Farm Level Economic, Environmental and Transport modelling of alternative feedstock solutions for regional anaerobic digestion plants in Ireland (FLEET)

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End of Project Report

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List of Acronyms

AD	Anaerobic Digestion
C	Carbon
CB	Carbon Budget
CCAC	Climate Change Advisory Council
CH_4	Methane
CHP	Combined Heat and Power
CO_2 eq	Carbon Dixoide Equivalent
CSO	Central Statistics Office
DAFM	Department of Agriculture, Food and the Marine
DCF	Discounted Cash Flow
DM	Dry Matter
ETS	Emissions Trading Scheme
EPA	Environmental Protection Agency
EU	European Union
FAPRI	Food and Agriculture Policy Research Institute
FiT	Feed In Tariff
FLEET	Farm Level Economic, Environmental and Transport
FYM	Farm Yard Manure
g	gram
GAP	Good Agricultural Practices for the Protection of Water
GHG	Greenhouse Gas
GIS	Geographical Information System
GFCM	Grange Feed Cost Model
ha	hectare
IPCC	Intergovernmental Panel on Climate Change

K	Phosphorous
KWh	Kilowatt Hour
LCA	Lifecycle Analysis
LESS	Low Emission Slurry Spreading
m	million
MSS	Multi Species Sward
MJ	Megajoule
N	Nitrogen
NFS	National Farm Survey
NH_3	Ammonia
N_20	Nitrous Oxide
NOC	Nutrient Opportunity Cost
NUE	Nitrogen Use Efficiency
P	Potassium
PRG	Perennial Rye Grass
PRG-RC	Perennial Rye Grass Red Clover
OII	Output Input and Income
REFIT	Renewal able Energy Feed In Tariff
RED	Renewable Energy Directive
t	tonne
TWh	TerraWatt Hour
UAA	Utilisable Agricultural Area

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Executive Summary

Background

- FLEET, **F**arm **l**evel **e**conomic, **e**nvironmental and **t**ransport modelling of alternative feedstocks for regional Anaerobic Digestion, is a project co-ordinated by Teagasc and funded by the Sustainable Energy Authority of Ireland (SEAI) and Gas Networks Ireland (GNI). The project has made extensive use of the Teagasc National Farm Survey (NFS) to assess the feasibility of the export of feedstock from farms to support biomethane generation through Anaerobic Digestion (AD).
- AD is a process involving the microbial decomposition of organic matter into biogas and digestate in the absence of oxygen. The organic matter required is typically sourced from agriculture and food production. It is used to produce biogas, while digestate, which is produced as a byproduct, is a nutrient rich fertiliser which can be returned and spread on agricultural lands completing the cycling of nutrients.
- Biogas is the main product of the AD process, which is mainly made up of methane and carbon dioxide which can be stored and used as a fuel, typically in either a combined heat and power (CHP) plant or upgraded to biomethane. Biomethane can be used as a transportation fuel or can be injected into the national gas grid for use across the country.

Objective of the Research

- In relation to the objectives of the SEAI RD&D programme, the FLEET prooject addresses objectives 1 and 4 specifically of the programme. Objective 1, which relates to 'the development and deployment in the Irish marketplace of competitive energy-related products, processes and systems', is addressed in the project by farm scale economic and environmental consequences of alternative feedstock solutions for regional AD supply. Objective 4 of the programme identifies the need 'for guidance and support to policy makers', which is clearly addressed by the FLEET work packages, which identify economic and environmental implications at a farm and national level. .

Research Approach

- The **literature review** conducted as part of the project provided an overview of the literature relating to the policy, economic, environmental and innovation barriers relating to the project objectives.
- The **microeconomic modelling** and **environmental modelling** carried out in the project used micro data from the Teagasc National Farm Survey (NFS). The Teagasc NFS is a stratified random sample of approximately 900 farms selected annually in conjunction with the Central Statistics Office (CSO). Each farm is assigned a weighting factor so that the results of the survey are representative of the national population of farms. Farms are

assigned into one of six farm systems on the basis of the dominant enterprise on the farm. The main systems of production represented in the survey are: dairying, cattle rearing, cattle other, sheep, tillage and mixed livestock.

- The Teagasc NFS collects a variety of economic and technical data across the farms and farm systems. While some sectors, such as dairying, exhibit consistently strong economic performance, other sectors are more economically vulnerable. The economic viability of some enterprises is low, thus a rationale exists for examining alternative enterprises which complement or replace existing systems.
- **Transport modelling:** The project examined the geographic structure underlying the sources of biomass products and manures using location-allocation modelling in a Geographic Information Systems (GIS) technology framework. High resolution spatial datasets including individual farm parcel information from the Land Parcel Identification System (LPIS) and a spatially detailed roads dataset from Tailte Eireann were used in the analysis.
- **Aggregate impact assessment modelling,** carried out as part of this project, used the FAPRI-Ireland model, which was developed under the auspices of the FAPRI Ireland Partnership, a joint venture between Teagasc and the Food and Agriculture Policy Institute (FAPRI) in the USA. The overall model is comprised of a set of individual econometrically estimated agricultural commodity models e.g. beef, dairy, sheep pigs and crops that are linked and solved simultaneously under different policy scenarios.

Farm Level Economic Feasibility Assessment

- **Economic sustainability at farm level:** An existing data gap relating to the economic case for the production of silage for Anaerobic Digestion (AD) in Ireland, was addressed by an analysis of the potential costs and returns at farm level, of supplying silage as a feedstock for a regional AD facility. This analysis used farm level survey data from the Teagasc National Farm Survey (NFS) for a perennial ryegrass sward (PRG), coupled with farm management data for a modelled crop of perennial ryegrass and red clover (PRG-RC) sward. Feedstock costs and returns were derived using a Discounted Cash Flow (DCF) analysis based on the production of silage for an off-farm AD facility. The analysis was based on farm level data for the period 2018-2020. Whilst there has been significant volatility in cost and output prices in the intervening years, the methodology for establishing competitiveness of feedstock supply has been established and will be updated in future research.
- **Economic sustainability at the farm level:** Economic analysis has shown that excluding the capital cost of land and silage storage facilities, while including the nutrient opportunity costs, the new enterprise of supplying silage to an AD plant could be competitive with existing farm enterprises such as specialist cattle rearing, specialist cattle other and specialist sheep when the price of silage is above €35 per tonne. However,

during the 2018-2020 time period, traded silage prices of €30 per tonne were recorded and these would be below the average cost of silage production.

- **Willingness to supply agricultural feedstocks:** The Teagasc NFS was used to determine farmers' willingness to engage in feedstock supply for an AD facility. The results indicated that farmers would be willing to supply a total weighted silage area of approximately 420,000 acres (175,000 hectares). The total amount of grassland area that is needed to reach the biomethane target of 5.7 TWh is estimated to be in the range of 110,000 to 130,000 ha, outlined in further detail in the aggregate sector level modelling conducted.

Environmental Sustainability Impact Assessment

- **GHG emissions:** The scenarios that involved replacing current actively levels with supplying grass as a feed stocking indicate between a 50-98% reduction in GHG emissions depending on the farm system and scenario examined on a stylised per hectare basis. These reductions are primarily driven by the removal of livestock from the activity levels per hectare under the different scenarios analysed, which eliminates all Enteric Fermentation (CH4), and manure management (CH4 & N2O) based emissions. Scenarios where biological N is the main supply for crop growth show the largest reductions in GHG emissions.
- **GHG emissions:** The scenarios that involved slurry being used as a feedstock resulted in emission reductions which were significantly less than the grass feedstock scenarios. This was because the livestock were assumed to remain on the farm and only slurry based emissions were excluded, hence this excluded emissions around the storage and land spreading of slurry. Results indicate between a 6.5-11.6% reduction in GHG emission depending on the scenarios and farm system type. The scenarios with biological N replacing slurry indicates the highest level of reduction followed by protected urea, then digestate.
- **NH_3 emissions:** The NH_3 emissions reductions varied by scenarios and systems when compared to the baseline. The greatest NH_3 emissions reductions were evident when N was provided entirely by biological N, which eliminates NH_3 emissions entirely. The scenarios with higher levels of digestate usage tended to have a negative impact on NH_3 emissions in some sectors due to higher NH_3 emissions associated with digestate.
- **NH3 emissions:** In the scenarios where slurry was used as a feedstock, the NH3 emission reductions were significant, between 58-78% depending on the scenario and farm system. All livestock manure housing, storage and land spreading emissions are assumed to be avoided in these scenarios, with just emissions associated with the land spreading of protected urea or digestate application remaining.

Transport Assessment

- **'Middle optimistic scenario':** The transport GIS modelling conducted shows that in the 'middle optimistic' (surplus grass) scenario, the National Biomethane Strategy target of 140 40 GWh plants could be relatively easily accommodated spatially, and with feedstocks supplying these plants largely coming from within a 10 km along road travelled distance.
- **'Pessimistic scenario':** The transport GIS modelling conducted shows that in the 'pessimistic' scenario with 15% of grass being made available, at farm level, suggests that travel distance must increase on average to 15 km and potentially greater. This would obviously have a negative economic and environmental impact.

Aggregate Economic and Environmental Impact Assessment

- The development of an AD industry that uses grass DM and animal slurries to achieve that national biomethane target of 5.7 TWh by 2030 is projected to lead to an increase in agricultural sector income and a decrease in agriculture sector GHG emissions relative to a baseline where the use of grass and slurry feedstocks for AD does not occur.
- The increase in sectoral income arises because the loss in cattle output value associated with the diversion of pastureland from bovine agriculture to use in AD is more than offset by savings in input expenditure associated with bovine agriculture (animal feed, fertiliser and veterinary services) and additional output value associated with the sale of grass dry matter to the AD industry.
- By 2030 agricultural sector income, where the AD industry meets that national Biomethane target by using grass dry matter and animal slurry as feedstocks, is projected to be between 1.2% and 1.3% higher (€49 - €53m) than under the Baseline. This is equivalent to an income of circa €425 per ha for land used for AD.
- The projected changes to agricultural activity levels, input usage and the diversion of animal slurries from use as nutrients in agriculture to use as feedstocks in AD is also reflected in reduced agricultural GHG emissions. By 2030 agricultural GHG emissions are projected to be 2.3% lower than under the baseline. Methane emissions are projected to decline by 1.8% and nitrous oxide emissions by 4% relative to the baseline by 2030.
- There is a trade-off between AD and beef production: While farm incomes rise, reduced cattle output may impact meat processing and related industries, though AD development creates new economic opportunities in biomethane production and infrastructure.

Next Steps

- While the economic and environmental sustainability of silage production for AD purposes was examined as part of the FLEET project, there is an ongoing need to update the analysis relating to the competitiveness of feedstock supply versus conventional farm production systems, in a changing agricultural and energy market environment.

Furthermore, the feedstocks examined as part of FLEET were limited to grass silage and slurry. With the publication of the Biomethane Strategy and the Biomethane Capital Grant announced in 2024, there is growing interest in a potentially wider range of feedstock supply and business models, not limited to the feedstocks and business model examined as part of FLEET. Hence, next steps in the research would benefit from an updated range of feedstock sustainability and business model assessment, from an economic, environmental, transport and aggregate sector modelling perspective.

1 Introduction

1.1 Context

Various European Union (EU) and Irish policy documents identify a role for bioenergy as a means to reduce greenhouse gas (GHG) emissions from agriculture and energy production in Ireland. Ireland's Climate Action Plan has several sectoral targets for emissions reductions by 2030, including: 50% in the transport sector; 35% in industry; and 25% in agriculture relative to the 2018 level. Ireland's Climate Action Plan also increased the target for Anaerobic Digestion (AD) to 5.7 terawatt-hours (TWh) of biomethane, recognising the role AD can play in reducing emissions and creating a circular bioeconomy. This 5.7 TWh target is equivalent to approximately 10% of the current natural gas usage in Ireland. A first key step to delivering on this ambitious target is the publication of the National Biomethane Strategy (DAFM, 2024). The National Biomethane Strategy sets out the necessary policy and regulatory measures, and provides a roadmap, to developing a biomethane industry at scale in Ireland.

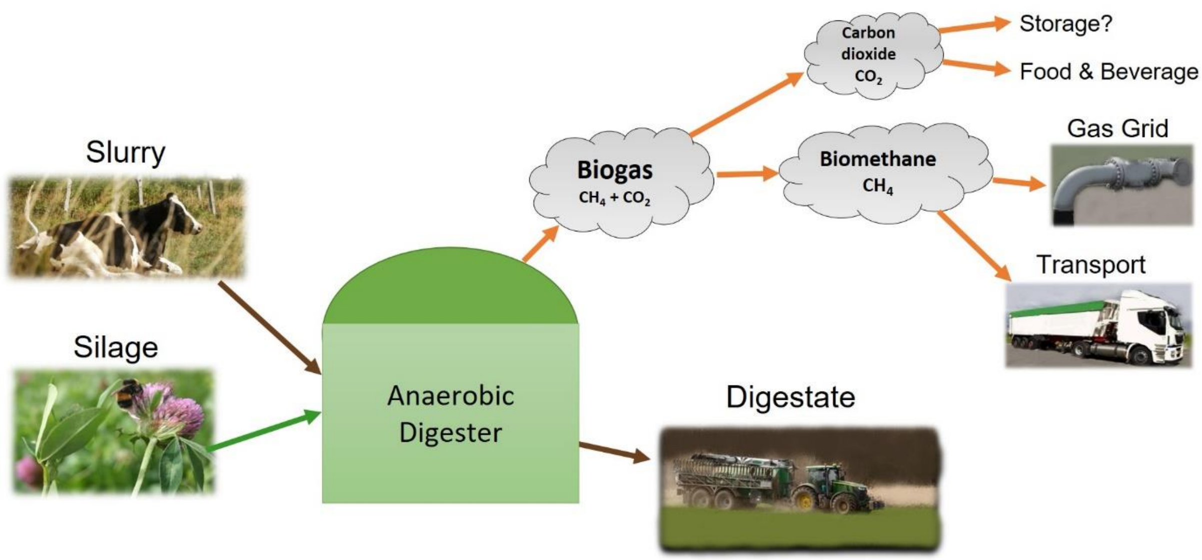
The EU has set a target of developing a net-zero carbon economy by 2050, as outlined in the European Green Deal, along with ambitious goals in the Farm to Fork strategy (Montanarella & Panagos, 2021). The Farm to Fork strategy targets a 50% reduction in pesticide use and nutrient losses from soils and a reduction in synthetic fertiliser usage by at least 20% by 2030 (Montanarella & Panagos, 2021). AD is specifically mentioned in the Farm to Fork strategy as part of the circular bio economy, as an opportunity for both farmers and cooperatives to digest waste and residues to produce renewable energy, while reducing methane emissions. (European Commission, 2020).

To date in Ireland the development of the AD sector has been slow by comparison to other European countries. A combination of complex planning and licensing issues, grid connection costs, unattractive electricity tariffs, financing issues and uncertainty in waste policy, have led to low levels of AD plant construction and operation in Ireland (Leonard, 2017). AD plants generally require policy and regulatory support to compete with fossil fuels (Auer et al., 2017), while currently the majority of the renewable energy generated in Ireland is from wind energy, which suffers from intermittency due to prevailing weather.

AD is covered by the EU Renewable Energy Directive (RED) II (European Parliament, 2018) which sets targets for renewable energy sources consumption of 32% EU-wide by 2030. RED II sets limits for the quantity of GHG emissions offset by the generation of renewable fuels from 65% for transportation fuels to 80% for electricity heating and cooling from 2026.

