt were to improve safety culture and risk awareness in the sector.

These were not considered 'new' accidents as the risks are well known in other industrial fields with similar operations. The Irish Chemical and Pharmaceutical Industry, from which such lessons can be learned, accounts for a substantial part of Irish Industrial production, approximately 45% of total Net Selling Value in 2015 [104]. Opportunities for collaboration and synergies with these sectors should be identified in order to ensure the safety of the product and a positive relationship with neighbours.

3.5 Implementing a certification scheme in Ireland

3.5.1 Establish a range of biomethane pathways that would be suitable for certification in the short term

Anaerobic digestion of wastes, slurry residues and grass have been identified as the most suitable pathways for green gas certification in Ireland. This is due to their economic viability, technology readiness level and resource availability.

3.5.2 Establish the key production processes that would need to be considered in the certification scheme

The key stages that need to be considered for certification are the cultivation of the resource in the case of grass biomass, or acquisition and treatment in the case of residues such as slurry or Food Waste. In the case of grass, the contribution of transporting the biomass to the digester to the

overall emissions was low as the resource was relatively close in the scenario analysed. The choices made for energy use in the conversion process will have an impact on the energy yield and emissions. Biogas could be used to generate the parasitic heat demand. However this reduces the biomethane yield. Alternatively combustion of carbon neutral wood chips, onsite solar thermal energy or a heat pump would also be a viable option to generate the low temperature heat required for the anaerobic digestion process.

3.5.3 Evaluate the ability of the biomethane systems to achieve the EU emissions savings targets for heat and transport in the RED recast

A simple greenhouse gas calculation based on BioGRACE has demonstrated that these pathways can meet the current proposed sustainability criteria for transport in the RED recast but not heat. In Ireland renewable heat may be the easiest route to market in the short-term as there is no need to change industrial process to accommodate green gas. Ruling out renewable heat as an end-use at this point is therefore cause for concern. Although there is currently limited infrastructure in place for renewable gas in transport, Gas Networks Ireland (GNI), the network operator, aim to have 70 CNG injection points by 2027.

3.5.4 Consider alternative pathways that would allow satisfaction of the sustainability criteria for renewable heat

In order to meet the proposed renewable heat sustainability requirements by 2026 advanced technologies such as power to gas and cascading bioenergy systems that maximise the use of resources and minimise GHG emissions may become a lot more relevant for Irish green gas systems. The International Energy Agency Energy Technology Perspectives [104] see BioEnergy and Carbon Capture (Use) and Storage (BECC(U)S) as essential to maintain a temperature rise below 2^{o}C. The use of Power to Gas systems which predominately use curtailed/constrained electricity and capture and reuse the carbon dioxide from the biogas stream can in theory greatly improve the sustainability and the GHG savings of the system [37]. The same is possible using microalgae to upgrade biogas to biomethane. Thus

the green gas technologies, which are seen as being at a low TRL, may be required by 2026 to allow 80% GHG savings as opposed to fossil fuel displaced in the renewable heat sector.

3.5.5 Highlighting the challenges relating to the interaction between policy, reporting and national infrastructure

In other EU countries, green gas certification has certified the fuel pathway for a particular end use, often to facilitate an incentive. If green gas were to be used as a transport fuel in Ireland, the pathway certified would include transport as the final end use. The SHARES tool is used to report renewable energy share for each country in the EU. It aims to facilitate reporting and as such has been updated regularly. It has recently been updated to account for the use of renewable gas as a transport fuel, given the small quantities on the grid. Otherwise, the gas is allocated to renewable heat [105]. Certifying the transaction, with an optional end use, would be an opportunity to direct the biomethane towards a preferred use for Ireland.

3.6 Conclusions

This review identified the main feedstocks and production processes for biomethane in Ireland. Wastes, slurry and grass could be used immediately in a green gas industry with Anaerobic Digestion as the dominant conversion technology. The production stages and processes that would need to be considered for certification are outlined in detail. Grass is the dominant source of green gas and it was shown that with present technologies and EU Directives that green gas from grass can satisfy emissions for use as a sustainable renewable transport fuel (especially if sequestration of carbon to grassland is included) but will struggle to satisfy renewable heat emission savings (unless co-digested with slurry). Understanding of all the process steps is essential to inform the development of a certification scheme for renewable gas. Considering the wider context, EU policy and reporting mechanisms appear to favour the use of the fuel for transport over heat. This is problematic as renewable heat requires little change on behalf of the end-user while renewable

transport requires the end-user to construct compressed natural gas service stations and purchase natural gas vehicles (NGV).

Acknowledgements:

This work was supported by Science Foundation Ireland (SFI) through the MaREI centre under. The work was carried out as part of the Green Gas Certification project led by the International Energy Research Centre (IERC) at the Tyndall National Institute, in collaboration with the Renewable Gas Forum Ireland (RGFI), Deutsches Biomasseforschungszentrum (DBFZ) and Deutsche Energie-Agentur (DENA). The authors are grateful for discussions with Dr Caiman Cahill of IERC and Dr Stephan Majer of DBFZ.

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4 Implications of European Union recast Renewable Energy Directive sustainability criteria for renewable heat and transport: Case study of willow biomethane in Ireland

Long, A.[1,2,3*], Bose, A.[1,2,3], O'Shea, R.[1,2,3], Monaghan, R.[1,4,5], Murphy, J.D.[1,2,3]

[1] MaREI Centre for energy, climate and marine, Ireland

[2] Environmental Research Institute, University College Cork, Cork Ireland

[3] School of Engineering, University College Cork, Cork, Ireland

[4] College of Engineering and Informatics, National University of Ireland, Galway, Ireland

[5] Ryan Institute for Environmental, Marine and Energy Research, Galway, Ireland

Abstract

The 2018 recast European Renewable Energy Directive (RED recast) sets emissions savings criteria for renewable fuels. This paper assesses the life-cycle emissions from gasification methanation of willow to produce renewable biomethane in order to compare the heat and transport 2026 sustainability criteria in the RED recast. The criteria are more stringent for use of the fuel as heat, with both a higher specified emissions savings criteria (80% versus 65% for transport) and a lower Fossil Fuel Comparator (80g CO_2 MJ^{-1} versus 94 CO_2 MJ^{-1} for transport). Scenarios tested were based on both the RED recast and the IPCC (Intergovernmental Panel on Climate Change) Global Warming Potential (GWP) values. Agro-chemical input data from Teagasc (the Irish Agriculture and Food Development Authority) was used for both mineral and organic fertilisers. Previous land use was shown to have a significant impact on the results of the analysis. Overall, 24 scenarios were tested. Converting land from grassland for

* = corresponding author details, 100094251@umail.ucc.ie

cultivation of willow results in greater emissions when compared to conversion from arable land. The gasification methanation pathway was found to meet emissions savings criteria for transport in most cases, and for heat when converting from arable land only. The highest emission saving of 97% was achieved through conversion from arable land for the transport end use.

Highlights

- Willow biomethane meets sustainability criteria in the RED recast for transport
- Converting from grassland as opposed to arable land results in higher emissions
- Willow biomethane from grassland does not meet sustainability criteria for heat

Keywords

Willow; Sustainability; Biomethane; Renewable Heat; Renewable Transport; Land use change.

4.1 Introduction

4.1.1 The technologies associated with green gas production

Biomethane from anaerobic digestion is considered the first stage in the nascent renewable gas industry, as it is the most commercially advanced technology for the production of green gas [1,2]. The green gas resource from anaerobic digestion depends on the sustainable economic availability of wastes, residues and sustainable crops such as grass. Previous research [3] has demonstrated that mono-digestion of grass for production of biomethane in an Irish context can meet emissions criteria in the recast Renewable Energy Directive [4] for transport but not for heat. Co-digestion with manure could improve the sustainability of grass biomethane to allow the pathway to meet emissions criteria for heat. Ireland has a large grass resource with ca. 90% of agricultural land under grass [5], that could be used for biomethane, along with a substantial resource of manure from cattle farming [6].

Gasification, followed by methanation for synthetic gas production, which may be upgraded to natural gas standard for gas grid injection, is considered the second stage of the green gas roadmap [1]. This gasification methanation pathway is not as developed as biomethane from anaerobic digestion pathway. The 20MW GoBiGas plant in Sweden, was the first to introduce gas-to-grid from woody crops at significant scale [7]. However, operations have now ceased at the plant due to financial sustainability [8].

4.1.2 The importance of emission savings and sustainability criteria in the green gas industry

A challenge of using biomethane for RES-H (Renewable Energy Supply - Heat) in the European Union, is the greenhouse gas (GHG) emissions savings criteria set by the RED recast [4]. There is a lower comparison threshold for heat compared to transport and electricity. Conversion efficiency must be taken into account for heat and electricity, which is not the case for transport. The emissions allowed, based on the criteria set out in Article 29 and Annex VI of the RED recast [4] are presented in Table 4-1

Table 4-1 Emissions allowed per end use as set out in RED recast

End use	Fossil fuel comparator (FFC) g $CO_{2\text{-eq}}$ MJ^{-1}	Typical conversion efficiency	Required emissions saving in 2026	Emissions allowed g $CO_{2\text{-eq}}$ MJ^{-1}
Heat	80	90 %	80 %	14.4
Electricity	183	50 %	80 %	18.3
Transport	94	N/A	65 %	32.9

4.1.3 The role of biomethane in decarbonisation

Within Europe and the United States (US) between 50 and 100% more energy is delivered to the end consumer as gas compared to electricity [9]. Gas grid operators in several European countries have demonstrated an interest in decarbonising the gas in the gas network; a number have committed to 100% decarbonisation by 2050 including Belgium, Denmark, France, Germany, Sweden, Switzerland and The Netherlands [10].
In Ireland most of the present 6.9% renewable energy supply in heat (RES-H) has been met through solid biomass, almost half of which (48%) is wood waste and wood residues consumed for heat in the wood processing sector [11].

While there are alternative means of decarbonising heat, such as heat pumps and biomass combustion, transport has been considered far more difficult to decarbonize than heat. In the Irish context, Gas Networks Ireland (GNI), the Irish gas grid operator, aim to facilitate the renewable gas industry by installing 70 Compressed Natural Gas (CNG) filling stations by 2028 [12] and 170 CNG filling stations by 2050 [13] so that the fuel can be used for transport [12]. The ambition is to supply advanced transport fuel to the hard to decarbonise areas of haulage and intercity buses which are not readily electrified.

4.1.4 Land use and carbon sequestration

The Sustainable Energy Authority of Ireland (SEAI) is Ireland's national sustainable energy authority. A report by SEAI on the potential for biomass has estimated that a total of 213,000 ha of land could be available to grow willow and miscanthus in Ireland. The report assumes conversion from

both arable and grassland and considers limits on land conversion imposed by the EU [14]. Land use conversion for biomass in Ireland is discussed in Section 3.4. At present Ireland has ca. 4.9 million ha of agricultural area used, of which about 4.1 million ha is under grass production [15]. Long-term soil carbon sequestration, associated with willow grown on tillage land, was found to have the potential to exceed the total life cycle emissions of small-scale domestic or commercial wood chip boilers replacing gas boilers [16]. Replacing maize cultivation with willow in Sweden increased Soil Organic Carbon [17]. Increase in soil organic carbon is considered a negative emission technology [18]. The potential for soil carbon sequestration associated with biomass cultivation can substantially contribute to a reduction in greenhouse gas emissions for these systems. This is very variable and depends, amongst other factors, on previous land use. Carbon sequestration of grassland in Ireland is not currently acknowledged in IPCC accounting methods as there is no evidence-based value reported [19].

4.1.5 Gap in the state of the art

Natural gas supplies 27% of Ireland's primary energy requirement and has a very significant food and beverage industry use with a large requirement of natural gas for industrial heat [11]. Natural gas is not readily displaced by electricity in generating industrial heat and there is a scarcity of literature that examines the implications of the RED recast on the viability of renewable gas as a vector for RES-H. Willow is a potential indigenous energy crop [20] for the second stage of a green gas roadmap. While it is normally used as a feedstock for combustion [21], it could also be converted to biomethane by gasification [22] and methanation. This is considered a future energy scenario [23]. The energy balance and logistics of 11 no. 50MW primary energy input gasifiers, with 35.2MW_{TH} output were previously assessed by Gallagher and Murphy, 2013 [24,25]. This analysis has an ambition to build on the work of Gallagher and Murphy, 2013 via a more detailed emissions analysis to determine if sustainability

criteria for renewable heat and renewable transport as outlined in the RED recast [4] can be met.

Review of the literature indicates a lack of studies considering the full pathway of cultivation of willow to gasification, subsequent methanation and end use. Studies have outlined greenhouse gas emissions on part of the biomethane pathway. Murphy et al., 2014 [26] assessed the life-cycle environmental impact, including emissions, on a 'cradle to gate' basis in Ireland. Also, in Ireland, Styles and Jones, 2006 [18] evaluated the potential of willow for electricity and heat production through direct burning of the biomass. Nordborg et al., 2018 [27] assessed the energy use in willow production in Sweden and identified the need for a complete assessment of willow to bioenergy, considering the full process from cultivation of the resource to the end use, to better inform policymakers.

4.1.6 Aims and objectives

This paper aims to: determine if gasification of willow in Ireland can meet the GHG emissions savings criteria for renewable heat and transport in the RED recast; assess the potential resource of green gas via the gasification methanation pathway; and consider this pathway in developing a green gas industry in Ireland. In Ireland, the renewable green gas industry is in its infancy. Production of biogas is mainly at landfill sites, with smaller quantities produced at agricultural installations [28].This assessment is therefore suggested to be a perspective on future applications of gasification technology and systems.

4.2 Method

The GHG calculation for willow gasification in Ireland in this paper is based on previous analysis conducted by Gallagher and Murphy, 2013 [24] and a model gas-to-grid plant designed to meet the requirements of the Irish natural gas grid proposed by Singlitico et al., 2019 [29]. The Singlitico et al., 2019 [29] model had three key stages; pre-treatment, steam-gasification, and cleaning and upgrading. The efficiency of the conversion process from biomass feedstock to biomethane was 62%.

To calculate the greenhouse gas emissions, Global Warming Potential (GWP) values of 25 for methane and 298 for nitrous oxide from the RED recast [4] were used. These values were then compared with the most recent IPCC recommended values of 28 and 265 for methane and nitrous oxide [30]. These were considered as two separate GWP scenarios.
At harvest, the moisture content of willow is approximately 55%. The feedstock needs to be dried before it can be added to the gasifier. This is part of the pre-treatment process. A summary of the assumptions made, and net energy yield is presented in Table 4-2. When energy from agriculture is included, the overall efficiency is 59%.

Table 4-2 Summary of assumptions of willow to methane system based on Gallagher and Murphy, 2013 [24] and Singlitico et al., 2019 [29]

Process step	Value	Unit
Willow yield	22.2	t wet weight ha^{-1} y^{-1}
Willow yield @ Mc[1] = 55%	10 .0	t Dry Matter (DM) ha^{-1} y^{-1}
Higher heating value (HHV) of willow	18.7	GJ t^{-1} DM
HHV of willow @ Mc = 55%	8.4	GJ t^{-1}
Latent heat of evaporation	2.5	GJ t^{-1}
Lower heating value (LHV) of willow @ Mc = 55%	7.0	GJ t^{-1}
Gross energy yield (HHV)	187 .0	GJ ha^{-1} y^{-1}
Conversion loses in gasification and methanation system	71.0	GJ ha^{-1} y^{-1}
Net yield	116.0	GJ ha^{-1} y^{-1}
Conversion energy efficiency (See Table 9)	62.0	%
Energy in agriculture (See Table 5)	2.8	GJ ha^{-1} y^{-1}
Conversion energy efficiency including agriculture	59.0	%

[1] Mc = moisture content

There is currently a limited willow resource in Ireland. An industry would require large-scale cultivation, with the first harvest commencing on Year 4. The analysis will therefore use emissions savings criteria from 2026 onwards as described in the RED recast [4]. Willow is cultivated on a 22-year cycle, with a harvest every three years for each land area, followed by a new round of agro-chemical application [32]. The yield of 10 dry tonnes per hectare is annualised over this 22-year cycle [25]. The plant size is considered as 50MW primary energy input and an output of $31MW_{SNG}$. This

section presents the key assumptions made for calculating the greenhouse gas emissions, the energy balance, and the associated results.

4.2.1 Emissions from agriculture

Cultivation, and in particular, nitrogen fertiliser application, can contribute significantly to $CO_{2\text{-eq}}$ emissions from willow [16]. Two separate scenarios were used for the nutrient input. Both are based on Teagasc nutrient guidelines [17]. Teagasc, the Irish Agriculture and Food Development Authority has a key role in scientific research to advise the agriculture sector. The mineral fertiliser scenario uses fertilisers from fossil fuels. As this can be economically unviable, an organic fertiliser scenario was also analysed. The organic fertiliser scenario uses cattle slurry as fertiliser, distributed through an irrigation system. Mechanical inputs are based on a cradle-to-gate Life Cycle Analysis (LCA) by Murphy et al., 2014 [26].

4.2.2 Agro-chemicals

The term pesticides is commonly used to refer to elements used in plant protection and includes herbicides [33]. Therefore, the emissions coefficient for pesticides used in the software package BioGrace [34] was applied to both herbicides and pesticides. The emissions factors in BioGrace are expressed as nitrogen (N), phosphate (P_2O_5) and potash (K_2O), whereas the input values are for the elemental form of nitrogen (N), phosphorous (P) and potassium (K). Phosphorous and Potassium are converted to their molecular forms of phosphate and potash respectively using molecular weights [27]. The conversions can be expressed in terms of the quantity required, as the following: 1 kg N -> 1.2 kg NH_3; 1 kg P -> 2.3 kg P_2O_5: 1 kg K -> 1.2 kg K_2O. The value for Nitrogen was not converted as the input was for the molecular form of N. The inputs for the mineral fertiliser scenarios was based on Soil Index 2 requirements for N, P, and K [35]. This is one of the higher requirements and was chosen as a conservative estimate. The nutrient requirement will most likely vary across plantations, depending on differences in the soil indices.

Table 4-3a presents input data from Wall et al., 2020 [35], using emissions based on RED recast [4], and the energy associated with manufacture of

the agro-chemicals. The willow planting material was assessed as 16,500 cuttings per hectare [26]. Willow cuttings are willow stalks which are planted in the ground. The energy associated with the agro-chemicals is taken from supplementary material to the energy analysis of willow production for bioenergy in Sweden [27]. The mineral and organic nutrient inputs result in different energy inputs and associated emissions over the life cycle. The energy associated with the mineral fertiliser scenario is presented in Table 4-3b.

Table 4-3a Agricultural inputs, adapted from Murphy et al., 2014 [27] and nutrient requirement from Wall et al., 2020 [35]

Substance	Sum of total (kg ha^{-1}) over life cycle	Application per annum (kg ha^{-1} y^{-1})	Application per annum (Molecular form) (kg ha^{-1} y^{-1})	Emissions coefficient – based on BioGrace	Emissions kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}
Pesticides	16[1]	0.72	0.72 kg ha^{-1} y^{-1}	11025.74 g $CO_{2\text{-}eq}$ kg^{-1}	7.94
Nitrogen	700[2]	31.82 kg N ha^{-1} y^{-1}	31.82 kg N ha^{-1} y^{-1}	5917.23 g $CO_{2\text{-}eq}$ kg^{-1} N	188.29
Phosphorous	238[2]	10.82 kg P ha^{-1} y^{-1}	24.89 kg P_2O_5 ha^{-1} y^{-1}	1013.51 g $CO_{2\text{-}eq}$ kg^{-1} P_2O_5	25.22
Potassium	945[2]	42.95 kg K ha^{-1} y^{-1}	51.54 kg K_2O ha^{-1} y^{-1}	579.25 g $CO_{2\text{-}eq}$ kg^{-1} K_2O	29.85
Total					251.30

Table 4-3b Energy associated with Agricultural inputs

Substance	Sum of total (kg ha^{-1}) over life cycle	Application per annum (kg ha^{-1} y^{-1})	Application per annum (Molecular form)	EnergyValue	Energy (MJ ha^{-1} y^{-1})
Pesticides	16	0.72	0.72 kg ha^{-1} y^{-1}	453 MJ kg^{-1}	326
Willow planting material	16,500 cuttings ha^{-1}			9.5[1] GJ ha^{-1}	432
Nitrogen	700	31.82	38.18 kg NH_3 ha^{-1} y^{-1}	37 MJ kg^{-1} NH_3	1412
Phosphorous	238	10.82	24.89 kg P_2O_5 ha^{-1} y^{-1}	13.2 MJ kg^{-1} P_2O_5	329
Potassium	945	42.95	51.54 kg K_2O ha^{-1} y^{-1}	5.9 MJ kg^{-1} K_2O	304
Total					2,803

[1] A scaling factor of 0.79 was applied as Nordborg et al., 2018 [27] used a lower number of cuttings compared to Murphy et al., 2014 [26], 13,000 cuttings ha^{-1} and 16,500 cuttings ha^{-1} respectively. This was then divided by 22 to reflect the 22-year cycle.

Cattle slurry was chosen as the organic fertiliser as it is widely available in Ireland and commonly used to offset expensive chemical fertiliser costs. The organic fertiliser nutrient content was based on the average nutrient content of cattle slurry in Wall et al., 2020 [35], which describes phosphorous as the limiting nutrient. The application volume of slurry per hectare was therefore calculated based on the phosphorous requirement for phosphorous soil index 2. The soil index refers to the ability of the soil to respond to fertilizers. A lower soil index indicates a definite response to fertilizers and a higher index indicates an unlikely or no response to fertilizers as there are already sufficient nutrients in the soil. The soil index of the same soil will be different for different nutrients [35]. Organic nitrogen is assumed as 60% bioavailable [36]. When the volume of cattle slurry applied is calculated to meet the requirement for phosphorous soil index 2 then the nitrogen available is considered sufficient to meet requirements for nitrogen for Soil Index 2,3, and 4. These inputs will have no associated emissions or energy associated with their production as they

use organic waste. All of the inputs are summarised in Table 4. The detail of the nutrient content of cattle slurry is presented in the Appendix A.

Table 4-4 Fertiliser inputs over Life Cycle

Input Sum of total (kg ha-1) over life cycle	Mineral fertilisers	Organic fertilisers
Pesticides	16	16
Nitrogen	700	1142
Phosphorous	238	238
Potassium	945	1666

4.2.3 Field emissions – Field N_2O

In addition to agro-chemicals applied, field emissions must also be calculated. This analysis uses IPCC Tier 1 methodology [31]. Based on the fossil fuel-derived nitrogen input of 31.82 kg N ha^{-1} y^{-1}; this equates to 176 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}, for the Teagasc input data. Table 5 presents the field emissions for the different agro-chemical input scenarios. This is considered a conservative estimate as Tier 1 calculations normally apply to a country as opposed to a particular operation. The detail of the nitrogen Emissions Calculations are presented in Appendix B.

The data and assumptions above are presented for the base case of RED recast Global Warming Potential and Teagasc mineral agro-chemicals. Using mineral and organic fertiliser data creates four input scenarios, which will have different emissions and energy requirements. There are no emissions associated with the production of organic fertilisers. Pesticides will still be required, so the emissions for the organic scenarios will be the emissions associated with using these, taken from Table 4a. The energy associated with the organic fertiliser scenario, is the energy associated with planting material and pesticides, taken from Table 4-4b. The different input scenarios are presented in Table 4-5.

Table 4-5 Summary of energy and emissions in agriculture for input scenarios

Scenario	Energy input associated with agro-chemicals (GJ ha^{-1} y^{-1})	Agro chemical emissions (kg $CO_{2\text{-eq}}$ ha^{-1} Y^{-1})	Field N_2O emissions (kg $CO_{2\text{-eq}}$ ha^{-1} Y^{-1})
RED recast – Mineral	2.8	251	176
IPCC – Mineral	2.8	242	157
RED recast– Organic	0.76	8	973
IPCC – Organic	0.76	8	865

4.2.4 Machinery for production and processing of willow

The emissions from diesel are based on the fuel required for site preparation, fertilizer, and pesticide application, harvesting, and then chipping. The RED recast states that "the manufacture of machinery and equipment shall not be taken into account" [4].

Input data from Murphy et al., 2014 [24] gives 7 L ha^{-1} y^{-1} for diesel use in cultivation, excluding harvesting. For the harvesting process, whole rod harvesting followed by outdoor drying was chosen for this analysis because it reduces the energy requirement for drying afterwards and can provide a better quality of biomass [32]. In the right conditions whole stem rods can dry to a level of up to 25% moisture content in Ireland without any energy input. While direct chipping is currently more common, the smaller particles can have a lower quality for biomass due to the growth of fungi and other spores [32]. Storing willow as rods first can reduce the moisture content, but leads to a higher fine particles content which *can result in losses from dispersal of material to the air* [37].

A whole stem harvester has a productivity of 0.2 – 0.5 ha hr^{-1} with a willow yield of 10 tonnes of dry matter (t DM) per hectare per year [26,32]. Considering an average of 0.35 ha hr^{-1}, diesel consumption of 50 litres ha^{-1}, and seven harvest operations in the 22-year period [26], the energy requirement for harvesting yields 572 MJ ha^{-1} y^{-1}.

As outdoor drying is used in this process, there is no energy requirement for drying. The energy requirement for the chipping operation is based on chipping branch hardwood at 20% moisture content from Spinelli et al., 2011 [38]. The operation required 2.6 litres of diesel per oven dried tonne for 11.9 tonnes Dry Matter (t DM) hr^{-1}. Based on a yield of 10 t DM ha^{-1} y^{-1}, the diesel required is assessed as 26 L ha^{-1} y^{-1} for this analysis. The diesel emission coefficient is 87.64 $gCO_{2\text{-eq}}$ MJ^{-1} [35] . This includes for emissions from production, transport, processing and combustion [39]. The total energy consumption for machine operations, summarised in Table 4-6 was assessed as 1,764 MJ ha^{-1} y^{-1}, which results in emissions of 155 $kgCO_{2\text{-eq}}$ ha^{-1} y^{-1}. These emissions are common to all scenarios.

Table 4-6 Summary of emissions from machine operations

Operation	Diesel requirement (L ha^{-1} y^{-1})	Energy (MJ ha^{-1} y^{-1})	Emissions (kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1})
Cultivation	7	252	22.09
Harvesting	16	576	50.48
Chipping	26	936	82.03
Total	49	1,764	154.6

For the 'organic' scenario, the cattle slurry and pesticides are diluted with water and delivered via an irrigation system. The energy requirement for the irrigation system of 600kWh_e ha^{-1} y^{-1} was based on the energy requirement of a 1 ha site in Northern Ireland. This corresponds with the medium to higher consumption in Abadia et al., 2010 [40].

Electricity from the grid is required for irrigation. A 2030 scenario of 50 % wind and 50 % fossil natural gas electricity production was assumed, based on an intermediate energy scenario for Ireland [41]. Energy projections from the Sustainable Energy Authority of Ireland estimate 55% Renewable Electricity supply for 2030 based on implementation of a proposed National Development plan and a high or low oil price [11]. This gives an assumed emissions factor of 0.2 kg CO_2 kWh_e^{-1}, and emissions of 120 kg CO_2 ha^{-1} y^{-1}.

4.2.5 Land Use Change

A gasification scenario set out by Gallagher and Murphy, 2013 [24,25] assumed a 5% uptake of willow planting within a 20 km radius of the plant. The total area of land required to cultivate the biomass for eleven $50MW_{input}$ facilities was 75kha. This is 21% of current arable land in Ireland, or 1.6% of total agricultural land. In Ireland, 92% of agricultural land is grassland and the remaining 8% is arable or cropland [42]. Conversion from grassland will be required in order to have a viable resource. EU cross-compliance rules restrict changes to land use [43]. The ratio of permanent grassland to total agricultural area should not decrease more than 5% [44] and a maximum change of 10% applies.

The SEAI, Ireland's national energy authority, assumed that 190,000 Ha of grassland and 23,000 Ha of arable land are available to convert to willow and miscanthus [14]. This assumes that as grassland is used more efficiently, more land becomes available for other uses, and is cognisant of the cross-compliance conversion limits. It is therefore necessary to consider conversion from grassland and from arable land as separate scenarios for this analysis. There is an estimated potential availability of willow for biomass of 625,000 t DM by 2030 and 1,400,000 t DM by 2035. The value chosen for carbon sequestration can have a significant impact on the sustainability of the biofuel [45,46]. There is a consensus that converting from arable land to willow results in an increase in Soil Organic Carbon (SOC), whereas converting from grassland to willow does not have the same advantage [47]. In a cradle-to-gate Life Cycle Analysis Murphy et. al., 2014 [26] did not consider carbon sequestration for conversion from grassland as grassland sequesters a greater amount of carbon than willow. Subsequently, Clarke et al., 2019 [48] advised that conversion of grassland to willow should be avoided because of the GHG emissions associated with the change in SOC. Styles and Jones., 2006 [21] reported that cultivation to short rotation coppice willow (SRCW) of destocked grassland would result in net GHG emission increases of 1,346 kg $CO_{2\text{-eq}}$ ha^{-1} y^{-1}. Applying this to a

fuel yield of 116 GJ ha^{-1} y^{-1} gives an emission increase of approximately 11.6 g $CO_{2\text{-eq}}$ MJ^{-1}.