There is a need to increase our understanding of both the economic and environmental benefits of AD and biomethane. Specifically, this requires an assessment of their contribution to the economic sustainability of farming in Ireland, and their capacity to support the achievement of GHG reduction targets. This study focuses solely on agricultural based feedstocks for AD. While other waste feedstocks are available, such as food waste, these 'waste' resources are finite in terms of achieving national targets (SEAI, 2022). The energy pathway being explored, as shown in Figure 1, is to operate AD plants off-farm and upgrade the biogas that is derived to create biomethane. This energy pathway allows the use of biomethane within Ireland's existing natural gas grid. It would also allow the use of biomethane within the transport sector, which is a particularly difficult sector to decarbonise, especially in the case of heavy goods vehicles.

Figure 1: Agricultural based AD and Biomethane



The two major agricultural feedstocks considered in this report are silage and animal slurries. Animal slurries have a low energy density, however when used in AD they have the potential to contribute to GHG emissions reductions, with an associated manure credit within RED II (European Parliament, 2018)(European Parliament, 2018). Grass silage has a far greater biomethane potential compared to animal slurries. Grass can provide between seven and ten times the energy density of animal slurries Auer et al., 2017; Wall et al., 2013). The use of grass silage for AD is considered an advanced biofuel (fuel made from non-food biomass) in RED II, which, when used in transport, is considered to have twice its energy content in terms of achieving targets. Full details are provided in Part A of Annex IX of RED II Directive (European Parliament, 2018).

To date few comprehensive appraisals of the potential economic and environmental viability of producing farm based feedstocks for AD purposes compared to existing enterprises have been carried out using Irish farm data. This study seeks to address s the information deficit. The research was carried out during the period 2020 to 2024.

The remainder of this chapter is organised as follows: Section 1.2 outlines the specific objectives of the project, 1.3 describes the materials and methods employed, and 1.4 contains an outline of the structure of the remainder of the report.

1.2 Objectives:

- Review existing literature on AD economic and environmental sustainability at farm and national level;
- Develop farm models to examine the economic sustainability of alternative farm based feed stock solutions for regional AD plants;
- Develop farm models to examine the environmental sustainability of alternative farm based feed stock solutions for regional AD plants;
- Develop transport models at a landscape level to provide a spatial analysis of the key locations of enterprises with biomass and manure production and their relative proximity to target users;
- Carry out an impact assessment of alternative economic and environmental scenarios previously assessed at the farm level;
- Plan and carry out outreach and stakeholder information activities.

1.3 Methodology

According to the typology of agricultural models outlined by Flichman and Allen (2014), there are three distinct levels at which bio-economic modelling can take place: farm level, landscape level and regional/national level. According to this typology the modelling exercises carried out in this research pertains to each of the three levels identified by Flichman and Allen (op cit.): farm level economic and environmental sustainability modelling; landscape level GIS transport modelling and national level modelling of farm level economic and environmental outcomes.

Following the aforementioned typology, there are four main areas of empirical analysis carried out in this research: farm level economic modelling, farm level sustainability modelling, GIS transport modelling and aggregate impact input/output modelling.

Farm level economic modelling carried out in this report used a mathematical programming approach, following an optimisation objective function. The approach involves first developing a baseline system model, which represents how the baseline system of interest works. This is followed by the use of the model in the provision of an ex ante impact assessment scenario, by determining the impact of changes in certain input criteria such as prices, subsidies, policy variables. The research methods used were similar to those previously employed using Teagasc National Farm Survey (NFS) data (which is part of the EU Farm Accountancy Data Network) by Clancy et al. (2011) and by Hennessy et al. (2007).

Environmental sustainability modelling carried out in this research uses detailed activity data available from the Teagasc NFS to examine detailed cropping patterns and organic manures volumes generated and stored at farm level to examine the cost effectiveness, from an environmental emission perspective, of supplying crops and manures as feedstocks to an

Anaerobic Digestor plant. The research builds on previous work in this area by Dillon et al. (2016) and Buckley et al. (2016a, 2016b), which examined gaseous emissions and nutrient use efficiency indicators at farm scale across Ireland.

Transport modelling carried out as part of this project examines the geographic structure underlying the sources of biomass products and manures using Geographic Information Systems (GIS) technology and location-allocation modelling. Fealy and Schroeder (2008) deployed highly spatially resolved geographic location data to provide a national assessment of pig manure transport distances analysed at near-farm scale. GIS has been used recently in other locations to examine location optimisation for biogas plant locations, but these are generally focussed on smaller, more local regions (Akca et al., 2023; Ferrari et al., 2022). In contrast, we have provided a full national analysis of the real, along-road network distances between modelled AD plant locations relative to their optimised potential feedstock locations.

This project has offered a significant opportunity to further leverage and refine previous significant national research through the application of new techniques in a GIS framework. These deliver an updated national source-target assessment method for relevant biomass products and organic manures. The methodology can be applied (and expanded) to provide additional refinement of the transport cost analysis component of AD plant location planning, both at individual plant level and as applied to the strategic development of the distributed country-wide network of AD facilities envisaged by national policy.

Aggregate Impact Assessment modelling, carried out as part of this project, used the FAPRI-Ireland model, which was developed under the auspices of the FAPRI Ireland Partnership, a joint venture between Teagasc and the Food and Agriculture Policy Institute (FAPRI) in the USA. The overall model is comprised of a set of individual econometrically estimated agricultural commodity models e.g. beef, dairy, sheep pigs and crops that are linked and solved simultaneously under different policy scenarios (Hanrahan, 2001).

Typically the model is used to analyse the impact of policy changes versus a Baseline (Business as usual) over a ten-year projection horizon. The model has a specific environmental component which can be used to project national level GHG emissions in a manner consistent with the Inter-governmental Panel on Climate Change (IPCC) national inventory reporting methodology. Previously the model has been used in collaborative work with colleagues working on energy modelling at UCC (Chiodi et al., 2016).

1.4 Report Structure

The remainder of this report is structured as follows:

- Chapter 2 provides background context to the research questions, including key literature and policy insights, relevant to the research questions.
- Chapter 3 provides the results from the economic sustainability farm level modelling of alternative feedstock solutions for a regional AD plant.

- Chapter 4 provides the results from the environmental sustainability farm level modelling of alternative feedstock solutions for a regional AD plant.
- Chapter 5 provides the results from the transport modelling of alternative feedstock solutions for a regional AD plant.
- Chapter 6 provides the results for the aggregate impact assessment of alternative feedstock solutions for a regional AD plant.
- Chapter 7 provides the main conclusions and implications of the research carried out.

2 Background

This chapter of the report outlines the findings from a comprehensive review of literature which focused on identifying (i) appropriate background material pertaining to the research question relating to motivation for the research, agronomic considerations and the policy landscape (ii) implementation strategies nationally and internationally and (iii) specific literature related to sustainability of AD at farm and landscape level.

2.1 Contribution of Agriculture to the Economy and GHG Emissions

The agricultural sector has traditionally been a very important primary producing sector within the Irish economy. In 2019, the exports of agricultural based products accounted for €14.5 billion, with 7.1% of the workforce employed in agri-food sector (DAFM, 2021).

Addressing climate change and the loss of biodiversity is increasingly been regarded as a high priority policy objective. While farms are economic operations providing economic return there are also wider benefits to society in the form of eco system services. The ecosystem services regulate soil and water quality, carbon sequestration, support biodiversity and cultural services (Power, 2010).

Across the EU, there is a policy shift towards the production of food in a way that reduces the impact on the environment. One means to do this is target reductions in synthetic fertilisers and crop protection use and an increase in organic farming targets. These can be seen in policies such as ‘European Green Deal’, ‘Farm to Fork’ Strategy and ‘Ag Climatise’ which have set targets for 2030 and 2050. The key goal for 2050 is for net zero emissions. While agriculture provides significant economic benefit to the wider economy, there are also effects of agriculture on the environment.

Agriculture in Ireland was responsible for 32% GHG of the countries emissions in 2019 while the equivalent figure for agriculture across the 27 member states of the EU 27 is 10% of total GHG emissions (Eurostat, 2021). The comparatively large proportion which agriculture contributes to Irish GHG emissions can partially be attributed to the relatively small size of other sectors such as the industrial sector which emits 11% GHG emissions in Ireland compared to the EU 27 average of 21% (Eurostat, 2021). Another reason is Ireland’s strong focus on grassland agriculture, which results in Ireland having a comparatively large ruminant agriculture sector relative to its human population.

When comparing agriculture sectors across the EU, Ireland has the highest percentage of land area under agriculture across the EU at 71%, with 90% of this area in permanent grassland. While this area represents 2.8% of the agricultural area within the EU, the national bovine herd is 8.5% of the European herd, with predominance of pasture based systems (Eurostat, 2021). GHG emissions per hectare in Ireland is outside the upper quartile of European countries, with a larger proportion of carbon dioxide equivalence attributed to methane than nitrous oxide (Eurostat, 2021).

The methodology used to calculate these GHG emissions is very important The current IPCC methodology for agriculture does not include the GHG emissions from the manufacturing of synthetic nitrogen fertilisers while a Lifecycle Assessment (LCA) approach does.

The emissions or sequestration from land use change is not defined to be part of agriculture in the IPCCGHG emissions accounting process. Ireland has taken the decision to continue to use the Kyoto Protocol when calculating its agricultural GHG emissions, which focuses only on reducing GHG emissions, accounting only for above ground emissions savings. On the other hand the Paris Agreement accounts for carbon above and below ground. Other EU member states, such as France, have adopted the Paris Agreement and farms are now generating carbon credits from soil carbon levels. Importantly companies such as large dairy processors operate within the Emissions Trading Scheme (ETS) and as such are aligned to the Paris Agreement, and must take the LCA approach also thus accounting for the GHG emissions of synthetic nitrogen fertilisers and also potentially the carbon content of the soil.

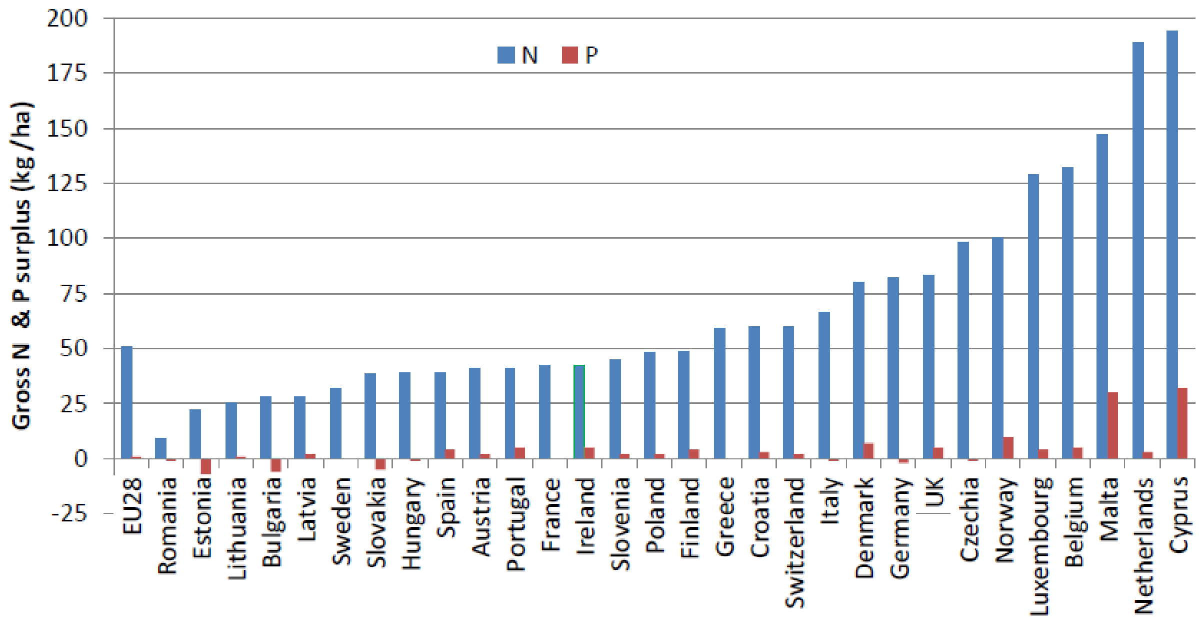
Fertiliser

One of the major innovations of the green revolution was the use of the Haber Bosch process to increase availability of synthetic nitrogen as a fertiliser. Together with innovations such as Norman Borlaug's dwarf grain varieties, these innovations allowed for substantial increases in the productivity of agriculture. The application of nitrogen fertiliser coincided with an increase in wheat yields (Hawkesford, 2014). When these innovations occurred there was no awareness of GHG emissions, nitrate pollution or loss of soil carbon within farmland (Nkoa, 2014).

The use of nitrogen has greatly increased the total output of agricultural products (Foy et al., 2022), which has come with a reduction in nitrogen use efficiency. While nitrogen is a key driver of farm productivity, it also has a detrimental environmental effect in the form of nitrous oxide emissions, which has a global warming potential equal to 296 times that of carbon dioxide. The application rate and timing has an effect on nitrous oxide emissions from nitrogen fertiliser, in particular, rates of fertiliser application exceeding crop requirements lead to nitrogen surpluses which reduces nitrogen use efficiency (NUE) and increases losses to the environment.

NUE is different across sectors, with the tillage sector having the highest NUE of 68%. The average NUE in Ireland was at 26.6% in 2019 (Buckley and Donnellan, 2020). In the wider EU context, an often used indicator of use efficiency is the gross nitrogen and phosphorus balance, shown in Figure 2, which estimates the potential nitrogen and phosphorus surplus on agricultural land. These gross balances are used as an indicator of the intensity of agriculture and potential risk to the environment. However, this relationship hasn't always held true, which reflects the important contribution of climate and changes in weather, farm practice and policy drivers.

Figure 2: Nitrogen (N) and phosphorus (P) surplus for EU countries in 2015



Source: Eurostat, 2019

Ruminants – Enteric Fermentation

A major contributor to agricultural GHG emissions in Ireland is the methane emissions of ruminant animals, in particular cattle. Methane is produced in the rumen of animals, also called enteric fermentation. Methanogens are micro-organisms which are responsible for the creation of methane within the rumen of the cow. Control mechanisms or strategies have been investigated to varying degrees of success such as; improved forage quality, use of nutritional supplements, genetic selection, soil methanotrophy and vaccination of cattle against methanogens (Thompson and Rowntree, 2020). These strategies generally try to effect the methanogens within the cow.

When animals are housed these methanogens are present in the slurry and can continue to create methane. In Ireland ruminants are typically housed for a period of 16-22 weeks during the winter. This period of housing creates slurry which is typically stored in underground tanks below slatted housing. The formation of methane (methanogensis) occurs in stored slurry with variable emission rates. It is estimated that between 20% to50% of the methane potential of the slurry can be emitted in storage prior to weather conditions becoming suitable for the application of slurry to land (Agostini et al., 2015). Further emissions occur when the slurry is spread on land. The use of AD to generate biogas (or biomethane) from animal slurry is a strategy to capture the methane which would otherwise be emitted and thus reduces the GHG emissions from ruminants.

Soil

Storage of carbon in soils is an important part of the carbon cycle, together with the oceans they are the two largest sinks for carbon terrestrially. While agriculture is a source of GHG emissions, it also has the capacity to remove carbon from the atmosphere and sequester it in the soil (McCabe, 2020). The Kyoto Protocol (2005-2020) focused on reducing above-ground GHG emissions savings and did not account for soil carbon storage within an existing land use. Soil emissions are complex and varied, some soils are net absorbers of carbon and methane while some emit depending on temperature, moisture, amongst many other factors. In an Irish context mineral soils are considered net absorbers of GHG while organic soils are associated with net emissions of GHG.

A major element of carbon sequestration in soils is the cycle between photosynthesis, typically being the carbon sink, while respiration of the soil releases the carbon back to the atmosphere. Thus there is a carbon cycle as opposed to a rigid store which is effected by management practices, weather and soil conditions. The main pathway to carbon sequestration in soil is by maximising photosynthesis to maintain and increase the flow of carbon into soil (Janzen, 2015).

2.2 Anaerobic Digestion as a Technology

Anaerobic Digestion is a mature technology which has generated interest during global events such as WWII and the 1970's energy crisis when there were energy shortages (Auer et al., 2017). Indeed in the developing world, when limited sources of firewood are available, AD has been prominent in supplying cooking fuel (Appels et al., 2011). Since the turn of the century, AD has come to some prominence with increasing environmental regulations and the move towards sustainable energy.

The focus of this report will be medium to large scale AD plants. However, it is important that regardless of scale, AD is considered to have mainly positive impacts on the environment and the same principles apply (Auer et al., 2017).

Non-farm feedstocks

While non-farm feedstocks are outside of the scope of this study, non farm based feedstocks are the majority of feedstocks used in current installations of anaerobic digestion in Ireland. (DAFM, 2024).

Anaerobic digestion can be used to treat industrial wastes with high organic content, such as dairy industry and sewage sludge. Currently, approximately half of the operating AD plants in Ireland operate on sewage sludge. The digestate from sewage sludge is not currently permitted on Bord Bia quality assured farms due to potential for transfer of pathogens or chemicals. Compared to the aerobic decomposition of these wastes, AD is less energy intensive, however, it has a longer residency time typically of the order of 30 days.

Food waste is a highly productive and economic fuel for anaerobic digestion, which is an important part of the circular bio-economy principle, returning nutrients that originated in agricultural soils, while generating renewable energy. Crucially, this is a feedstock stream which commands a gate fee (charges imposed by the operators of the AD facility on waste accepted for disposal at their facilities) and currently a number of operational anaerobic digestors within Ireland operate in part based on this feedstock.

Farm based feedstocks

The FLEET project is targeted at investigating farm based feedstocks, which are manures, residues and energy crops. Agricultural AD can reduce the GHG emissions from manure management and can generate renewable energy. Combined with the potential for increased photosynthesis with catch crops and increased soil organic matter from practices of conservation agriculture, some literature suggests that these feedstocks can result in negative emissions as part of a circular bio-economy (McCabe, 2015).

Organic wastes: animal manures

Animal manures generate methane, particularly when stored in the open (Moller et all., 2004), so anaerobic digestion captures the methane, which would otherwise be released into the atmosphere, to generate renewable gas.

Typical agricultural production systems across Ireland are based on animals, which require a minimum storage of manures during winter months of 18-22 weeks. Manures can be in solid form, known as farm yard manure (FYM) when animals are on a bedding system, typically straw bedding for younger animals (0-1 years). The largest proportion of manures is in liquid form of slurry stored in underground tanks in slatted houses (Buckley et al., 2020). Methanogenic organisms then generate methane from the slurries which is emitted during storage and on land spreading (Nolan et al., 2020).

Slurries pose a risk to both farmers and the environment. The Health and Safety Authority reports that, in the period of 2011-2020,10% of farm accidents were associated with drowning/gas, of which 43% were associated with slurry and agitation of slurry. Moreover, the improper land application of slurries can lead to a reduction in water quality, particularly nitrates (Nolan et al., 2021).

Slurries are generated when animals are housed during winter when land is generally saturated and grass growth rates are at the lowest. Effective management of manure require storage from the point when the slurries are generated to when it is suitable to apply it to soil. The rules surrounding slurry storage capacity, application of inorganic and organic fertilisers and livestock stocking densities are covered by the Good Agricultural Practice for Protection of Waters (GAP) Regulations (Government of Ireland, 2018).

Buckley et al., (2020) found that the three year average housing period, from 2016-2018, for dairy cows and bulls was 121 days, while other livestock were housed between 147 to150 days. Animal manures and slurries are considered as an ideal substrate to commission and maintain the stability of the AD process (FNR, 2013). This is due to the methanogenic bacteria already present in slurry from the rumen of animals. However, the yield of biogas from animal slurry is not as high as that obtained from other feedstocks, such as energy crops, which can yield almost seven times more biogas on a weight basis (Wall et al., 2013). An important consideration is that when using liquid in AD plants there is a limit to the liquid/total solid ratio. Thus, energy crops require a substrate, with slurry often a preferred substrate to balance total solids.

Bedding systems are still prevalent, straw bedding is particularly used in Ireland when calving cows and this generates a more solid manure known as farm yard manure (FYM). Typically FYM is composted which generates elevated temperatures which breaks down the liable carbon and generates methane. The carbon remaining in compost is recalcitrant, which is stable over the long term within soil. FYM can be anaerobically digested once the material particle size has been reduced by shredding, pulping or macerating (Ricardo Energy & Environment, 2020).

Crop residues

The main residues are straw, leaves from beet production and other waste material from vegetable production. Under the European Renewable Energy Directive these are considered an agricultural waste. Woody biomass is not suitable for the AD process due to its high lignin content. Crop residues require pre-processing, such as shredding, pulping or macerating and might be most suitable for solid digestion.

Biorefining of crops such as grass is a concept to extract the high value chemicals such as fructolicosaccarides, proteins suitable for monogastrics and high fibre feed for cattle. The residue from this process can be used in an AD process, while the high value constituents can be used in higher value chains. This system has the potential to provide energy as well as protein, which can be fed to monogastrics, such as pigs, offsetting the demand for imported soya.

Energy crops

Energy crops can also be anaerobically digested to generate methane. These produce a higher yield than animal manures due to higher energy density (Wall et al., 2013). This makes anaerobic digestion plants more efficient in terms of biogas yields and profitability (Himanshu, 2019).

The drawback of energy crops is that the land used to grow them could be used in food production. There is an increasing emphasis on tension between producing food or energy, particularly since 2007/2008 when along with other factors there was a large spike in the price of food, following on from a sharp rise in fossil energy prices.

Farming and food production is dependent on weather conditions. With increasing uncertainty in weather systems, there is increasing uncertainty regarding forage availability each year. In

2018, Ireland experienced a wet spring followed by a drought in summer, which led to a fodder shortage in the following winter period (Beausang et al., 2021). With the push to increase efficiency this leads to smaller fodder surpluses. AD plants based on silage as a feedstock could provide a buffer feedstock for animals in event of a shortfall in silage from periods of drought (RGFI, 2019). These energy crops for AD could facilitate more efficient farm systems with buffers for extreme weather events.

Digestate

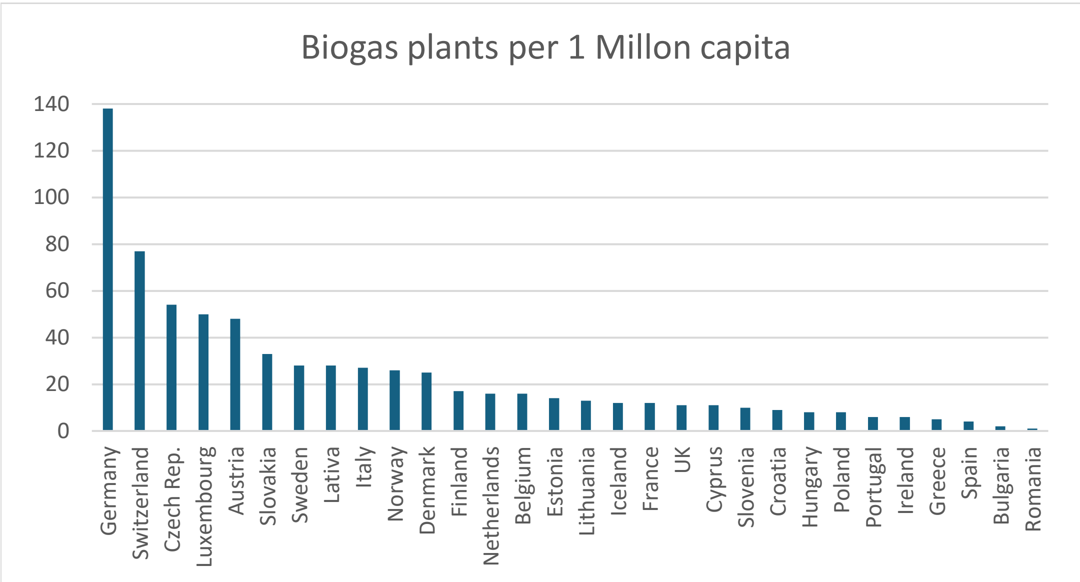
Digestate is the by-product of the anaerobic digestion process, it is typically a liquid material which is spread on agricultural land as a fertiliser. In the case of animal manures, digestate can provide a 20 to 30% increase in yield of crops content compared to raw manure, which is linked to better nitrogen availability in digestate relative to raw manure. This is an outcome of the AD process, which transforms N in feedstock into ammonium, which makes the nitrogen more available for plants. This higher ammonia content in digestate compared to slurry, could lead to an increased environmental risk when inappropriately stored or land applied, either through the release of gaseous nitrogen emissions and/or nutrient leaching and runoff to ground or surface waters. The improved agricultural performance of digestate extends to cover crops, which can be harvested and digested to produce biogas. Frøseth et al., (2014), found that, within an organic system, when cover crops were anaerobically digested and the digestate returned to the subsequent crop as opposed to mulched in field, there was an apparent increase in N recovery of 9%. Organic farmers in Germany noted a 22% increase in yields and quality of cash crops from digestate fertilisation without additional land use, while reducing GHG emissions of livestock manures and soils (Blumenstein, 2015).

There is a particular economic benefit when a surplus of manure beyond the nutrient requirements of the farmland is available for upgrading to organic fertilizer (Pierie, 2017). This highlights the potential role of AD in the circular bio-economy. The management of animal manures via AD plants has a role to play in the distribution of nutrients to farmland in need. This would reduce the potential negative effects of over application of slurries and reduce overall need for synthetic nitrogen based fertilisers.

2.3 Anaerobic Digestion in Ireland

To date in Ireland the development of the AD sector, as presented in Figure 3, has been slow by comparison to other European countries. A combination of complex planning and licensing issues, grid connection costs, unattractive electricity tariffs, financing issues and uncertainty in waste policy, have led to the low number of plants operational in Ireland (Leonard, 2017). AD plants generally require financial support to allow biogas or biomethane compete with fossil fuels, while in Ireland until recently there have been ambiguous government policies towards waste and renewable energy (Auer et al, 2017). Whilst the National Biomethane Strategy was launched in 2024 (DAFM, 2024), with ambitious plans for developing the biomehane sector, the majority of the renewable energy generated in Ireland currently remains to be sourced from wind energy which suffers from intermittency.

Figure 3: Number of Biogas plants in EU countries per Million capita



Source: EBA Statistical Report 2019

In 2006, Ireland developed a Renewable Energy Feed in Tariff (REFIT) program providing funding for AD combined heat and power (CHP) for up to 15 years. The tariff offered to producers (2.78-4.17 euro cents per MJ) has generally been lower than that across other European countries, for instance Germany has a rate of 1.63-6.59 (euro cents per MJ) and the UK had a rate of 3.17 – 4.56 euro cents per MJ (Auer *et al.*,2017). Consequently, AD plant operators in Ireland have made the system economically viable by charging gate fees for the receipt of food waste (Auer et al., 2017). The EU requires Member States to achieve 3.5% advanced biofuels in transport by 2030. As an advanced biofuel, renewable gas from AD could contribute to this target , while it would be possible to provide fuel for 10% of transportation from co-digestion of cattle slurry and grass silage (Wall et al., 2013).

According to DAFM (2024) Ireland has only two operational biomethane facilities injecting biomethane into the gas grid. The volume of biomethane injected into the grid remains small. According to the EBA (2020) there are also a number of other biogas facilities in Ireland (less than 50), used in electricity generation and is not upgraded to biomethane. These AD biogas plants could be upgraded to develop biomethane, which is seen as a more efficient use of resources than electricity production. Experiences across the EU

The growth of AD has primarily been driven by regulations and incentives, in both developing and developed countries (Vasco-Correa et al., 2018). The scale of digesters varies across the world, with small scale digesters typically found in developing countries. Since the 1990s, the preferred scale has tended towards mainly larger AD facilities, which are costly to run and are based on intensive energy crops for feedstock. These facilities contribute to national renewable energy targets and are compensated for generating renewable energy, through various national policy incentive schemes. Further details on the development of AD industries in key European countries is provided in Appendix I.

2.4 Legislation

Anaerobic Digestion as a technology has been operational on a small scale in niche areas particularly since the oil crisis in late 1970's. In Germany the pioneers of AD were organic farms digesting animal slurries and separately using waste streams from industry (Blumenstein et al., 2016).

More recently, the growth in the sector in the 1990's was driven by legislation and incentives. The legislation has in some countries, for example the UK, increased taxation on food waste to landfill incentivising companies to engage in alternative more environmentally friendly methods of disposing of such waste material. Incentives have also been created to stimulate the reduction of emissions and the generation of renewable energy towards low carbon economies in the future.

The following sections will outline general policy drivers, the legislative base, specific Irish policy, and the EU policy context.

General Policy Drivers

The EU has set the target of building a net-zero carbon economy by 2050, as outlined in the European Green Deal, along with ambitious goals in the Farm to Fork strategy (Montanarella and Panagos, 2021). This is in line with the Paris Agreement objective of keeping global temperature increases to below 2°C and a target of 1.5°C. This will require large changes across virtually every sector of the economy.

The Farm to Fork strategy recognises that food systems account for nearly one-third of global GHG emissions, consume a large amount of natural resources, results in biodiversity loss and negative health impacts, while not allowing fair economic returns and livelihoods for all actors, in particular primary producers. The strategy aims to make food systems fair, healthy and environmentally friendly. The Farm to Fork strategy targets a 50% reduction in the use of pesticides and nutrient losses from soils and a reduction in synthetic fertiliser usage by at least 20% by 2030 (Montanarella and Panagos, 2021). Achieving these goals will place large emphasis on recycling of nutrients within the circular bioeconomy, as well as sustainable soil management strategies.

Within the EU, agriculture is the only sector with a common policy across all member states, the Common Agricultural Policy (CAP), which is funded almost entirely from the EU Budget. The CAP is seen as a key tool for implementing policies as part of the Farm to Fork strategy and is currently being reformed with a shift in emphasis from production of food, towards reducing the burden of food production on the environment.

Cross compliance is the mechanism within CAP that links direct financial support with requirements to observe rules on environmental management and also ensure that the land is in good agricultural and environmental conditions, such as maintaining soil structure, preventing soil erosion and maintaining soil organic matter at minimum appropriate levels.

The Nitrates regulations sets down legal maximum limits for fertiliser application (organic and chemical) based on stocking rate, crop requirements and crop rotation. The aim of the nitrates regulations is to protect water quality from pollution or potential pollution and sets a limit of livestock manure nitrogen per hectare.

AD is specifically mentioned in the Farm to Fork strategy as part of the circular bio economy, citing the opportunity for farmers and their cooperatives to digest waste and residues to produce renewable energy while reducing methane emissions. There is also mention of untapped potential within advanced biorefineries to produce bio-fertilsers, protein, bioenergy and bio-chemicals as part of the shift to climate neutrality and creation of jobs in primary production (European Commission, 2020).

Irish Policy

The Irish government published ‘Ag Climatise’ which is the national climate and air roadmap for the agriculture sector, with a target of becoming climate neutral by 2050. Included are targets to reduce methane by 24-47% by 2050 and reduce chemical nitrogen use to achieve a 40% reduction in nitrous oxide emissions, increase Low Emission Slurry Spreading (LESS) to 60% by 2023, covers in slurry stores by 2028, usage of clover in all grass reseeds by 2022 and usage of leguminous crops. Targets are also included to improve animal performance and improve grassland management to improve feed digestibility and quality. Targets are also included to increase organic agriculture to 10% by 2030.