Teagasc figures indicate that willow can sequester 0.12 t Carbon ha^{-1} y^{-1} [32]. Converting this to CO_2 gives 0.44 t CO_2 ha^{-1} y^{-1}. For grassland Korres et al., 2010 [45] assumed a sequestration rate of 0.6 t Carbon ha^{-1} y^{-1}. While it is assumed that temperate grasslands do sequester carbon, a value has not yet been established for Ireland for inclusion in IPCC accounting methodology [19]. The conservative values of 0.6 t Carbon ha^{-1} y^{-1} for grassland and 0.12 t Carbon ha^{-1} y^{-1} for willow have been chosen for this study in order to reduce the potential for sustainability to be dependent on high carbon sequestration values.

Land use change is included in the overall emissions calculation specified in the Annex VI methodology of the RED recast, which outlines how GHG emissions are calculated [4]. The carbon emissions on maturity of the plant after 20 years are compared with the reference, or previous land use. A sample calculation for conversion of grassland to willow based on the carbon sequestration values above is presented in Box 1. The input values from references in formula are already annualised, so the number of years is not included in the final calculation.

$e_I = (CS_R – CS_A)$ X 3.664 X 1/T X 1/P – e_B

Where:

- e_I = annualised emissions from carbon stock changes caused by land-use change
- CS_R = Carbon stock per unit area for reference land use, what the land was used for in 2008, or 20 years previous. Reference land use = grass from [43] CS_R = 0.6 t Carbon $ha^{-1}\,y^{-1}$
- CS_A = Carbon stock per unit area for actual land use. From [31] this is 0.12 t Carbon $ha^{-1}\,y^{-1}$ for willow
- T = number of years
- P = productivity of the crop (measured as biomass fuel energy per unit area per year) GJ $ha^{-1}\,y^{-1}$
  From Table 3, this is 116 GJ $ha^{-1}\,y^{-1}$
- e_B = bonus of 29 $gCO_{2\text{-}eq}\,MJ^{-1}$ for restoring degraded land. This is not considered in the current analysis

$e_I = (CS_R – CS_A)$ X 3.664 X 1/20 X 1/P – e_B

= (0.6 – 0.12) t Carbon $ha^{-1}\,y^{-1}$ X 3.664 X 1/116 GJ $ha^{-1}\,y^{-1}$

= 15.16 kg $CO_{2\text{-}eq}\,GJ^{-1}$ (* 1000 to convert to g $CO_2\,MJ^{-1}$)

= 15.16 g $CO_{2\text{-}eq}\,MJ^{-1}$

Box 4-1 Emissions from land use change, based on Annex V methodology

The RED recast aims to limit biofuels, bioliquids and biomass fuels produced from food and feed crops. Such crops are listed in Annex VIII of the Directive. Willow is not on the list of plants under Part A Annex VIII of the RED recast [4]. In addition to this, conversion from grassland leads to direct land use change, the emissions from which are calculated as part of Annex VI methodology (as in Box 1). Therefore, the emissions for indirect land use change of this crop are estimated as zero.

4.2.6 Storage and Transportation of biomass

Following drying and chipping at the cultivation site, it is assumed that the biomass is transported to the gasification plant at a moisture content of

25%. A storage facility is needed on-farm for the chipped biomass so that it can be transported to the gasification plant on-demand. A 20 km catchment was chosen for supply as this is the optimal maximum delivery distance for coppice chip to a conversion plant [32].This would require 6,800 ha of willow for one $50MW_{input}$ gasifier [25]. If the gasification plant is supplied by willow cultivation with a 20 km radius, the average transport distance is assumed at 13.3 km, based on the average radius in a circle of 2R/3, where R is the radius. This is multiplied by a tortuosity factor of √2 to account for Irish roads [6]. This gives a round trip of 37.6 km. The calculation of emissions from transport is presented in Box 2. It should be noted that in a future scenario the fuel to fuel this transport may be the produced biomethane from the gasification methanation facility.

Values from BioGrace [34]
Transport efficiency of Diesel Truck for Dry Product = 0.94 MJ $t.km^{-1}$
Diesel Fuel Emissions Factor = 87.64 g CO_2 MJ^{-1}
Fuel Use = 0.94 MJ $t.km^{-1}$ * 13.3 $t.ha^{-1}$ y^{-1} * 37.6 km = 470 $MJha^{-1}$ y^{-1}
Emissions = 470 MJ $ha^{-1}y^{-1}$ * 87.64 g CO_2 MJ^{-1} /1000= 41.2 kg CO_2 ha^{-1} y^{-1}
= 41.2 kg CO_2 ha^{-1} y^{-1} / 116 GJ ha^{-1} y^{-1} = 0.355 g CO_2 MJ^{-1}

Box 4-2 Emissions from transport of Biomass to Plant

4.2.7 Thermal conversion process

The conversion process is based on an optimised model of forestry residues to Bio-Synthetic Natural Gas (Bio-SNG), described in detail by Singlitico et al., 2019 [29]. The model is representative of the $20MW_{Bio\text{-}SNG}$ GoBiGas dual fluidized bed gasification plant process in Sweden [49]. The process demand for electricity and heat was recovered from within the system, such that there was no external energy demand. There was a surplus of electricity of $0.13MW.MW^{-1}_{SNG}$ that could be sold to the grid.

The gasification methanation technology comprises four key stages: pre-treatment; gasification; methantion; and cleaning and upgrading. The pre-

treatment stage dries the feedstock with air and steam to a moisture content (M_c) of 8% before entering the gasifier. This stage consumes heat and power. The cold gas efficiency of the gasification step is modelled as 73% [29]. This includes the heat required for the gasification process which comes from burning the char and tar produced and also part of the syngas. The cleaning and upgrading to Bio-SNG step modelled included four in-series adiabatic reactors with inter-cooling with an efficiency of 85%. Each efficiency was calculated dividing the output energy by the input energy on an LHV dry and ash-free basis and the overall Biomass to Bio-SNG efficiency was 62.1% [29]. Emissions during this process were considered biogenic. The key stages are illustrated in Figure 4-1.

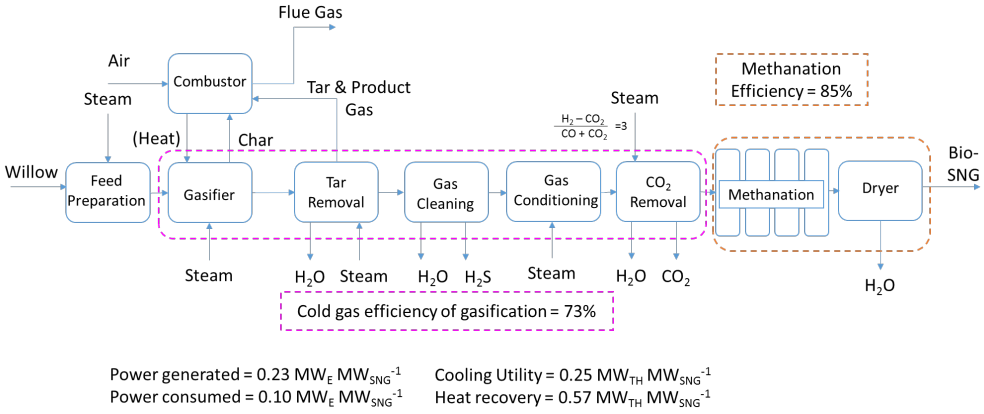


Figure 4-1 Biomass to Bio-SNG process adapted from Singlitico et al., 2019 [29]

A key consideration for gasification and upgrading of woody crops is achieving a $\frac{H_2-CO_2}{CO-CO_2}$ ratio of 3 [29]. To achieve a hydrogen-enriched syngas suitable for subsequent methanation, steam gasification is the most suitable technology [50]. Indeed, considering willow as the feedstock, the H_2 content in syngas from steam gasification could be as high as 39.2% at a bed temperature of 850°C [50] as compared to around 10% for a bed temperature of 800°C with air as the gasification agent [51]. These operating conditions significantly improve downstream methanation efficiency [28]. A further enrichment of the H_2 relative to CO fraction in the syngas could be achieved by optimisation of multiple gasification

parameters [52] including: increase in temperature; increase in steam flow rate relative to the biomass feed; catalysts; and type of biomass. However, unlike temperature, an increase in steam flow rate significantly increases tar formation [52], which would severely restrict effective downstream application of the product syngas.

Irrespective of local availability, willow is one of the most favourable feedstocks for hydrogen production by steam gasification, enabling easier methanation and better process economics. This can be substantiated by comparing the results of Pala et al., 2017 [53], whereby a H_2/CO ratio of 2.86 was obtained for green wastes, with a composition similar to that of willow [510] at 900°C and steam to biomass ratio of 0.2. In comparison, for forest residue, the corresponding H_2/CO ratio was 1.37. Thus, downstream processing of syngas for methane production from willow gasification could be considerably simplified as compared to that employed by Singlitico et al., 2019 [29] assessing gasification of forest residues.

Three scenarios for cold gas efficiency were chosen to consider the potential variation in the system due to the change of feedstock from forest residues to SRC willow. Ul Hai et al., 2019 [51] observed a cold gas efficiency of 50% for gasification of SRC willow in a 10 kW pilot-scale bubbling fluidized bed gasifier with air as the gasifying medium. This was selected as the lowest efficiency. The cold gas efficiency of 73% from Singlitico et al., 2019 [29] was chosen as the mid-range efficiency. The highest cold gas efficiency was 85%, based on gasification of fuelwood [54] which achieved efficiencies of 86-87%. The methanation efficiency of 85%, as used in the Singlitico et al., 2019 [29] model remained the same in all cases. Experience from the GoBiGas plant in Sweden is that methanation offers close to 100% conversion [7]. The gasification cold gas efficiencies and methanation efficiency are used to calculate the overall process efficiency, as outlined in Table 4-7.

Table 4-7 Process efficiency assumptions – See Figure 4-1

Process efficiency assumption	Cold gas efficiency of gasification	Methanation efficiency	Overall process efficiency (Cold gas efficiency * methanation efficiency)
Low efficiency	50%	85%	42.5%
Mid-range efficiency	73%	85%	62%
High efficiency	85%	85%	72%

4.2.8 Input scenarios

In addition to GWP values and agro-chemical use, land use conversion from grass or arable land had an impact on the emissions. This led to a total of 24 scenarios numbered from 1 to 24. A summary of the variables used is presented in Table 4-8.

Table 4-8 List of Scenarios and variables – Process efficiencies from Table 4-7

Scenario	Global warming potential	Agro-chemicals	Previous land use	Overall process efficiency
1	RED recast	Mineral	Grass	72%
2	RED recast	Mineral	Arable	72%
3	IPCC	Mineral	Grass	72%
4	IPCC	Mineral	Arable	72%
5	RED recast	Organic	Grass	72%
6	RED recast	Organic	Arable	72%
7	IPCC	Organic	Grass	72%
8	IPCC	Organic	Arable	72%
9	RED recast	Mineral	Grass	62%
10	RED recast	Mineral	Arable	62%
11	IPCC	Mineral	Grass	62%
12	IPCC	Mineral	Arable	62%
13	RED recast	Organic	Grass	62%
14	RED recast	Organic	Arable	62%
15	IPCC	Organic	Grass	62%
16	IPCC	Organic	Arable	62%
17	RED recast	Mineral	Grass	42.5%
18	RED recast	Mineral	Arable	42.5%
19	IPCC	Mineral	Grass	42.5%
20	IPCC	Mineral	Arable	42.5%
21	RED recast	Organic	Grass	42.5%
22	RED recast	Organic	Arable	42.5%
23	IPCC	Organic	Grass	42.5%
24	IPCC	Organic	Arable	42.5%

4.2.9 Transportation via gas grid

Fugitive emissions or leaks from transmission pipelines are a source of GHG emissions, which may need to be included in GHG calculations. Boothroyd et al., 2018 [55] found that in the UK, where the transmissions grid operates at pressure of 85 bar, there were fugitive emissions of methane of 62.6 kt CH_4 per annum.

In Ireland the transmission grid operates at a pressure of 70 bar. Transmission of unaccounted for gas (UAG) ranged from approximately 0.015 to 0.43% of the network throughput. Potential causes of

unaccounted for gas include *network leakage, gas escapes, theft of gas, gas quality variation, long-term no access and unregistered consumption* [56] . Additional emissions occur related to the fuel required to transport the gas. If 50% of UAG is assumed to be CH_4 losses to the atmosphere, then transmission emissions are estimated as approximately 1.22 g $CO_{2\text{-eq}}$ MJ^{-1}, and 1.27 g $CO_{2\text{-eq}}$ MJ^{-1}, for a GWP of 25 and 28 respectively. This calculation is presented in Table 4-9 for CH_4 with a GWP of 25. The average carbon footprint for grid operation is 139,400 t CO_2 y^{-1}, approximately 1.35% of the carbon footprint of combustion of all the gas distributed [56]. The emissions factor of 1.22 g $CO_{2\text{-eq}}$ MJ^{-1} equates to about 2.5% of the carbon footprint from combustion of 1MJ of natural gas (53g CO_2 MJ^{-1} CH_4). The Irish data, which includes both fuel usage for transport and potential grid emissions was chosen for this analysis. If the unaccounted gas was a negative value then the emissions associated with transport could be assumed to be 0 g CO_2 MJ^{-1}.

Table 4-9 Emissions from grid transportation

Average 2013 – 2017	Amount	Unit
Total gas transported per year	52,631	GWh
Fuel usage to transport the gas @ 1.3 %	684	GWh
Average carbon footprint of fuel usage for grid operation[1] @ 204.7 g CO_2 kWh^{-1}	139,400	t CO_2
Average 100% unaccounted for gas @ 0.2% throughput	105	GWh
Assume 50% of unaccounted for gas lost as CH_4 emissions	53	GWh
Average emissions from unaccounted for gas (GWP = 25)	92,033	t $CO_{2\text{-eq}}$
Total emissions	231,433	t $CO_{2\text{-eq}}$
Emissions factor	4.39	t $CO_{2\text{-eq}}$ GWh^{-1}
Emissions factor - conversion to MJ	1.22	g $CO_{2\text{-eq}}$ MJ^{-1}

[1] data from [56]

4.3 Results and Discussion

4.3.1 Emissions summary

The energy required and associated emissions of each scenario were calculated, an example of which is summarised in Table 10. In this example, considering Scenario 9, mineral fertiliser data and GWP was derived from Teagasc [32], and RED recast [4] respectively, while assuming the conversion of grassland.

Table 4-10 Sample Emissions calculation for Scenario 9 (mineral fertiliser, conversion from grass land, process efficiency of 62%)

Process-step	Energy Required GJ ha^{-1} y^{-1}	Net Energy GJ ha^{-1} y^{-1}	Fuel Yield GJ ha^{-1} y^{-1}	Emissions $kgCO_{2eq}$ ha^{-1} y^{-1}	Emissions $gCO_{2\text{-}eq}$ MJ^{-1}
Gross energy yield HHV		187.0	187		
Agro-chemicals (Table 4-3a & 4-5)	2.8	184.2		251	2.2
Production machinery (Table 4-6)	1.8	182.4		155	1.3
Field N_2O (Table 4-5)		182.4		176	1.5
LUC (Box 4-1)		182.4		1759	15.2
Carbon sequestration (Section 4.1.4)		182.4		440	
Transport to plant via truck (Box 4-2)	0.4	182.1	187	41	0.4
Process efficiency @ 62% efficiency (Table 4-7)	71	111.1	116		
Transport via grid (Table 4-9)			116		1.2
Efficiency = 116/187 = 62%		Efficiency	0.62	Total emissions	21.8
				Conversion 90%[1]	24.2
[1]Heat - RED recast states a field to wheel analysis (24.2 $gCO_{2\text{-}eq}$ MJ^{-1})				FFC	80
				Emissions Saved	0.70
				Criteria	0.80
Transport - RED recast states a field to tank analysis (21.78 $gCO_{2\text{-}eq}$ MJ^{-1})				FFC	94
				Emissions Saved	0.77
				Criteria	0.65

Gasification and methanation efficiency are both 85% in this scenario, with an overall efficiency of 72%. Conversion efficiency for heat is assumed as 90%. The emissions in agriculture per MJ are calculated by dividing the emissions ha^{-1} y^{-1} by the final fuel yield of 116 GJ ha^{-1} y^{-1}. In Table 9, the Net Energy includes the energy in agriculture and transport for the entire process. The fuel yield refers to the energy available in the final fuel.

Most of the emissions, (approximately 90%) come from the cultivation of the energy crop, or from land use change when converting from grassland. The lower emissions during processing are largely due to the gasification model using energy recovery for the heat and electricity required. For most scenarios, it is possible to meet the criteria for transport. When converting from arable land to willow it was possible to meet the criteria for heat. None of the scenarios converting grassland to willow met the criteria for heat, demonstrating the impact that land use change will have in determining the end use of the fuel. Table 11 and Table 12 present the emissions and emissions savings for the transport and heat end uses. The fossil fuel comparator (FFC) and emissions savings required for the transport and heat end uses are as required in the RED recast [4], and outlined in Table 1.

Table 4-11 Emissions from Willow Gasification for Transport end use

Scenario	GWP	Agro-chemicals	Previous land use	Emissions g $CO_{2\text{-eq}}$ MJ^{-1}	Emissions transport end use g $CO_{2\text{-eq}}$ MJ^{-1}	Transport FFC g $CO_{2\text{-eq}}$ MJ^{-1}	Emissions saved – transport end use	Transport criteria	Meets transport criteria
1	RED recast	Mineral	Grass	18.83	18.83	94	0.80	0.65	Yes
2	RED recast	Mineral	Arable	2.52	2.52	94	0.97	0.65	Yes
3	IPCC	Mineral	Grass	18.68	18.68	94	0.80	0.65	Yes
4	IPCC	Mineral	Arable	2.37	2.37	94	0.97	0.65	Yes
5	RED recast	Organic	Grass	23.83	23.83	94	0.75	0.65	Yes
6	RED recast	Organic	Arable	7.52	7.52	94	0.92	0.65	Yes
7	IPCC	Organic	Grass	18.68	18.68	94	0.80	0.65	Yes
8	IPCC	Organic	Arable	2.37	2.37	94	0.97	0.65	Yes
9*	RED recast	Mineral	Grass	21.78	21.78	94	0.77	0.65	Yes
10	RED recast	Mineral	Arable	2.82	2.82	94	0.97	0.65	Yes
11	IPCC	Mineral	Grass	21.63	21.63	94	0.77	0.65	Yes
12	IPCC	Mineral	Arable	2.67	2.67	94	0.97	0.65	Yes
13	RED recast	Organic	Grass	27.58	27.58	94	0.71	0.65	Yes
14	RED recast	Organic	Arable	8.62	8.62	94	0.91	0.65	Yes
15	IPCC	Organic	Grass	21.63	21.63	94	0.77	0.65	Yes
16	IPCC	Organic	Arable	2.37	2.37	94	0.97	0.65	Yes
17	RED recast	Mineral	Grass	31.14	31.14	94	0.67	0.65	Yes
18	RED recast	Mineral	Arable	3.52	3.52	94	0.96	0.65	Yes
19	IPCC	Mineral	Grass	30.79	30.79	94	0.67	0.65	Yes
20	IPCC	Mineral	Arable	3.17	3.17	94	0.97	0.65	Yes
21	RED recast	Organic	Grass	31.24	31.24	94	0.67	0.65	Yes
22	RED recast	Organic	Arable	3.62	3.62	94	0.96	0.65	Yes
23	IPCC	Organic	Grass	30.89	30.89	94	0.67	0.65	Yes
24	IPCC	Organic	Arable	3.27	3.27	94	0.97	0.65	Yes

*See Table 4-10 for Sample Calculation for this scenario

Table 4-12 Emissions from willow gasification for heat end use

Scenario	GWP	Agro-chemicals	Previous land use	Emissions g $CO_{2\text{-}eq}$ MJ^{-1}	Emissions heat end use g $CO_{2\text{-}eq}$ MJ^{-1}	Heat FFC g $CO_{2\text{-}eq}$ MJ^{-1}	Emissions saved heat end use	Heat Criteria	Meets heat criteria
1	RED recast	Mineral	Grass	18.83	20.92	80	0.74	0.8	No
2	RED recast	Mineral	Arable	2.52	2.8	80	0.97	0.8	Yes
3	IPCC	Mineral	Grass	18.68	20.76	80	0.74	0.8	No
4	IPCC	Mineral	Arable	2.37	2.63	80	0.97	0.8	Yes
5	RED recast	Organic	Grass	23.83	26.48	80	0.67	0.8	No
6	RED recast	Organic	Arable	7.52	8.36	80	0.90	0.8	Yes
7	IPCC	Organic	Grass	18.68	20.76	80	0.74	0.8	No
8	IPCC	Organic	Arable	2.37	2.63	80	0.97	0.8	Yes
9*	RED recast	Mineral	Grass	21.78	24.2	80	0.70	0.8	No
10	RED recast	Mineral	Arable	2.82	3.13	80	0.96	0.8	Yes
11	IPCC	Mineral	Grass	21.63	24.03	80	0.70	0.8	No
12	IPCC	Mineral	Arable	2.67	2.97	80	0.96	0.8	Yes
13	RED recast	Organic	Grass	27.58	30.64	80	0.62	0.8	No
14	RED recast	Organic	Arable	8.62	9.58	80	0.88	0.8	Yes
15	IPCC	Organic	Grass	21.63	24.03	80	0.7	0.8	No
16	IPCC	Organic	Arable	2.37	2.63	80	0.97	0.8	Yes
17	RED recast	Mineral	Grass	31.14	34.6	80	0.57	0.8	No
18	RED recast	Mineral	Arable	3.52	3.91	80	0.95	0.8	Yes
19	IPCC	Mineral	Grass	30.79	34.21	80	0.57	0.8	No
20	IPCC	Mineral	Arable	3.17	3.52	80	0.96	0.8	Yes
21	RED recast	Organic	Grass	31.24	34.71	80	0.57	0.8	No
22	RED recast	Organic	Arable	3.62	4.02	80	0.95	0.8	Yes
23	IPCC	Organic	Grass	30.89	34.32	80	0.57	0.8	No
24	IPCC	Organic	Arable	3.27	3.63	80	0.95	0.8	Yes

*See Table 4-10 for Sample Calculation for this scenario

In all cases, converting from grassland resulted in higher emissions, due to a combination of emissions from land use change and a much lower carbon sequestration rate when compared to conversion from arable land.

Emissions from organic fertilisers were higher, due to the higher nitrogen input and volatilization compared to mineral fertiliser.

The RED recast states '*allocation of GHG to co-products should be reviewed in cases where electricity or heating are produced in co-generation or multi-generation plants'*. The emissions that could be allocated to surplus electricity are the same as the emissions from electricity delivered to the process. The electricity demand for the process described was met within the system. In addition to this, the Directive requires that co-products are defined as a primary ambition of the process; it is assumed that this is not the case in the scenarios tested. Therefore, in this analysis, the authors have decided that allocation of emissions is entirely to the main product, biomethane.

4.3.2 Emissions savings criteria

The RED recast [4] GWP values correspond to IPCC recommendations from their fourth assessment report carried out in 2007. The current recommended values are from the fifth assessment report, which was published in 2014 [57]. Should the EU adopt the most recent IPCC GWP values in future, the pathways described will still be compliant with the criteria. As the scientific understanding of emissions values evolves, the IPCC recommended values may continue to change in subsequent iterations.

The sustainability criteria in the RED recast [4] appear to direct the use of the resource towards transport, given the higher emissions allowed for transport compared with other uses, as outlined in Table 4-1. The emissions calculated were higher for heat in all cases.

4.3.3 Land use

The national Climate Action Plan published by the Irish government in 2019 proposed to plant approximately 8,000 ha of forestry annually up to 2030 and beyond [58]. The current planting rate has been approximately 4,000 ha per annum. Cross-compliance rules distinguish between afforestation and woody crops for energy production [43]. This would mean that

development of willow plantations is in addition to the afforestation proposed in the Climate Action plan.

The 11 no. gasifiers scenario proposed by (Gallagher and Murphy, 2013) [25] required 75,000 ha of land. As outlined in Section 2.6, the SEAI, Ireland's national energy authority estimates that up to 213,000 ha of land could be available for biomass cultivation. 75,000 ha equates to 37% of the land available for energy crops as identified by the SEAI, or 1% of the total land mass in Ireland. If all of the 23,000 ha available arable land were to be used, then a minimum of 52,000 ha of grassland would be required. This is approximately 25 % of the grassland area that could be converted under cross-compliance rules. For all scenarios, emissions were higher when converting from grassland.

It has been recommended to prioritize conversion of arable land for bioenergy crops to achieve greater overall GHG reduction and that conversion from grassland should be avoided [46]. Converting grassland may be allowed to a limited extent under cross-compliance, but it would not be considered 'in the spirit' of the regulation.

4.3.4 Biomethane for Renewable Heat

The resource from 11 no. gasifiers of 50MW primary energy input was assessed as 10.4 PJ [25] from 74,800 ha as a means of satisfying RES-H targets for Ireland by 2020. Applying the net energy yield in this paper of 116 GJ ha^{-1} y^{-1} (Table 2) for the median scenario gives 8.7 PJ y^{-1}. Applying the lowest net energy yield of 79.5 GJ ha^{-1} y^{-1} , which is based on overall process efficiency of 42.5% gives 5.9 PJ y^{-1}; alternatively at this yield, 110,000 Ha of land would be required to provide 8.7 PJ y^{-1}.

If all of the 213,000 ha for bioenergy crops, as proposed by SEAI, were available for willow, then the theoretical resource, based on the 116 GJ ha^{-1} y^{-1} would be 24.7 PJ, approximately 12% of all heat use in Ireland in 2017 [11]; this matches the 12% RES-T target for 2020 [58].

The resource for heat is significantly constrained, as converting from grassland will not meet the emissions savings criteria. In this case, 23,000

ha of arable land is potentially available nationally, as discussed in Section 2.6. Applying the median energy yield of 116 GJ ha^{-1} y^{-1} this equates to a resource of approximately 2.7 PJ, or 1.3% of heat use in Ireland. Given the large area of grassland cover in Ireland, it is recommended to consider this energy crop as a potential source of biomethane for transport, to avoid incurring emissions penalties associated with land use change. In a country with a larger share of arable land that can be converted to willow, this is less of a concern.

4.3.5 Biomethane for Renewable transport fuel

Willow is on the list of feedstocks for advanced biofuels in transport in the RED recast. Advanced biofuels must provide a minimum of 1% share of final consumption by 2025 and 3.5% by 2030 in each member state. According to Article 25, final consumption of energy in transport from biofuels must be at least 14% in each member state by 2030. Applying the double credit associated with advanced feedstocks Wall et al., 2013 assessed that co-digestion of grass silage from a quantity equivalent to production from 1.1% of Irish grassland resource together with slurry on a 50:50 volatile solids basis could meet 10% of energy in transport [59] Adding the willow resource at double the energy content, as per RED recast, could ensure that Ireland exceeds this minimum target. The resource from 11 no. 31MW_{SNG} gasifiers equates to 8.7PJ. At double the energy content, this is 17.4 PJ, or approximately 8% of the 2017 energy use in transport in Ireland [60].

The emissions savings criteria for transport is cradle to tank as it does not require efficiency of conversion to be taken into consideration. CNG fuels have a lower well-to-wheel efficiency range compared to conventional diesel and gasoline [61]. The tank-to-wheel efficiency of a natural gas engine ranges from 75 to 88% that of a diesel or petrol car. This would increase the effective emissions by up to 2.3 g $CO_{2\text{-eq}}$ MJ^{-1} or by 33% if conversion efficiency for transport were to be taken into account, using the

example of Scenario 1. Not requiring tank to wheel analysis gives transport a very significant advantage over heat as an end use.

Approximately 15% of energy in transport in 2017 in Ireland was associated with Heavy Goods Vehicles (HGVs). Using this resource as a transport fuel would require the deployment of Natural Gas Vehicles (NGVs) and Compressed Natural Gas (CNG) service stations. This is an added requirement, and barrier to the industry for transport, which is not a requirement for renewable heat.

4.3.6 Uncertainties and limitations in the study

Land use change is the greatest contributor to the overall emissions, given the large difference between grassland and willow plantation carbon sequestration. The greatest influence on results is the overall process efficiencies. Given the very limited data on gasification plants that have operated at full-scale it is difficult to obtain empirical data, and therefore models are necessary to carry out analysis. Higher process efficiencies result in lower overall emissions across the system.