The strategy aims to engage with stakeholders to maximise the potential opportunities from AD for agriculture by setting targets for levels of biomethane injection into national gas grid and funding mechanisms, and developing the necessary research, policies and measures to provide certainty to the AD industry (DAFM, 2020)

The 2030 Agri-Food Strategy published in April 2021 recommends scaling-up renewable energy sources through anaerobic digestion, solar energy and energy efficiency.

The National Biomethane Strategy was published in 2024 (DAFM, 2024) and has set a pathway to replace up to 10 percent of the country's fossil gas needs with biomethane by 2030. It is Ireland's first major policy statement on biomethane and is a significant milestone in developing an indigenous sector.

The afore mentioned polices aim to make the sector more resilient with an increased emphasis on principles of the circular economy.

Legislative Base

AD is covered by EU legislation known as the Renewable Energy Directive (RED) II. The RED II Directive sets targets for renewable energy sources consumption by 2030 at 32%, with a commitment for member states to require transport fuel suppliers to supply a minimum of 14% as renewable energy.

The RED II Directive lists default values for GHG savings for common biofuel production pathways to ease the administrative burden. Producers can demonstrate compliance with required minimum GHG emissions, by showing the actual GHG savings from their production process.

These default values and GHG saving thresholds exclude the usage of maize as the sole feedstock to an AD plant built after January 2021 for electricity generation or biomethane. The default values also highlight large improvement in GHG emissions savings when closed digestate storage is used compared to open storage. While digestate is stored at ambient temperature methanogensis still occurs at a slow rate with methane being produce which can be captured and utilised.

GHG emissions savings on farm can be taken into account when evidence of soil carbon increases can be provided or if it is reasonable to expect an increase over the time period. These measures would include reduced or zero-tillage, improved crop rotations, use of cover crops, including crop residue management and the use of organic soil improver such as compost and digestate.

There is also an added incentive for advanced biofuels and biogas for transport being considered to be twice their energy content. The target share of advanced biofuels and biogas of final consumption of energy in the transport sector will be at least 0.2 % in 2022, at least 1 % in 2025 and at least 3.5 % in 2030. The feedstocks for the production of these advanced biofuels and biogas include food and feed crop residues, straw, husk, grassy energy crops with a low starch content, as well as cover crops, before and after main crops, and ley crops, with a full list given in Part A of Annex IX of RED II Directive (European Parliament, 2018).

Summary of Supporting Policies in the EU context

This section will review supporting policies that have been implemented across the EU to assist in encouraging the uptake of AD technologies, whereby the gap between cost of production and market costs of fossil fuel are addressed.

In general in Europe, there is a strong presence of government policies and incentive programs in the areas of renewable energy, agriculture, and waste management compared to other developed regions such as the United States (Vasco-Correa et al., 2018). Feed-in tariffs (FiTs) have been widespread throughout Europe and have created the conditions that allowed the AD industry to rapidly expand. The advantage of the fixed FiT is that it provides investor security with payment levels independent of market price. The European Commission's long term goal is to move to a Feed-in Premium, where payments are based on market price to incentivise market responsiveness by producers (Torrijos, 2016).

Within agricultural policies, the nitrates directive controls land application of synthetic and animal nitrogen. In particular digestate contains higher quantities of ammonia compared to animal slurries, which is beneficial for plant growth, equally the ammonia is liable to leeching if improperly applied to land (Nkoa, 2014). AD plants can be considered agricultural plants or industrial plant depending on various factors and jurisdictions (Banja et al., 2019). Generally farm based AD plants which do not import feedstock, have the lowest regulation. Once industrial wastes, such as animal by-products, are used in the plant, then pasteurisation is required and waste is considered industrial.

Holst et al., (2014) in a review of policies promoting the use of flowering cover crops for biogas found that both incentives and penalties were effective to improve the uptake. The penalty policy lead to a stronger increase in the size of the cultivated area of flowering cover crops with the same income effect, demonstrating that human behaviour is influenced substantially by loss aversion (Holst et al., 2014). The ecological benefit of biogas production from cover crops was also evaluated by Maier et al (2017) showing that the use of catch crops generated renewable energy as well as additional ecological benefits, leaving the main crop untouched for food and feed purposes (Maier et al., 2017).

AD has a role to play in rural development, given that the majority of feedstock is rural and the disposal of the digestate is dependent on access to farmland. AD technology has been found to aid rural development in terms of job creation and investment in rural areas (Plieninger et al., 2026). Indeed, in the UK and US, funding for AD infrastructure can be obtained from rural development agencies (Vasco-Correa et al., 2017).

One of the challenges with AD is that the primary factor influencing the deployment of the AD technology is the regulations and incentives (Vasco-Correa et al., 2017), yet the technology has effects on many sectors and not principally a single sector, such as other renewable technologies, including wind or solar. These sectors include agriculture, energy and waste. Oehmichen et al., 2017 came to conclusion that AD should be implemented under both energy and agriculture policies (Oehmichen and Thran, 2017), in line with findings from Vasco-Correa et al 2018.

2.5 Farm Level Sustainability of Anaerobic Digestion

This section reviews the literature relating to the potential impact of AD adoption on farm level sustainability, from an economic, environmental and social sustainability perspective.

Economics

The cost of feedstock is a significant factor in the financial viability of any biofuel facility. Mceniry et al., (2011) found that when comparing grass, sugar beet and wheat grain in the Irish context, grass silage represented the cheapest feedstock per GJ of biofuel produced while also qualifying as a second generation biofuel under the RED II Directive, as grass is not directly consumable by humans. Importantly, arable land is not needed for growing grass and direct food substitution is not required. In a further study, which focused on beet and grass, it was found that grass offers a better net return in an Irish context, while maize was not considered suitable in the northern climate (Murphy and Power, 2009).

O'Connor et al., (2020) investigated the technical, economic and environmental considerations of the operation of small scale (<100kW electrical) AD on Irish dairy farms. Co-digestion of slurry and grass silage was evaluated on dairy farms of 100 to 250 cows, housed for the 16 week winter period. The dairy enterprise was modelled as the primary income source, with the AD plant supplemented with surplus crops. The AD plant was shown to be capable of supplying the farm's energy demands, with a surplus for export to the electricity grid and with the heat exported to a district heating system. Electricity consumed onsite was charged at a business rate, while it was assumed that the Renewable Energy Feed-in-Tariff (REFIT) was re-opened at 15.8 c€ kWh−1. It was found that with a dairy herd above 100 cows, the AD system was an economically sustainable method of mitigating GHG emissions from the agricultural sector (O'Connor et al., 2020).

A capital subvention grant of 50% was also investigated, which has been successful in UK, France and Sweden. For a 100 dairy cow herd the capital subvention grant reduced the discounted payback period from about 24 years to 8 years (O'Connor et al., 2020).

Blumenstein et al (2016) investigated the economics of anaerobic digestion on conventional and organic farms in Germany and found that recent shifts in policy will inhibit biogas investments in the country. The agricultural benefits of AD plants were evaluated, even though they are typically excluded as these do not affect the economics of the AD plant. The AD plant improves farm level: nitrogen use efficiency due to lower loses during storage, higher proportions of readily available ammonia and improves synchronisation of N supply and crop demand. The agronomic effects of integrated biogas and organic agriculture would lead to higher proportions of cash crops within the system and lead to higher profitability.

Imeni et al., (2020) carried out a technical and economic analysis of co-digestion of cattle manure and wheat straw for small and medium dairy farms in Spain. The analysis showed that sole digestion of manure returned a negative Net Present Value for a 250 cow herd. The co-digestion of straw resulted in a positive NPV from a herd size of 156 cows, which derived from an increase in the organic loading of the plant improving the production of the facility.

Dennehy et al., (2017) applied stochastic modelling to input variables of food waste availability, renewable electricity tariff, gate fees and digestate disposal cost to assess the economic viability of on farm co-digestion of pig manure and food waste in Ireland (Dennehy et al., 2017). The results demonstrated that long-term and stable supplies of co-substrates, which drive the methane production and revenue generation, are crucial to viability of AD plant.

Himanshu et al., (2019) investigated the cost of methane production on a farm based AD plant in Ireland from cattle slurry and grass silage, finding costs were 87% higher for cattle slurry. The recycling of digestate from the AD facility was not considered, with synthetic fertiliser continuing to be used instead. The non-recycling of nutrients lead to 38% of the cost of silage produced being attributed to fertiliser. The use of digestate and mutli species swards could significantly reduce this cost, while improving environmental performance of the soils.

The effect of grass silage cost on biomethane production was investigated by McEniry et al., (2011). While grass represented the cheapest feedstock when compared to wheat or beet when considering the full costs of production from a small on farm facility, the cost of sugarbeet in a large industrial facility was the cheapest option. However, this monetary comparison of a large scale facility with a decentralised generation did not account for environmental or societal benefits.

Tisocoo et al., (2024) examined the farmland area required to provide slurry and grass silage for a 40 GWh biomethane plant and subsequently quantified greenhouse gas (GHG) emissions reductions. Results indicated that 130 farms of 50 ha and a livestock unit (LU) of 2.1 LU/ha were required to meet the feedstock requirements of the 40 Gwh AD plant. Furthermore, farm level GMG emissions were reduced by 24% compared to the superseded beef enterprise, when 15% of the area was diverted to producing grass silage. Tisocoo et al., (2025) further examined the economic implications of the previous grass silage supply scenario and found that methane yield of AD silage, along with biomethane certificate and silage prices were key variables impacting the farm level economics of feesstock supply.

Environmental Aspects

In Ireland grass as a feedstock has both significant yields and a good biomethane energy balance, while it does not require land use change or the use of tillage crops. An important factor is that farmers are familiar with growing grass (Smyth et al., 2009). Indeed it has been estimated that the co-digestion of cattle slurry and grass in Ireland on a 50:50 volatile solids basis would generate over 10% renewable energy for transport (Wall et al., 2013). Furthermore, it has been suggested that there is potential to produce grass based feedstock on marginal land with no significant difference in yield (Meehan et al., 2017).

In terms of GHG emissions, slurry has a significant saving relating to offsetting methane which would be emitted, however the digestion of slurry even when supplied free of charge comes with an increased cost of biogas production compared to grass silage (Himanshu et al., 2019). Grass silage produces seven times the quantity of methane per fresh weight when compared to slurry (Wall et al., 2013), with biogas being the key economic return for the facility (Himanshu et al., 2019).

When considering a consequential life cycle assessment the optimum environmental performance was based on the ratio of 40:60 of volatile solids of silage to slurry was found in an Irish context (Beausang, 2021). This feedstock ratio is based on a business as usual approach using standard grass production models. Care must be exercised in projecting an increase of grass silage availability by increasing the additional N fertiliser as this increases environmental footprint and is at odds with the Farm to Fork strategy which aims to reduce fertiliser usage by 20%.

An increase from current production rates of a grass based feedstock combined with a reduction in nitrogen inputs is possible with the adoption of conservation agriculture approaches described later in this chapter. This would improve economic and environmental performance of the grassland while digestion of slurry would reduce methane emissions of ruminants. This more holistic and multi-dimensional assessment approach should be applied to evaluate the full sustainability benefits of A D (Vaneeckhaute et al., 2018).

Scale and Transport

The efficiency and capital costs of AD plants is dependent on the scale of the installation. The levelised cost of electricity from a centralised CHP plant for a 125 dairy cow herd is over twice the cost of that for 1000 diary cow herds (Oreggioni et al., 2017). Small scale and decentralised AD has only been adopted in limited scale due to low overall profitability of these AD plants (Vaneeckhaute et al., 2018).

Equally there is a limit to increase in scale whereby transportation of waste feedstock reduces the GHG emission savings of the AD plant. O'Shea et al., (2017a) showed that decentralised AD and transportation by pipeline or road compared favourably to large centralised AD facility (O'Shea et al., 2017). Further work by O'Shea et al assessed the optimal location of biomethane injection to the national grid from centralised anaerobic digestion facilities handling household waste showing the limit to economies of scale. Whilst the largest facilities (200GWh/a) would increase biomethane production these would also increase the levelised cost (O'Shea et al., 2016).

O'Shea et al (2017b) assessed the financial viability of biomethane facilities and locations in Ireland based on the resource of cattle slurry and grass silage. The point at which the plant net present value was maximised was investigated while the impact of plant size, grass silage price, grass silage to slurry ratio and incentive per unit of energy were examined. The levelised cost of energy decreased with increasing plant size and grass silage to slurry ratio.

Social Sustainability/Acceptability

Concerns from residents surrounding biogas plants surrounding traffic and odour issues have delayed and even caused abandonment of new biogas plants (Ely_Mazzega, 2019). Experience has showed that awareness campaigns started early in the setting up process of an AD facility can reduce concerns.

There is a large variation in the type of AD plants, from facilities that treat sewage, industrial waste and agricultural residues. Röder (2016) found from stakeholder engagement that on-farm AD is viewed more an additional activity integrated into existing agricultural systems than a renewable energy technology.

O'Connor et al (2021) found that in an Irish context farmers preferred self-owned and operated plants with a strong positive interest in joining a cooperative. A cooperative is most likely to achieve sufficient scale to achieve economies of scale (Ní Ruanaigh and McGrory, 2021). Farmer participation was seen as crucial to the success of a cooperative with farmers showing interest in AD technology.

In terms of the scale of farming in Ireland, with a typical farm in Ireland (32.4ha), this would suggest that a centralized AD plant would be suitable for development in an Irish context. A survey carried out by O'Connor et al (2021) that 41% of respondent were interested in installing AD on their farming enterprise while the preferred models were self-ownership or co-operative scheme. Barriers were seen as lack of information and high capital costs along with uncertainty of government based supports (O'Connor et al., 2021). Ruanaigh (2011) investigated the development of cooperatives in Ireland for AD finding that feasibility is dependent on environmental benefits being considered and gate fees in current conditions.

International studies on AD deployment and social acceptance were scare in the literature, with only one such study found based on a case study in Sweeden. Stakeholder acceptability of digestate in southern Sweden was found to be positive with quality assurance and nutrient measurement seen as crucial issues (Vaneeckthaute et al., 2018).

Technology Transition

When considering agricultural feedstocks for AD, particularly with RED II requirements, the concepts surrounding low emissions agriculture are becoming more common place. While production of high input energy crops such as maize for AD plants has been the focus of large scale AD plants particularly in Germany, questions have been raised regarding the long term sustainability of this intensive monoculture production for this purpose and more recently has led to limits being imposed on its usage. The marginal GHG emissions of electricity generated by fossil fuels in the EU is 752 g CO_2 per kWh while maize based biogas is 202 grams CO_2 per kWh while coupling of conservation agriculture and digestion of manure can lead to a range of marginal lifecycle GHG emissions of 25 to -335 g CO_2 per kWh (Valli et al., 2017).

Usage of grass based feedstock is considered a second generation biofuel, as grass is not directly digestable by humans limiting the food vs fuel debate.

One of the key technologies when considering low emissions agriculture in a grassland context is the use of multi species swards. The inclusion of legumes allows for biological nitrogen fixation rather than application of carbon intensive synthetic nitrogen while maintaining productivity levels (Nyfeler et al., 2009). Furthermore, the use of multi species increases the yield stability of grasslands with the potential of additional eco-system services such as enhanced carbon sequestration and pollinator food (Lorenz et al., 2020). Recent research has shown that the use of clover grass leys as a biogas substrate has the potential to reduce green house gas emissions by 2 t CO_2 equivalents per hectare per year (Stinner, 2015). Inclusion of mixtures of plantain with red clover and grasses when unfertilised was found to achieve a 60% reduction in GHG emissions of biogas compared to fossil fuel (Cong et al., 2017).

The use of multi species swards would therefore reduce the requirement for application of nitrogen, even if sourced from circular source such as the digestate from the AD Plant. This is important from a sustainability perspective but would also increase the scope for the AD plant to export digestate as a biofertiliser and further offset the usage of synthetic fertilisers.

Multi species swards (MSS) have increasingly become the focus of research and interest at farm level. Some of the quoted benefits associated with the adoption of MSS include reduced fertiliser cost, increased animal performance and health while reducing nitrous oxide emissions (Cummins et al., 2021). In an Irish context any discussion of clover raises the question of bloat which relates to importation of a variety of large leafed white clover which caused issues with bloat in cattle in the past.

There are questions about the persistence of multispecies swards which appear not to be as tolerant of mal-practice as perennial ryegrass swards are. In particular the major management tool typically used to increase grass production is the application of synthetic nitrogen however research shows that the application of synthetic nitrogen has a greatly reduced efficacy on production in multi species swards (Moloney et al., 2020). This is due to the legumes supplying the nitrogen thus as nitrogen is supplied there is simply less demand for nitrogen from legumes.

With regards to preserving silage there is a common belief that multi species swards are difficult to preserve as silage. Research would suggest that when MSS are ensiled under more challenging crop conditions, in particular the third cut, that MSS appear to have a greater requirement for an adequate wilt or preservative to be evenly applied (Moloney et al., 2021). Grace et al (2019) found improved dry matter yield when cutting compared to grazing.

Despite research showing that incorporating white clover into grassland reduces the requirement for chemical N by up to 100 kg N/ha and increases animal performance (Dineen et al., 2018), the adoption of this technology at farm level has been very limited. Dillon et al (2020) states that "it will require a number of years before there are sufficient uptake to replace significant levels of chemical N fertilizer" along with requiring considerable knowledge transfer and a continued research programme to get significant adoption (Dillon et al., 2020).

A possible approach to technology adoption would be to link MSS and AD technology, this would create a niche for MSS to be adopted by farmers reducing emissions from grasslands while also stimulating development of AD technology which would reduce the emissions of slurry storage.

Anaerobic Digestion can be described as a metal stomach, the reason being that it is a microbiological process which can require similar management practices as ruminant animals. In particular a balanced and stable diet is what allows for a stable process to operate.

High nitrogen in feedstock, such as food waste, cereals, grass, meat products can inhibit the digestion process by the presence of ammonia, this is particularly affected by higher operating temperatures as well as higher organic feeding rates. Mono-digestion of grass silage can cause inhibitory effects and risk process imbalance (Thamsiriroj et., 2012). Reducing the temperature and feed rates can increase the stability of the AD process as well as addition of trace elements. High nitrogen feedstock can also be controlled through design of the AD plant with anti foaming systems; water spray systems, enzymes, anti foaming agents and trace element balancing.

While clover has a relatively high nitrogen content compared to grass with a lower carbon to nitrogen ratio, the digestion of mono cultures of legumes may have inhibitor effects due to ammonia (Wahid et al., 2018). The co-digestion of grass with legumes and forage herbs has been shown to improve methane yield which is attributed to the nutrient balance composition of the multi species compared to the monoculture of grass (Cong et al., 2018).

The importance of multi species is that it could potentially intensify temporary grassland to provide an additional biomass with improved environmental performance (Wiche et al., 2020). This could also provide another niche for low emissions technology that could stimulate the transition in a broader level in Irish agriculture. These niches are important in the wider context of technology transition (Geels, 2020).

3 Farm Level Modelling of Alternative Feedstock Solutions for a Regional AD Plant

3.1 Introduction

To date in Ireland the development of the AD sector has been slow by comparison to other European countries. A combination of complex planning and licensing, grid connection costs, unattractive electricity tariffs, financing issues and uncertainty in waste policy have led to low levels of AD plant construction and operation in Ireland (Leonard, 2017). AD plants generally require policy and regulatory support to compete with fossil fuels (Auer et al., 2017) while currently the majority of the renewable energy generated in Ireland is from wind energy which suffers from intermittency due to prevailing weather.

There is a need to increase our understanding of the economic consequences of AD and biomethane. Specifically this requires an assessment of their contribution to the economic sustainability of farming in Ireland. This chapter will focus solely on agricultural based feedstocks for AD.

The remainder of the chapter is organised as follows: Section 2 describes the background to the research question, section 3 outlines the materials and methods along with the assumptions employed. Section 4 outlines the results of the analysis and Section 5 contains a discussion of results. Section 6 outlines conclusions from the results.

3.2 Background

The energy pathway being explored, as shown in Figure 1, is to operate the AD plant off-farm and upgrade the biogas that is derived to create biomethane. This energy pathway allows the use of biomethane within Ireland's existing natural gas grid. It would also allow the use of biomethane within the transport sector which is a particularly difficult sector to decarbonise, especially in the case of heavy goods vehicles. The two major feedstocks considered in this chapter are silage and animal slurries. Animal slurries have a low energy density, however when used in AD they have the potential to contribute to GHG emissions reductions with an associated manure credit within RED II(European Parliament, 2018). Grass silage has a far greater biomethane potential compared to animal slurries. Grass can provide between seven and ten times the energy density of animal slurries(Auer et al., 2017; Wall et al., 2013). The use of grass silage for AD is considered an advanced biofuel (fuel made from non-food biomass) in RED II which when used in transport, is considered to be twice their energy content in terms of achieving targets., with full details provided in Part A of Annex IX of RED II Directive(European Parliament, 2018).

Agriculture in Ireland is dominated by grassland, it accounts for over 90% of the utilizable agricultural area (UAA) and is mainly used for dairy and cattle production. The majority of this forage is utilized by grazing animals in pasture based systems, but there is a requirement to preserve silage for the winter housing period. Conversion of grassland to growing annual crops for AD (such as maize) would constitute a land use change and potentially increase carbon emissions due to the release of soil carbon in the case of adoption of inversion tillage. Conversely, silage used in AD would not constitute a land use change and the pre-existing knowledge and experience in the farming community of silage making increases the probability of farmers being willing to engage with this activity. Consequently, this paper investigates whether silage production for AD is an economically viable diversification opportunity for farmers.

Making silage to supply off farm AD means all the nutrients in the silage are exported from the farm by comparison to the existing practice of feeding silage as fodder to animals, creating slurry on the farm containing nutrients to fertilise the subsequent crop. The nutrient opportunity cost (NOC) is used to value the export of major nutrients; nitrogen, phosphorus and potassium in the silage. The AD process creates digestate that contains the nutrients from feedstock. When digestate is returned to the same farm to fertilise subsequent crops it completes the circular system. However digestate can also be used to fertilise crops on other farms offsetting the use of chemical fertiliser. The use of the nutrient opportunity costs allows for these scenarios to be compared.

To date few comprehensive appraisal of the potential impact on economic viability of producing farm based feedstocks for AD purposes compared to existing enterprises has been carried out using Irish farm data. Most studies use modelled data such as McEniry et al., 2011 as opposed to farm data, this is the approach which was taken in SEAI National Heat Study (2022) which assumed a silage cost of production. Geoghegan & O'Donoghue (2023) compared a profitability of a modelled silage production system adapted from McEniry et al., 2011 with a market silage price to compare the gross margin of the silage production to the average Irish farm systems. This study seeks to address some of the information deficit concerning the economics of silage crops in Ireland and the comparison to existing farm systems. This paper uses historic farm level data from the Teagasc National Farm Survey (NFS) for a perennial ryegrass (PRG) sward to estimate costs for silage production across existing farming systems as well as the existing farm enterprises.

Given the environmental sustainability constraints set out in RED II and the consequential need to limit synthetic nitrogen usage for growing feedstocks for AD, the role of nitrogen fixing swards in the production of feedstock was also examined. Clover is a legume which is capable of biological fixation of nitrogen and supplying companion plants such as grass and herb with nitrogen, thus no longer requiring input of chemical nitrogen typically made with fossil gas, which is assumed in previous studies (McEniry et al., 2013). In the absence of historic survey data for nitrogen fixing grass clover swards, farm management data was used to cost a perennial ryegrass – red clover (PRG-RC) sward to estimate typical costs of silage production on a hypothetical farm. This is an update of previous analysis by (McEniry et al., 2011).

3.3 Methods

This chapter uses a Discounted Cash Flow (DCF) approach to evaluate economic returns of PRG and PRG-RC as sward types for production of silage for use in an AD plant using historic and modelled data. It also evaluates the effects of variation in use of digestate for fertilisation of crop and the use of the nutrient opportunity cost on the sward performance. The results of the DCF are presented in terms of an annualised gross margin, to allow comparison with superseded enterprises in Teagasc National Farm Survey (NFS), which are evaluated based on an annual production system (dairy, beef, sheep and tillage) with economic criterion reported in annual terms.

The historic data from the Teagasc, NFS was used for calculating the production cost of PRG, while the Grange Feed Cost Model (GFCM) was modified to quantify the cost of producing and utilising a red clover sward, for which no historic data was available. The GFCM is static agro-economic simulation model for the calculation of the cost of feed (Finneran et al., 2010). The cost analysis is based on a single year deterministic input framework, but is re-simulated under different annual conditions.

Cost and Return of Silage Crops

This section covers the production costs and returns from both the PRG (NFS based) as well as the modelled PRG-RC silage crop. The existing costs of producing PRG silage in Ireland are based on data generated through the Teagasc, NFS from 2018-2020. The economic performance of exporting that silage for AD is then compared at farm level to existing enterprises to assess the viability and competitiveness of the alternative scenario.

For the purposes of this analysis silage is defined as the fresh weight of silage harvested from the field, this does not include preservation and feed out losses which may vary with management practices. When conserving silage for animal feed the liquid effluent is considered a loss however this liquid can be used as a feedstock for AD if it is captured. The cost of silage are also referred to on a per ton of dry matter (DM) basis which excludes the water content of the silage.

Data on existing silage systems

The majority of farms in Ireland use a contractor to make silage, thus to overcome issues of allocation of fixed costs associated with owned machinery, farms that used contractors for the majority of field operations of making silage were selected. To achieve this, farms without any contractor charges were excluded, along with the 5% of the remaining farms with the lowest contracting charges per ton of silage produced to exclude any nominal/outlying values (Clancy et al., 2009) . The remaining farms had a machinery hire cost greater than 60% of total direct cost of silage. This allows for all machinery and labour costs assumed to be variable costs.

Farms without any expenditure on fertiliser for silage were also excluded to remove organic farms, but this resulted in the exclusion of a relatively small number of farms, since the small number of organic farms in the NFS sample is reflective of the low percentage of organic farms in the farm population in Ireland.

Farms that did not produce silage were excluded along with the lowest 5% of farms in terms of tonnes of silage produced. This resulted in a yield of silage greater than 50 tonnes per farm which is a quantity of silage sufficient to fill a truck for transportation to an AD plant.

Population weights are applied to the resultant farms to extrapolate to the national population, as shown in Table 1. This selection process does not affect the weights used to represent the population. The assigned weights to individual sample farms are based on a size/system sampling frame and weighted to the population based on information from the CSO. However, it is important to note that due to the exclusion of some farms, as already described, the total number of farms represented (63,200) is smaller than the full population of farms (92,500) represented in the NFS. In addition the average farm size, measured in UAA, for this cohort of farms which are currently producing silage is larger than the national average.

The “average total yield of silage per ha adjusted to entire year” is theoretical reduced area that the entire year’s crop is harvested for silage. This is an adjustment made to account for the yield from silage area which is not harvested as silage but grazed by animals instead. This would for instance occur if only a single cut of silage is harvested in June and grazed by animals for the rest of the growing season. Therefore the adjusted area is a reduction in area compared to the area on which the actual silage is harvested, as it is simulating harvesting silage on this adjusted area over the course of the entire year.

The average yield of silage harvest is the yield of silage over the total area harvested for silage in that year. Typically the first cut of silage has the highest yield per ha, which on average is 21-24t fresh silage per ha, normally with the fields being closed to grazing from late March to early April and harvested in late May. If silage harvesting is delayed the yield of silage may increase, however after the seed head appears the digestibility of the grass reduces.

A second or third cut of silage is possible, with typically lower yields of silage per ha, than the first cut. However, the second and third cut typically also have a lower fibre content which can limit energy availability (Khalsa et al., 2014). Analysis of the NFS farms show that across all farms 49% operate a single cut system for making silage, with 44% operating with a 2 cut system. On dairy farms a two cut system is predominant at 62% of farms, while on beef farms single cuts are more predominant at 59% of farms.

McElhinney et al (2016) investigated silage quality in Ireland across 2 years. Findings indicated a typical dry matter content for silage of 24.7% DM for pit silage, while bale silage was 30.7% DM. However, there was significant variation, with values ranging from 19% DM to over 40% DM

(Mcelhinney et al., 2016). It must also be noted that for instance a 3 cut system, while more expensive per tonne of silage, it may have increased dry matter yield and therefore quality. Data on the dry matter content of silage is not collected as part of the NFS. Hence, in this analysis the average figure of bale and pit silage of 27.7% DM is assumed.

The fertiliser cost is the cost of the Nitrogen, Phosphorus and Potassium (NPK) chemical fertiliser used to produce the silage crop, along with the costs of the animal slurries are also used to supplement these nutrients. The costs of using in animals slurries include the opportunity cost of NPK nutrients in animal slurry and the cost of spreading. This is calculated based on the silage crop requirement, the availability of animal slurry and contracting rates for application of slurry. In a typical livestock system silage is being produced as feed for animals which creates animal slurry containing nutrients from the silage which will be available for fertilising subsequent crops. However, when silage is exported for AD these nutrients are exported off farm. Thus, the opportunity cost of replacing these nutrients are included.

Fertiliser applied to grass silage is predominantly nitrogen, in total 67% of the mass of nutrient spread is nitrogen. This has most significant implications for GHG savings in the AD process given the RED II constraints in this area. The renewable energy directive (RED II) sets GHG emissions savings criteria to allow the energy created from AD to be classified as renewable. The most significant in terms of GHG emissions is nitrogen, as this is associated with Nitrous Oxide (N2O) emissions. One tonne of N2O has a Global Warming Potential (GWP) equivalent to 265 times that of carbon dioxide according to IPCC (IPCC, 2014).

Incorporating legumes such as clover or multi species sward (MSS) into grass silage swards can reduce or remove the application of synthetic nitrogen on silage swards, due to their ability to fix atmospheric nitrogen, and therefore could be seen as essential feedstock to improve the overall sustainability of the AD facility compared to grass-only swards. The adoption rates of grass-clover and MSS are low across the typical farming systems in Ireland and thus these crops were modelled using research data on yields and typical rates for operations.

Grange Feed Cost Model (GFCM) for Red Clover based sward

The GFCM was adapted to model production of a Perennial Ryegrass (PRG) and a Perennial Ryegrass-Red Clover (PRG-RC) silage under a multi cut system (Finneran et al., 2010). The economic input variables for machinery hire and fertiliser purchases are based on data from the Farm Contractors of Ireland(FCI) costings list and the Central Statistics Office(CSO), respectively, based on prevailing 2018-2020 & 2022 prices. The long term field data from Teagasc Grange (Clavin et al., 2017) was used for a 4 cut silage system. However, the 4th cut is not harvested for silage and instead it is either grazed or zero-grazed due to the potentially high cost per tonne of silage produced and possible challenges with ensiling. This 4th cut was assumed to be grazed and the associated value was included in the evaluation. The analysis is based on an assumed yield of 14t Dry Matter (DM) per ha of ensiled silage with 1.4t DM aftermath (grass post 3rd cut) for both

PRG and PRG-RC, which are conservative values based on Clavin et al. (2017) who achieved 16 t DM/ha.