The energy value was assumed from Gallagher and Murphy,2013 [13] and the analysis was broadly applied to Irish agriculture, assuming conservative values for nutrient application. For an individual system, more specific nutrient values based on local soil conditions would be available and an ultimate analysis would be needed to calculate the final energy yield and overall emissions for that specific pathway.

The scenarios where grassland was converted to willow did not meet the heat emissions savings criteria. In these scenarios the land-use change emissions had the greatest influence on the emissions savings. The land-use change emissions were calculated based on the soil-carbon sequestration for the different land uses. The value for grassland soil carbon sequestration was conservative as there is limited clarity provided on soil C of grassland in Ireland [19, 45]. A greater understanding of soil

carbon sequestration of grassland and willow could give more clarity on the emissions saved.

The region where Willow is grown could have an impact on the fertiliser required to achieve a similar yield. The nitrogen fertiliser mass used in this study corresponded to the N-medium scenario in Nordborg et.al., 2018 [27], which had a lower DM yield of 7.4 t DM ha^{-1} y^{-1} compared to the 10 t DM ha^{-1} y^{-1} used in this study. Using a greater amount of nitrogen to achieve a higher crop yield will lead to higher emissions.

Even though energy crops are part of the solution to climate change, ongoing climate change will affect growing conditions. As the temperature continues to rise and rainfall patterns change crop yield times and amount will vary. This variation will affect the nutrients required, and if organic nutrients need to be supplemented with synthetic nutrients [62].

A limitation of this study, and of the Renewable Energy Directive, is that $CO_{2\text{-eq}}$ emissions are the only LCA category considered for sustainability. This could lead to fuel pathways deemed sustainable which may have significant environmental impacts. Further research is necessary to determine how policy can contribute to mitigating the potential impact of this energy pathway on other environmental categories.

4.4 Conclusions and recommendations

This study carried out an assessment of the equivalent CO_2 emissions for the willow biomethane pathway via gasification and upgrading, in order to determine if it could meet EU sustainability criteria. For any biomethane pathway, meeting the emissions savings will determine the role that it can play in the green gas industry in EU states.

In terms of policy implications the RED recast positions transport as a more favourable pathway than heat. This can be seen in five ways:

1. GHG savings required by the RED recast are lower for transport than heat (65% vs 80%);
2. The FFC is higher for transport than heat (94 g $CO_{2\text{-eq}}$ MJ^{-1} vs 80 g $CO_{2\text{-eq}}$ MJ^{-1}) making it easier to satisfy transport.

3. The efficiency of heat conversion must be included.
4. For transport, the RED recast methodology employs a field to tank analysis as opposed to a cradle to wheel. If the analysis were field to wheel typically biomethane underperforms as compared to diesel by about 75% [45]. The combination of points 1 to 4 lead to a requirement for biomethane to limit emissions to 32.9 g $CO_{2\text{-eq}}$ MJ^{-1} for transport as opposed to 14.4 g $CO_{2\text{-eq}}$ MJ^{-1} for heat.
5. This effect is further exacerbated by the fact that the RED recast counts advanced transport biofuel as twice the energy in the fuel when counted towards meeting national renewable energy in transport targets.
The analysis undertaken in this paper used conservative estimates for input values such as agro-chemicals and carbon sequestration and assumed heat and power recovery during the thermal conversion process. It should be noted that the RED recast GWP values are based on superseded recommendations from the IPCC.

Biomethane for renewable heat has the potential to initiate a green gas industry as it does not require capital investment by the end user. However, in converting from grassland to willow it is not possible to meet the emissions criteria for heat. Due to the portions of agriculture land in Ireland which are arable and which are in pasture the resource of willow biomethane that is sustainable is limited to 0.5% of the heat market. Considering the Irish context of a large area of grassland cover, and climate recommendations to limit conversion from grassland, the potential for grass as an energy crop in Ireland should be explored further. This recommendation is specific to the Irish context, as converting other land uses to grassland may not be appropriate depending on land cover in other countries.

The paper concludes that willow biomethane can meet EU emissions savings criteria for both heat and transport, using a range of scenarios for emissions from cultivation, when converting from arable land. The pathway

can meet EU emissions savings criteria for transport, when converting from arable land or grassland. However, biomethane for transport would require significant investment by the end user to facilitate the CNG refuelling infrastructure and purchase of NGVs. Using willow as a feedstock for biomethane requires significant investment on the supply side to develop the resource. Developing a substantial resource of willow in Ireland is dependent on the ability to convert both arable and grassland to energy crops, for both gasification and combustion, and a national capacity to convert a large land area in addition to Climate Action goals.

Acknowledgements

This work was supported by Science Foundation Ireland (SFI) through the MaREI centre under Grant No. 12/RC/2302_P2. The authors are grateful for discussions with MaREI colleagues Dr. Alessandro Singlitico, Dr Shane McDonagh and Dr. Chen Deng, Barry Caslin, Donal O'Brien and Tom Houlihan at Teagasc, and industry experts David Hynes and Chris Johnston.

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HTML - TH-AL-21-015-EN-Q- ISBN 978-92-9480-407-5 ISSN 1977-8449 - doi: 10.2800/458052

5 Evaluating the best end use for agricultural biomethane from an EU energy and emissions policy perspective

Long, A.[a,b,c], O'Shea, R.[a,b,c], Murphy, J.D.[a,b,c]

[a] MaREI Centre for energy, climate and marine, Ireland

[b] Environmental Research Institute, University College Cork, Cork Ireland

[c] Discipline of Civil, Structural and Environmental Engineering, School of Engineering, University College Cork, Cork, Ireland

Abstract – 260 words

Biomethane produced via anaerobic digestion (AD) can be used as a means of displacing natural gas in industrial installations that are part of the EU Emissions Trading System (ETS), or alternatively can be used as a biofuel for transport which is not part of the ETS but contributes to national emissions reduction targets under the EU effort sharing greenhouse gas (GHG) emissions reduction targets. As a circular economy system biomethane production and use can simultaneously reduce GHG emissions in agriculture (also non ETS and part of national emissions).

The Irish dairy sector is chosen as a case study as the number of cows in the country has increased leading to increased GHG emissions and increased slurry output which is a feedstock for AD. It is proposed that the slurry is co-digested with grass to achieve a greater energy yield than from slurry alone. The biomethane can be used in dairy processing in a circular economy approach, in residential heat or as a fuel for heavy goods transport.

The Renewable Energy Directive (RED) recast sets life cycle GHG emissions criteria that must be met for the fuel to be considered sustainable. Criteria

are set lower for transport when compared to heat, with the effect that transport appears as the more favourable end use. Here we show that a transport end use will achieve a greater emission saving for EU and national emissions savings targets as compared to heat and will contribute to the RED recast 14% renewable energy in transport target. Using biomethane in the ETS sector will not contribute to national non-ETS targets set by the EU.

Keywords

Biomethane; Renewable Heat; Renewable Transport; Emissions; Sustainability

Highlights

Transport is a better end use than heat from an emissions reduction perspective

Transport with system CH_4 loss of 3.55% has lower emissions than heat with 1% loss

Transport end use contributes more to EU effort sharing emissions reduction targets

A transport end use contributes to the 14% RES-T target in the RED recast

Transport as an end use will have a greater contribution towards EU policy goals

5.1 Introduction

5.1.1 State of the art of policy to reduce dairy emissions and produce sustainable biomethane

This paper concentrates on Ireland as an exemplar of a country within the EU with large number of dairy cows and associated production of milk products. The EU milk quota that limited milk production was lifted in 2015 [1]. The dairy industry in Ireland was prepared for this [2] and dairy production had increased gradually prior to 2015. Data from the Irish Central Statistics Office and Department of Agriculture on dairy cow numbers is presented in Figure 5-1 [3]. Dairy cow numbers are set to continue expanding until 2025 [4]. The sector is a significant part of the food export strategy for Ireland [2]. Dairy processing by large thermal energy users with in excess of 20MW of installed thermal capacity in Ireland, as for other EU states, is part of the Emissions Trading System (ETS), which aims to reduce emissions from energy production and installations with large installed thermal capacities. There are 19 dairy processing facilities in Ireland in the ETS [5]. Extensive studies are available on the life cycle emissions of the dairy sector in Ireland and throughout the world. These are available at individual farm level [6] and from a national perspective [7,8]. While most of the greenhouse gas (GHG) emissions associated with dairy products are from the agricultural life cycle stage there is potential to reduce emissions in the sector through fuel substitution at the processing stage.

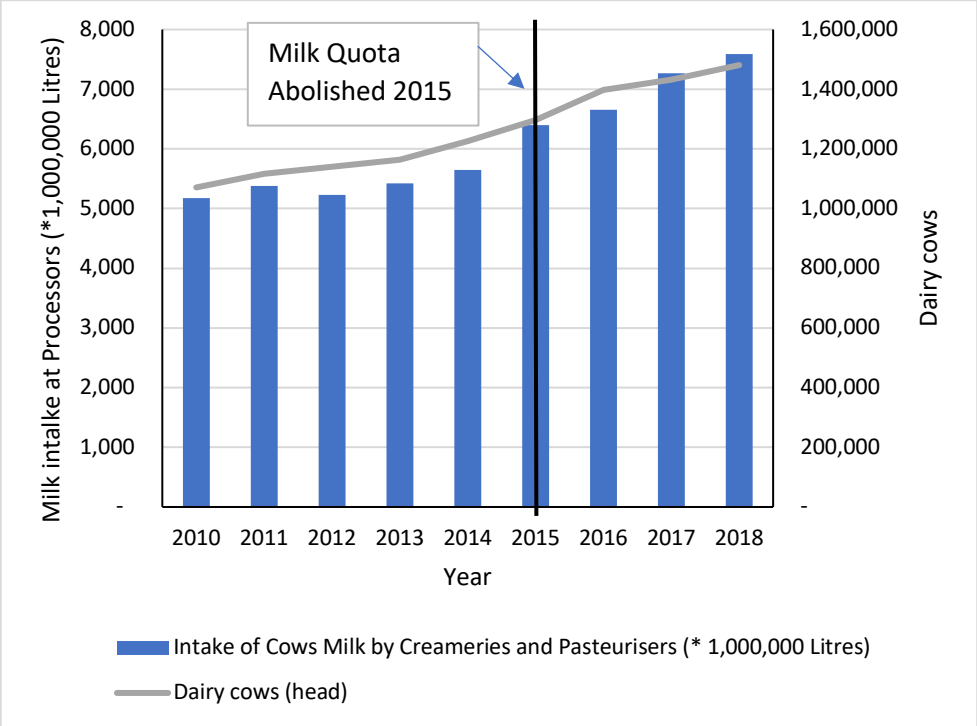


Figure 5-1 Dairy Cows and Milk Production in Ireland - Data from CSO

Renewable heat production in the ETS and non-ETS sectors is a possible end-use of renewable gas produced from anaerobic digestion (AD) [9] to displace natural gas and reduce GHG emissions. The Irish Agriculture and Food Development Authority ,Teagasc, has proposed the use of biomethane for combined heat and power (CHP) and renewable heat production as a GHG mitigation measure, while acknowledging that a transport end use could potentially save more GHG emissions [10]. This led to biomethane in heat being considered as a potential option in the Climate Action Plan [11]. However, GHG emissions savings criteria in the recast Renewable Energy Directive (RED recast) [12] tend to place more emphasis on transport as an end use [13]. The Irish EPA has also expressed concern about the lack of policy progress in renewable freight transport [14], which is considered a particularly suitable end use for renewable gas [15]. As such there are subtle differences in priorities between industry and policy makers as to the use of biogas.

Deploying biomethane successfully requires a series of best-practice management across the circular economy system. It is not a given that these benefits will be realised when anaerobic digestion is introduced. In

some cases, introducing biomethane is a catalyst for improving farming practices. For example, fugitive methane emissions from open slurry tanks are captured in the digester for use as energy. Spreading digestate using low emissions slurry spreading techniques, spreading at optimum times in relation to weather and soil conditions, and measuring soil nutrients can result in improvements in water quality in comparison with splashplate slurry spreading [16]. Odours from existing farming practices can be reduced significantly by covering storage tanks and using low emission slurry spreading [17].

Sustainability in this paper refers to the GHG emissions from the life cycle $CO_{2\text{-eq}}$ emissions of the biomethane production pathway in comparison to the requirements of the EU RED recast [12], in force since July 1st 2021. As compared to the previous version of the directive [18] there is an increased threshold of GHG emissions savings (or sustainability criteria) required for potential energy sources to be considered a sustainable renewable energy supply. The parameters chosen for calculating the life cycle GHG emissions have an impact in determining the sustainability of the biomethane. These include system methane fugitive emissions, CO_2 sequestration, energy use and biomethane purity [19–21]. The end use of the biomethane is also an important determinant of the fuel sustainability. Meeting the sustainability criteria is necessary to be eligible for financial aid, to contribute to renewable energy supply targets and for certification schemes [12]. The Irish Climate Action Plan focuses on measures that can maximise GHG emissions saved with the lowest cost of investment [11]. The existing measures proposed however are not sufficient to meet EU effort sharing targets for Ireland [22], and so greater ambition is required. At the time of writing the Irish government is preparing an updated climate action plan.

5.1.2 Gap in the state of the art

Most of the research available focuses on the GHG emissions and environmental impact of dairy cows in Ireland. Where biofuels meet the GHG emissions savings criteria in the RED [18], the GHG emissions from combustion are calculated as zero for national reporting purposes [23]. In

the IPCC methodology, GHG emissions from biomass-based products are considered zero at the combustion stage as life cycle GHG emissions are reported in other categories [24]. Considering GHG emissions reduction in agriculture, technological options such as anaerobic digestion (AD) are often favoured over cattle reduction in an analysis of 21 countries [25]. While research has demonstrated how life cycle GHG emissions from AD of agricultural feedstocks can be reduced [26], there is limited discussion on how this will translate into compliance with EU policy reporting requirements for 2030.

5.1.3 Aims and objectives

The aim of the paper is to evaluate the potential of AD to mitigate GHG emissions from the dairy sector, including agriculture and milk processing, and to understand the policy implications. Ireland is used in this paper as a case study of an EU State which could use a significant resource of dairy cow slurry as a feedstock for AD with the resulting biogas being upgraded to biomethane. Three potential end uses are considered. In all cases, the gas grid is used for transportation of the biomethane. The first end use is in large dairy processing facilities in the ETS as a means of displacing natural gas use. The second use is as source of renewable heat in the non-ETS sector, and the third use is displacing transport fuel (also non-ETS). The dairy industry in Ireland was chosen for analysis as changes in livestock numbers in recent years have led to increased GHG emissions [27]. It was also necessary to limit the scope of the analysis for simplicity. The methodology in this paper can be applied to any agricultural livestock sector in EU countries.

The objectives of the study are to assess (i) the sustainability of the biomethane resource for renewable energy supply in heat (RES-H), or transport (RES-T) according to the RED recast [12], (ii) the degree to which natural gas can be replaced by biomethane in dairy processing in a circular economy approach, (iii) how each scenario can contribute to national targets set for EU energy and GHG emissions policies as the number of dairy cows increases.

5.2 Method

This analysis considered the GHG emissions associated with dairy cows only. These GHG emissions arise from enteric fermentation, manure management, and agricultural soils. The agricultural soils category was included as this accounts for GHG emissions from manure deposits on pasture and slurry spreading. When AD was introduced, the GHG emissions associated with the cultivation of the additional grass feedstock were added as this is additional to the grass requirement to feed cattle and is included in the IPCC methodology [28,29]. The number of dairy cows is expected to increase in Ireland until 2026. For this reason, the analysis was applied to the predicted number of dairy cows up until 2030 [4] to understand the GHG emissions mitigation potential of AD with increasing dairy cow numbers.

The national GHG emissions and sustainability of the feedstock mix was assessed for all of the potential Volatile Solids Ratio (VSR) combinations outlined in Wall et al. [30], namely Grass silage:Cattle slurry 100:0, 80:20, 60:40, 50:50, 40:60, 20:80, 0:100. System methane losses of 1%, 2% and 3.55% were chosen for analysis, corresponding to an ideal system, a good system and a system with open storage respectively [28,31]. For example O'Shea et al. [20] used a system methane loss of 0.5% for a profitable scenario; this was used for Scenario 2 only (Table 1). The variations of VSR combinations and system methane losses led to multiple scenarios that could potentially be considered for discussion. In order to make a considered assessment of the potential for emissions reduction, scenarios for further anaysis were selected based on their ability to meet

sustainability criteria in the RED recast [12]. The process of narrowing down scenarios is outlined in Figure 5-2.

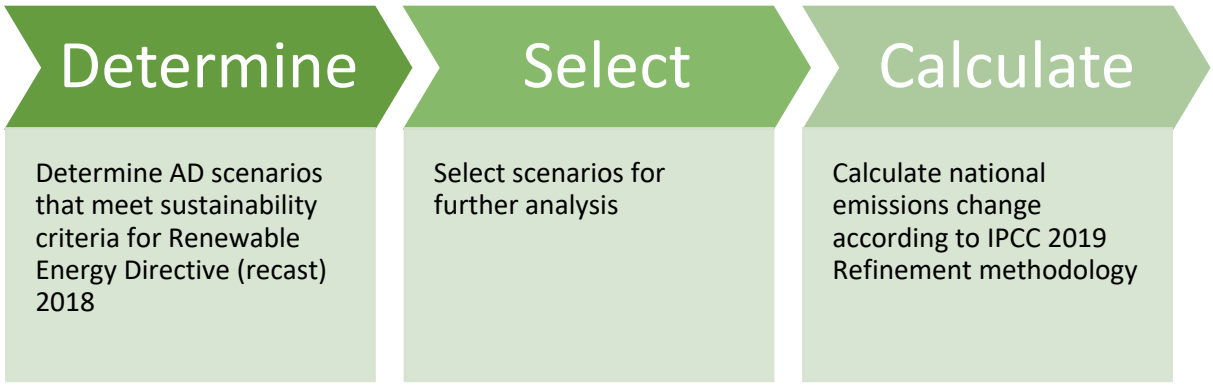


Figure 5-2 Method Flow Chart

5.2.1 AD Scenarios

The GHG emissions from a 'No change scenario' and 23 AD scenarios were analysed. All scenarios are outlined in Table 5-1. For Scenario 1, the GHG emissions are calculated using data from the 2017 national inventory report [27] and updated to reflect the 2019 Refinement of IPCC methodology for calculating GHG emissions [28,29]. The Profitable scenario (Scenario 2) is based on a scenario from O'Shea et al., 2017 [20] where 1,559 kt FW grass per annum and 1,632 kt FW slurry per annum are digested in 42 digesters processing approximately 75,000 t FW each per annum. The 'Digest all slurry' scenarios (Scenarios 3-8, 10-15, 17-22) represent a situation where AD is used as a means of both processing slurry and maximising the resource of energy from farm-based biogas systems on a national level and assumes that all potentially available slurry is processed by AD. The slurry available is the slurry collected from the winter period when dairy cattle are housed indoors. In 2017, this was 28.02% of all slurry produced [27]. The current form of slurry collection is referred to as Pit Storage Animal Waste Management System (AWMS). It is assumed that all slurry that is currently stored in Pit Storage will be diverted to AD in the 'Digest all slurry' scenarios. An average distance of

40km was assumed for transporting the slurry to a digester, giving a round trip of 80 km.

Table 5-1 Scenarios for sustainability assessment

Scenario	Description	Volatile Solids Ratio (VSR) Grass silage : Cattle slurry	Methane Production – from Wall, 2013 [30] m^3 CH_4 t^{-1} FW	System methane loss – including AD plant and digestate storage
1	Current Practice: No AD – existing data updated to IPCC 2019 Refinement methodology	-	-	-
2	Profitable scenario from (O'Shea et al., 2017) [20]	80:20	78.7	0.5%
3	Digest all slurry - 100% slurry	100:0	16	1%
4	Digest all slurry	20:80	26.8	1%
5	Digest all slurry	40:60	40.3	1%
6	Digest all slurry	50:50	51.6	1%
7	Digest all slurry	60:40	60.3	1%
8	Digest all slurry	80:20	78.7	1%
9	100% Grass silage	0:100	107.4	1%
10	Digest all slurry - 100% slurry	100:0	16	2%
11	Digest all slurry	20:80	26.8	2%
12	Digest all slurry	40:60	40.3	2%
13	Digest all slurry	50:50	51.6	2%
14	Digest all slurry	60:40	60.3	2%
15	Digest all slurry	80:20	78.7	2%
16	100% Grass silage	0:100	107.4	2%
17	Digest all slurry - 100% slurry	100:0	16	3.55%
18	Digest all slurry	20:80	26.8	3.55%
19	Digest all slurry	40:60	40.3	3.55%
20	Digest all slurry	50:50	51.6	3.55%
21	Digest all slurry	60:40	60.3	3.55%
22	Digest all slurry	80:20	78.7	3.55%
23	100% Grass silage	0:100	107.4	3.55%

5.2.2 Feedstock supply

The slurry available in each of the 'Digest all slurry' scenarios was based on the slurry available in 2017 [27]. This was approximately 439 kt DM per annum or 5,015 kt FW per annum. The mass of grass required for co-digestion was then calculated by applying the VSR of the mix for the scenario under consideration. The total theoretical grass resource in excess of livestock requirements for the Republic of Ireland (with c. 4,000,000 ha of grassland) was estimated as 12,204 kt DM y^{-1} [32], based on the maximum yield possible in a scenario which assumed maximum N fertiliser

application, an increased grass utilisation rate by cattle, and approximately 1,394,850 dairy cows. This is in line with 2017 data of 1,388,000 dairy cows [27]. The number of cows in Ireland is expected to increase to 1,619,000 dairy cows in 2025 [4]. For the selected scenarios, the additional grass required for co-digestion was compared with the potentially available grass resource in excess of livestock requirements using methodology and data established by [32], updated livestock data for 2020 from Ireland's Central Statistics Office [33] and the projected number of dairy cows in 2025.

5.2.3 Sustainability criteria

The sustainability criteria from 2026 were applied to the feedstock mix [12] as the AD industry in Ireland is nascent and it is unlikely many facilities will be constructed in advance of 2026. The sustainability analysis should be considered broad and not applicable to an individual system. Conservative assumptions and data were used to test the potential for the feedstock to meet the criteria. The feedstock parameters used to calculate sustainability are based on Wall et al., 2013 [30] as presented in Table 5-2. For upgrading the biogas, amine scrubbing was chosen as this can achieve high methane recovery. In this study, the methane recovery of 99% is assumed, the electricity demand chosen is 0.11 kWh_e $m_n^{-3}{}_{biogas}$, and the parasitic heat demand is 0.58 kWh_{th} $m_n^{-3}{}_{biogas}$ [34]. The electricity and heat demands are based on a methane concentration of 55% in the raw biogas, which is consistent with the value reported by [30] for the slurry and grass feedstock. Irish legislation requires that slurry is pasteurised prior to digestion when sourced from multiple epidemiological units and combined in a single AD plant [35]. This heat demand is met by the combustion of biogas and the grass is heated using recovered heat from the pasteurised slurry to minimise heat demand. The N_2O emissions were calculated based on digestate used as fertiliser to reflect a worst-case scenario for these emissions as some of the national feedstock will be cultivated in this way. Previous research has based the analysis of grass biomethane on an N input of 250 kg ha^{-1} y^{-1} and a DM yield of 12 t DM ha^{-1} y^{-1} [13,36]. The maximum N application allowable is 225 kg ha^{-1} y^{-1} for 2 cuts of silage [37].

Farmers participating in the Teagasc PastureBase programme have reported DM yield of 11.1 to 14.4 t DM ha^{-1} y^{-1} [38]. Therefore, an N application rate of 225 kg ha^{-1} y^{-1} will be applied and a DM yield of 12 t DM ha^{-1} y^{-1} assumed.

Table 5-2 Feedstock parameters - from (Wall et al., 2013)[30]

Parameter	Slurry (feedstock n_1)	Grass silage (feedstock n_2)	Unit
Dry solids	87.5	292.7	g kg^{-1}
Volatile solids	66.9	268.4	g kg^{-1}
Moisture content	912.5	707.3	g kg^{-1}
Gas production	16	107.4	m^3 CH_4 t^{-1} FW

Annex VI of the RED Recast sets out the criteria for calculating the sustainability of co-digested feedstocks. In the case of slurry an emissions credit of 54 kg $CO_{2\text{-eq}}$ t^{-1} Fresh Weight (FW) is allowed for improved agricultural and manure management [12]. The GHG emissions in the case of co-digestion are based on the fresh weight of the substrates. Formulas for calculating the GHG emissions from co-digestion of substrates are taken from Annex VI of the RED Recast:

Equation 1: Annual input to digester of substrate n [tonne of fresh matter], from [12]

$$I_n = \frac{VS_{n,mix}}{VS_n} \Big/ \left(\frac{VS_{1,mix}}{X_{VS_1}} + \frac{VS_{2,mix}}{X_{VS_2}}\right)$$

I_n = Annual input to digester of substrate n [tonne of fresh matter]

$VS_{1,mix}$ = Share of volatile solids of feedstock n1 in the mix g VS kg^{-1} VS_{mix}

$VS_{2,mix}$ = Share of volatile solids of feedstock n2 in the mix g VS kg^{-1} VS_{mix}

X_{VS_1} = Share of volatile solids in feedstock n1 gVS $kg^{-1}{}_{n1}$

X_{VS_2} = Share of volatile solids in feedstock n2 gVS $kg^{-1}{}_{n2}$

Where weighting factor of substrate n is;

Equation 2: weighting factor of substrate n, from [12]

$$Wn = \frac{I_n}{\sum_1^n I_n}$$

Equation 3: Share of feedstock n in biomethane energy content, from [12]

$$Sn = \frac{P_n * W_n}{\sum_1^n P_n * W_n}$$

P_n = energy yield [MJ] per kilogram of wet input of feedstock n

In the final version of the RED recast [12] it is assumed that a typographical error omits $\sum_1^n P_n$ in the denominator, and as a result, the share of feedstock from multiple sources does not sum to 1. Consulting previous versions of the document [39] and JRC guidance [40] the formula used in Equation 3 is deemed correct.

The GHG emissions in the case of co-digestion of n substrates is defined in the RED recast as;

Equation 4: Actual GHG emissions in the case of co-digestion of n substrates, from [12]

$$E = \sum_1^n S_n * \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr}$$

E = total GHG emissions from the production of the biogas or biomethane before energy conversion;

S_n = Share of feedstock n, in fraction of input to the digester;

$e_{ec,n}$ = emissions from the extraction or cultivation of feedstock n;

$e_{td,feedstock,n}$ = emissions from transport of feedstock n to the digester;

$e_{l,n}$ = annualised emissions from carbon stock changes caused by land-use change, for feedstock n;

$e_{sca,n}$ = emission savings from improved agricultural management of feedstock n;

e_p = emissions from processing;

$e_{td,product}$ = emissions from transport and distribution of biogas and/or biomethane;

e_u = emissions from the fuel in use, that is greenhouse gases emitted during combustion;

e_{ccs} = emission savings from CO2 capture and geological storage; and

e_{ccr} = emission savings from CO2 capture and replacement.

A sample sustainability calculation which includes the net energy yield is included in Appendices E and F.

5.2.4 Energy resource

The national energy resource of the biomethane for each selected scenario is calculated considering the mass of feedstock and the biomethane energy yield for the VSR mix outlined in Wall et al., 2013 [30] as per Table 5-1. The feedstock quantity for the Profitable scenario is taken from O'Shea et al., 2017 [20] as per Table 5-1. This did not change as the number of cows increased. For the remaining *Digest all slurry* scenarios, the grass silage feedstock was calculated based on the quantity of slurry available and the VSR. The final energy resource was calculated based on the net energy resource calculated in the sustainability analysis.

5.2.5 GHG emissions

The updated guidelines for calculating national inventory GHG emissions, the IPCC 2019 Refinement (2019R) are applied to all scenarios. The formulae used are presented in Table 5-3. Where values specific to Ireland are used in the National Inventory Report [27] these same values are used in the 2019R analysis. Where default values are used based on tables in the 2006 IPCC guidelines, then default values are also used in the updated analysis that was based on the 2019R methodology. The IPCC uses the term co-digestate for the feedstock that is co-digested with slurry. In this study

the grass is referred to as co-feedstock to avoid confusion with the digestate associated with additional grass that is used. As the number of cows is expected to increase, the calculations for each scenario were projected to 2030 using dairy herd estimates [4]. The overall change in GHG emissions is related to the displacement of fossil fuels, the change in emissions from manure management, and the change in emissions from agricultural soils.

Three potential fuel displacement options are considered within each AD scenario. The first is thermal energy production by milk processors in the dairy sector that are in the ETS, as this is a potential circular economy application of the biomethane from slurry. The second is heat production in the non-ETS sector and the third is as a fuel in the heavy transport sector (also non-ETS). Both non-ETS heat and transport contribute to EU effort sharing GHG emissions savings [41]. The natural gas demand of dairy processing was estimated based on a national analysis of dairy processing by [8]. This data was related to 2012, so it was compared with the energy requirement in the food processing, beverage, and tobacco category in the EPA National Inventory Report for the same year. As the number of dairy cows increases, dairy processing energy demand and the amount of dairy cow slurry potentially available will also increase. It is assumed that the natural gas demand identified can be supplemented with biomethane transported via the gas grid or using an off-grid mobile solution [42]. Where thermal energy is displaced, the efficiency of the fuel in use is assumed to be the same as the displaced fuel. For transport, the fuel consumption of biomethane relative to diesel can range from 114% to 119% [43]. In this analysis a conservative value of 114% was chosen.

Table 5-3 Methods used to calculate GHG emissions - formulae from IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, data from (Duffy et al., 2019)

Process	Method used to calculate GHG emissions
Enteric Fermentation CH_4	Mass CH_4 (kg) = EF * N_{cows} [28] EF = $(GE * \left(\frac{Y_m}{100}\right) * 365)/55.65$ Where: GE = Gross energy intake = 255 MJ head^{-1} day^{-1} [27] Y_m = Share of gross energy in feed converted to methane = 6% (Table 10.12) [26]
Manure management CH_4	Mass CH_4 (kg) = $EF_{(T)}$ * N_{cows} [28] $EF_{(T)}$ = annual CH_4 emission factor for livestock category T = $(VS_T * 365)\left[B_{0(T)} * 0.67 * \sum_{S,k} \frac{MCF_{S,k}}{100} * AWMS_{(T,S,k)}\right]$ kg CH_4 animal^{-1} yr^{-1} Where: VS_T = daily volatile solid excreted for livestock category T = 3.09 kg DM animal^{-1} yr^{-1} [27] $B_{0(T)}$ = maximum methane producing capacity for manure produced by livestock category T = 0.24 m^3 CH_4 kg^{-1} VS [27] $MCF_{(S,k)}$ = methane conversion factors for each manure management system S by climate region k,% $AWMS_{(T,S,k)}$ = fraction of livestock category T's manure handled using animal waste management system S in climate region k
Manure management Direct N_2O	Mass N_2O (kg)= $EF_{3,(S)}$* kg N * (44/28) [29] Where: $EF_{3,(S)}$ = emission factor for direct N_2O emissions from manure management system S, kg N_2O-N (kg N input)$^{-1}$
Manure management Indirect N_2O – Volatilised N	Mass N_2O (kg) = $Frac_{GasMS}$ * EF_4 * kg N * (44/28) [27] $Frac_{GasMS}$ = fraction of managed manure nitrogen for livestock category T that volatilises as NH_3 and NO_x in the manure management system S EF_4 = emission factor for N_2O emission from atmospheric deposition of N on soils and water surfaces, kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$
Agricultural Soils Direct N_2O	Mass N_2O (kg) = (EF_1 * kg N_{inputs} + $EF_{3,PRP}$* kg N_{PRP}) * (44/28) [27] Where EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O-N (kg N input)$^{-1}$ [29] N_{inputs} = N inputs from applied synthetic and organic fertiliser $EF_{3,PRP}$ = emission factor for N_2O emissions from urine and dung N deposited on pasture by grazing animals, kg N_2O-N (kg N input)$^{-1}$ [27] N_{PRP} = N inputs from grazing animals
Agricultural Soils Indirect N_2O – Volatilised N	Mass N_2O (kg) = $Frac_{GASM}$ * EF_4 * kg N * (44/28) [29] Where $Frac_{GASM}$ = fraction of applied organic N fertiliser materials and of urine and dung N deposited by grazing animals that volatilises as NH_3 and NO_x = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ EF_4 = emission factor for N_2O emission from atmospheric deposition of N on soils and water surfaces, kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$
Agricultural Soils Indirect N_2O – Leaching and runoff	Mass N_2O (kg)= $Frac_{LEACH(H)}$ * EF_5 * kg N * (44/28) [29] Where $Frac_{LEACH(H)}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$ EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O-N (kg N leached and runoff)$^{-1}$

Energy	
Fuel displaced CO_2	Mass CO_2 (kg)= TJ Fuel * EF CO_2 TJ^{-1} * Fuel consumption factor relative to diesel
Synthetic Fertiliser Required/Displaced	
Agricultural Soils Direct N_2O	Dkg N_2O = kg N * EF_1 * (44/28) [28] Where: EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O-N (kg N input)$^{-1}$
Agricultural Soils Indirect N_2O – Volatilised N	Mass N_2O (kg) = $Frac_{GASF}$ * EF_4 * kg N * (44/28) [29] Where: $Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x = 0.085 kg N volatilised (kg of N applied)$^{-1}$ EF_4 = emission factor for N_2O emission from atmospheric deposition of N on soils and water surfaces, kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$
Agricultural Soils Indirect N_2O – Leaching and runoff	Dkg N_2O = $Frac_{LEACH}$ * EF_5 * kg N * (44/28) [29] Where: $Frac_{LEACH(H)}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$ EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O-N (kg N leached and runoff)$^{-1}$

The digestate is assumed to be capable of displacing both slurry as fertiliser and synthetic nitrogen fertiliser. The Nitrogen availability of the synthetic fertiliser, F_{SN}, provided in the 2017 National Inventory Report [27] is assumed as 100%. The nitrogen availability of the digestate spread using

Grass yield = 12 t DM ha^{-1}

N required = 225 kg ha^{-1} y^{-1}

DM content of grass silage = 0.29 t DM tFW^{-1}

N requirement = (225 kg N ha^{-1} y^{-1} / 12 t DM ha^{-1})* 0.29 t DM t FW^{-1}

= 5.4 kg N t FW^{-1}

Box 5-1 Nitrogen required for grass cultivation. N: nitrogen. DM: Dry Matter. FW: Fresh Weight.

precision techniques is approximately 60% [44]. For comparability of systems low emission slurry spreading was also assumed, with a nitrogen availability of 50% [45]. The nitrogen required for grass cultivation is taken from Smyth et al., 2009 [36] and outlined in Box 5-1.

The nitrogen content of grass silage was 2% of the grass volatile solids [46]. Considering the N availability in the slurry and digestate, the change in synthetic N (F_{SN}) is defined as;

Equation 1: Change in Synthetic N (kg)

$$DF_{SN} = N_{DisplacedSlurry} + N_{required} - N_{Digestate}$$

If the mass of available slurry N displaced and the mass of additional N required for the additional grass cultivation for AD are less than the mass of N available in the digestate then DF_{SN} will be a negative value and the additional digestate N can replace synthetic fertiliser. Where the additional N required, and the N displaced are greater than the mass of N available in the digestate then additional synthetic fertiliser will be required. This is illustrated in Figure 5-3.

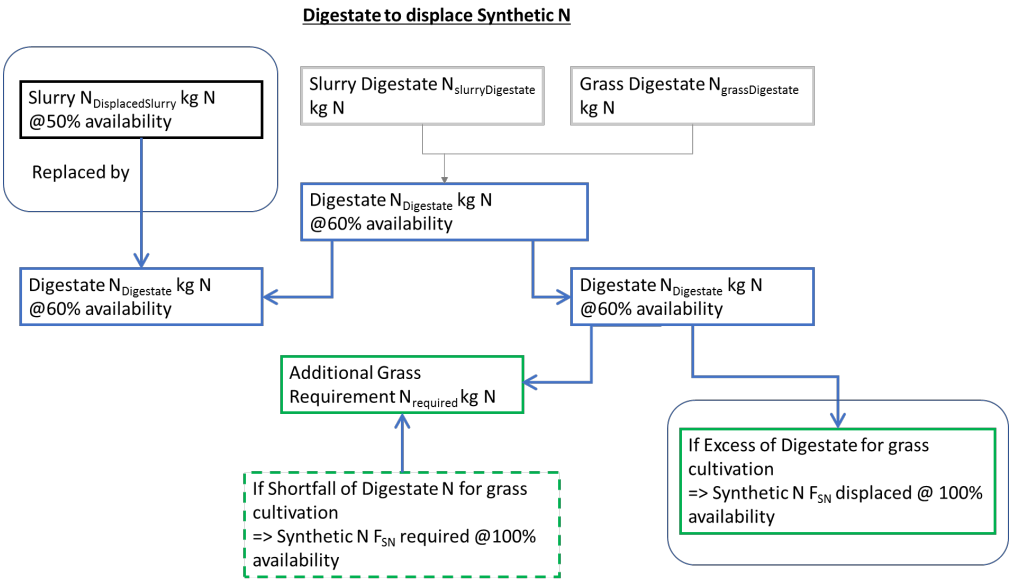


Figure 5-3 Change in Synthetic N

5.2.6 Contribution to policy targets

This research will assess how pursuing a strategy of developing AD and the different potential end uses will contribute to a number of key energy and emissions policies. These are as follows:

- RED recast: This has an EU-wide target of 27% renewable energy supply and a national target for Ireland of 14 % renewable energy in Transport [12].
- EU Effort Sharing agreement: This has a target for Ireland of 30 % reduction in relation to non-ETS 2005 GHG emissions by 2030 [41]. The

overall effort sharing GHG emissions reduction target for non-ETS emissions Ireland by 2030 is 14,191 kt $CO_{2\text{-eq}}$ y^{-1} in 2030. This is based on 2005 effort sharing emissions of 47,304.01 kt $CO_{2\text{-eq}}$ [22].

- Irish Climate Action and Low Carbon Development Bill 2021: National target of 51 % reduction in relation to reported 2018 GHG emissions by 2030 [47], a reduction of 31,077 kt $CO_{2\text{-eq}}$ [27,47]. This is based on reported 2018 emissions of 60,924.54 kt $CO_{2\text{-eq}}$ [22].

The emissions saved are calculated as the difference between the total dairy sector emissions from the no-AD scenario and the scenario under analysis. Ireland is one of the EU countries that has availed of the 'flexibility' option in relation to ETS emissions. This means that Ireland can use a portion of the ETS emissions saved to contribute towards the EU Effort Sharing national target. [48]. The maximum offset amount allowed is 4% of the 2005 effort sharing GHG emissions which is 1,892 kt $CO_{2\text{-eq}}$ [22]. Considering the EPA 'With Existing Measures' scenario, the 'Ireland's Greenhouse Gas GHG Emissions Projections' reports the total proposed GHG emissions saved in the ETS sector in 2030 as potentially 6,298 kt $CO_{2\text{-eq}}$ [22], which is greater than the flexibility allowed. Therefore, the GHG emissions saved from digesting slurry with grass in this analysis would be additional to the proposed existing measures in the ETS sector. In this case, using the biomethane in the ETS sector will have no additional contribution to the Effort Sharing target if the GHG emission savings are accrued by the facility in the ETS. If the measures proposed in the Climate Action Plan are not applied, then there will be the potential for emissions saved from anaerobic digestion and energy use in the ETS to contribute to the effort sharing target.

In order to determine the value of AD of agricultural feedstocks in energy policy the contribution towards the mandatory country level target of 14% energy in transport [12] is estimated. The numerator in this case is twice the energy contribution as allowed under Article 27 in the RED recast for advanced feedstocks as listed in Annex IX [12]. Under Article 7 the share of

aviation in a member state's gross final consumption of energy is capped at 6.18 % in the calculation methodology [12]. The denominator is the current total energy consumption in transport based on SEAI data [49] and modified to account for the 6.18% cap as the share of energy in Irish aviation is approximately 9%. The energy use in transport in 2030 was estimated as 40% of gross final energy in a projected scenario based on the current trajectory [50]. Current data and 2030 projections are presented in Table 5-4. The share of energy in aviation decrease in 2020 is due to the impact of Covid-19 restrictions on the aviation sector. For 2030 it is assumed that normal aviation has returned with a 9% energy share, similar to 2018 and 2019.

Table 5-4 Energy in Transport denominator for calculating progress to targets in 2030

Year	Gross final consumption of energy (TJ)	Aviation (TJ)	% Share in aviation	Max share in Aviation (TJ) (6.18% of GFC)	Final energy in Transport (TJ)	Final energy in Transport including aviation max (TJ)
2018	520629	46222	9%	32175	217504	203457
2019	520419	46725	9%	32162	219095	204532
2020	470638	16705	4%	29085	162322	162322
2030	602899	54261	9%	37259	241160	224158

5.3 Results and Discussion

There is no change to the GHG emissions associated with enteric fermentation as this is directly related to livestock numbers. The manure management systems in Ireland assessed are Pasture, (where dung is directly deposited by dairy cows) Pit Storage of slurry during the indoor winter period, and Deep Bedding during the winter storage period. When AD is introduced, some or all of the slurry that was held in pit storage is diverted to the anaerobic digester, and the digestate from AD is spread on land. As grass is the co-feedstock in all AD scenarios the additional GHG emissions associated with this are also considered. In IPCC terminology, this is referred to as the co-digestate [28]. In the Profitable scenario, both digestate and slurry are spread on land. In the Digest All Slurry scenarios,

all the slurry associated with pit storage is digested and the digestate is spread on land.

5.3.1 Sustainability

Where all other system and input values are equal, scenarios with higher system methane loss and higher shares of grass silage are more likely to be unsustainable for the heat end use. Table 5-5 outlines the GHG emissions and sustainability for each end use for all the scenarios assessed. Sample calculations for sustainability are presented in Supplementary Data Appendices E and F. Consistent with previous research [13] when the sustainability criteria of the RED recast [12] are applied, transport is a more favourable end use when compared to heat.

Table 5-5 Compliance with sustainability criteria

Scenario (See Table 1)	Feedstock Mix (% Volatile Solids)	System Methane Loss (%)	Total emissions (g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	Emissions allowed for Heat @ 90% efficiency (g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	Emissions allowed for Transport (g $CO_{2\text{-eq}}$ MJ^{-1})	Pathway sustainable for Heat	Pathway sustainable for Transport
2	80% Slurry 20% Grass silage	0.50%	11.31	14.4	32.9	YES	YES
3	100% Slurry	1%	-92.04	14.4	32.9	YES	YES
4	80% Slurry 20% Grass silage	1%	-22.75	14.4	32.9	YES	YES
5	60% Slurry 40% Grass silage	1%	-0.59	14.4	32.9	YES	YES
6	50% Slurry 50% Grass silage	1%	5.54	14.4	32.9	YES	YES
7	40% Slurry 60% Grass silage	1%	8.48	14.4	32.9	YES	YES
8	20% Slurry 80% Grass silage	1%	12.24	14.4	32.9	YES	YES
9	100% Grass silage	1%	13.18	14.4	32.9	YES	YES
10	100% Slurry	2%	-88.29	14.4	32.9	YES	YES
11	80% Slurry 20% Grass silage	2%	-18.44	14.4	32.9	YES	YES
12	60% Slurry 40% Grass silage	2%	4.11	14.4	32.9	YES	YES

13	50% Slurry 50% Grass silage	2%	10.26	14.4	32.9	YES	YES
14	40% Slurry 60% Grass silage	2%	13.26	14.4	32.9	YES	YES
15	20% Slurry 80% Grass silage	2%	17.01	14.4	32.9	**NO**	YES
16	100% Grass silage	2%	17.97	14.4	32.9	**NO**	YES
17	100% Slurry	3.55%	-82.47	14.4	32.9	YES	YES
18	80% Slurry 20% Grass silage	3.55%	-11.30	14.4	32.9	YES	YES
19	60% Slurry 40% Grass silage	3.55%	11.47	14.4	32.9	YES	YES
20	50% Slurry 50% Grass silage	3.55%	17.88	14.4	32.9	**NO**	YES
21	40% Slurry 60% Grass silage	3.55%	20.79	14.4	32.9	**NO**	YES
22	20% Slurry 80% Grass silage	3.55%	24.70	14.4	32.9	**NO**	YES
23	100% Grass silage	3.55%	25.63	14.4	32.9	**NO**	YES

5.3.2 Selected Scenarios

The following scenarios were selected for further analysis; Scenario 2 as it represents a profitable and therefore likely scenario for Ireland, Scenarios 4, 11, and 18 as these scenarios were sustainable for heat at the 20% slurry 80% grass silage VSR mix and at all levels of system methane loss used. Scenarios 6 and 13 were sustainable up to 2% system methane loss (50% slurry 50% grass silage VSR mix); Scenario 13 represents the cut-off point in terms of methane losses (2%) as system methane loss above this level are no longer sustainable for heat. The GHG emissions associated with livestock and displaced fuel for these scenarios are mapped in Figure 5-4.

The potentially available grass supply in Ireland was assessed as 34,167,732 t DM [32]. Using projected dairy cow data for 2025 of 1,619,000 cows [4] and June 2020 data for all other livestock [33], the grass requirement for the number of dairy cows in 2025 is calculated as 8,363,754 t DM and for all cattle and sheep as 25,310,180 t DM in Table 5-6. This leaves a potential

resource of 8,857,552 t DM in excess of livestock requirements that can be used for AD.

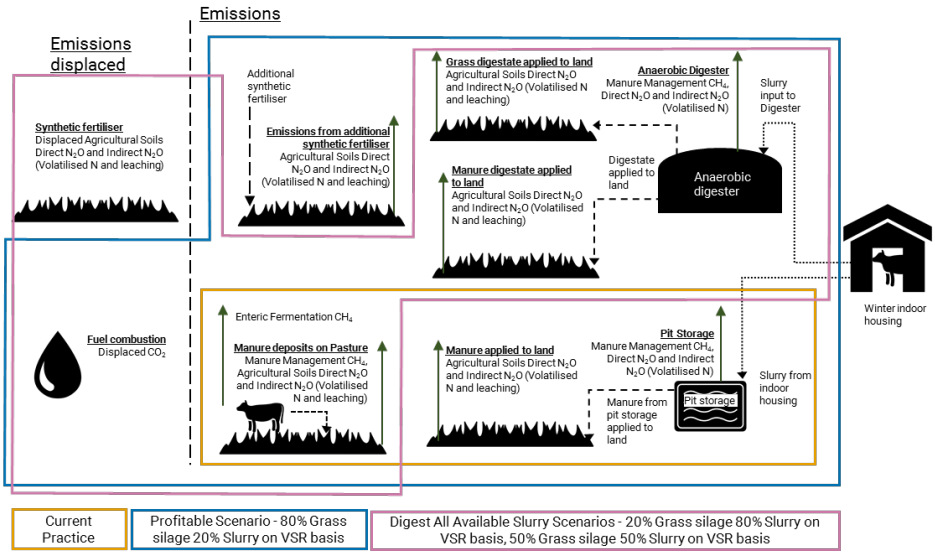


Figure 5-4 GHG Emissions Schematic

Table 5-6 Annual grass required - based on methodology and data from (McEniry et al., 2013), projected dairy cows from (Kelly et al., 2017) and all other livestock from (CSO, 2021)

Animal category	Animal numbers	Grass intake[1] (kg DM/head)	Silage intake[1] (kg DM/head)	Grass required[2] (kg DM/head)	Silage required[3] (kg DM/head)	Total required[4] (kg DM/head)	Annual grass required[5] (t DM)
Cattle							
Dairy cows	1,618,570	2,937	1,091	3,671	1,495	5,166	8,361,533
Other cows	983,300	2,125	1,269	2,656	1,738	4,394	4,320,620
Bulls (breeding only)	52,200	2,125	1,269	2,656	1,738	4,394	229,367
Cattle male: 2 years and over	409,600	1,390	103	1,738	141	1,879	769,638
Cattle female: 2 years and over	388,900	1,221	573	1,526	785	2,311	898,748
Cattle male: 1-2 years	789,900	1,546	930	1,933	1,274	3,207	2,533,209
Cattle female: 1-2 years	1,005,800	,1221	573	1,526	785	2,311	2,324,404
Cattle male: under 1 year	1,013,200	533	495	666	678	1,344	1,361,741
Cattle female: under 1 year	1,103,900	556	477	695	653	1,348	1,488,057
Sheep							
Ewes: lowland & upland	2,070,300	584	65	730	89	819	1,695,576
Other sheep > 1 year	629,800	526	69	658	95	753	474,239
Rams	84,800	526	59	658	81	739	62,667
Other sheep (mainly lambs	2,746,200	204	23	255	32	287	788,159
						Total	**25,310,180**

[1] Data from [32]

[2] Grass required = Grass intake/ 0.8

[3] Silage required = Silage intake/0.73

[4] Total required = Grass required + Silage required

[5] Annual grass required = Total required * Animal numbers

The mass of slurry will determine the mass of grass required for co-digestion for the scenarios selected. This grass required for co-digestion is presented in Table 5-7.

Table 5-7 Grass required for co-digestion, based on 2017 data (Duffy et al., 2019)

	Profitable (Scenario 2)	Digest all slurry VSR GS:Sl 50:50 (Scenarios 6 & 13)	Digest all slurry VSR GS:Sl 20:80 (Scenarios 4, 11 & 18)
Slurry FW kt_{wwt} y^{-1} (Section 2.1)	1,632	5,013	5,013
% of overall slurry produced	9.11%	28.02%	28.08%
Slurry DM (kt DM y^{-1}) (8.75% FW)	142	439	439
Slurry VS kt VS y^{-1} (6.7% FW)	109	335	335
VSR GS:Sl	80:20	50:50	20:80
Grass VS kt VS y^{-1} (26.8% FW)	418	335	84
Grass DM (kt DM y^{-1}) (29.3% FW)	456	366	92
Grass FW kt_{wwt} y^{-1}	1,559	1,251	313

The range of slurry and grass silage combinations led to different amounts of digestate generated by each scenario. Feedstock mixes with a higher ratio of grass to slurry require additional synthetic fertiliser to cultivate the grass required for co-digestion. The digestate displaces synthetic fertiliser in the 'Digest all slurry VSR GS:Sl 20:80' scenario. The mass of synthetic fertiliser required or displaced is presented in Table 5-8.

Table 5-8 Change in Synthetic Fertiliser, calculated from N content and availability in slurry, grass silage and digestate - based on 2017 dairy cow data (Duffy et al., 2019)

Scenario	Profitable GS:Sl 80:20 (Scenario 2)	Digest all slurry VSR GS:Sl 50:50 (Scenarios 6 & 13)	Digest all slurry VSR GS:Sl 20:80 (Scenarios 4, 11 & 18)
Total slurry (kt_{wwt} y^{-1})	1,632	5,013	5,013
Grass FW (kt_{wwt} y^{-1})	1,559	1,251	313
$N_{required}$ for additional grass (kt N y^{-1}) (See Box 5-1 - 5.4 kg N t FW^{-1})	8.418	6.755	1.69
N_{cows}	1,388,000	1,388,000	1,388,000
N excreted (kg $animal^{-1}$ y^{-1})	102.81	102.81	102.81
Fraction of total slurry produced in manure management system (AWMS)	0.911	0.28	0.28
Total slurry N content (kt N y^{-1}) (N_{cows} * N excreted * AWMS	13.01	39.985	39.985
$N_{DisplacedSlurry}$ = Available N in slurry (kt N y^{-1}) (Total slurry N content * 50% availability)	6.51	19.992	19.992
Total grass N content (kt N y^{-1}) (2% of the grass VS, grass VS from Table 5-)	8.36	6.7	1.84
Total organic N (kt N y^{-1}) (Slurry N + Grass N content)	21.37	46.66	41.83
$N_{Digestate}$ = Digestate N available (kt N y^{-1}) 60% available of Total organic N	12.82	28	25.1
Equation 1: Change in Synthetic N (kg) $DF_{SN} = N_{DisplacedSlurry} + N_{required} - N_{Digestate}$	2.11	-1.25	-3.42
F_{SN} required or displaced*	Required	Displaced	Displaced

*A positive value implies a shortfall of N and therefore synthetic nitrogen is required, a negative value implies a surplus of N due to digestate and therefore synthetic nitrogen can be displaced.

5.3.3 National GHG emissions

The $CO_{2\text{-eq}}$ emissions for Scenario 6 are presented in Table 5-9 and Table 5-10 as an example. Full calculations are presented in Supplementary Data Appendix G. In this example the emissions from deep bedding are not included as they are negligible, the emissions associated with pit storage are replaced with emissions from anaerobic digestion, and the emissions associated with slurry spreading are displaced by digestate. In this scenario further synthetic fertiliser will be required, which will result in additional

emissions. A transport end use will displace more fossil fuel GHG emissions as diesel has a higher emissions factor than natural gas.

Table 5-9 Emission Factors – Digest all slurry GS:SI Scenario 50:50 Methane loss = 1% (Scenario 6) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [29] $AWMS_{(T,S,k)}$ = 0.70% [29]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [29]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [29] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [29]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [27] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [29]	100,032,896	51.53
Anaerobic Digester			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [28] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [27]	n/a	17.63
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [26]	46,692,062	13.12
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [28]	13,073,777	61.22
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [29]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [29] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [29]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [29] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [29]	39,984,618	20.60
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [29]	6,707,443	18.85

Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [29] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [29]	6,707,443	2.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [29] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [29]	6,707,443	3.46
Energy Emissions displaced			
Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [51] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [51] Fuel consumption factor relative to diesel for transport = 114% [42]		-588 -680
Synthetic Fertiliser Displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [26]	-1,265,928	-7.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [29] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [29]	-1,265,928	-0.15
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [27] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [29]	-1,265,928	-0.65

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

Table 5-10 Emissions summary for Scenario 6 – 2017 data

Process	Transport energy end use Emissions (kt $CO_{2\text{-eq}}$)	Thermal energy end use Emissions (kt $CO_{2\text{-eq}}$)
Enteric Fermentation	3,659	3,659
Livestock excretions on Pasture	514.94	514.94
Anaerobic Digester	91.97	91.97
Manure digestate applied to land	148.87	148.87
Grass digestate applied to land	24.99	24.99
Energy Emissions displaced	-680	-588
Synthetic Fertiliser Displaced	-8.15	-8.15
Total emissions	3,801	3,893

When the 2019R accounting methodology is applied to current data instead of the 2006 methodology, there is a reduction in enteric fermentation from 3,998 to 3,659 kt $CO_{2\text{-eq}}$ and an increase in manure

management emissions, from 359 to 409 kt$CO_{2\text{-eq}}$ respectively. This was calculated so that both the baseline and the change in emissions would be calculated according to the same methodology, and in line with EPA reports [27]. When AD is introduced the greatest change in GHG emissions is from the fuel displaced. This can be seen in Table 5-9 and is representative of all the scenarios analysed. In all cases using the biomethane for transport results in greater GHG emissions savings compared with using the biomethane for heat. In Scenario 2, the overall GHG emissions with AD assessed in 2025 of 5,083 kt $CO_{2\text{-eq}}$ when biomethane is used to produce heat are greater than the 2017 current agricultural dairy GHG emissions from dairy cattle with no AD of 4,788 kt $CO_{2\text{-eq}}$ (see Figure 5-5). When the number of dairy cows has reached the projected maximum in 2025, the GHG emission saving gained from digesting dairy cattle slurry with grass in Scenario 2 is cancelled out by the increase in overall GHG emissions from increases in cattle numbers compared to 2017. For the scenarios digesting all slurry, the overall GHG

emissions saving is greater when more grass is co-digested as more fuel is displaced. This is as expected due to the higher energy yield of grass.

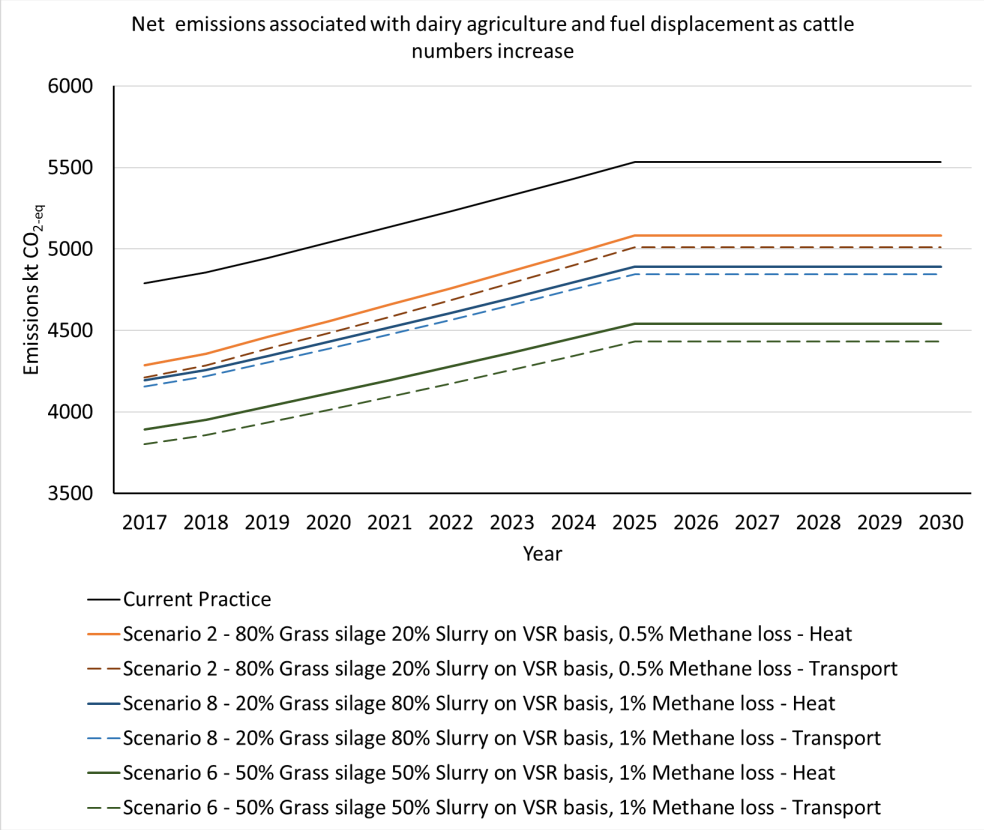


Figure 5-5 GHG emissions as cattle numbers increase – Comparison of VSR Scenarios

Examining the 20% Grass 80% Slurry scenarios in more detail as these had the greatest range of methane loss values while still being classified as sustainable; when the biomethane is used for heat, the GHG emissions are higher than when the fuel is used for transport for all system methane loss scenarios (1%, 2%, 3.55%) chosen (Figure 5-6). A system with methane loss of 3.55% and a transport end use will however have higher net GHG emissions than a lower system methane loss of 1% and a heat end use. As such, careful attention will need to be paid to system methane loss when designing and operating AD systems in order to ensure the benefits of the selected end use are realised.