The crops are fertilised based on equivalent nutrients taken off in the silage. This ensures fertility is maintained, with the exception of nitrogen on red clover. Red clover is a legume which has nodules on its roots which contain bacteria (Rhizobia) that are capable of biological nitrogen fixation and therefore the crop does not require nitrogen fertilisation. Indeed Clavin et al showed a slight decrease in yield when applying 50kg/ha of chemical nitrogen (Clavin et al., 2017). However, in practice red clover crops are fertilised with slurry to return phosphorus and potassium which also contains nitrogen. This is not an efficient use of this resource, as this nitrogen is not demanded by the crops. Hence, there is an opportunity cost associated with the readily available nitrogen component of this slurry which could be better utilised elsewhere in the agricultural system.

The possible flow of nutrients within an AD system is outlined in Figure 2. Theoretically the most efficient use of digestate would be to fertilise other crops which are not capable of biological nitrogen fixation, thereby offsetting GHG emissions of the chemical nitrogen fertiliser currently used on these crops. In the scenario assumed here, chemical P and K fertiliser is used to fertilise the PRG-RC crop, however this is offsetting the use of N,P and K fertiliser on another crop that is receiving digestate. A more circular system would use the proportion of digestate that came from silage to fertilise the subsequent silage crop, thereby recycling the nutrients to where they came from. This however is returning nitrogen to the silage crop which could be utilised to fertilise another crop and is therefore not the most efficient in terms of GHG emissions.

To investigate the use of digestate, an opportunity cost is applied to nutrient in digestate minus the additional cost of spreading digestate versus the cost of spreading chemical fertiliser. This is to account for the higher cost of spreading digestate compared to the cost of spreading chemical fertiliser. The delivery cost of digestate is not accounted for. Four scenarios for crop fertilisation were investigated:

- **Scenario A: PRG-RC with 0% of digestate** from that crop returned and instead chemical fertiliser is used to supply crop P and K requirements. The digestate is used elsewhere within the wider agricultural system;
- **Scenario B: PRG-RC with 42% of digestate** from that crop returned to fertilise the first cut of silage and subsequent cuts of silage are fertilised with chemical P and K fertiliser;
- **Scenario C: PRG-RC with 100% of digestate** from that crop is returned in a fully circular system whereby all silage nutrient requirements are provided by digestate.
- **Scenario D: PRG with 100% of digestate** from that crop is returned along with additional nitrogen fertiliser to meet crop demands.

The nitrogen content of slurry and digestate in the ‘readily plant available form’ of ammonia is assumed to be 58% and 85% respectively, while the remaining nitrogen in the slurry and digestate is in more stable slow release forms, which is not accounted for in this analysis. The quantity of ammonia available to the plant also depends on the losses during spreading which are dependent on temperature at application and application equipment such as Low Emissions Spreading Systems (LESS), which is assumed to be used as part of best practice.

Discounted cash flow assumptions

The discounted cash flow method is used to compare annualised gross margin of growing silage for AD and the different farm enterprises from the Teagasc NFS. The annualised gross margin discount rate of 5% is used over a time period of 5 years following (Boehlje & Eidman, 1984, Clancy et al., 2007, Styles et al., 2007 and Gebrezgobher et al 2010)) The margin of the superseded enterprise is deducted from the net margin of the silage for the AD crop annually. The working capital released from the previous enterprise is not accounted for and the maintenance costs remain on the buildings and infrastructure assets, assuming that the farmer may wish to maintain the option to return to the original farm enterprise.

A discount rate of 5% is used, while general inflation of 2.3% and energy inflation of 3% are used based on Clancy et al., 2007. The War in Ukraine caused a volatility in energy prices, with spike in energy inflation followed by deflation which was ongoing at the time of writing. It is assumed that conditions will return to a more steady state thus values used from Clancy et al., 2007 with volatility in inflation rates left for future work.

Following previous examples, (such as Clancy et al., 2007, Styles et al., 2007 and Gebrezgobher et al 2010) of net present value application to farm based production decisions, both inflation and discount rates were applied to the farm level data examined. Whilst there are various schools of thought regarding the use of both inflation rates and discount rates in the same ex ante exercise, it is important to explicitly specify the approach taken. Precedence applied in previous farm level data exploration using Irish farm level data were applied in this example.

The limitation of bioenergy is the finite land availability. The opportunity cost of land has been used in studies on the investment returns in agriculture (Clancy et al., 2009, 2012; Lewandowski et al., 2000). In the GFCM, land rent is included in the costs of production, however in the NFS no charge is calculated for owned land, while some land may be rented at a financial cost which is recorded. To allow comparison of both cost approaches, land charge is excluded in this cost of production analysis. The opportunity cost of land is valued in terms of superseded enterprises. The paper abstracts from issues of scale of production by conducting the evaluations in per hectare terms.

Capital expenditure on the silage pit and effluent tanks are a considerable investment, with a typical 20 year time horizon. If a farm was to use existing infrastructure, or if the silage was to be exported immediately for preservation, off farm capital investment would not be required. Equally there are technologies available to bag or bale silage without these capital costs. Within the NFS, farmers typically have existing farm infrastructure for the preservation of silage, with associated costs accounted for in depreciation and maintenance. For comparison to the existing data within the NFS, the capital expenditure is excluded

Within the NFS the sale of silage is much less prevalent than the production of silage, as farmers use the silage on farm. Notwithstanding this the data for silage sales in NFS would suggest that the average price was approximately €30 per ton of in the years 2018-2020, this would be similar to figures quoted in media (Geoghegan & O'Donoghue, 2023). This is just above the average cost of production in Table 1, thus to study the effect of price of silage on the economic returns the price was increased increments to €35 and €40 per ton which are within the variance in prices paid for silage in the NFS in that time period.

The enterprise is evaluated as financially viable if it generates a positive NPV. It is widely accepted that farmers are not purely profit maximizing actors, as there are many social and cultural barriers which provide inertia in decision making and prevent the pursuit of profitable opportunities (Clancy et al., 2011). As a means of accounting for this inertia, a threshold of €400 per ha extra net margin was used as this is the same value as the 2022 Tillage Incentive Scheme in Ireland which did not achieve the maximum farmer participation level that was set out. This is the clearest example of an incentive for farmers to change enterprise and thus is used to benchmark the price of silage required to achieve this economic return.

Methods for assessing farmer willingness to engage in AD feedstock delivery and AD development

An additional survey was deployed using the National Farm Survey (NFS) sampling frame to conduct this study. Teagasc has been running the NFS on an annual basis since 1972 (Dillon *et al*, 2023). The survey on farmer's willingness to adopt AD took place in 2023 as part of the annual additional survey for the NFS for 2022.

Its purpose was to investigate farmer's willingness to adopt AD. The survey consisted of eight questions, the first section included five questions asking farmers were they willing to:(a) supply silage for biogas production; (b) produce silage for AD using multispecies or clover; (c) supply slurry for the production of biogas; (d) receive digestate generated by AD plants; (e) a co-operative of farmers, with a view to engaging in AD development.

The second section was to ascertain farmers preferred arrangement for the supply of silage. The options for the supply of silage were (i) selling silage on a per ton of DM Basis, (ii) sell standing crop in field, (iii) lease the land to a contractor on a year to year basis, (iv) lease the land to a contractor on a long term agreement. The final section of the survey was used to determine how much grassland area farmers would consider devoting to growing feedstock for an AD plant.

There was a total of 900 surveys were handed out to farmers that are members of the NFS, with a return of 626 surveys. A brief description of the new technology was handed out to farmers along with the survey, to help them gain a better understanding of AD and how it can benefit them. The survey responses were weighted based on the farms size and system.

Further analyse was carried out using the software IBM Statistical Package for the Social Sciences (SPSS), to assess the reasons behind farmers unwillingness to adopt AD. The following statistical methods were carried out descriptive statistics, frequency tables, chi squared test.

3.4 Economics of Feedstock Production at the Farm Level

Baseline results for PRG from Teagasc, NFS (2018-2020)

Analysis of the data was carried out to evaluate the distribution of direct cost of silage per tonne of silage produced are shown in Figure 3. The top, middle and bottom percentiles of performing farms by production cost from the Teagasc NFS indicated average direct costs of €21, €29 and €37 per tonne of silage, respectively. This shows the range of silage production costs that is prevalent on farms in Ireland. The top performing farms achieved the highest yields per ha, while also using the least amount of synthetic fertiliser per ha. Contractor charges are typically based on the area cut rather than the volume harvested, thus maximising yield minimises this cost. Fertiliser is the largest cost after contracting.

It must be noted that the analysis of the direct cost of silage production per tonne is based on an assumed average dry matter content of 27.7% and thus does not account for variation in dry matter of the silage produced. It is possible for farmers in the bottom group on the basis of their direct cost to be harvesting a relatively lower total yield per hectare of above 30% DM silage with high digestibility, and operating three cuts per year. The data does reflect the fact that while three cut silage systems operate on higher cost per tonne of silage, the farm gross output is higher on such farms.

While farm management has a very important role in productivity of silage production, the nutrient status of the soil also has a major impact. This is dependent on soil physical characteristics as well as the long term nutrient and pH balance of the land area in question. For the purposes of this analysis, the performance of the middle cohort in the distribution is assumed.

GFCM Results

The study period are the years 2018-2020 inclusive, whereby input costs were relatively stable. This is to align with the study period of the NFS data presented in the previous section. The modelled cost of a three cut PRG silage scenario, including the NOC, as seen in Figure 4 shows good agreement with the total cost of silage from the NFS data for PRG in Table 1, at €30 per tonne of silage produced. This is to be expected, as the GFCM uses a bottom up costing approach employing standard costs and yield when in some situations higher yields and lower costs are achievable.

The costs of production of PRG-RC silage, shown in Scenarios A-C in Figure 4, are lower than those of PRG in Scenario D and NFS. The major cost difference is due to the elimination of chemical nitrogen used to fertilise the PRG in scenario D. The reduction in nitrogen from the digestate used to fertilise the PRG-RC in Scenario A & B, as seen in Table 1, further reduces the cost of production of PRG-RC silage when the opportunity cost of the nitrogen in the digestate is included (incl. NOC). However, when the opportunity cost of the nitrogen content of digestate is excluded (excl. NOC), the cost of production of PRG-RC silage increases compared to scenario C due to the cost of chemical fertiliser usage to replace nutrient off takes of the silage. In scenario A where 0% digestate is used, the chemical phosphorus and potassium fertiliser used to fertilise the PRG-RC can be related to a reduction in usage of NPK fertiliser elsewhere in the farming system due to it being replaced with digestate. This reduction in fertiliser, specifically Nitrogen, has an associated GHG emissions saving (SEAI, 2022). This would suggest Scenario A is the most economic and environmentally efficient scenario when opportunity cost of nutrients can be realised.

While detailed farm level data is available for the time period of 2018-2020 from the Teagasc NFS, the advantage of the GFCM model is that the data on the price shocks (such as 2022) can be evaluated to demonstrate the changes in cost of production. The GFCM model shows that the economic benefit of using a PRG-RC over PRG has increased significantly between 2018-2020 and 2022. The projected cost of PRG-RC silage in scenario C, fertilised solely by digestate, has increased from €26.26 per tonne in 2018-2020 to €39.69 per ton in 2022, an increase of 51%. While in Scenario A, the PRG-RC silage fertilised using 0% digestate, the projected cost of production increase from €23.71 per ton to €32.78 per ton of silage or a 38% increase when the opportunity cost of the nutrient is accounted.

The results also highlight the importance of accounting for the opportunity cost of the nutrient content of digestate, particularly in a high fertiliser price environment like 2022. The opportunity cost of the nutrient off take per ha of 14t DM of silage increased from €400 to €977 between 2018-2020 and 2022. Many previous studies do not account for this nutrient opportunity cost, which may not be as important in a beef system when the silage and slurry remains on farm.

When accounting for the opportunity cost of nutrients in the digestate a significant proportion of the value is accounted for by the nitrogen content, which is not required by the red-clover based sward, due to the nitrogen fixing ability of the crop. The utilization of the digestate in another enterprise or farm and replacing nutrients with synthetic fertiliser would lead to a 17% cost saving in a PRG-RC system and 33% saving compared to a PRG system (see Table 3).

Comparison of the model silage crop with existing NFS farm enterprises

The NFS categorises farms based on the dominant enterprise on the farm such as specialist dairy, cattle rearing (suckler cow based), cattle other (non-suckler cow based), specialist sheep or specialist tillage. The average profit or net margin per ha of these enterprises (excluding decoupled direct payments) was calculated using the same data set as used for the grass silage production figures, outlined in section 4.1. This excludes farms which currently make less than 50 tons of silage and for the purposes of this analysis it is assumed that the capital infrastructure to store silage already exists on the farm.

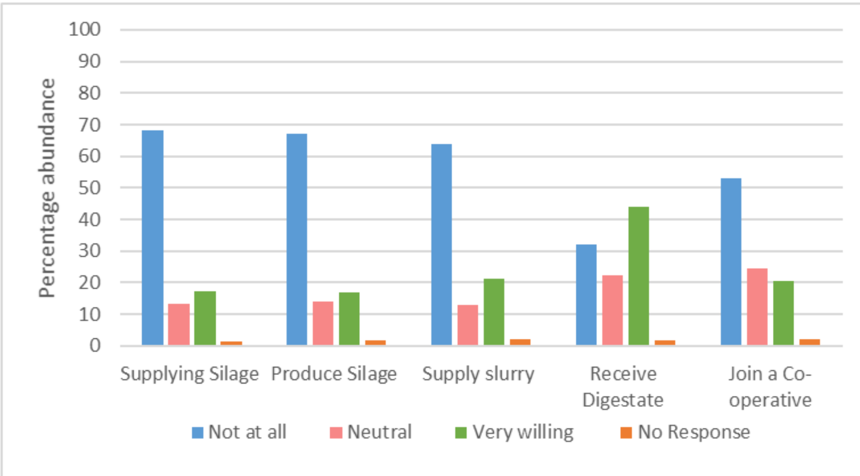
The average net margin per ha of existing farm enterprises are compared to the Scenario B - modelled PRG-RC crop, with the 1st cut of silage fertilised with digestate, including the nutrient opportunity cost for subsequent 2nd and 3rd cuts of silage, based on data from 2018-2020. The results are shown in Figure 6 for varying silage sales prices per ton of silage delivered. The clear finding is that the specialist dairy system is highly unlikely on economic grounds to supply silage for AD. Provided a sufficient price for silage of at least €35 per tonne is available, the specialist cattle rearing, specialist cattle other and specialist sheep systems would likely adopt the practice of supply silage for AD. However, a silage price of €40 per tonne would exceed the profit increase of €400 per ha which is the same level of remuneration as the tillage incentive scheme, which may be needed to overcome farmer inertia to change enterprises.

The specialist tillage system on average looks unlikely to switch towards growing silage for AD, however this does not account for individual crops within crop rotation. While winter wheat has a strong financial performance, growing a crop of silage fertilised with digestate may be competitive with a lower margin crop while providing a disease break and additional fertility benefits to subsequent arable crops. More detailed analysis would be required of these enterprises to determine their role in a rotational system.

3.5 Farmer Level Willingness to Engage in AD Feedstock Provision

The respondents were asked five questions on their willingness to adopt AD. Answers ranged from 1 (not at all) to 3 (Very willing). Farmer's willingness to adopt had no real differences between 4 of the questions suppling silage (1.52 ± 0.784), producing silage using multispecies and clover (1.51 ± 0.777), supplying slurry (1.63 ± 0.851) and joining a co-operative (1.71 ± 0.827). Although, there was a higher willingness amongst respondents regarding receiving digestate (2.16 ± 0.827).

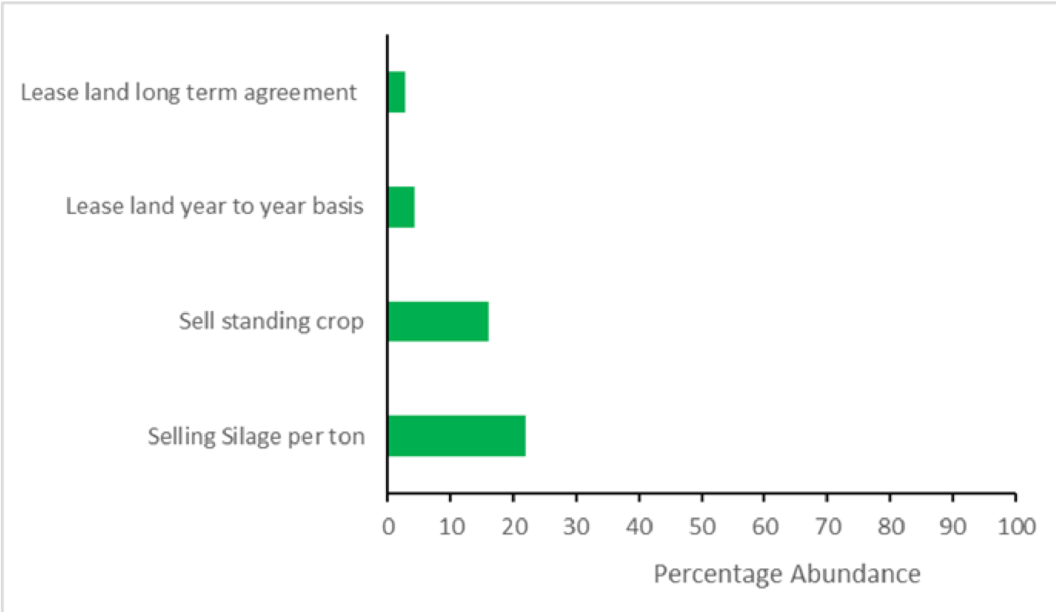
Figure 4: Willingness of farmers to participate in the adoption of AD.



Source: Author's estimates based on NFS data

In total, 17% of the weighted population (n=14682) responded "Very willing", 13% (n=11431) responded "neutral" and 68% (n=58244) responded "Not at all" for supplying silage. When asked regarding willingness to produce silage using multispecies and clover, 17% (n=14574) responded "Very willing", 14% (n=12130) "neutral" and 67% (n=57291) responded "Not at all". When asked regarding supplying slurry to an AD plant 21% (n=18088) responded "Very willing", 13% (n=11216) "neutral" and 64% (n=54430) responded "Not at all". Receiving digestate had the highest willingness to adopt rate, 44% (n=37478) responded "very willing", 22% (n=18980) "neutral" and 32% (n=27447) responded "not at all". The final question to join a co-operative yielded 21% (n=17527) responding "very willing", 24% (n=20802) "neutral" and 53% (n=17527) responded "not at all", to join a co-operative for the purpose of developing an AD plant as seen in Figure 4.

Figure 5: Preferred arrangement for the sale of silage.



Source: Author's estimates based on NFS data

From the farmers that were willing to produce and supply silage, their preferred arrangement for the sale of silage was selling silage per ton (22%). Lease of land through long term leasing agreements was the least popular arrangement for the sale of silage (3%) as seen in Figure 5.

The final question asked was whether or not farmers were willing to produce silage for AD and how much area would they consider growing for AD. Table 1 shows that of the farmers willing to grow silage as a feedstock for AD purposes, the farmers were willing to devote on average 20 acres of utilisable agricultural area, with a minimum area of 2 acres and a maximum area of 200 acres recorded. In total, based on the farmers that indicated that they would be willing to supply silage, they indicated they would supply a total weighted area of approximately 420,000 acres (175,000 hectares). The total amount of grassland area that is needed to reach the biomethane target of 5.7 TWh is estimated to be in the range of 110,000 to 130,000 ha, outlined in further detail in chapter 6.

Table 1: Area farmers would consider growing for AD in acres

	Total area	Average area	Minimum area	Maximum area
	acres			
Area of Silage for AD	420,000	20	2	200

Source: Author's estimates based on NFS data

3.6 Discussion

Economic analysis was carried out comparing historic silage production of existing enterprises to a model crop of silage based on a red-clover sward, for use as a feedstock in an AD plant. At present, in a livestock system silage is not generally considered a product for sale, but an intermediate product to sustain animal feed requirements through the indoor winter period. The production and sale of silage for AD would shift the focus of silage production to that of an end product from which farm income could be directly derived. The modelled crop with three cuts is likely to be most reflective of a farmer maximising silage production as a saleable product. Notwithstanding this limitation, there is good agreement between the average silage production costs in the NFS and the cost of production of the modelled crop.

Clover based silage such as the PRG-RC modelled in this study is shown to have a lower cost of production in all years compared to the existing PRG system which is predominant in Ireland. Assuming profit maximisation and perfect information, this technology should be the predominant silage sward in an AD feedstock supply scenario. While it is acknowledged that there would be heightened grazing management techniques required to maintain PRG-RC in the typical 1-2 cut silage systems in Ireland, this should not be a limitation within a 3+ silage system with only grazing occurring on the 4th cut or indeed replacing with zero-grazing. An interesting area for future study would be to extend the current analysis to examine on a whole farm basis, rather than the per hectare basis used in the current study, the net impact on income of looking at feedstock supply as a diversification option.

It is also acknowledged that a high level of technical management is required to maintain high levels of red clover in the sward over a number of years compared to PRG. The use of a clover-based sward as a specific crop for AD may aid in the adoption of this technology across the farming community by building knowledge and experience with these crops. The use of PRG-RC in a livestock system would likely have added complexity of grazing management however this could be built on initial learnings in an AD system with limited grazing.

The increase in input prices (and inorganic fertiliser nitrogen) between the study's time period of 2018-2020 and 2022 as shown in Figure 4 and Figure 5 shows an increased cost saving to be made from adopting clover based swards. This increase in the cost of production may be sufficient to overcome farmers' inertia to change and has anecdotally driven an increased area in clover based systems. The Red Clover Silage Measure (DAFM, 2023b) and Multi-Species Sward Measure (DAFM, 2023a) were also introduced to incentivise clover and multi species swards to reduce nitrogen usage in Ireland, however at the time of writing the effect within the NFS is not yet available.

This analysis assumes that pit silage is the method of preservation and storage of silage with the farm using existing infrastructure. In this scenario the capital expenditure of the silage pit and effluent tank are 'sunk' costs requiring maintenance. If growing silage for AD is required in excess of this current capacity then capital expenditure would have to be included, with an associated increase in the cost of silage production.

In existing farming enterprises silage is generally fed to animals on the farm and thus nutrients are cycled within the system. Indeed, when concentrates are imported and also fed with silage there would be additional nutrients in the slurry than solely from the silage. This paper is based on the assumption that when silage is being exported from the farm the nutrient opportunity cost of the material must be accounted for in the costs of production. When this is accounted for there are financial savings to be made on the costs of production of clover based swards relative to PRG based swards. Along with a financial saving this would further help to reduce synthetic nitrogen fertiliser usage and enhance the environmental sustainability credentials of the farming system.

While this study has abstracted away from scale by making evaluations on a per hectare basis, the selection criteria has meant that the only farms included in the evaluation were those with sufficient suitable land area and already making silage. Farms outside of this scope however could chose to supply silage such as specialist sheep or tillage farms. However, on the other hand, some farms may not be on land that is suitable to traffic silage making machinery.

While silage was traded in the study years at an average of €30 per ton, this analysis would suggest that on average this price would be unattractive for farmers to adopt growing silage for AD from an economic return perspective. It is therefore imperative in future analysis to build in an economic return for farmers to ensure economic sustainability along with environmental sustainability. The exact level of this financial return and level of risk would need to be studied further.

Given the increased importance attributed to AD in the case of Ireland recently, there are a number of specific research areas unexplored in this paper which appeared as particularly pertinent. Nutrient separation, particularly with a focus on nitrogen, could enable more reuse of digestate enabling a circular system, while exporting excess nitrogen production to locations of demand. While this work has focussed on silage, the use of separation technology in slurry would equally be important for economic and environmental sustainability reasons.

The economic case for growing silage for AD has been made, however over coming issues of inertia and social acceptability is an important element of establishing a successful AD industry. Whilst the NFS survey data has indicated that 25 percent of farmers would be willing to supply grass silage in sufficient quantities to reach the 5.7TWt target, inertia is present in the farming system and the risks involved in adopting a new technology may require sufficient financial incentive to realise sufficient adoption. In depth spatial, enterprise and whole farm analysis is required to evaluate how the adoption of agricultural AD could complement existing farm enterprises in terms of the three dimensions of sustainability; economics, environmental and social.

3.7 Conclusions

Economic analysis of a new enterprise of growing PRG-RC silage for AD has been modelled and compared to existing farm enterprises. The analysis has shown that excluding capital cost of land and silage storage facility, while including the nutrient opportunity costs, the new enterprise of supplying silage to an AD plant would be competitive with existing farm enterprises such as specialist cattle rearing, specialist cattle other and specialist sheep when the price of silage is above €35 per tonne. However, during the 2018-2020 time period, traded silage prices of €30 per tonne were recorded and these would be below the average cost of production.

The economic advantages of a red clover-based sward over PRG was demonstrated particularly in a high input cost scenario. This economic advantage applies to livestock systems as well as AD however grazing management for livestock is factor when producing silage for AD.

The valuing of nutrients in digestate and the use of digestate across the entire farming system has been highlighted in terms of economic benefits and a reduction in the use of synthetic nitrogen fertiliser and associated GHG emissions. Full utilisation of the economic value of nutrients in digestate may require capital investments in on farm or local storage facilities to spread digestate during peak crop demand, equally large scale adoption of growing silage would require capital investment in infrastructure which would increase the cost of feedstock.

4 Environmental Farm Modelling of Alternative Feedstock Solutions for a Regional AD Plant

4.1 Introduction

This chapter uses data from the Teagasc National Farm Survey to assess the effect of supplying biomass and animals wastes for anaerobic digestion. The research explores the effect across multiple environmental dimensions such as Ag. based GHG emissions, nitrogen balances and use efficiencies as well as likely effects on biodiversity. This analysis is conducted across a range of farm systems (dairy, cattle, sheep, tillage farms). The analysis elucidates the environmental efficiency of different scenarios in terms of biomass and organic waste supply to an anaerobic digestor. In addition, results from a preliminary qualitative assessment of potential biodiversity impacts of AD feedstock supply is outlined.

4.2 Methodology

Effect on GHG emission of supplying biomass & organic manures for AD

The baseline for this analysis is based on data from the Teagasc National Farm Survey. Teagasc publishes an annual sustainability report (Buckley & Donnellan, 2024) which details the average Intergovernmental Panel on Climate Change (IPCC) based GHG emissions by farm system. This analysis covers the main land based systems of agricultural production e.g. dairy, cattle, sheep and tillage. Table 2 outlines the profile of farms used in this analysis by farm system and covers the years 2021 to 2023. It also filters out farms that conserve less than 50 tonnes of silage per annum. This was deemed as a cut-off point around viability of grass dry matter export for AD purposes. The data presented are on a whole farm basis and for the silage area.

Table 2: Profile of sample used in the analysis by Farm System 2021- 2023

Farm Type	Dairy	Cattle	Sheep	Tillage	All Farms
Average Sample No.	312	322	75	39	748
Population Represented	14,885	44,042	13,979	2,977	70,955
Farm profile of NFS farms (average)					
Utilisable Agricultural Area (ha^{-1})	65.4	35.4	54.1	79.4	46
Grassland Area (ha^{-1})	64	34.7	52.9	38.1	43.3
Silage adjusted hectares*	14.8	5.5	4.9	7.1	7.5
Tillage Area (ha^{-1})	1.4	0.7	1.2	41.2	2.7
Dairy Cow Livestock Units	95.6	0	0	0	20
Cattle Livestock Units	42.4	43.5	24.7	48.6	40.9
Sheep Livestock Units	0.4	1.8	40.9	13.2	7
Total Livestock Units	138.4	45.3	65.6	61.8	67.9
Chemical N application (kg ha^{-1})	156.6	52	40.4	87.3	73.9
Chemical P application (kg ha^{-1})	11.6	6.5	6.4	15.4	7.9
Chemical K application (kg ha^{-1})	32.1	16.1	14.7	48.1	20.6
Tonnes of slurry applied (m3 ha^{-1})	8.9	5.8	2.8	2	5.9
Total tonnes of slurry applied (m3)	582.1	205.3	151.5	158.8	271.4
Organic N land spread in slurry (kg N ha-1)	21.3	14	6.8	4.9	14.3
Available Organic N land spread in slurry (kg N ha-1)	10.1	6.6	3.2	2.3	6.8
Organic P land spread in slurry (kg N ha-1)	7.1	4.7	2.3	1.6	4.7
Organic K land spread in slurry (kg N ha-1)	31.1	20.4	9.9	7.1	20.9
Whole Farm Nitrogen Rate	166.7	58.6	43.6	89.6	80.7
Whole Farm Phosphorus Rate	18.7	11.2	8.7	17.0	12.6
Whole Farm Potassium Rate	63.2	36.5	24.6	55.2	41.5
Tonnes of lime	33.1	9.7	14.9	33.1	16.3
Silage Area Chemical Nitrogen Rate	311.2	174.0	156.4	202.2	202.1
Silage Area Chemical Phosphorus Rate	24.6	22.1	27.8	27.1	23.5
Silage Area Chemical Potassium Rate	71.5	57.8	66.7	81.3	62.7
Silage Area Total Nitrogen Rate	321.3	180.6	159.6	204.5	208.9
Silage Area Total Phosphorus Rate	31.7	26.8	30.1	28.7	28.2
Silage Area Total Potassium Rate	102.6	78.2	76.6	88.4	83.6
Grass silage yield per adjusted hectare (Tonnes Dry Matter per hectare)**	15.6	12.3	11.9	12.8	12.9

***Adjusted hectare accounts for amount of time the area is dedicated to silage production as it may also be grazed by livestock for a period of the year ** A dry matter content of 27.7% was assumed based on McElhinney et al., 2015.**

Table 3 provides a breakdown of the profile and average GHG emissions (CO2 equivalent) per hectare by IPCC category for Agriculture (Category 3 under IPCC reporting) by farm system on a whole farm basis. This does not include energy based emissions associated with agricultural production (e.g. fuel, electricity). This outlines how dairy farms generate the highest level of economic return but also have the highest level of GHG emissions. The lowest level of emissions are associated with tillage farms, these have the second highest level of economic returns. Livestock farms (cattle and sheep) have the lowest economic returns with emissions circa half way between dairy and tillage systems. It should be noted that the majority of the emissions on farms with livestock (dairy, cattle, and sheep) are associated with Enteric Fermentation (69-72%). These emissions relate directly to the quantity of livestock on the farm. This is important to note when implementing scenario analysis later. Manure management and management of agricultural soils are the next two largest categories and could be significant in the analysis depending on the scenario being explored. Ammonia emissions (NH_3) are also reported in Table 2, the major sources of NH_3 emissions relate to the storage and spreading of animal manure and application of chemical fertilisers. Similar to baseline results for GHG emissions, the NH_3 emissions are highest on Dairy farms followed by Cattle farm. Hence, the per hectare GHG and NH_3 emissions outlined in Table 3 form the baseline scenario from which scenario analysis is imposed.