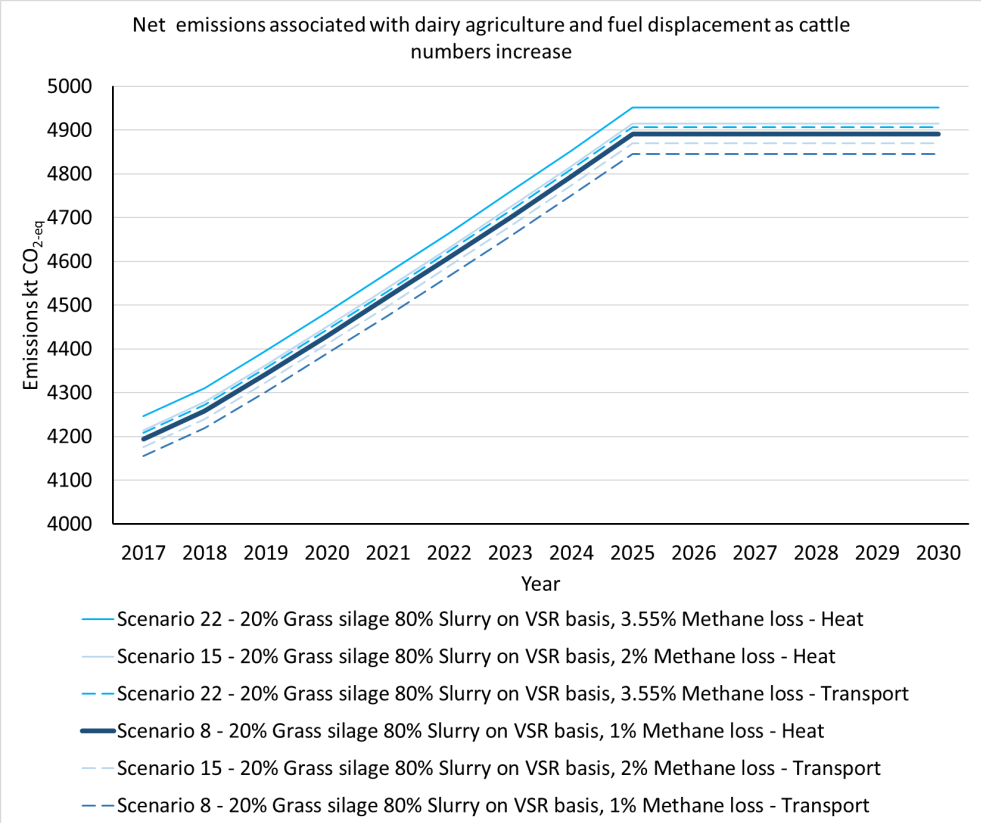


Figure 5-6 GHG emissions as cattle numbers increase – Comparison of methane loss Scenarios

5.3.4 Contribution to national policy goals

5.3.4.1 RED recast transport target

To investigate the contribution to the RED recast 14% share of energy in transport the energy yield from each scenario is compared to the current transport demand of 216,632 TJ y^{-1}. This takes account of the allowance for twice the energy content in Annex IX of the RED recast [12]. Using Scenario 6 as an example the energy yield for both heat and transport is calculated in Box 5-2 Net energy production - based on Scenario 6.

In 2017 the share of renewable energy in transport was 7.2% [51]. The Profitable scenario, which uses 9% of slurry produced, could meet 7.6% RES-T by 2030. This includes the double credit for transport. The target for RES-T is 14% [12]. When this is added to the current share of the transport target reached of 7.2% then the 14% target can be surpassed, assuming the energy in transport demand remains somewhat the same. The Climate Action Plan 2019 [11] aims to increase the share of EVs and increase biofuel blending. Improving the CNG fuelling network and increased use of

Net Energy Production = 1682.55 $MJ_{biomethane}$ t^{-1} FW for 50:50 VSR mix of Grass silage and Slurry (Supplementary Data)

N_{cows} in 2030 = 1,618,570 (Kelly et. al., 2017) [4]

Daily solids production = 3.09 kg DM $animal^{-1}$ day^{-1} (Duffy et. al., 2017) [25]

Fraction of total slurry produced in manure management system = 0.28

Annual DM = 1,618,570 animals * 3.09 kg DM $animal^{-1}$ day^{-1} * 365 days * 0.28 = 512 kt DM slurry y^{-1}

Slurry VS = 76.5% DM = 391 kt VS slurry y^{-1} (Wall et al., 2013, See Table 2) [28]

Slurry VS = 66.9 g kg^{-1} (Wall et al., 2013, See Table 2) [28]

Slurry FW = 5,846 kt FW y^{-1}

Grass silage VS = Slurry VS = 391 kt VS Grass silage y^{-1}

Grass silage VS = 268 g kg^{-1} (Wall et al., 2013, See Table 2) [28]

Grass silage FW = 1,459 kt FW y^{-1}

Net energy production = (5,846 kt FW y^{-1} + 1,459kt FW y^{-1}) * 1683 $MJ_{biomethane}$ t^{-1} FW = 12.29 PJ

Box 5-2 Net energy production - based on Scenario 6

biofuels are included, these however are not specific to the use of biomethane. The potential to meet the transport target for the selected scenarios is presented in Table 5-11.

Table 5-11Contribution to EU target of 14% RES-T in 2030, based on 2030 data, projected 1,618,570 cows, transport demand based on projections is 224.16 PJ (See Table 5-4)

Scenario	Energy Produced (PJ)	Energy with double credit for Transport (PJ)	Contribution to Transport Target (including double credit %)
Profitable Scenario 2 - 80% Grass silage 20% Slurry on VSR basis, 0.5% Methane loss	8.21	16.42	6.8%
Digest all Slurry Scenario 6 - 50% Grass silage 50% Slurry on VSR basis, 1% Methane loss	12.29	24.58	10.19%
Digest all Slurry Scenario 8 - 20% Grass silage 80% Slurry on VSR basis, 1% Methane loss	5.15	10.31	4.27%
Digest all Slurry Scenario 13 - 50% Grass silage 50% Slurry on VSR basis, 2% Methane loss	12.17	24.34	10.09%
Digest all Slurry Scenario 15 - 20% Grass silage 80% Slurry on VSR basis, 2% Methane loss	5.10	10.21	4.24%
Digest all Slurry Scenario 22 - 20% Grass silage 80% Slurry on VSR basis, 3.55% Methane loss	5.02	10.04	4.16%

5.3.4.2 Natural gas energy demand

Dairy processing data is often commercially sensitive and details of plant operation are not normally made public. The total natural gas fuel consumption of gaseous fuels in the food processing, beverages and tobacco category of the National Inventory Report was 6.6 PJ in 2012 [52] and 7.2 PJ in 2019 [27]. Dairy processing is included in this sector. Applying the 2019 GHG emissions factor for natural gas of 55.738 $gCO_2\ MJ^{-1}$ [53] to 7.2 PJ gives total GHG emissions for the food processing, beverages and tobacco category of 401.3 kt CO_2. It is possible to meet the natural gas demand for the food processing, beverages and tobacco category with the 8.2 PJ energy yield of the Profitable scenario. This would also be a circular economy application of the energy produced from dairy slurry. The 2018 natural gas demand by all industry in Ireland was 33 PJ [49]. The Digest All Slurry Scenario 6 – 50% Grass silage 50% Slurry on a VSR basis with 1% methane loss, could meet 37% this demand with an energy yield of approximately 12.29 PJ. If the energy produced from any scenario is used

as renewable heat within the ETS sector, then there will be no contribution to the effort sharing emissions target. There will be a contribution towards Ireland's own national target and the 27% renewable energy target for the EU.

5.3.4.3 EU Effort sharing emissions savings

The emissions saved in 2030 are calculated by comparing the net emissions with no AD to the net emissions for the scenario being analysed. In 2030 the emissions with no AD (Scenario 1 No change) were 5,534 kt $CO_{2\text{-eq}}$. Box 5-3 demonstrates how the emissions saved and contribution to national and EU targets were calculated comparing Scenario 1 (No change) with Scenario 2.

Net emissions for Scenario 1 (No change) = 5,534 kt $CO_{2\text{-eq}}$

EU Effort sharing emissions savings target = 14,191 kt $CO_{2\text{-eq}}$

Net emissions Scenario 2 – Heat end use= 5,083 kt $CO_{2\text{-eq}}$

Emissions saved = 5,534 – 5,083 = 451 kt $CO_{2\text{-eq}}$

Contribution to EU target = 451/14,191 *100= 3.18%

Box 5-3 Example of emissions savings calculation for 2030 - Scenario 2

When the biomethane produced is used for heat in the non-ETS sector or as a transport fuel, then the emissions saved will contribute towards Ireland's effort sharing target. Table 5-12 presents the emissions saved and the contribution to the overall effort sharing target for Ireland. In all cases, using the biomethane for transport will have a greater contribution to the emissions savings target.

Table 5-12 Contribution to EU effort sharing target - Overall savings target of 14,191 kt $CO_{2\text{-}eq}$ y^{-1}in 2030

Scenario	Total emissions saved for heat end use (kt $CO_{2\text{-}eq}$)	Contribution to 2030 emissions saving target (%)	Total emissions saved for transport end use (kt $CO_{2\text{-}eq}$)	Contribution to 2030 emissions saving target (%)
Profitable Scenario 2 - 80% Grass silage 20% Slurry on VSR basis, 0.5% Methane loss	451	3.18%	523	3.69%
Digest all Slurry Scenario 6 - 50% Grass silage 50% Slurry on VSR basis, 1% Methane loss	594	7.00%	1102	7.77%
Digest all Slurry Scenario 8 - 20% Grass silage 80% Slurry on VSR basis, 1% Methane loss	643	4.53%	688	4.85%
Digest all Slurry Scenario 13 - 50% Grass silage 50% Slurry on VSR basis, 2% Methane loss	967	6.81%	1073	7.56%
Digest all Slurry Scenario 15 - 20% Grass silage 80% Slurry on VSR basis, 2% Methane loss	619	4.36%	664	4.68%
Digest all Slurry Scenario 22 - 20% Grass silage 80% Slurry on VSR basis, 3.55% Methane loss	583	4.11%	627	4.42%

5.3.4.4 Contribution to national targets

It is assumed that the emissions savings target for the National Climate Action Bill of 51% is based on total emissions from 2018 [47]. As the emissions saving target set out in the National Climate Action Bill is greater than the EU effort sharing target the difference between the contribution from either heat or transport becomes less significant.

Table 5-13 Contribution to national target - Overall target of 31,077 kt $CO_{2\text{-}eq}$ y^{-1} in 2030

Scenario	Total emissions saved for heat end use (ETS or non-ETS) (kt $CO_{2\text{-}eq}$)	Contribution to 2030 emissions saving target (%)	Total emissions saved for transport end use (kt $CO_{2\text{-}eq}$)	Contribution to 2030 emissions saving target (%)
Profitable Scenario 2 - 80% Grass silage 20% Slurry on VSR basis, 0.5% Methane loss	451	1.45%	523	1.68%
Digest all Slurry Scenario 6 - 50% Grass silage 50% Slurry on VSR basis, 1% Methane loss	594	3.20%	1102	3.55%
Digest all Slurry Scenario 8 - 20% Grass silage 80% Slurry on VSR basis, 1% Methane loss	643	2.07%	688	2.21%
Digest all Slurry Scenario 13 - 50% Grass silage 50% Slurry on VSR basis, 2% Methane loss	967	3.11%	1073	3.45%
Digest all Slurry Scenario 15 - 20% Grass silage 80% Slurry on VSR basis, 2% Methane loss	619	1.99%	664	2.14%
Digest all Slurry Scenario 22 - 20% Grass silage 80% Slurry on VSR basis, 3.55% Methane loss	583	1.88%	627	2.02%

The examples in Tables 5-12 and 5-13 demonstrate how the use of biomethane in the ETS sector, non-ETS heat or transport could contribute to national policy targets. While it is an overall advantage to reduce ETS emissions, these will not contribute to effort sharing savings beyond the 4% flexibility allowance. The Profitable scenario, which has been discussed from a policy perspective [53], can contribute to both energy and GHG emissions policy, with a greater contribution to national RED recast and EU Effort Sharing targets when biomethane is used as a transport fuel. Existing discussions have focused on a heat or CHP end use [10,53]. In all cases,

using the biomethane for transport can make the greatest contribution to national renewable energy in transport and GHG emissions targets for EU policy compliance. The contribution to the effort sharing target from the Profitable scenario is relatively small at 1.05% due to the lower amounts of feedstock digested. Scenarios 8, 15 and 22, where all available slurry is digested on a 20% grass silage 80% slurry VSR basis, can meet the 14% RES-T target, contribute over 4% to the EU effort sharing 2030 target, and also displace synthetic fertilisers. Higher methane loss values do not have a significant impact on the contribution to RES-T targets at a national level. They do however have an impact on sustainability of the pathways.

5.3.5 Uncertainties and limitations of the work

The sustainability assessment and energy yield calculations were carried out on a national basis using conservative values. In reality, a sustainability assessment will be required for individual commercial pathways of renewable gas for certification [13]. It will also be possible to design systems to meet sustainability criteria, rather than assuming a particular feedstock mix is not sustainable.

This work has focused on $CO_{2\text{-eq}}$ emissions as the sole environmental impact discussed. Introducing AD of grass may have negative environmental consequences associated with fertiliser use to achieve grass yields as well as mitigating $CO_{2\text{-eq}}$ emissions that this work has not considered.

5.4 Conclusions

This research examined if AD could mitigate the GHG emissions in the Irish dairy sector. The Irish dairy sector was chosen as a case study given the recent expansion of the sector and the scale of production in Ireland. The results show that any GHG emissions saved from AD will be offset by the continued increase in the cattle numbers when applying Scenario 2, which has limited use of dairy cow slurry with 80% grass silage and 20% slurry on a volatile solids basis. From a national policy perspective, the end-use of the biomethane will matter. Taking Scenario 6 as an example, which

represents a scenario where all the available slurry is digested with grass on a 50:50 VSR basis, when the biomethane produced is used as a transport fuel, a greater amount of GHG emissions are saved (987 $ktCO_{2eq}$ in 2017 for Scenario 6), and the end use will contribute more to national EU effort sharing targets as well as minimum EU targets for renewable energy in transport. Using the biomethane as renewable heat within the ETS can reduce ETS emissions (895 $ktCO_{2eq}$ in 2017 for Scenario 6). Where biomethane is used for heat in the non-ETS sector it can contribute to effort sharing GHG emissions (saving of 895 $ktCO_{2eq}$ in 2017 for Scenario 6), but not to the same extent as transport. Using biomethane for heat would also require Ireland to develop other options to meet the 14% renewable energy in transport target. These findings will increase our understanding of the interaction between EU energy and GHG emissions policies in relation to the end use of biomethane systems.

Acknowledgements

This work was supported by Science Foundation Ireland (SFI) through the MaREI centre under Grant No. 12/RC/2302_P2.

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6 Infant feeding and the energy transition: A comparison between decarbonising breastmilk substitutes with renewable gas and achieving the global nutrition target for breastfeeding

Aoife Long[a,b,c], Kian Mintz-Woo[b,d], Hannah Daly[a,b,c], Maeve O Connell[e], Beatrice Smyth[f], Jerry D Murphy[a,b,c]*

[a] MaREI Centre for Energy, Climate and Marine,

[b] Environmental Research Institute, University College Cork, Cork, Ireland

[c] School of Engineering, University College Cork, Cork, Ireland

[d] Department of Philosophy, University College Cork, Cork, Ireland

[e] School of Healthcare Studies, Cardiff University, Cardiff, United Kingdom

[f] School of Mechanical and Aerospace Engineering, Queens University Belfast, University Rd, Belfast, United Kingdom

[*]Corresponding author Present Address: School of Engineering, University College Cork, Cork, Ireland
100094251@umail.ucc.ie

Abstract

Renewable gas has been proposed as a solution to decarbonise industrial processes, specifically heat demand. As part of this effort, the breast-milk substitutes industry is proposing to use renewable gas as a substitute for fossil natural gas. However, decarbonising the industrial processing of breast-milk substitutes can increase social license for these products, potentially undermining breastfeeding. World Health Organisation nutrition targets aim to increase exclusive breastfeeding to at least 50% globally by 2025 to improve maternal, infant, and young child health and nutrition. This target will have implications for the energy transition. A weakness of existing energy models is that demands for end-use products such as breast-milk substitutes are typically not considered explicitly. This paper develops an analytical framework for explicitly representing infant

feeding methods in energy systems models. We compare the emissions saved in Ireland from decarbonising the industrial processing of breast-milk substitutes with renewable gas with the emissions saved by an increase in exclusive breastfeeding to 50% in both Ireland and a key export market, China. We demonstrate that the emissions saved from achieving the minimum global breastfeeding target are greater than when renewable gas is used to displace natural gas in the production of breast-milk substitutes in Ireland. We discuss the decarbonisation of breast-milk substitutes in relation to the principle of justice as non-maleficence, a principle based on the commitment to avoid harm, a novel application of a principle of justice. We conclude that breastfeeding support can be considered a demand-side measure for mitigating climate change by reducing the demand for energy services to produce breast-milk substitutes. A key recommendation is to position breastfeeding support as both a public health and a climate justice issue that is relevant for a just transition. The framework developed for this paper could be applied to support the inclusion of a wider range of mitigation options with social justice outcomes in energy system models.

Keywords: Breastfeeding support; Breast-milk substitutes; Climate Justice; Decarbonisation; Just Transition; Renewable Gas

Highlights

- Breastfeeding and breastfeeding support can contribute to mitigating climate change
- Achieving global nutrition targets will save more emissions than fuel-switching
- Breastfeeding support programmes support a just transition
- This work can support the expansion of mitigation options in energy system models

6.1 Introduction

Breastfeeding is the biologically normal method of infant feeding which ensures optimal infant nourishment and development [1]. The World Health Organisation recommends exclusive breastfeeding (EBF), where an infant is only breastfed for the first 6 months, and continuing for a duration of two years for optimal infant health [2]. Yet no country currently meets all the objectives recommended by the World Health Organisation (WHO) to support mothers to breastfeed [3]. According to *The Lancet* Breastfeeding Series [4,5] displacing and replacing breastfeeding can have adverse and long-term effects for mothers, infants, and children. The World Health Organisation (WHO) Global Nutrition Target no. 5 aims to increase the rate of exclusive breastfeeding in the first 6 months to at least 50% globally by 2025 [6]. An increased rate of breastfeeding with a corresponding decrease in the demand for breast-milk substitutes (BMS) could have important implications for the energy services demand to produce breast-milk substitutes, given the interdependency between the agriculture, processing and socio-cultural systems that influence infant feeding.

It has been established that breast-milk substitutes have a larger carbon footprint in comparison with breastfeeding for four countries, while noting that breastfeeding and breast-milk substitutes are functionally different [7]. Following the analysis by Karlsson et al., 2019, it has been proposed that support for breastfeeding is an environmental imperative [8,9]. However, an environmental imperative to support breastfeeding has the potential to hold women responsible for mitigating climate risks and "jeopardise women's reproductive rights, which include how women use their breasts" [10]. Instead, Williams et al., 2019 suggest engaging with food manufacturers to reduce the carbon footprint of the production of breast-milk substitutes.

Most of the carbon footprint of milk powder (84%) is from the emissions associated with raw milk production which are Scope 3 emissions for the

producer. A much smaller share of the emissions is from the processing stage (14%), which includes natural gas use which are scope 1 emissions for the producer and as such directly the responsibility of the producer. The remaining 2% is from other life cycle stages [11,12]. Renewable gas has been proposed to reduce the emissions associated with production of breast-milk substitutes, by replacing the natural gas currently in use [13]. Biogas can be produced from anaerobic digestion of organic material and can be upgraded to a renewable methane gas that is the same quality as natural gas. Manure from dairy cattle can be used as a feedstock for anaerobic digestion to produce biogas [14], with the potential to decarbonise production in the dairy industry as part of a circular economy approach. In Ireland, it is proposed that this will be mixed with grass silage to ensure sufficient biomethane yield [15]. Displacing natural gas with renewable gas use will have an impact on the 14% share of GHG emissions associated with the processing stage.

Recently there have been calls for greater attention to be placed in energy models on greenhouse gas (GHG) mitigation from energy service demands [16,17]. Research on the energy transition often has a focus on energy consumption, whereby a change in supply is typically compared with the existing demand [18]. We argue that the demand for energy services is an integral part of the energy transition. Creutzig et al. (2016) outlined a comprehensive set of climate change mitigation options from a demand-side perspective [19]. While healthy diet was included under the 'Agriculture and other land use' category, breastfeeding was not specifically mentioned. Bartle (2020) has stated that WHO policies to protect breastfeeding can be considered a legitimate part of climate change mitigation, a view that is not represented in energy modelling literature [20]. While there are publications relating to the environmental impact of breastfeeding and breast-milk substitutes, there are no studies that translate this research to energy modelling, where it can potentially inform policy decisions in this area.

The innovation in this paper is to build on the work of Karlsson et al. (2019) [7] by proposing an analytical framework to incorporate infant feeding into large scale energy system models. The main objective of the work is to consider the previously unstudied moral implications of an engineering intervention to improve production from an environmental perspective. This is achieved through the following aims:

1. to demonstrate that the emissions saved from decarbonising BMS production have an opportunity cost
2. to discuss the decarbonisation of BMS in relation to the principle of justice of non-maleficence
3. to argue that breastfeeding support can be considered a demand side measure for mitigating climate change

6.2 Background

While the ‘greening’ of breast-milk substitutes could reduce carbon emissions, the public health impacts of continued widespread use of breast-milk substitutes are problematic. Approximately 800,000 annual deaths of children under five globally are attributed to suboptimum breastfeeding [21]. Neonatal implications of not breastfeeding include higher infectious morbidity and mortality; increased acute otitis media (type of ear infection) during the first two years of life; reduced protection against diarrhoea; and increased severity of respiratory infections. For mothers, the benefits of breast feeding include lower breast cancer rates; improved birth spacing; and a potentially lower risk of diabetes and ovarian cancer. Even in countries with clean water and good sanitation, infants who are not breastfed are at increased risk of morbidity and mortality [5].

Reasons for low breastfeeding rates are multi-faceted since breastfeeding is a complex behaviour dependent on mother and infant individual characteristics, public health systems, family, community and professional support and wider cultural values. Some of these factors are non-modifiable such as maternal age and socioeconomic status, but other factors may be modifiable such as self-efficacy, mode of birth, social and professional support. Promotion of breast-milk substitutes is recognised as one of the factors undermining breastfeeding [4,6]. Despite the introduction of the WHO code [22], and the clarification that it applies to all milk marketed for feeding infants and young children, including follow-on milk and growing-up milk [23], the marketing of breast-milk substitutes remains pervasive [24]. Marketing narratives focus on the use of breast-milk substitutes as a simple and easy, equal choice, while breastfeeding is portrayed as painful, difficult, embarrassing and sleep depriving [25]. Concerns have also been expressed about the involvement of manufacturers in the development of nutrition guidance and research [20]. While breast-milk substitutes will remain a legitimate product, this paper is concerned additional demand that arises from aggressive marketing practices while support for mothers who do choose to breastfeed is low.

6.3 Methods

6.3.1 Case study details

The production of breast-milk substitutes in Ireland is used as a case study in this paper. The Irish Government has set a target of a national 51% reduction on reported 2018 emissions by 2030, a reduction of 31,077 kt $CO_{2\text{-eq}}$ [26,27]. The analysis in this paper focuses on decarbonising the manufacture of Irish breast-milk substitutes with renewable gas which can reduce the direct emissions associated with production. These are Scope 1 emissions under the GHG protocol [12]. While there are also potential effects on land-use if the demand for breast-milk substitutes is reduced, only the emissions associated with the product are considered in this analysis; as such Scope 3 emissions (such as those associated with cattle) are not included. The scope of the study is the first six months of infant feeding. The only foods recommended to be consumed by infants in the first six months are breast-milk or a substitute. The markets considered are Ireland, the country of production, and China, a major international export destination for Ireland. The 50% target is the minimum global nutrition target of at least 50% of children exclusively breastfed for six months [6]. Food miles involved in export to China are not considered in the study.

Of the approximately 40 to 50 [8] milk powder processing plants globally, four are in Ireland [28]. These produced approximately 165,000 tonnes of milk powder for export in 2017 [29]. The European Union (EU) milk quota which limited milk production was abolished in 2015 [30]. To benefit from this, the number of dairy cows in Ireland has expanded significantly in the last decade, from just over 1 million cows in 2010 to 1.4 million cows in 2017 [31]. This number is projected to increase to over 1.6 million cows by 2025 [32]. The FoodWise 2025 strategy, which is the Irish food industry plan for future growth in agri-food, aims to focus on an export-driven market with a particular emphasis on the emerging markets in Asian and African countries [30].

China has been a major market for Ireland, with exports of approximately 10,000 tonnes of breast-milk substitutes to China in the first three months of 2020, and a similar amount in the same period in 2019 [33]. Increasing demand in China has been driven by a drop in breastfeeding rates compared to previous generations [34], and loss of confidence in local producers [35]. Expansion of the Chinese market has also been driven by the increase in products marketed as 'follow-on' and 'toddler' milks [36]. Although such milks are outside the scope of this study, they are a significant part of the breast-milk substitutes market in China as approximately three quarters of sales are of such follow-on milks [37].

6.3.2 An analytical framework for modelling infant feeding

Energy systems models are mathematical representations of a country or region's energy system, explicitly distinguishing sources of supply, transformation, and energy service demands. They are commonly used for energy planning, particularly for long-term decarbonisation at the national level [38,39] and form the backbone of many of the Integrated Assessment Models (IAMs) which inform the Intergovernmental Panel on Climate Change (IPCC) assessments on meeting the Paris Agreement targets [40]. Under the current IPCC methodology, the emissions associated with producing breast-milk substitutes are accounted for in the country and sector of production rather than those of consumption. Similarly, where bioenergy is used for energy consumption, it is considered zero emissions in the Energy sector, as the emissions would already be captured within the Agriculture, Forestry and Other Land Use sector [41].

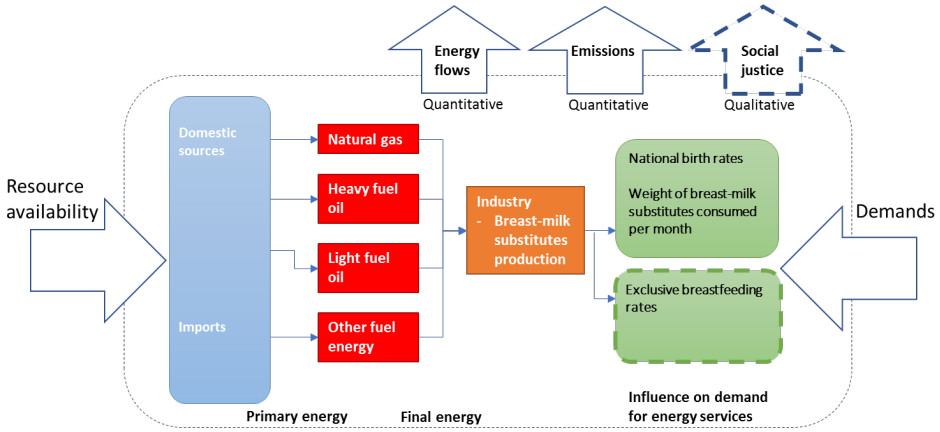


Figure 6-1 Proposed analytical framework schematic

This section will consider an analytical framework related to breastfeeding in energy systems models, based on the existing carbon accounting system in place in energy modelling (See Figure 6-1) [39]. To estimate the impact on energy systems models, the consumption of breast-milk substitutes per child must be estimated. Following the nomenclature normally used in IPCC National Inventory, the emissions from breast-milk substitutes consumption can be estimated as follows:

Equation 1: Breast-milk substitutes consumed per country

$$F_{C\,cn} = N * \sum_{M1}^{M12} (1 - EBF_{Mn}) * F_{Mn}$$

Where:

$F_{C\,cn}$ = Breast-milk substitutes consumed in country of consumption C_{cn}, (kg product per year)

N = Average number of infants born in a country of consumption

EBF_{Mn} = Fraction of infants exclusively breastfed in country of consumption in month n, dimensionless

F_{Mn} = Mass of breast-milk substitutes consumed in country of consumption in month n per infant, (kg product child^{-1} month^{-1})

Equation 2: Fuel consumption in country of production as a result of breast-milk substitutes production per country, based on (Finnegan et al., 2017) [11]

$$E_{C_{pn}} = F_{C_{pn}} * (E_{TH_{NG}} + E_{TH_{HFO}} + E_{TH_{LFO}} + E_e + E_{TH_{OF}})$$

Where:

$E_{C_{pn}}$ = Fuel consumption in country of production C_{pn}, MJ

$F_{C_{pn}}$ = Breast-milk substitutes produced in country of production C_{pn}, kg product

$E_{TH_{NG}}$ = Natural gas energy demand per kg product, MJ kg^{-1} product

$E_{TH_{HFO}}$ = Heavy fuel oil energy demand per kg product, MJ kg^{-1} product

$E_{TH_{LFO}}$ = Light fuel oil energy demand per kg product, MJ kg^{-1} product

E_e = Electricity energy demand per kg product, MJ kg^{-1} product

$E_{TH_{OF}}$ = Other fuel energy demand per kg product, MJ kg^{-1} product

The emissions from breast-milk substitutes can then be calculated by multiplying the breast-milk substitutes consumed in the country by the emissions associated with the production of breast-milk substitutes in the country of origin.

Equation 3: Emissions from consumption of breast-milk substitutes per country

$$e_{c_{pn}} = \sum_{c_{cn}}^{c_{ci}} F_{c_{cn}} * MC_{pn} * ef_{(f,C_{pn})}$$

Where:

$e_{C\,pn}$ = Annual emissions from consumption of breast-milk substitutes produced in country of production C_{pn} and consumed in country of consumption C_{cn}, kg $CO_{2\text{-}eq}$ yr^{-1}

C_{ci} = Country of consumption where I = country number (i = 1,2….,n)

$F_{C\,cn}$ = Breast-milk substitutes consumed nationally in country of consumption C_{cn}, kg product

MC_{pn} = Fraction of breast-milk substitutes consumed in country of consumption C_{cn} that was produced in country of production C_{pn}, dimensionless

$ef_{(f,Cpn)}$ = Annual emission factor for production of breast-milk substitutes in country of production C_{pn}, kg $CO_{2\text{-}eq}$ kg^{-1} product

6.3.3 Data and assumptions

The overall life cycle emissions associated with milk powder production in Ireland are 9.731 kg $CO_{2\text{-}eq}$ kg^{-1} product on a cradle-to-factory gate basis [42]. The emissions associated with natural gas use are 0.75 kg $CO_{2\text{-}eq}$ kg^{-1} product [11]. Milk powder in the research by Finnegan et al. (2017) [11,42] refers mainly to whole milk and skim milk powders. Breast-milk substitutes are normally referred to as specialised nutrition powder by the dairy industry [43]. The analysis by Karlsson et al. (2019) estimated the carbon footprint of BMS production as 9.2 ± 1.4, 7.0± 1.0, 11 ± 2 and 8.4 ± 1.3 kg $CO_{2\text{-}eq}$ kg^{-1} BMS in New Zealand, USA, Brazil and France respectively [7]. The data for Irish milk powder is assumed as the greenhouse gas emissions associated with Irish BMS production as it is broadly in line with emissions for production internationally. The potentially available renewable gas supply is based on a profitable scenario from O'Shea et al. (2017) [15]. This scenario describes 42 anaerobic digesters producing a total of 12 PJ renewable gas per annum from grass silage and cattle slurry at an approximate volatile solids ratio of 80% grass silage and 20% cattle slurry.

When natural gas is displaced with renewable gas, it is assumed that the emissions associated with renewable gas are zero, as per the IPCC methodology [44].

Data on breastfeeding rates are available internationally from UNICEF [34], and in national studies. UNICEF data used for China reported an exclusive breastfeeding rate of 20.8% in the first five months. In this study, it is assumed that this is the exclusive breastfeeding rate for the six months under consideration. The most current Irish information available came from the *ESRI Growing up in Ireland* longitudinal study [45] which reported an initial exclusive breastfeeding rate of approximately 30% in month one that decreases to 2% by month six. For the Irish scenario, the volume of breast-milk substitutes consumed per infant is estimated and multiplied by the annual birth rate. The rate of consumption will likely change depending on the child, so standard guidelines are used to estimate the volume consumed. There is limited information on partial or mixed feeding in Ireland, so assumptions around combination feeding are difficult. To account for the potential for combination feeding, the calculated amount of BMS consumed was increased by 20%.

A key assumption made is that if the breastfeeding rate increases, formula consumption and therefore production will decrease accordingly. However, a standard challenge with modelling is that product consumption is not necessarily linked to production capacity. It is reasonable to assume that the capacity for production of breast-milk substitutes is greater than the actual demand. Therefore, a reduction in demand linked to breastfeeding may not lead to a direct corresponding reduction in production capacity. For simplicity, the assumption remains that if breastfeeding rates increase, then there will be a corresponding decrease in the production of breast-milk substitutes that is assumed to be proportional to current market share.

The analytical framework proposed considers only natural gas consumption in relation to production of breast-milk substitutes.

Additionally, emissions associated with increased calorie consumption are considered. Moving beyond energy modelling to incorporate emissions from agriculture (scope 3 emissions for the breast-milk substitutes industry) is more challenging. Karlsson et al. (2019) include the agriculture emissions associated with producing the product, and the additional calories consumed by the mother when breastfeeding [7]. The diet of Irish mothers is assumed to be the same as the UK diet as the UK diet is most likely to resemble the Irish diet due to proximity and cultural relationships. In the scenarios considered here, the emissions associated with the increased calories consumed are considered total emissions given the global nature of world food markets.

In this case study, the emissions associated with natural gas energy demand is displaced. The scenarios consider the reduced emissions from displacing natural gas only, from reaching exclusive breastfeeding targets only, and then from a combination of reaching the minimum global nutrition target and displacing natural gas in the remaining product. The emissions saved are then compared with emissions reduction targets for Ireland. The following scenarios are applied to both the Irish and Chinese market for breast-milk substitutes:

- Scenario 1: Potential emissions saved from decarbonising current consumption of product produced in Ireland with renewable gas
- Scenario 2: Potential emissions saved from achieving 50% EBF rate
- Scenario 3: Potential emissions reduction from achieving 50% EBF rate and displacing natural gas in remaining product

6.3.4 Introducing the principle of justice as non-maleficence

While some prioritise engagement with BMS manufacturers to reduce GHG emissions, alternative strategies arise from the principle of 'first do no harm' in relation to such environmental imperatives. We can systematically consider the variety of harms and benefits of changing support for

breastfeeding by appealing to a principle of justice such as justice as non-maleficence, proposed by Bufacchi (2020) as follows:

> The primary goal of just institutions in the distribution of goods and resources, opportunities and rights, is to fulfil a legitimate duty to reduce harm. Any harm that derives from the criteria of distribution being endorsed must be accepted by the parties being harmed, after due consultation and deliberation, to ensure that their voices have been heard, and their opinions duly acknowledged. [46]

The broad definition of harm that is considered within the scope of the principle of justice as non-maleficence is what Joel Feinberg calls a setback to welfare interests [47]. These interests include exercising positive normal bodily functions, which Bufacchi (2020) indicates are covered by justice as non-maleficence, and which include breastfeeding.

Introducing the principle of justice as non-maleficence helps to draw attention to costs or harms that breast-milk substitutes are associated with, both in social and environmental terms. In this paper, it is employed to assign importance to the results and draw attention to the moral implications of the engineering intervention. The principle applies in this instance with respect to the public health implications of breastfeeding, the well-being of the mother and child, and parenting values and practice. While the decision between breastfeeding or breast-milk substitutes is an individual decision, it is made in a context that is not always fully supportive of the decision that is made, whether materially or culturally. Due to these harms, the environment in which this decision is made is subject to questions of ethics and justice. Indeed, we endorse a stronger claim: that practically supporting the decision to breastfeed for those who are able can contribute to both social and climate justice, and that this support can contribute to more sustainable, population-level health. In particular, the principle of justice as non-maleficence is applied on the basis that decarbonising production will lead to harms due to a potential

increase in the social licence of the product and associated marketing methods used.

The potential interactions between breastfeeding and the social licence of breast-milk substitutes can be traced, noting that the breastfeeding relationship and influences on it can be complex (Figure 6-2). In relation to the agri-food sector, price and 'greenness' are factors in consumer decisions that can influence supply chain design to optimize both profits and sustainability [48]. In addition, companies in the food and beverage industry and other sectors that address sustainability challenges either directly or indirectly can significantly outperform business-as-usual scenarios in terms of reputation and social licence [49]. The term 'social licence' has origins in the extractive industries and is understood in place when a company's activities are seen as acceptable and legitimate by the local community and other stakeholders [50].

A key concern is that decarbonising the production of breast-milk substitutes without addressing the associated agricultural emissions is problematic because it potentially increases social licence. This greater social licence could lead to further increases in consumption of breast-milk substitutes and associated decreases in breastfeeding, a larger carbon footprint, and even greater demands on agricultural production.

Furthermore, once the demand for renewable gas for production of breast-milk substitutes is established, the renewable gas industry has the potential to become dependent in turn on the aggressive promotion of breast-milk substitutes that undermines the breastfeeding experience for many mothers. The production of renewable gas could therefore become 'locked-in' to the production of breastmilk substitutes. All these potential implications of increased social licence are negative; and combined may be even more so.

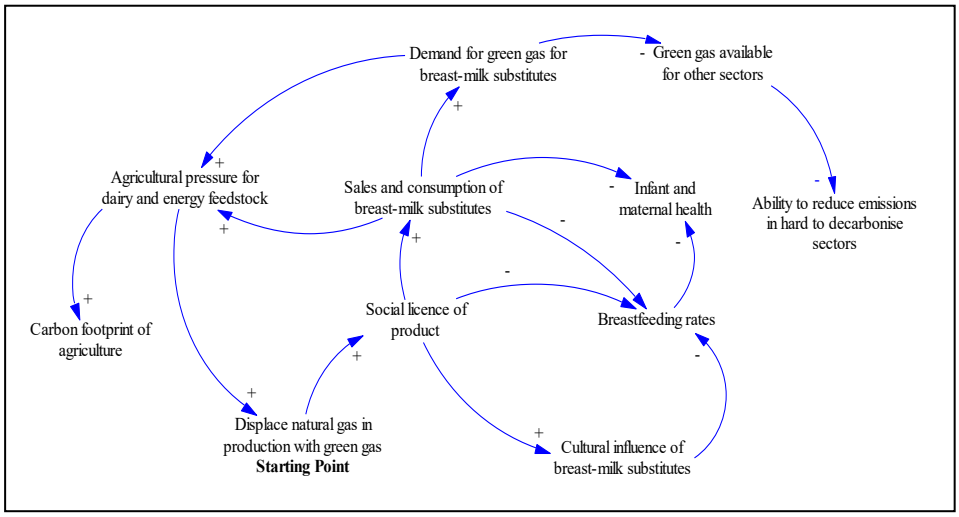


Figure 6-2 Potential impacts of decarbonising breast-milk substitutes with renewable gas

6.4 Results

6.4.1 Availability of renewable gas in relation to BMS production energy demand in Ireland

To make a credible claim of zero carbon (scope 1 emissions) processing of breast-milk substitutes, a steady and reliable supply of renewable gas will need to be in place, with contracts to provide a guarantee of supply. A potentially profitable scenario for renewable gas in Ireland was described by O'Shea et. al. (2017) as 42 anaerobic digesters producing 12 PJ per annum of renewable gas from grass silage and cattle slurry [15]. One such digester could generate approximately 54 GWh per annum, equivalent to a 2 MW_e facility producing electricity at 35% efficiency, which equates to 194,400 GJ per annum. One large breast-milk substitutes plant can secure a steady supply from four anaerobic digesters producing biomethane for grid injection (See Box 1). There are four major breast-milk substitutes manufacturing plants in Ireland. Assuming a typical large plant produces 40,000 tonnes of milk powder per year, this equates to a maximum thermal energy demand of 5.44 kWh (or 19.6 MJ) kg^{-1} milk powder produced [42].

Plant production = 40,000 tonnes milk powder
Maximum energy demand = 19.6 MJ kg^{-1} milk powder
Total thermal energy requirement: 19.6 MJ kg^{-1} milk powder * 40,000

tonnes milk powder = 784,000 GJ

From O'Shea et al. (2017) [15]:

Digester treating 76 kt wet weight feedstock per annum with a volatile solids ratio of 4.2:1 Grass silage: Cattle slurry = 194,400 GJ per annum

Number of anaerobic digesters providing energy = 784,000 GJ / 194,000 GJ = 4

Box 1 Calculation of average number of anaerobic digesters required for production plant

6.4.2 Emissions reduction from improved breastfeeding rates

6.4.2.1 Consumption of Irish products in Ireland

The average breast-milk substitutes consumption in the first six months, based on packaging guidance, is 23.84 kg per individual infant. When breastfeeding rates are applied to this a national average consumption of 20.42 tonnes is estimated. In Ireland, the birth rate is approximately 60,000 infants born annually [51]. Considering Irish rates of exclusive breastfeeding [45], approximately 1,225 tonnes of breast-milk substitutes are consumed in Ireland in the first six months (Table 1). Accounting for combination feeding by adding 20% to this value gives 1,470 tonnes. If the global nutrition target of at least of 50% [6] of infants exclusively breastfed for at least six months were reached, the consumption is reduced to approximately 715.2 tonnes (Table 6-1).

Table 6-1 Comparison of current breast-milk substitutes consumption in Ireland and Exclusive Breastfeeding Rate (EBF) of at least 50% [6] (WHO Nutrition Target)

Time period of feeding by Age	**Consumption (kg)**	**Exclusive Breastfeeding Rate (EBF)**	**1-EBF$_n$**	**Consumption per child in time period (kg)**	**Number of infants**	**Consumption in country (tonnes)**
						Current consumption
<2 weeks	1.16	0.32	0.68	0.79	-	47.3
2-4 weeks	1.29	0.304	0.696	0.9	-	53.8
4-8 weeks	3.45	0.24	0.76	2.6	-	157.3
8-12 weeks	4.14	0.2	0.8	3.3	-	198.7
3-4 months	4.14	0.12	0.88	3.6	-	218.6
4-5 months	4.83	0.08	0.92	4.4	-	266.6
5-6 months	4.83	0.024	0.976	4.7	-	282.8
Total	**23.84**			**20.42**	**60,000**	**1,225.2**
						WHO Nutrition Target
0-6 months	**23.84**	**0.5**	0.5	**11.92**	**60,000**	**715.2**

6.4.2.2 Consumption of Irish products in China

The data available on exclusive breastfeeding rates for China is less detailed than that available for Ireland so a total EBF rate is used to estimate consumption. Given the larger share of consumption in China it is expected that reaching the global nutrition target would result in a greater emissions reduction. The current estimated annual consumption of Irish breast-milk substitutes in China is 40,000 t BMS [33]. Therefore, approximately 20,000 t BMS have been assumed to be consumed over the first six months, noting that information on the type of product exported is

not available. This consumption is assumed to decrease on a pro-rata basis as exclusive breastfeeding increases from the current rate of 20.8% [34] to the minimum target of 50% EBF. The potential consumption of Irish breast-milk substitutes in China is 12,626 tonnes of product [(20,000/79.2%)*50%].

6.4.2.3 Emissions savings

For both markets, the emissions savings achieved from achieving the minimum 50% EBF target are greater than decarbonising the current consumption with renewable gas alone. The emissions savings are the greatest when a combination of effort is utilised to achieve the global nutrition target and decarbonise the product. This remains the case when the diet of the mother is considered. The results of the empirical analysis are presented in Table 6-2. Ireland has committed to reduce its GHG emissions by 51% in compared to 2018 by 2030; this gives an emissions savings target of 31,077 kt $CO_{2\text{-eq}}$ [26,27]. The potential emissions saved from achieving the 50% EBF rate in China and decarbonising the natural gas demand of the remaining product could contribute towards 0.26% of this target in 2030. While this may appear low, emissions reduction should be seen as a co-benefit of breastfeeding support, and not the primary aim.

Table 6-2 Comparison of emissions saved

Emissions per product	Irish Market	Chinese Market	Unit
e_{NG} = Emissions associated with natural gas energy demand per kg product = 0.75 kg CO_2 kg^{-1} product [11]	0.75	0.75	kg CO_2 kg^{-1} product
$ef_{(f,Cpn)}$ = Annual emission factor for production of breast-milk substitutes in country of production C_{pn}, kg $CO_{2\text{-}eq}$ kg^{-1} product = 9.731 kg $CO_{2\text{-}eq}$ kg^{-1} milk powder [42]; this includes emissions associated with natural gas	9.731	9.731	kg CO_2 kg^{-1} product
Consumption per market			
Current consumption of product produced in Ireland	1470.2	20000	tonnes of product
Estimated consumption if minimum target of 50% EBF is reached	715.2	12626	tonnes of product
Potential reduction in consumption	755	7374	tonnes of product
GHG Emissions Saved – Energy only			
Scenario 1: Potential emissions saved from decarbonising current consumption of product produced in Ireland with renewable gas	1102.7	15000	t CO_2
Scenario 2: Potential emissions saved from achieving 50% EBF rate	7346	71756	t CO_2
Scenario 3: Potential emissions reduction from achieving 50% EBF rate and displacing natural gas in remaining product	7883	81226	t CO_2
GHG Emissions Saved – Energy and agriculture			
Carbon footprint from the average diet in each consumption case country [7]	6.9	6.5	kg CO_2 kg^{-1} product
Total potential emissions saved from achieving 50% EBF rate, including increased diet of mother	2137.5	23825	t CO_2
Total potential emissions saved from achieving 50% EBF rate, including increased diet of mother, and displacing natural gas in remaining product	2673.9	33294.5	t CO_2

6.4.3 Applying the principle of justice as non-maleficence

In addition to the physical health benefits, Brown (2018) has argued that, for women, breastfeeding has intrinsic value beyond the achievement of basic nutrition for their infant [1]. It is a means of parenting, of bonding with the child, and provides a sense of achievement for meeting their goals as a mother. These values must be recognised as an intrinsic part of mothering for those who aspire to breastfeed. Mothers who do not achieve their breastfeeding goals may be affected by depression, anxiety,

pain and guilt, and conversely, mothers who choose not to breastfeed are negatively affected by messaging that breastfeeding is the safest and best option for infant feeding [52]. This messaging can also negatively impact mothers who choose to breastfeed, when expectations are raised without breastfeeding support and protection to realise this aspiration [1].

The influence of the breast-milk substitutes industry can have a negative effect on the breastfeeding experience of mothers. The harms that are the focus in this discussion are related to health, society, and the environment. Our claims are, firstly, that in each context there are harms associated with breast-milk substitutes; and secondly, that these harms will be exacerbated if greater social license is granted to breast-milk substitutes via decarbonised production, with a greater demand for breast-milk substitutes a potential risk. After discussing these harms, this section concludes by considering the role of public deliberation.

The public health harms of breast-milk substitutes involve both health losses to the mother and the infant, and increased mortality rates. We recognise that there are cases where breast-milk substitutes may be medically necessary; however, major health organisations indicate clearly that we are in a global context with too little breastfeeding as opposed to too much [6]. The social harms of breast-milk substitutes involve the costs to mothers of removing the maternal identity associated with breastfeeding. Lessening chances for bonding and experiencing a normal bodily function are significant potential harms [1].

While many reasons point towards encouraging breastfeeding as opposed to feeding with breast-milk substitutes, one obvious concern is that diverting renewable gas to other uses would harm the breast-milk substitutes industry, because it would reduce potential options to lower Scope 1 emissions, such as direct on-site emissions from natural gas combustion associated with production. However, there are important considerations which point against drawing this conclusion, namely, that the process has not yet occurred; renewable gas is not currently used in

the production of breast-milk substitutes in Ireland. It would be harmful to the industry if it had already implemented renewable gas in the production chain at scale; however, since it has not yet done so, it is relatively undisruptive to divert it at this point to, for instance, freight transport, which is responsible for 14% of transport emissions in Ireland [53] and has limited existing options for decarbonisation [54].

The health concerns are exacerbated by the potential social licence that could accrue from decarbonising breast-milk substitutes which may increase demand for the product when compared to the current manufacturing process. The potential preferrable route for green gas in transport justifies removing the sustainability endorsement of using renewable gas for breast-milk substitutes, since increased demand can be expected to increase the health, social and environmental harms associated with the product. Indeed, the case is worse because increasing the social licence for breast-milk substitutes produced in Ireland is likely to add to their potential overconsumption. Even if green gas had already been implemented at scale, we believe these various social harms decisively outweigh benefits to industry. However, given that renewable gas has not been pursued at scale by the dairy industry, the case is more straightforward.

Some may disagree with the evaluation so far. This brings us to the second part of Bufacchi's principle: the role of public deliberation. In this context, there are two special concerns about putting the use of renewable gas to produce breast-milk substitutes to public deliberation. The first concern is that one of the primary impacted groups potentially affected by increases or decreases in breastfeeding is infants, who clearly cannot advocate for themselves. While parents and the medical community could advocate on behalf of infants, there is a large disparity between the financial and social power of large manufacturers of breast-milk substitutes and these groups. The power dynamic between industry and the medical community of doctors, nurses and midwives is complicated by the role that

manufacturers assume in influencing medical practice through sponsorship of research and events [55]. The capacity and resources of manufacturers to advocate for their product can be expected to be far greater than that of parents. For these reasons we should expect that having others advocate for infants and their mothers or not having their needs represented would systematically underestimate the benefits of breastfeeding. This reason justifies avoiding public deliberation on this policy choice.

6.5 Discussion

The analysis shows that the emissions savings achieved by meeting the minimum WHO nutrition target of 50% are much greater than the emissions saved from fossil fuel substitution alone in the processing stage. While producers of breast-milk substitutes can accurately report that production is lower carbon for Scope 1 emissions when renewable gas is used, the remaining Scope 1 emissions and emissions from agriculture and transport (Scope 3 emissions) would still need to be offset. Equations 1, 2 and 3 allow us to estimate the potential emissions reduction from increasing the share of breastfeeding and reducing the emissions associated with breast-milk substitutes. When emissions associated with food processing are explicitly represented in energy modelling it is possible to incorporate breastfeeding rates. It can therefore be recommended to consider the breastfeeding support required to meet WHO nutrition target no. 5 a demand-side measure in the energy transition, while remaining cognisant of reproductive rights in policy recommendations.

A focus of this work was to consider decarbonising the processing of breast-milk substitutes as an appropriate end-use for renewable gas. We suggest that decarbonising a single product type will need to be considered in the context of the wider energy system of multiple products and energy uses. Green gas will be a limited resource that can address the decarbonisation needs of heavy transport systems that have limited decarbonisation options [54]. The transport sector could be considered a

priority for this resource as a result. For the dairy sector, alternatives such as wood chips are an option to meet the remaining energy demand once global nutrition targets are met. The principle of justice as non-maleficence would also be applicable in this case, and as such, is a relevant consideration for future research.

The analysis established that the harms associated with marketing of breast-milk substitutes will increase if the product processing is decarbonised with renewable gas, which is not aligned with a just transition. The authors do not suggest that manufacturers should not aim to reduce emissions. The onus is on the regulatory environment to apply measures already in place such as the WHO code and to take practical steps to protect and support breastfeeding. Where efforts are made to decarbonise the product, then efforts to protect and support breastfeeding can make a legitimate claim to access just transition funding. Just transition funds are a means of assisting groups of people that are adversely affected by the low carbon transition [56]. The emissions analysis demonstrated that the greatest saving can be achieved through a combined effort of meeting the WHO minimum nutrition target and decarbonising breast-milk substitutes. Where this effort takes place in tandem, prioritising meeting breastfeeding targets is compatible with the principle of justice as non-maleficence.

6.5.1 Uncertainties, limitations, and further research

This study establishes an analytical framework to incorporate breastfeeding and breastfeeding support and protection into energy system models. While this study considered only the first six months of infant feeding, future work could explore potential emissions savings from decarbonising the ‘follow-on’ and ‘toddler’ milks which are driving market growth. Further research to apply the principle of justice as non-maleficence to these ‘follow-on’ and ‘toddler’ milks is potentially important given the difference in the nature of the product and the context in which these products have been developed.

This paper sought to move beyond emissions and consider the social justice elements of the energy transition. The principle of justice as non-maleficence applied in this case could be applied when considering the justice implications of decarbonising a wide range of 'status quo' or business as usual scenarios.

6.6 Conclusions

The analysis in this paper finds that when decarbonising production of breast-milk substitutes in Ireland with renewable gas is compared with reaching WHO minimum breastfeeding targets in key countries of consumption, the GHG emissions savings are far greater when breastfeeding targets are reached. If the WHO minimum breastfeeding target is reached in China and the remaining product demand is decarbonised with renewable gas, 81kt $CO_{2\text{-eq}}$ will be saved. This is 0.26% of Ireland's GHG reduction target for 2030. This is applicable for the first 6 months of infant feeding. The analysis also demonstrates the link between breastfeeding rates and GHG emissions associated with consumption of breast-milk substitutes. Breastfeeding rates will have an influence on the demand for energy services associated with breast-milk substitutes; therefore, this influence needs to be incorporated into energy models.

A contention of this paper is that, although fuel-substitution with renewable gas appears to be a solution for decarbonisation, it does not necessarily align with social long-term value. When women are not supported to reach their breastfeeding goals, and breast-milk substitutes are decarbonised, then decarbonising breast-milk substitutes does not meet the principle of justice as non-maleficence. Thus, breastfeeding support can simultaneously be a public health and a climate justice issue. Consequently, breastfeeding support programmes can make a legitimate claim to access to just transition funds. Positioning access to breastfeeding support as a climate justice issue can mitigate the concern with jeopardising women's reproductive rights or interfering with

their individual choices. Furthermore, understanding that both breastfeeding or use of breast-milk substitutes are functionally different and reproductive rights [7,10] will be imperative to discussing implications in modelling.

Acknowledgements

This work acknowledges the support from Science Foundation Ireland (SFI) through the Centre for Marine and Renewable Energy (MaREI) under Grant nos. 12/RC/1181 2302_P2 and 16/SP/3829.

The authors appreciate comments from all anonymous reviewers for the Journal of Cleaner Production and want to especially thank Reviewer 2 for their considered and comprehensive review that has substantially improved the paper.

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7 Conclusion

7.1 Overview

The overall theme of this thesis was the end use of biomethane. Chapter 3 initially established that transport was the preferred end use of grass biomethane according to EU sustainability criteria. Applying the same criteria to gasification of willow and co-digestion of grass and slurry confirmed this preferred end use in the EU. Considering national emissions savings, transport as an end use results in greater greenhouse gas emissions savings when compared to heat. While industry have an interest in using biomethane for industrial heat, when the fuel is used in ETS installations then it is unlikely to contribute to Irish emissions savings targets for meeting EU Effort sharing emissions savings targets. Beyond energy and emissions targets, there are moral implications of deploying biomethane as industrial heat. Using the example of decarbonising breast-milk substitutes (BMS) this research established that this end use does not meet social justice criteria for a just transition according to the principle of justice as non-maleficence.

7.2 Conclusions

7.2.1 Biomethane feedstocks in Ireland

This research identified the main feedstocks and production processes for biomethane in Ireland. Wastes, slurry and grass could be used immediately in a green gas industry with anaerobic digestion as the dominant conversion technology. The production stages and processes that would need to be considered for certification are outlined in detail. Grass is the dominant resource of green gas and it was shown that with present technologies and EU Directives that green gas from grass can satisfy emissions for use as a sustainable renewable transport fuel (especially if sequestration of carbon to grassland is included) but will struggle to satisfy renewable heat emission savings (unless co-digested with slurry).

Understanding of all the process steps is essential to inform the development of a certification scheme for renewable gas.

An assessment of the equivalent CO_2 emissions for the willow biomethane pathway via gasification and upgrading, was carried out in order to determine if it could meet EU sustainability criteria. The analysis undertaken used conservative estimates for input values such as agro-chemicals and carbon sequestration and assumed heat and power recovery during the thermal conversion process.

In converting from grassland to willow it is not possible to meet the emissions criteria for heat. Due to the portions of agriculture land in Ireland which are arable, and which are in pasture the resource of willow biomethane that is sustainable is limited to 0.5% of the heat market. Considering the Irish context of a large area of grassland cover, and climate recommendations to limit conversion from grassland, the potential for grass as an energy crop in Ireland should be explored further. This recommendation is specific to the Irish context, as converting other land uses to grassland may not be appropriate depending on land cover in other countries. Developing a substantial resource of willow in Ireland is dependent on the ability to convert both arable and grassland to energy crops, for both gasification and combustion, and a national capacity to convert a large land area in addition to existing Climate Action goals to develop forestry, and significant investment on the supply side to develop the resource.

7.2.2 End use of biomethane in Ireland

In terms of policy implications, the RED recast positions transport as a more favourable pathway than heat. This can be seen in five ways:

1. GHG savings required by the RED recast are lower for transport than heat (65% vs 80%);

2. The FFC is higher for transport than heat (94 g $CO_{2\text{-eq}}$ MJ^{-1} vs 80 g $CO_{2\text{-eq}}$ MJ^{-1}) making it easier to satisfy transport.

3. The efficiency of heat conversion must be included.

4. For transport, the RED recast methodology employs a field to tank analysis as opposed to a cradle to wheel. If the analysis were field to wheel typically biomethane performs at about 75% of efficiency of diesel in terms of km MJ^{-1} [1]. The combination of points 1 to 4 lead to a requirement for biomethane to limit emissions to 32.9 g $CO_{2\text{-eq}}$ MJ^{-1} for transport as opposed to 14.4 g $CO_{2\text{-eq}}$ MJ^{-1} for heat.

5. This effect is further exacerbated by the fact that the RED recast counts advanced transport biofuel as twice the energy in the fuel when counted towards meeting national renewable energy in transport targets.

For any biomethane pathway, meeting the emissions savings criteria will determine the role that it can play in the green gas industry in EU states. Considering the wider context, EU policy and reporting mechanisms appear to favour the use of the fuel for transport when compared to heat as an end use. This could be problematic as renewable heat requires little change on behalf of the end-user while renewable transport requires the end-user to construct compressed natural gas service stations and purchase natural gas vehicles (NGV). Biomethane for renewable heat has the potential to initiate a green gas industry as it does not require capital investment by the end user. Biomethane for transport would require significant investment by the end user to facilitate the CNG refuelling infrastructure and purchase of NGVs.

From a national policy perspective, the end-use of the biomethane will matter. When the biomethane produced is used as a transport fuel, a greater amount of GHG emissions are saved (when displacing diesel), and the end use will contribute more to national EU effort sharing targets as well as minimum EU targets for renewable energy in transport. Using the biomethane as renewable heat within the ETS can reduce ETS emissions. Where biomethane is used for heat in the non-ETS sector it can contribute to effort sharing GHG emissions, but not to the same extent as transport.

Using biomethane for heat would also require Ireland to develop other options to meet the 14% renewable energy in transport target where the hard to abate sectors of heavy transport reside). The findings in this thesis will increase our understanding of the interaction between EU energy and GHG emissions policies in relation to the end use of biomethane systems.

7.2.3 Biomethane and social justice

The analysis in this paper finds that when decarbonising production of breast-milk substitutes in Ireland with renewable gas is compared with reaching WHO minimum breastfeeding targets in key countries of consumption, the GHG emissions savings are far greater when breastfeeding targets are reached. If the WHO minimum breastfeeding target is reached in China and the remaining product demand is decarbonised with renewable gas, 81kt $CO_{2\text{-eq}}$ will be saved. This is 0.26% of Ireland's GHG reduction target for 2030. This is applicable for the first 6 months of infant feeding. The analysis also demonstrates the link between breastfeeding rates and GHG emissions associated with consumption of breast-milk substitutes. Breastfeeding rates will have an influence on the demand for energy services associated with breast-milk substitutes; therefore, this influence needs to be incorporated into energy models.

A contention of this research is that, although fuel-substitution with renewable gas appears to be a solution for decarbonisation, it does not necessarily align with social long-term value. When women are not supported to reach their breastfeeding goals, and breast-milk substitutes are decarbonised, then decarbonising breast-milk substitutes does not meet the principle of justice as non-maleficence. Thus, breastfeeding support can simultaneously be a public health and a climate justice issue. Consequently, breastfeeding support programmes can make a legitimate claim to access to just transition funds. Positioning access to breastfeeding support as a climate justice issue can mitigate the concern with jeopardising women's reproductive rights or interfering with their individual choices. Furthermore, understanding that both

breastfeeding or use of breast-milk substitutes are functionally different and reproductive rights [2,3] will be imperative to discussing implications in modelling.

7.2.4 Introducing biomethane in any country

This research focused on biomethane production in Ireland, and as Ireland is an EU-country it will be most applicable to other EU countries. There are however generalized lessons regarding the introduction of biomethane in any country that can provide guidance for any country that is developing a plan for biomethane. The key considerations are feedstock, technology and end use. As energy crops are dependent on local geography, a co-located energy crop and end use will be the most advantageous, particularly in countries that do not have an extensive gas grid for transport of the biomethane. Grass silage is a suitable resource for Ireland given the extensive grassland in situ and limitations on converting land in EU Policy and legislation. In other countries the appropriate crop will be different. For existing and potential crops, the crop and energy yield per hectare will be important factors in selecting suitable crops as feedstock.

Considering technology, anaerobic digestion is the most common technology discussed in scientific literature and in place in countries with biomethane production. While gasification is considered mature technology, implementation rates are low.

The end use is ideally a difficult to decarbonise sector in the country. This is the rationale behind the EU Renewable Energy Directive (recast). This does however need to be balanced with the demand for renewable energy in different end use sector. In the Irish case study, there is a clear demand for biomethane as renewable heat. Pursuing this demand could limit options for renewable transport fuels. Incentivisation is necessary in most cases to encourage the industry, so introducing biomethane at scale will need to be a national policy decision.

7.3 Recommendations for policymakers and industry

7.3.1 Sustainability as a design criterion

The analysis in Chapters 3, 4 and 5 demonstrated that the potential end use of the biomethane will need to be considered as part of the design process. This is especially the case where heat is the proposed end use, or if the end use is unknown. Agro-chemical inputs to feedstock cultivation, system methane loss and land use conversion will have a larger impact on overall sustainability compared to other parameters. If the proposed end use is heat, it is better for developers to know if the sustainability criteria can be met for this end use at an early stage of any proposed development.

7.3.2 Transport as a priority end use

The clear preference in EU policy to direct the end use towards transport should be considered in national decarbonisation strategies. Although there may be more immediate demand for biomethane for heat [4], transport as a sector is more difficult to decarbonise as the options for decarbonisation are more limited [5]. Investing in transport as an end use for biomethane will allow Ireland and other EU countries to meet renewable energy in transport and national emissions savings targets to a greater extent.

7.3.3 Demand for energy services and social justice

Beyond energy and emissions targets, the analysis in Chapter 6 demonstrated that there are wider public health targets that will have an impact on the demand for energy services. Reducing demand for energy services in an equitable way needs to become a more prominent discussion in the energy transition.

7.4 Potential for future research

7.4.1 Evaluate additional renewable gas pathways

This research focused on establishing the ability of linear biofuel pathways to meet EU sustainability criteria. To contribute to a circular economy biomethane has the potential to be one of many outputs from an

integrated system. Future research is necessary to test the applicability of the RED recast criteria for such systems to inform future sustainability policy.

7.4.2 Consider end use of green hydrogen

During the course of this work, the potential for green hydrogen became more prominent in policy and research discussions. This work is applicable to the end use of green hydrogen to determining the most appropriate end use of this resource.

7.4.3 Include breastfeeding as a climate mitigation option

This research established an analytical framework for including breastfeeding as a mitigation option in the energy transition. This work can be further developed to widen mitigation options from non-energy uses and to integrate breastfeeding rates into energy models to inform policy.

7.4.4 The principle of justice as non-maleficence

The case study in Chapter 6 demonstrated that this social justice principle is applicable to the energy transition. Further research to apply this principle to other proposed decarbonisation pathways would be of value to inform social justice discussions. An example is potentially the electrification of passenger car transport, that retains the severance and social limitations of traffic in cities as opposed to town planning as a means to encourage walking, cycling and public transport and disincentivising private car intrusion into the city space.

7.4.5 Improving input data

This work relied heavily on data from other sectors, and in particular from agriculture and public health. In some cases, this data is out of date or incomplete. There is limited research on carbon sequestration rates of various energy crops or pastureland in Ireland. Establishing this data can provide more accurate inputs to establishing overall emissions savings. Similarly, if breastfeeding is to be considered as a mitigation option that has the potential to reduce demand for energy services, then more

accurate data is required in relation to breastfeeding rates from infancy and beyond up to two years.

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Appendix A – Nutrient content of cattle slurry

Cattle Slurry Nutrient Content

The nutrient content is based on data from the Teagasc [1]. Cattle slurry contains an average of 2.4kg N m^{-3}, 0.5 kg P m^{-3} and 3.5 kg K m^{-3}, and 1 tonne of slurry equals 1 m^3 volume. Phosphorous is the limiting nutrient, and therefore the slurry used will be the slurry required to meet the Phosphorous Soil Index 2, which is 34 kg ha^{-1}.

Slurry required to meet phosphorous demand is:
34 kg ha^{-1}/ 0.5 kg P m^{-3} = 68 m^3 slurry = 68 tonnes slurry

	N	P	K	
Nutrient Amount in 68 m^3 slurry	163.2	34	238	kg ha^{-1}
Total applications	7	7	7	
Total application	1142.4	238	1666	kg
Application per annum	51.9	10.8	75.7	Kg ha^{-1} y^{-1}

Nitrogen bioavailability in slurry = 40%

N available = 163.2 * 40% = 65.28 kg ha^{-1}

N index 3-4 requires 75-40 kg N ha^{-1}

References

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Appendix B – N2O emissions

1 Field emissions

Field emissions are calculated based on IPCC 2006 Guidelines [1] Tier 1 methodology. A challenge with this method is that "Tier 1 calculations are intended for use at large spatial scales, and they can generate substantial errors in predictions at finer levels" [2]. For this analysis Tier 1 calculations, which may overestimate the field emissions, are applied. These are considered conservative and are in line with the Tier 1 methodology used in BioGrace. For the emissions from land-use change the EPA emissions report was consulted for data pertaining to Ireland. This reported 0 emissions related to land-use change to the IPCC [3] .

2 Emissions from mineral fertilisers

2.1 Equation 11.1 Direct N_2O emissions from managed soils

$N_2O\text{-}N_{DIRECT} = F_{SN} \text{ X } EF_1$

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}
EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$(Table 11.1)

F_{SN} = 31.82 kg ha^{-1} y^{-1} - From Table 4a in main paper

From Table 11.1 [1]

EF_1 = 0.01

$N_2O\text{-}N_{DIRECT}$ = 31.82 X 0.01 = 0.32 kg N_2O-N ha^{-1} y^{-1}

Note that EF_1 used to be 0.0125. This will appear in papers that applied the IPCC 1996 methodology. This factor was changed to 0.01 following further research as outlined in the notes related to Table 11.1.

2.2 Equation 11.8 Emissions as a result of loss of soil C through change in land use or management

F_{SOM} = Field emissions from loss of soil organic matter due to land use change. For Ireland this is 0 [3].

2.3 Equation 11.9 Emissions Volatised from Managed Soils

$N_2O_{(ATD)}\text{-}N = F_{SN} \text{ X } Frac_{GASFi} \text{ X } EF_4$

$N_2O_{(ATD)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilised from managed soils, kg N_2O–N yr^{-1}
F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}
$Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$ (Table 11.3)
EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces,
[kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$] (Table 11.3)

From Table 11.3 [1]

$Frac_{GASFi}$ = 0.1

EF_4 = 0.01

$N_2O_{(ATD)}$-N = 31.82 X 0.1 X 0.01 = 0.032 kg N_2O-N ha^{-1} y^{-1}

2.4 Equation 11.10 Emissions from leaching/runoff from managed soils in regions where leaching runoff occurs

$N_2O\text{-}N_{LEACH}$ = F_{SN} X $Frac_{LEACH}$ X EF_5

$Frac_{LEACH}$ = 0 in regions where soil water-holding capacity is not normally exceeded during rainy season. The risk of nitrogen leaching from SRC willow plantations is relatively low compared with normal arable situations given the long term perennial nature of the crop and the absence of soil disturbance through cultivation [4]. The lower range value of 0.1 was chosen for $Frac_{LEACH}$ on this basis. This corresponds to the data used for Ireland by the EPA in the National Inventory Report [3].

From Table 11.3 [1]

EF_5 = 0.0075

$Frac_{LEACH}$ = 0.1

$N_2O\text{-}N_{LEACH}$ = 31.82 X 0.1 X 0.0075 = 0.024 kg N_2O-N ha^{-1} y^{-1}

2.5 Total Field Emissions

N_2O-N = Sum (Eqn.11.1, Eqn.11.9, Eqn.11.10)

= 0.32 + 0.032 + 0.024

= 0.376 kg N_2O-N ha^{-1} y^{-1}

Convert to N_2O = 0.376 X 44/28 = 0.59 kg N_2O ha^{-1} y^{-1}

Convert to $CO_{2\text{-}EQ}$ = 0.59 X 298 = 176 kg $CO_{2\text{-}EQ}$ ha^{-1} y^{-1}

3 Emissions from organic fertilisers

3.1 Equation 11.1 Direct N_2O emissions from managed soils

$N_2O\text{-}N_{DIRECT}$ = F_{ON} X EF_1

F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (Note: If including sewage sludge, cross-check with Waste Sector to ensure there is no double counting of N_2O emissions from the N in sewage sludge), kg N yr^{-1}
EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$(Table 11.1)

F_{ON} = 51.9 kg ha^{-1} y^{-1} – From Supplementary Data Part A

From Table 11.1 [1]

EF_1 = 0.01

$N_2O\text{-}N_{DIRECT}$ = 51.9 X 0.01 = 0.519 kg N_2O-N ha^{-1} y^{-1}

3.2 Equation 11.8 Emissions as a result of loss of soil C through change in land use or management

F_{SOM} = Field emissions from loss of soil organic matter due to land use change. For Ireland this is 0 [3].

3.3 Equation 11.9 Emissions Volatised from Managed Soils

$N_2O_{(ATD)}$-N = F_{ON} X $Frac_{GASM}$ X EF_4

$N_2O_{(ATD)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilised from managed soils, kg N_2O–N yr^{-1}
F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions
applied to soils, kg N yr^{-1}
$Frac_{GASM}$ = fraction of applied organic N fertiliser materials (F_{ON}) and of urine and dung N deposited by
grazing animals (F_{PRP}) that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied or deposited)$^{-1}$ (Table 11.3)
EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces,
[kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$] (Table 11.3)

From Table 11.3 [1]

$Frac_{GASM}$ = 0.2

EF_4 = 0.01

$N_2O_{(ATD)}$-N = 51.9 X 0.2 X 0.01 = 0.104 kg N_2O-N ha^{-1} y^{-1}

3.4 Equation 11.10 Emissions from leaching/runoff from managed soils in regions where leaching runoff occurs

N_2O-N_{LEACH} = F_{ON} X $Frac_{LEACH}$ X EF_5

$Frac_{LEACH}$ = 0 in regions where soil water-holding capacity is not normally exceeded during rainy season. The risk of nitrogen leaching from SRC willow plantations is relatively low compared with normal arable situations given the long term perennial nature of the crop and the absence of soil disturbance through cultivation [4]. The lower range value of 0.1 was chosen for $Frac_{LEACH}$ on this basis. This corresponds to the data used for Ireland by the EPA in the National Inventory Report [3].

From Table 11.3 [1]

EF_5 = 0.0075

$Frac_{LEACH}$ = 0.1

N_2O-N_{LEACH} = 51.9 X 0.1 X 0.0075 = 0.039 kg N_2O-N ha^{-1} y^{-1}

3.5 Total Field Emissions

N_2O-N = Sum (Eqn.11.1, Eqn.11.9, Eqn.11.10)

= 0.519 + 0.0.104 + 0.039

= 0.66 kg N_2O-N ha^{-1} y^{-1}

Convert to N_2O = 0.66 X 44/28 = 1.04 kg N_2O ha^{-1} y^{-1}

Convert to $CO_{2\text{-eq}}$ = 1.04 X 298 = 309.92 kg $CO_{2\text{-EQ}}$ ha^{-1} y^{-1}

4 References

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Appendix C - Feedstock Mix Parameters

Parameter	Slurry	Grass	Unit	[1]
Dry solids	87.5	292.7	g kg^{-1}	
Volatile solids	66.9	268.4	g kg^{-1}	
Moisture content	912.5	707.3	g kg^{-1}	

Mix on VS basis = 80% slurry 20% grass

Feedstock	VS g kg^{-1}	FW (g)	DS (g)	Mc (g)
slurry	800	11958	1046	10912
grass	200	745	218	527
mix	1000	12703	1264	11439

Parameters on basis of kg t^{-1} FW_{mix}

VS	FW	DS	Mc
63	941	82	859
16	59	17	41
79	1000	100	900

Check 1000

Mix on VS basis = 60% slurry 40% grass

Feedstock	VS g kg^{-1}	FW (g)	DS (g)	Mc (g)
slurry	600	8969	785	8184
grass	400	1490	436	1054
mix	1000	10459	1221	9238

Parameters on basis of kg t^{-1} FW_{mix}

VS	FW	DS	Mc
57	858	75	782
38	142	42	101
96	1000	117	883

Check 1000

Mix on VS basis = 50% slurry 50% grass

Feedstock	VS g kg^{-1}	FW (g)	DS (g)	Mc (g)
slurry	500	7474	654	6820
grass	500	1863	545	1318
mix	1000	9337	1199	8138

Parameters on basis of kg t^{-1} FW_{mix}

VS	FW	DS	Mc
54	800	70	730
54	200	58	141
107	1000	128	872

Check 1000

Mix on VS basis = 40% slurry 60% grass

Feedstock	VS g kg^{-1}	FW (g)	DS (g)	Mc (g)
slurry	400	5979	523	5456
grass	600	2235	654	1581
mix	1000	8214	1177	7037

Parameters on basis of kg t^{-1} FW_{mix}

VS	FW	DS	Mc
49	728	64	664
73	272	80	192
122	1000	143	857

Check 1000

Mix on VS basis = 20% slurry 80% grass

Feedstock	VS g kg^{-1}	FW (g)	DS (g)	Mc (g)
slurry	200	2990	262	2728
grass	800	2981	872	2108
mix	1000	5971	1134	4836

Parameters on basis of kg t^{-1} FW_{mix}

VS	FW	DS	Mc
33	501	44	457
134	499	146	353
167	1000	190	810

Check 1000

References

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Appendix D - Inventory of emissions associated N input for grass cultivation

calculated based on IPCC 2019 Refinement Guidelines

1 Emissions for grass cultivation

1.1 Emissions from Synthetic Fertiliser

N input = 225 kg N ha^{-1} yr^{-1}

1.1.1 Direct N_2O from Managed Soils

IPCC Volume 4 Chapter 11 Section 11.2.1 Direct N_2O emissions

From IPCC Chapter 11, N_2O Emissions from managed soils, and CO_2 emissions from lime and urea application [1]

Direct N_2O emissions from synthetic fertilisers
Equation 11.1A Direct N_2O emissions from managed soils – Adapted from Equation 11.1
N_2O_{Direct}-N = N_2O-$N_{Ninputs}$ = F_{SN} * EF_1
F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}
EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O-N (kg N input)$^{-1}$ (Table 11.1)
Conversion of $N_2O_{(ATD)}$-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:
N_2O = N_2O-N *44/28

EF_1 = 0.0124 kg N_2O-N kg N^{-1} Calculated value for Ireland [2]

Table 1 Direct N_2O emissions from synthetic fertilisers 2019R

Parameter	N imput				Unit	Source
F_{SN}	225				kg N yr^{-1}	
EF_1	0.0124				kg N_2O-N kg N^{-1}	Table 11.1 [1] EPA Report
N_2O-$N_{Ninputs}$	2.79				kg N_2O-N	
Conversion 44/28						
N_2O	4.38				kg N_2O yr^{-1}	
GWP for N_2O	298					
$CO_{2\text{-eq}}$ emissions	1,307				kg $CO_{2\text{-eq}}$	

N_2O emissions = 4.38 kg N_2O yr^{-1}
$CO_{2\text{-eq}}$ emissions = 1306.52 kg $CO_{2\text{-eq}}$

1.1.2 Indirect N_2O from Managed Soils

1.1.2.1 Indirect N_2O from atmospheric deposition of volatilised N - displaced emissions

EPA Section 5.5.2 Indirect Emissions from Managed Soils: Category 3D2

IPCC Volume 4 Chapter 11 Section 11.2.2 Indirect N_2O emissions

From IPCC Chapter 11, N_2O Emissions from managed soils, and CO_2 emissions from lime and urea application [1]

Indirect N_2O emissions from atmospheric deposition of volatilised N - from synthetic fertilisers
Equation 11.9A Direct N_2O emissions from managed soils – Adapted from Equation 11.9
$N_2O_{(ATD)}\text{-}N = F_{SN} * Frac_{GASF} * EF_4$
F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}
$Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$ (Table 11.3)
EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg $N\text{-}N_2O$ (kg $NH_3\text{-}N + NO_x\text{-}N$ volatilised)$^{-1}$] (Table 11.3)
Conversion of $N_2O_{(ATD)}$-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:
$N_2O_{(ATD)} = N_2O_{(ATD)}\text{-}N * 44/28$

$Frac_{GASF}$	0.025	kg N volatilised (kg of N applied)$^{-1}$	Calculated value for Ireland
EF_4 =	0.01	kg N_2O-N (kg $NH_3\text{-}N + NO_x\text{-}N$ volatilised)$^{-1}$	EPA Report

Table 2 Indirect N_2O displaced from atmospheric deposition of N volatilized from managed soils 2019R

Parameter	Displaced N				Unit	Source
F_{SN}	225				kg N yr^{-1}	
$Frac_{GASF}$	0.025				kg N volatilised (kg N applied or deposited)$^{-1}$	EPA Report - Calculated value for 2017 [2]
EF_4	0.01				kg N_2O-N (kg $NH_3\text{-}N + NO_x\text{-}N$ volatilised)$^{-1}$	Table 11.3 [1,2]
$N_2O_{(ATD)}\text{-}N$	0				kg N_2O-N yr^{-1}	
Conversion 44/28						
$N_2O_{(ATD)}$	0				kg N_2O yr^{-1}	
GWP for N_2O	298					
$CO_{2\text{-eq}}$ emissions	26				kg $CO_{2\text{-eq}}$	

N_2O emissions =	0.088	kg N_2O yr^{-1}
$CO_{2\text{-eq}}$ emissions =	26.34	kg $CO_{2\text{-eq}}$

1.1.2 Indirect N_2O from Managed Soils

1.1.2.2 Indirect N_2O from leaching runoff

From IPCC Chapter 11, N_2O Emissions from managed soils, and CO_2 emissions from lime and urea application [1]

Indirect N_2O emissions from leaching/runoff - from synthetic fertilisers
Equation 11.10A Direct N_2O emissions from managed soils – Adapted from Equation 11.10
$N_2O_{(L)}\text{-}N = F_{SN} * Frac_{(LEACH\text{-}(H))} * EF_5$
F_{SN} = annual amount of synthetic fertiliser N applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}
$Frac_{(LEACH\text{-}(H))}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$ (Table 11.3)
EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N-N_2O (kg N leached and runoff)$^{-1}$ (Table 11.3)
Conversion of $N_2O_{(ATD)}$-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:
$N_2O_{(L)} = N_2O_{(L)}\text{-}N * 44/28$

$Frac_{LEACH\text{-}(H)}$ =	0.01	kg N (kg N additions or deposition by animals)$^{-1}$	[2]
EF_5 =	0.011	kg N_2O-N (kg N leaching/runoff)$^{-1}$	Table 11.3 Ch11 Default value [1]

Table 3 Indirect N_2O emissions displaced from N Leaching/Runoff from managed soils in regions where leaching/runoff occurs 2019R

Parameter	N Displaced				Unit	Source
F_{SN}	225				kg N yr^{-1}	
$Frac_{LEACH\text{-}(H)}$	0.1				kg N (kg N additions or deposition by animals)$^{-1}$	EPA Report - Calculated value for 2017 [2]
EF_5	0.011				kg N_2O-N (kg leaching/runoff)$^{-1}$	Table 11.3 [1]
$N_2O_{(L)}$-N	0.248				kg N_2O-N yr^{-1}	
Conversion 44/28						
$N2O_{(L)}$	0.389				kg N_2O yr^{-1}	
GWP for N_2O	298					
$CO_{2\text{-}eq}$ emissions	116				kg $CO_{2\text{-}eq}$	

N_2O emissions =	0.39	kg N_2O yr^{-1}
$CO_{2\text{-}eq}$ emissions =	115.90	kg $CO_{2\text{-}eq}$

2 Summary of emissions

Table 4 Summary of emissions displaced - Profitable scenario

	Emissions $kg\ CO_{2\text{-}eq}\ ha^{-1}\ y^{-1}$
Direct N2O from Agricultural soils	1306.52
Indirect N2O from Atmospheric Deposition	26.34
Indirect N2O from Leaching/Runoff	115.90
Total	1,449

References

[1] IPCC. 2019 Refinement to the 2006 IPCC Guidlines for National Greenhouse Gas Inventories, Volume 4 Chapter 11: N2O Emissions From Managed Soils, and Co2 Emissions From Lime and Urea Application. vol. 4. Geneva: 2019.

[2] Duffy P, Black K, Hyde B, Ryan AM, Ponzi J. Ireland's National Inventory Report 2019 Greenhouse Gas Emissions 1990-2017. Johnstown Castle, Co. Wexford: 2019.

Appendix E - Sustainability calculation for 20% Slurry and 80% Grass (VSR) & 1% Methane loss

VSR	Slurry	20	80	Grass

Parameters on basis of kg t^{-1} FW_{mix}

Dry solids	190	kg t^{-1} FW_{mix}	[1]
Volatile solids	167	kg t^{-1} FW_{mix}	[1]
Moisture content	810	kg t^{-1} FW_{mix}	
Gas production	78.7	m^3 CH_4 t^{-1} FW	[1]
Methane energy value	37.78	MJ m_n^{-3}	[2]
Specific heat capacity of water	4.184	kJ kg^{-1} $°C^{-1}$	
Gross energy yield	2973.29	$MJ_{biomethane}$ t^{-1} FW_{mix}	

Slurry Pasteurisation

Final Temp	70	°C	Required for pasteurisation
Starting Temp	10	°C	Normal temp Irl [3]
Temperature change	60	°C	
Water content of feedstock	457	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	1.91	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	114.6	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	3.03	m^3 CH_4 t^{-1} FW	
	3.85%	of energy in biomethane	

Heat demand for grass

Final Temp	37	°C	Required for operation
Starting Temp	10	°C	Normal temp Irl [3]
Temperature change	27	°C	
Water content of feedstock	353	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	1.48	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	39.96	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	1.06	m^3 CH_4 t^{-1} FW	
	1.34%	of energy in biomethane	

Heat recovery from pasteurisation of slurry

Final Temp	37	°C	Required for operation
Starting Temp	70	°C	Pasteurisation temp
Temperature change	-33	°C	
Water content of feedstock	457	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	1.91	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	-63.03	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	-1.67	m^3 CH_4 t^{-1} FW	
	-2.12%	of energy in biomethane	

Total heat parasitic demand	2.42	m^3 CH_4 t^{-1} FW
	3.07%	of energy in biomethane

Electricity Demand	emissions factor from grid		
Macerating grass - electricity demand =	2	kWh t^{-1}	[4]
Macerating grass	0.499	t Grass t^{-1} FW_{mix}	Appendix C
Macerating - electricity demand	0.998	kWh t^{-1} FW_{mix}	[4]
Mixing 10% DS =	10	kWh t^{-1}	[5]
Total electricity demand	10.998	kWh t^{-1} FW_{mix}	
Biogas Upgrading & Compression			
Energy available for upgrading	2881.86	MJ_{biogas} t^{-1} FW_{mix}	
CH_4 content in biogas	55%		[1]
Biogas available for upgrading	138.69	m^3 biogas t^{-1} FW	
Upgrading energy requried	0.58	kWh_{th} Nm^{-3}_{biogas}	[6]
Upgrading parasitic demand	289.58	MJ t^{-1} FW_{mix}	
Methane available for upgrading	68.62	m^3 CH_4 t^{-1} FW	
Energy required for compression =	0.11	kWh_e $m^{-3}_{biomethane}$	[6]
CH_4 concentration	99.00%		
Energy required from grid =	8.32	kWh_e t^{-1} FW_{mix}	
Biomethane yield	69.31	m^3 biomethane t^{-1} FW_{mix}	
System Methane Loses			
System Methane Loss (%)	1.00%		
System Methane Loss (m^3 CH_4 t^{-1} FW_{mix})	0.69	m^3 CH_4 t^{-1} FW_{mix}	
Convert to MJ	**2618.65**	$MJ_{biomethane}$ t^{-1} FW_{mix}	

Grass emissions up until digestion — adapted from (Long and Murphy, 2019) [7]

Stage	Emissions: g $CO_{2\text{-eq}}$ ha^{-1} y^{-1}	g $CO_{2\text{-eq}}$ t^{-1} FW_{grass}	g $CO_{2\text{-eq}}$ $MJ^{-1}_{Biomethane}$
Cultivation	1,839,000	33,712	9.33
Field N2O	1,449,000	26,563	7.35
Transport @ 10.5km*	94,372	1,730	0.48
Carbon sequestration	2,200,000	40,330	11.16

* Round trip = 21km

Emissions before processing 6.00

Emissions from transport - estimated using BioGrace calculation tool [Biogas from wet manure as CNG] [8]

Round trip = 80 km

Biograce parameters

Diesel emissions factor	87.64	g $CO_{2\text{-eq}}$ MJ^{-1}
Truck for liquids	1.01	MJ ton.km^{-1}
Manure Energy Yield	10	MJ kg^{-1} DM
Moisture content	92	%

Emissions: 7.08 kg CO_2 t^{-1} FW_{slurry}

Emissions from biogas generation

Electricity Emissions Factor	0.2	kg CO_2 kWh^{-1}	[9]	
Electricity Demand =	10.998	kWh t^{-1} FW_{mix}		
Emissions =	2.2	kg CO_2 t^{-1} FW_{mix}	**0.84**	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Emissions from upgrading

Electricity Demand =	8.32	kWh t^{-1} FW_{mix}		
Emissions =	1.66	kg CO_2 t^{-1} FW_{mix}	**0.63**	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Methane Loss =	0.69	m^3 CH_4 t^{-1} FW_{mix}		
Methane density =	0.71	kg CH_4 m^{-3}	[5]	
CH_4 GWP =	25			
Emissions =	12.25	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	**4.68**	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Total emissions from processing

	16.11	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	**6.15** g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Emissions from grid transportation

Emissions factor	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	[9]	
Methane Yield	2618.65	$MJ_{biomethane}$ t^{-1} FW_{mix}		
Emissions =	**3.19**	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Equation 1. I_n = Annual input to digester of substrate n [tonne of fresh matter]

$$In = \frac{VS_{n1,mix}}{VS_{n1}} / \left(\frac{VS_{n1,mix}}{VS_{n1}} + \frac{VS_{n2,mix}}{VS_{n2}} \right)$$

[10]

Equation 2. Wn = weighting factor of substrate n defined as:

$$Wn = \frac{I_n}{\sum_1^n I_n}$$

[10]

Equation 3. Sn = Share of feedstock n in energy content

$$Sn = \frac{P_n * W_n}{\sum_1^n P_n * W_n}$$

[10]

$$E = \sum_1^n S_n * \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n} \right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr}$$

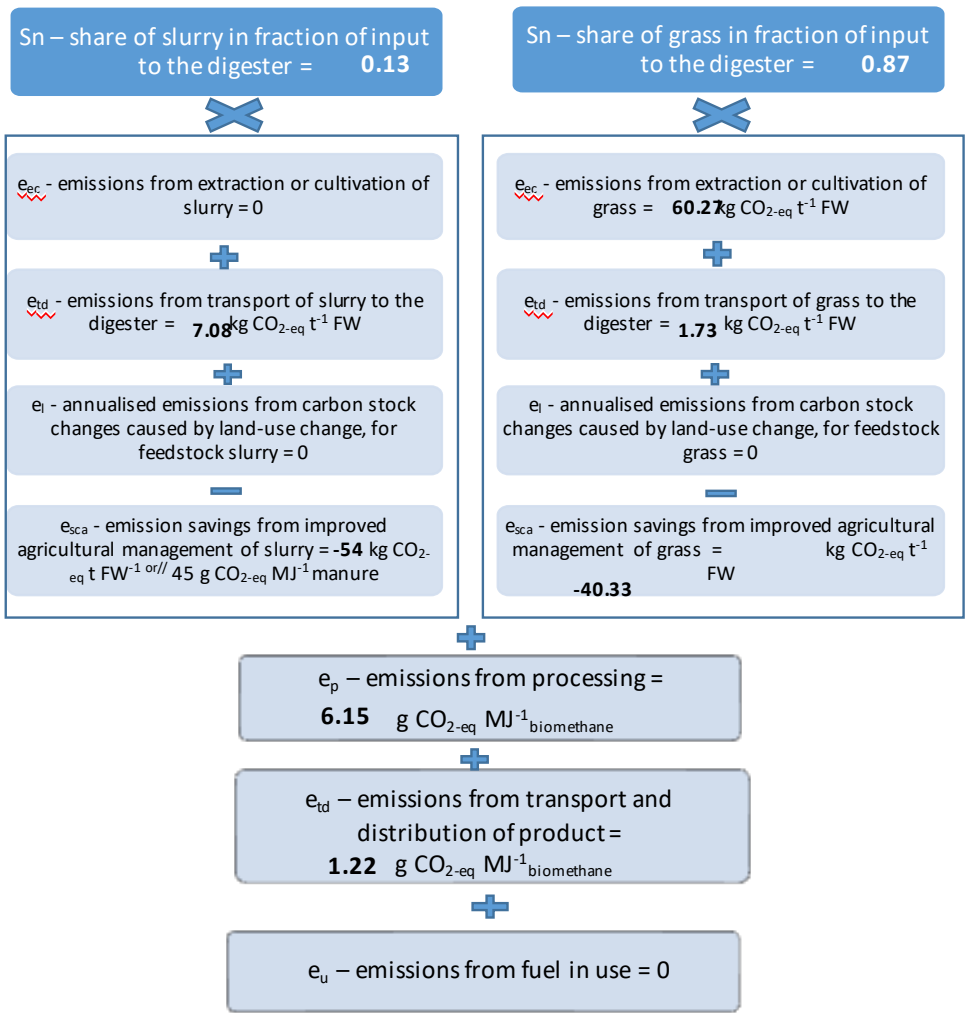
[10]

37.78 MJ/m_n^3 [5]

Parameter	Slurry n_1	Grass n_2	Unit	
Volatile solids in mix	200	800	g kg^{-1}	
Dry solids	87.5	292.7	g kg^{-1}	[1]
Volatile solids	66.9	268.4	g kg^{-1}	
Moisture content	912.5	707.3	g kg^{-1}	
Gas production	16	107.4	m^3 CH_4 t^{-1} FW	
P_n - energy yield	0.6	4.06	MJ kg^{-1} FW	
I_n - input to digester	0.50000	0.50000	t FW_n t^{-1} FW_{mix}	
W_n - weighting factor	0.50000	0.50000		
S_n - share of energy content	0.13	0.87	Sum =	1

Emissions	Slurry	Grass	
Cultivation (incl N_2O)	0	60.27	kg $CO_{2\text{-eq}}$ t^{-1} FW
Transport to digester	7.08	1.73	kg $CO_{2\text{-eq}}$ t^{-1} FW
Emissions savings	-54	-40.33	kg $CO_{2\text{-eq}}$ t^{-1} FW

Emissions from processing	6.15	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from transport and distribution	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from fuel in use	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$



Energy yield per t FW_{mix}	2618.65	$MJ_{biomethane}$ t^{-1} FW_{mix}
Emissions before processing	4.87	g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$
Emissions from processing	6.15	g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$
Emissions from transport and distribution	1.22	g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$
Emissions from fuel in use	0	g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$

Sustainability Check	Heat	Transport	
Total Emissions	12.24	12.24	g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$
Conversion to heat @90% efficiency	13.6		g $CO_{2\text{-}eq}$ $MJ^{-1}_{biomethane}$
Heat FFC	80	94	g $CO_{2\text{-}eq}$ MJ^{-1}
Emissions saved	83.00%	87%	
Criteria	80%	65%	
	Sustainable for Heat	Sustainable for Transport	

References

[1] Wall DM, O'Kiely P, Murphy JD. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour Technol 2013;149:425–31. doi:10.1016/j.biortech.2013.09.094.

[2] Murphy JD, Thamsiriroj T. Chapter 5 Fundamental science and engineering of the anaerobic digestion process for biogas production. Biogas Handb., Woodhead Publishing Online; 2013, p. 104–30. doi:10.1533/9780857097415.1.104.

[3] Duffy P, Black K, Hyde B, Ryan AM, Ponzi J. Ireland's National Inventory Report 2019 Greenhouse Gas Emissions 1990-2017. Johnstown Castle, Co. Wexford: 2019.

[4] Smyth B. Grass biomethane as a renewable transport fuel. University College Cork, 2011.

[5] Murphy JD, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. Appl Energy 2004;77:407–27. doi:10.1016/j.apenergy.2003.07.005.

[6] Beil M, Beyrick W. Chapter 15 Biogas upgrading to biomethane. In: Wellinger A, Murphy J, Baxter D, editors. Biogas Handb., Woodhead Publishing Online; 2013, p. 342–77. doi:10.1533/9780857097415.3.342.

[7] Long A, Murphy JD. Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and or transport? Renew Sustain Energy Rev 2019;115. doi:10.1016/j.rser.2019.109347.

[8] BioGrace.net. BioGrace-I calculation rules. 2015.

[9] Long A, Bose A, O'Shea R, Monaghan R, Murphy JD. Implications of European Union recast Renewable Energy Directive sustainability criteria for renewable heat and transport: Case study of willow biomethane in Ireland. Renew Sustain Energy Rev 2021;150:111461. doi:10.1016/j.rser.2021.111461.

[10] EU. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. vol. 2018. 2018.

Appendix F - Sustainability calculation for 50% Slurry and 50% Grass (VSR) & 1% Methane loss

VSR	Slurry	50	50	Grass

Parameters on basis of kg t^{-1} FW_{mix}

Dry solids	128	kg t^{-1} FW_{mix}	[1]
Volatile solids	107	kg t^{-1} FW_{mix}	[1]
Moisture content	872	kg t^{-1} FW_{mix}	
Gas production	51.6	m^3 CH_4 t^{-1} FW	[1]
Methane energy value	37.78	MJ m_n^{-3}	[2]
Specific heat capacity of water	4.184	kJ kg^{-1} $°C^{-1}$	
Gross energy yield	1949.45	$MJ_{biomethane}$ t^{-1} FW_{mix}	

Slurry Pasteurisation

Final Temp	70	°C	Required for pasteurisation
Starting Temp	10	°C	Normal temp Irl [3]
Temperature change	60	°C	
Water content of feedstock	730	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	3.05	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	183	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	4.84	m^3 CH_4 t^{-1} FW	
	9.39%	of energy in biomethane	

Heat demand for grass

Final Temp	37	°C	Required for operation
Starting Temp	10	°C	Normal temp Irl [3]
Temperature change	27	°C	
Water content of feedstock	141	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	0.59	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	15.93	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	0.42	m^3 CH_4 t^{-1} FW	
	0.82%	of energy in biomethane	

Heat recovery from pasteurisation of slurry

Final Temp	37	°C	Required for operation
Starting Temp	70	°C	Pasteurisation temp
Temperature change	-33	°C	
Water content of feedstock	730	kg t^{-1} FW_{mix}	
Thermal demand of feedstock	3.05	kJ kg^{-1} FW_{mix} $°C^{-1}$	
Thermal demand	-100.65	kJ kg^{-1} FW_{mix}	
Heat Parasitic Demand	-2.66	m^3 CH_4 t^{-1} FW	
	-5.16%	of energy in biomethane	

Total heat parasitic demand	2.6	m^3 CH_4 t^{-1} FW	
	5.04%	of energy in biomethane	

Electricity Demand	emissions factor from grid		
Macerating grass - electricity demand =	2	$kWh\ t^{-1}$	[4]
Macerating grass	0.2	$t\ Grass\ t^{-1}\ FW_{mix}$	Appendix A
Macerating - electricity demand	0.4	$kWh\ t^{-1}\ FW_{mix}$	[4]
Mixing 10% DS =	10	$kWh\ t^{-1}$	[5]
Total electricity demand	10.4	$kWh\ t^{-1}\ FW_{mix}$	
Biogas Upgrading & Compression			
Energy available for upgrading	1851.22	$MJ_{biogas}\ t^{-1}\ FW_{mix}$	
CH_4 content in biogas	55%		[1]
Biogas available for upgrading	89.09	$m^3\ biogas\ t^{-1}\ FW$	
Upgrading energy requried	0.58	$kWh_{th}\ Nm^{-3}_{biogas}$	[6]
Upgrading parasitic demand	186.02	$MJ\ t^{-1}\ FW_{mix}$	
Methane available for upgrading	44.08	$m^3\ CH_4\ t^{-1}\ FW$	
Energy required for compression =	0.11	$kWh_e\ m^{-3}_{biomethane}$	[6]
CH_4 concentration	99.00%		
Energy required from grid =	5.34	$kWh_e\ t^{-1}\ FW_{mix}$	
Biomethane yield	44.53	$m^3\ biomethane\ t^{-1}\ FW_{mix}$	
System Methane Loses			
System Methane Loss (%)	1.00%		
System Methane Loss ($m^3\ CH_4\ t^{-1}\ FW_{mix}$)	0.44	$m^3\ CH_4\ t^{-1}\ FW_{mix}$	
Convert to MJ	**1682.55**	$MJ_{biomethane}\ t^{-1}\ FW_{mix}$	

40 km = round trip of 80km

Grass emissions up until digestion — adapted from (Long and Murphy, 2019) [7]

Emissions

Stage	g $CO_{2\text{-eq}}$ ha^{-1} y^{-1}	g $CO_{2\text{-eq}}$ t^{-1} FW_{grass}	g $CO_{2\text{-eq}}$ $MJ^{-1}_{Biomethane}$
Cultivation	1,839,000	33,712	9.33
Field N2O	1,449,000	26,563	7.35
Transport @ 10.5km*	94,372	1,730	0.48
Carbon sequestration	2,200,000	40,330	11.16

* Round trip = 21km

Emissions before processing 6.00

Emissions from transport - estimated using BioGrace calculation tool [Biogas from wet manure as CNG] [8]

Round trip = 80 km

Biograce parameters

Diesel emissions factor	87.64	g $CO_{2\text{-eq}}$ MJ^{-1}	Emissions
Truck for liquids	1.01	MJ ton.km^{-1}	7.08 kg CO_2 t^{-1} FW_{slurry}
Manure Energy Yield	10	MJ kg^{-1} DM	
Moisture content	92	%	

Emissions from biogas generation

Electricity Emissions Factor	0.2	kg CO_2 kWh^{-1}	[9]
Electricity Demand =	10.4	kWh t^{-1} FW_{mix}	
Emissions =	2.08	kg CO_2 t^{-1} FW_{mix}	**1.24** g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Emissions from upgrading

Electricity Demand =	5.34	kWh t^{-1} FW_{mix}	
Emissions =	1.07	kg CO_2 t^{-1} FW_{mix}	**0.64** g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Methane Loss =	0.44	m^3 CH_4 t^{-1} FW_{mix}	
Methane density =	0.71	kg CH_4 m^{-3}	[9]
CH_4 GWP =	25		
Emissions =	7.81	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	**4.64** g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Total emissions from processing

10.96	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	**6.52** g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Emissions from grid transportation

Emissions factor	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	[9]
Methane Yield	1682.55	$MJ_{biomethane}$ t^{-1} FW_{mix}	
Emissions =	**2.05**	kg $CO_{2\text{-eq}}$ t^{-1} FW_{mix}	1.22 g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Equation 1. I_n = Annual input to digester of substrate n [tonne of fresh matter]

$$In = \frac{VS_{n,mix}}{VS_n} / \left(\frac{VS_{1,mix}}{VS_1} + \frac{VS_{2,mix}}{VS_2} \right)$$

[10]

Equation 2. Wn = weighting factor of substrate n defined as:

$$Wn = \frac{I_n}{\sum_1^n I_n}$$

[10]

Equation 3. Sn = Share of feedstock n in energy content

$$Sn = \frac{P_n * W_n}{\sum_1^n P_n * W_n}$$

[10]

Equation 4. E = Actual greenhouse gas emissions in the case of co-digestion of n substrates

$$E = \sum_1^n S_n * \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n} \right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr}$$

[10]

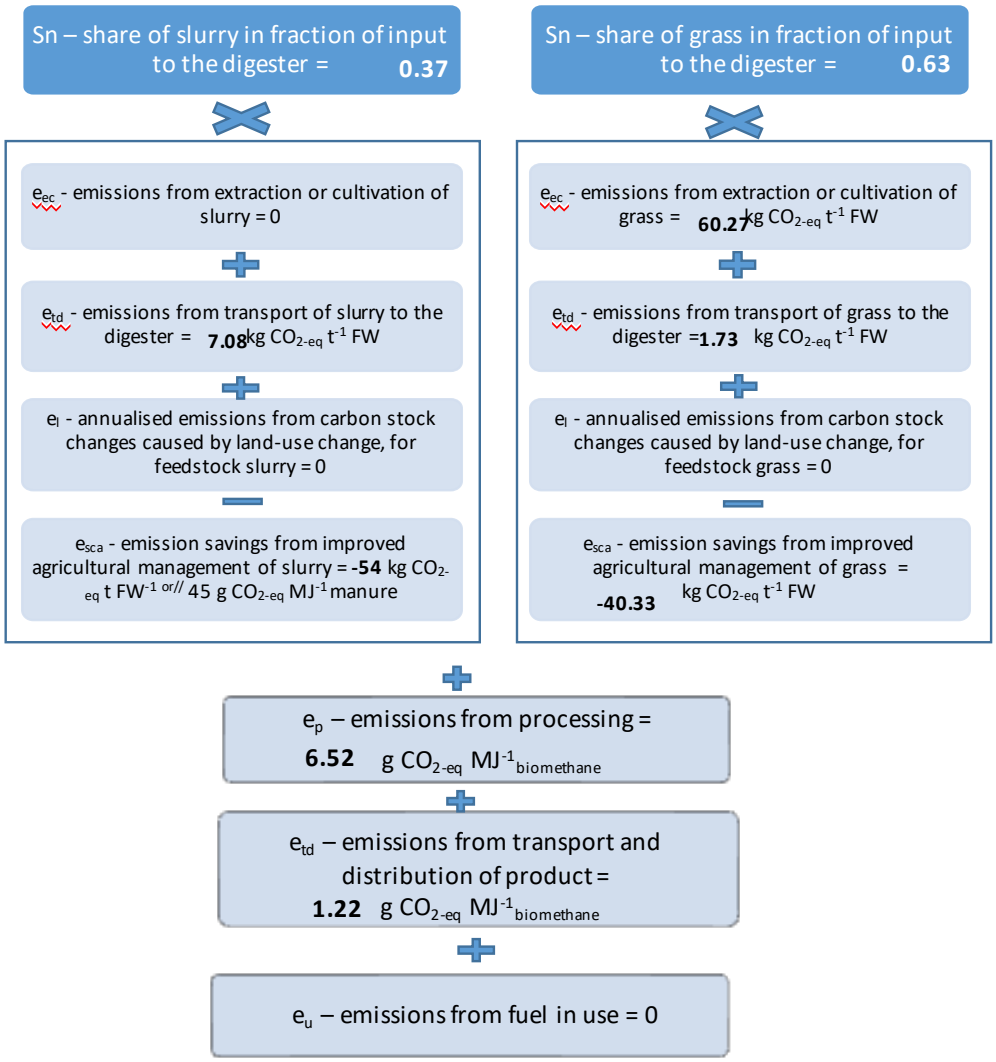
Methane energy value 37.78 MJ/m_n^3 [5]

Parameters for feedstocks

Parameter	Slurry n_1	Grass n_2	Unit	
Volatile solids in mix	500	500	g kg^{-1}	
Dry solids	87.5	292.7	g kg^{-1}	[1]
Volatile solids	66.9	268.4	g kg^{-1}	
Moisture content	912.5	707.3	g kg^{-1}	
Gas production	16	107.4	m^3 CH_4 t^{-1} FW	
P_n - energy yield	0.6	4.06	MJ kg^{-1} FW	
I_n - input to digester	0.8	0.2	t FW_n t^{-1} FW_{mix}	
W_n - weighting factor	0.8	0.2		
S_n - share of energy content	0.37	0.63	Sum =	1

Emissions	Slurry	Grass	
Cultivation (incl N_2O)	0	60.27	kg $CO_{2\text{-eq}}$ t^{-1} FW
Transport to digester	7.08	1.73	kg $CO_{2\text{-eq}}$ t^{-1} FW
Emissions savings	-54	-40.33	kg $CO_{2\text{-eq}}$ t^{-1} FW

Emissions from processing	6.52	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from transport and distribution	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from fuel in use	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$



Energy yield per t FW_{mix}	1682.55	$MJ_{biomethane}$ t^{-1} FW_{mix}
Emissions before processing	-2.20	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from processing	6.52	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from transport and distribution	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Emissions from fuel in use	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$

Sustainability Check	Heat	Transport	
Total Emissions	5.54	5.54	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Conversion to heat @90% efficiency	6.15		g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$
Heat FFC	80	94	g $CO_{2\text{-eq}}$ MJ^{-1}
Emissions saved	92.31%	94%	
Criteria	80%	65%	
	Sustainable for Heat	Sustainable for Transport	

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Emissions from transporting the biomass - from BioGrace calculation tool [Biogas from wet ma

Round trip =	40	km	
Diesel emissions factor	87.64	g $CO_{2\text{-eq}}$ MJ^{-1}	Emissions
Truck for liquids	1.01	MJ $ton.km^{-1}$	7.08 kg CO_2 t^{-1} FW_{slurry}
Manure Energy Yield	10	MJ kg^{-1} DM	
Moisture content	92	%	

Appendix G – Emissions calculations Chapter 5 Selected Scenarios

Table 5-1 Emission Factors – Digest all slurry GS:SI Scenario 50:50 Methane loss = 1% (Scenario 6) – Deep bedding is not included in the table, it is in the overall results – 2017 data – in main manuscript

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	17.63
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	46,692,062	13.12
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	13,073,777	61.22
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.60
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	6,707,443	18.85
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	6,707,443	2.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	6,707,443	3.46
Energy Emissions displaced			
Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-588 -680
Synthetic Fertiliser Displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	-1,265,928	-7.35

Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	-1,265,928	-0.15
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	-1,265,928	-0.65

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

Table G-1 Emission Factors – No change (Scenario 1) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Pit storage			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	264.5
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.002 kg N_2O-N (kg N input)$^{-1}$ [1]	39,984,618	37.45
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	11,195,693	52.43
Slurry applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.01 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	187.24
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.60

Table G-2 Emission Factors – Profitable GS:Sl Scenario 80:20 Methane loss = 0.5% (Scenario 2) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [1] $AWMS_{(T,S,k)}$ = 0.091% Digest all slurry scenarios [2]	n/a	2.87
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	21,354,131	6.00
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	5,979,157	28.00
Pit storage			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [1] $AWMS_{(T,S,k)}$ = 0.189% Digest all slurry scenarios [2]	n/a	178.51
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.002 kg N_2O-N (kg N input)$^{-1}$ [1]	26,985,655	25,273
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	7,555,983	35,83
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	12,998,963	36,523,373
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	12,998,963	5.17
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	12,998,963	6.70
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	8,555,168	23,48
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	8,355,168	3.33
Agricultural Soils Indirect	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	8,355,168	4.3

N_2O – Leaching and runoff			
Slurry applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.01 kg N_2O-N (kg N input)$^{-1}$ [3]	26,985,655	126,37
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	26,985,655	10.74
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	26,985,655	13.9
Energy Emissions displaced			
Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-458 -530
Additional Synthetic Fertiliser			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	2,105,003	12
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	2,105,003	0.25
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	2,105,003	1.08

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

Table G-3 Emission Factors – Profitable GS:Sl Scenario 20:80 Methane loss = 1% (Scenario 8) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			
Manure management CH_4	$MCF_{(S,k)}$ = 1% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	17.63
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	41,661,479	11,71
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	11,665,214	54.62
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.6
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	1,676,861	4.71
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	1,676,861	0.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	1,676,861	0.86
Energy Emissions displaced			

Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-246 -285
Synthetic Fertiliser displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	-3,315,579	-19.25
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	-3,315,579	-0.39
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	-3,315,579	-1.71

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

Table G-4 Emission Factors – Profitable GS:Sl Scenario 50:50 Methane loss = 2% (Scenario 13) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			
Manure management CH_4	$MCF_{(S,k)}$ = 2% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	35.27
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	46,692,062	13.12
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	13,073,777	61.22
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.60
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	6,707,443	18.85
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	6,707,443	2.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	6,707,443	3.46
Energy Emissions displaced			

Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-582 -673
Synthetic Fertiliser displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	-1,265,928	-7.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	-1,265,928	-0.15
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	-1,265,928	-0.65

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

References

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Table G-5 Emission Factors – Profitable GS:Sl Scenario 20:80 Methane loss = 2% (Scenario 15) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			

Manure management CH_4	$MCF_{(S,k)}$ = 2% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	35.27
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	41,661,479	11,71
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	11,665,214	54.63
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.6
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	1,676,861	4.71
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	1,676,861	0.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	1,676,861	0.86
Energy Emissions displaced			
Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-244 -282
Synthetic Fertiliser displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	-3,315,579	-19.25
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	-3,315,579	-0.39
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	-3,315,579	-1.71

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use

Table G-6 Emission Factors – Profitable GS:Sl Scenario 20:80 Methane loss = 3.55% (Scenario 22) – Deep bedding is not included in the table, it is in the overall results – 2017 data

Process	Emission Factors	N input (kg N y^{-1})	Emissions (kt $CO_{2\text{-eq}}$)
Livestock excretions on Pasture			
Manure management CH_4	$MCF_{(S,k)}$ = 0.47% for Pasture [1] $AWMS_{(T,S,k)}$ = 0.70% [2]	n/a	20.73
Agricultural Soils Direct N_2O	$EF_{3,PRP}$ = 0.0086 kg N_2O-N (kg N input)$^{-1}$ [2]	100,032,896	402.86
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	100,032,896	39.82
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	100,032,896	51.53
Anaerobic Digester			

Manure management CH_4	$MCF_{(S,k)}$ = 3.55% [1] $AWMS_{(T,S,k)}$ = 0.2802% Digest all slurry scenarios [2]	n/a	62.6
Manure management Direct N_2O	$EF_{3,(S)}$ = 0.0006 kg N_2O-N (kg N input)$^{-1}$ [1]	41,661,479	11,71
Manure management Indirect N_2O – Volatilised N	$Frac_{GasMS}$ = 0.28 EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [1]	11,665,214	54,62
Manure digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	39,984,618	112.35
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	39,984,618	15.92
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	39,984,618	20.6
Grass digestate applied to land			
Agricultural Soils Direct N_2O	EF_1 = 0.006 kg N_2O-N (kg N input)$^{-1}$ [3]	1,676,861	4.71
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASM}$ = 0.085 kg N volatilised (kg of N applied or deposited)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	1,676,861	0.67
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	1,676,861	0.86
Energy Emissions displaced			
Fuel displaced CO_2	Thermal Energy: Natural Gas – EF = 55.74 CO_2 TJ^{-1} [4] Transport Energy: Diesel/ Gas Oil* – EF = 73.3 CO_2 TJ^{-1} [4] Fuel consumption factor relative to diesel for transport = 114% [5]		-240 -278
Synthetic Fertiliser displaced			
Agricultural Soils Direct N_2O	EF_1 = 0.0124 kg N_2O-N (kg N input)$^{-1}$ [1]	-3,315,579	-19.25
Agricultural Soils Indirect N_2O – Volatilised N	$Frac_{GASF}$ = 0.025 kg N volatilised (kg of N applied)$^{-1}$ [3] EF_4 = 0.01 kg N-N_2O (kg NH_3-N + NO_x-N volatilised)$^{-1}$ [3]	-3,315,579	-0.39
Agricultural Soils Indirect N_2O – Leaching and runoff	$Frac_{LEACH(H)}$ = 0.1 kg N (kg of N additions)$^{-1}$ [3] EF_5 = 0.011 kg N_2O-N (kg N leached and runoff)$^{-1}$ [3]	-3,315,579	-1.71

* Fuel consumption relative to diesel = 114% for Transport end use and not applicable for heat end use