Scenario analysis examines the effect on GHG & NH_3 emissions of supplying grass for AD and secondly the GHG & NH_3 effect of supplying slurry as a feedstock. A number of sub-scenarios are also examined and further detail provided in the results section.

Table 3: Ag. based GHG emissions by NFS Farm System 2021-2023

Farm Type	Dairy	Cattle	Sheep	Tillage	All Farms
			Economic Returns		
Gross margin (€ ha^{-1})	3,012	1,049	973	1,562	1,473
Family Farm Income (€ ha^{-1})	1,603	359	376	681	636
		Category 3: Ag GHG Profile of NFS farms (average)			
3.A Enteric Fermentation (tonnes CO_2e per ha^{-1})	6.7	3.1	3.0	1.8	3.8
3.B Manure management (tonnes CO_2e per ha^{-1})	1.0	0.5	0.3	0.3	0.6
3.D Agricultural Soils (tonnes CO_2e per ha^{-1})	1.8	0.9	0.7	0.8	1.0
3.G Liming (tonnes CO_2e per ha^{-1})	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0.05	0.006	0.007	0.007	0.01
Total Ag. GHG emissions (tonnes CO_2e per ha^{-1})	9.7	4.6	4.2	3.0	5.6
		Ammonia (NH_3) Emissions (average)			
NH3 emissions kg ha^{-1} – manure management	39.4	21.3	13.5	11.9	23.7
NH3 emissions kg ha^{-1} – chemical N fertilisers	9.2	2.1	2.2	2.8	3.6
Total NH_3 kg ha^{-1}	48.6	23.4	15.7	14.7	27.3

Potential Biodiversity Impacts of AD Plants

During 2024, a focus group approach was used to assess the potential effect on farm level biodiversity outcomes across a range of farm systems arising from the supply of various biomass products and organic manures for anaerobic digestion under different scenarios.

The use of a focus group approach to understanding a research question was outlined in detail by Nyumba et al., (2018), whereby the researcher adopts the role of a "facilitator". The researcher facilitates a focus group discussion amongst the participants, notably the discussion does not happen between the researcher and the participants. The "facilitator" takes a peripheral role in the focus discussion, which primarily happens between the participants of the group.

The sample of experts consulted as part of this task were internal Teagasc experts, with knowledge in the area of biodiversity. Eight experts participated in the online workshop, facilitated by three independent facilitators, that were researchers working on the FLEET project.

Following a very brief overview of the potential of AD in Ireland and the associated technology, participants were introduced to two scenarios on which potential impacts on biodiversity were ascertained. A MURAL board was introduced, on which participants were invited to insert their opinions and a facilitated discussion was then held to further understand the opinions of participants. The two scenarios introduced were:

- Scenario 1 (S1): Impact of a shift from slurry application to digestate application on biodiversity components: species and ecosystems;
- Scenario 2 (S2): Impact of a shift to silage production as a feedstock for AD compared to an existing farm system, on biodiversity components: species and ecosystems.

The participants' opinions were categorised according to a positive, neutral or negative impact on two biodiversity components: species and ecosystems. The sub components of species were defined as microbes, plants and animals. The sub components of ecosystem were defined as water, soil and air.

4.3 Results

Effect of supplying grass as a feedstock for AD

This section outlines a number of sub-scenarios examined around growing grass for AD and substituting away from baseline status quo activities. It is assumed here that grass is grown using a perennial rye-grass (PRG) and red clover (RC) sward with different levels of Digestate returned (0%, 42% and 100%) to the sward to replace nutrient off-takes (phosphorus & potassium mainly). The baseline is assumed to be a perennial rye-grass sward with chemical N and slurry applied. The emission factors applied for GHG emissions are in line with the IPCC national inventory reporting (EPA, 2024), a national inventory approach was also followed for NH_3 in line with Hyde et al., (2024) in line with the approach used in the Teagasc Sustainability Report (Buckley & Donnellan, 2024). Emission factors for Digestate were not available for Ireland so the emissions factors from the UK national inventory report were applied (Brown et al., 2023).

Scenario 1: PRG-RC with 0% Digestate

Scenario 1 is based on the assumption that the grass feedstock is grown with a grass clover sward with no chemical, slurry or digestate N applied. Results are based on a standard 1 hectare of land under grassland where all the grass is harvested as a feedstock and replaces all animal-based emissions. Hence, under the IPCC based approach emissions associated with the keeping and housing of livestock are removed. Liming is the only remaining source of emissions under the IPCC framework. The assumptions and emissions associated with this scenario are detailed in Table 4 below. Additional quantities of phosphorus and potassium are required to maintain grass dry matter yield. Biological fixation of N via clover and mineralisation from the soil are assumed to be the only source of nitrogen under this scenario, results can be compared with Clavin et al (2016) where 14.9 tonnes of dry matter were grown using red clover with no chemical nitrogen. As no organic or chemical N is applied under this scenario and no livestock are retained under this scenario NH_3 emissions are eliminated and CO2e emissions are reduced to what is associated with liming.

Table 4: **Assumptions & gaseous emissions results PRG-RC with 0% Digestate scenario**

	Dairy	Cattle	Sheep	Tillage	All Farms
Grass silage yield per adjusted hectare (Tonnes Dry Matter)	15.6	12.3	11.9	12.8	12.9
Chemical N application (kg ha-1)	0	0	0	0	0
Organic N land spread in slurry (kg N ha-1)	0	0	0	0	0
Digestate (N kg ha-1)	0	0	0	0	0
Biological Nitrogen (N kg ha-1)	312	246	238	256	258
Chemical P application (kg ha-1)	46.8	36.9	35.7	38.4	38.7
Chemical K application (kg ha-1)	312	246	238	256	258
Livestock units	0	0	0	0	0
3.A Enteric Fermentation (tonnes CO2e per ha-1)	0	0	0	0	0
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	0	0	0	0	0
3.G Liming (tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0	0	0	0	0
Total Ag. GHG emissions(tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
NH3 emissions kg per hectare	0	0	0	0	0
Change in GHG vs baseline (tonnes CO2e per ha-1)	-9.5	-4.5	-4.0	-3.0	-5.4
Change in NH3 vs baseline (NH3 kg ha-1)	-48.6	-23.4	-15.7	-14.7	-27.3

Scenario 2: PRG-RC with 42% Digestate

Scenario 2 is based on the assumption that the grass feedstock is grown with a grass clover sward with no chemical or slurry based N applied but digestate applied accounts for 42% of crop N requirement. The remaining nitrogen is assumed to be supplied via biological sources. Additional chemical P and K are assumed to be applied to maintain crop yield. Results are again based on a standard 1 hectare of land under grassland where all the grass is harvested as a feed stock and replaces all animal based emissions. Hence, under the IPCC based approach emissions associated with the keeping and housing of livestock are removed. The remaining GHG emissions under the IPCC framework are based on Digestate applied under 3.D (Agricultural soils) and lime applied (3.G). Digestate is the only source of ammonia emissions under this scenario. As all livestock have been removed under this scenario results follow that of scenario 1 but GHG emissions reductions are somewhat less due to the addition of digestate. Digestate is a significant source of ammonia emissions and in this instance there is an increase in ammonia emissions on the standard hectare of tillage land. Baseline levels of emissions on tillage farms were the lowest of all the farm systems.

Table 5: Assumptions & gaseous emissions results underpinning PRG-RC with 42% Digestate scenario

	Dairy	Cattle	Sheep	Tillage	All Farms
Tonnes of grass DM yield – Silage baseline	15.6	12.3	11.9	12.8	12.9
Chemical N application (kg ha-1)	0	0	0	0	0
Organic N landspread in slurry(kg N ha-1)	0	0	0	0	0
Tonnes of Digestate applied ha-1	30.0	23.6	22.8	24.6	24.8
Digestate (N kg ha-1)	77.0	60.7	58.7	63.2	63.7
Biological Fixation (N kg ha-1)	244.3	185.9	179.9	193.4	195.2
Digestate P application (kg ha-1)	18.9	14.9	14.4	15.5	15.6
Digestate K application (kg ha-1)	139.9	110.3	106.7	114.8	115.7
Chemical P application (kg ha-1)	27.9	22.0	21.3	22.9	23.1
Chemical K application (kg ha-1)	172.1	135.7	131.3	141.2	142.3
Total Nitrogen required based on offtakes	312.0	246.0	238.0	256.0	258.0
Total P Required based on offtakes (P kg ha-1)	46.8	36.9	35.7	38.4	38.7
Total K Required based on offtakes (K kg ha-1)	312.0	246.0	238.0	256.0	258.0
Livestock units	0	0	0	0	0
3.A Enteric Fermentation (tonnes CO2e per ha-1)	0	0	0	0	0
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	0.45	0.36	0.35	0.37	0.38

3.G Liming (tonnes CO2e per ha-1)	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**
3.D Urea (tonnes CO2e per ha-1)	**0**	**0**	**0**	**0**	**0**
Total Ag. GHG emissions (tonnes CO2e per ha-1)	**0.65**	**0.46**	**0.55**	**0.57**	**0.58**
NH3 emissions kg per hectare	**19.6**	**15.4**	**14.9**	**16.1**	**16.2**
Change in GHG vs baseline (tonnes CO2e per ha-1)	**-9.0**	**-4.1**	**-3.7**	**-2.4**	**-5.0**
Change in NH3 vs baseline (kg NH3 per ha-1)	**-29.0**	**-8.0**	**-0.8**	**1.4**	**-11.1**

Scenario 3: PRG-RC with 100% Digestate

Scenario 3 is based on the assumption that the grass feedstock is grown with a grass clover sward with no chemical or slurry based N applied. However, Digestate applied accounts for 100% of applied nitrogen with the remainder of requirements coming from biological fixation. Under this scenario the crop required phosphorus and potassium is fully provided for by the Digestate, hence there is no need for chemical fertiliser supplementation. Results are again based on a standard 1 hectare of land under grassland where all the grass is harvested as a feed stock and replaces all animal based emissions. Hence, under the IPCC based approach emissions associated with the keeping and housing of livestock are removed. The remaining GHG emissions under the IPCC framework are based on Digestate applied under 3.D (Agricultural soils) and lime applied (3.G). Digestate is the only source of ammonia emissions under this scenario. Again as all livestock have been removed under this scenario results follow that of scenario 1 & 2 but GHG emissions reductions are somewhat less due to the addition of 100% digestate. Digestate is a significant source of ammonia emissions and in this instance there is an increase in ammonia across all farm systems except dairying, which has the highest level of baseline emissions.

Table 6: Assumptions & gaseous emissions results underpinning PRG-RC with 100% Digestate scenario

	Dairy	**Cattle**	**Sheep**	**Tillage**	**All Farms**
Tonnes of grass DM yield – Silage baseline	**15.6**	**12.3**	**11.9**	**12.8**	**12.9**
Chemical N application (kg ha-1)	**0**	**0**	**0**	**0**	**0**
Organic N landspread in slurry(kg N ha-1)	**0**	**0**	**0**	**0**	**0**
Tonnes of Digestate	**70.5**	**55.6**	**53.8**	**57.8**	**58.3**
Digestate (N kg ha-1)	**181.2**	**142.8**	**138.2**	**148.6**	**149.8**
Biological Nitrogen (N kg ha-1)	**140.2**	**103.8**	**100.4**	**107.9**	**109.1**
Digestate P application (kg ha-1)	**44.4**	**35.0**	**33.9**	**36.4**	**36.7**
Digestate K application (kg ha-1)	**329.1**	**259.5**	**251.1**	**270.1**	**272.2**

Chemical P application (kg ha-1)	**0**	**0**	**0**	**0**	**0**
Chemical K application (kg ha-1)	**0**	**0**	**0**	**0**	**0**
Total Nitrogen required based on offtakes	**312.0**	**246.0**	**238.0**	**256.0**	**258.0**
Total P Required based on offtakes (P kg ha-1)	**46.8**	**35.0**	**33.9**	**36.4**	**36.7**
Total K Required based on offtakes (K kg ha-1)	**312.0**	**259.5**	**251.1**	**270.1**	**272.2**
Livestock units	**0**	**0**	**0**	**0**	**0**
3.A Enteric Fermentation (tonnes CO2e per ha-1)	**0**	**0**	**0**	**0**	**0**
3.B Manure management (tonnes CO2e per ha-1)	**0**	**0**	**0**	**0**	**0**
3.D Agricultural Soils (tonnes CO2e per ha-1)	**1.07**	**0.84**	**0.82**	**0.88**	**0.88**
3.G Liming (tonnes CO2e per ha-1)	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**
3.D Urea (tonnes CO2e per ha-1)	**0**	**0**	**0**	**0**	**0**
Total Ag. GHG emissions (tonnes CO2e per ha-1)	**1.27**	**0.94**	**1.02**	**1.08**	**1.08**
NH3 emissions kg per hectare	**46.1**	**36.3**	**35.2**	**37.8**	**38.1**
Change in GHG vs baseline (tonnes CO2e per ha-1)	**-8.4**	**-3.7**	**-3.2**	**-1.9**	**-4.5**
Change in NH3 vs baseline (kg NH3 per ha-1)	**-2.5**	**12.9**	**19.5**	**23.1**	**10.8**

Scenario 4: PRG-RC with Digestate + protected urea

Scenario 4 is based on the assumption that the grass feedstock is grown with a perennial rye grass clover sward with no slurry based N applied. The crop required N comes from a combination of Digestate and chemical N in the form of protected urea. Under this scenario the crop required phosphorus and potassium is fully provided for by the Digestate, hence there is no need for chemical fertiliser supplementation for these elements. Results are again based on a standard 1 hectare of land under grassland where all the grass is harvested as a feed stock and replaces all animal based emissions. Hence, under the IPCC based approach emissions associated with the keeping and housing of livestock are removed. The remaining GHG under the IPCC framework are based on Digestate and protected urea applied under 3.D (Agricultural soils) and lime applied (3.G). Digestate and protected urea are the sources of ammonia emissions under this scenario. Results are in line with previous scenarios in terms of GHG emissions but the magnitude of reduction is not as large. Due to significant quantities of digestate (which is high in ammonia) in conjunction with protected urea fertiliser NH3 emissions are higher than the baseline across all farm systems. The increase in larger across non-dairy systems (dairying had the highest baseline emissions).

Table 7: Assumption & Gaseous emissions results underpinning PRG with Digestate + protected urea

	Dairy	Cattle	Sheep	Tillage	All Farms
Tonnes of grass DM yield – Silage baseline	15.6	12.3	11.9	12.8	12.9
Chemical N application (kg ha-1)	140.2	103.2	99.8	107.4	108.2
Tonnes of Digestate	70.5	55.6	53.8	57.8	58.3
Digestate (N kg ha-1)	181.2	142.8	138.2	148.6	149.8
Biological Fixation (N kg ha-1)	0.0	0.0	0.0	0.0	0.0
Digestate P application (kg ha-1)	44.4	35.0	33.9	36.4	36.7
Digestate K application (kg ha-1)	329.1	259.5	251.1	270.1	272.2
Chemical P application (kg ha-1)	0	0	0	0	0
Chemical K application (kg ha-1)	0	0	0	0	0
Total Nitrogen required based on offtakes	312.0	246.0	238.0	256.0	258.0
Total P Required based on offtakes (P kg ha-1)	46.8	36.9	35.7	38.4	38.7
Total K Required based on offtakes (K kg ha-1)	312.0	246.0	238.0	256.0	258.0
Livestock units	0	0	0	0	0
3.A Enteric Fermentation (tonnes CO2e per ha-1)	0	0	0	0	0
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	1.5	1.2	1.1	1.2	1.2
3.G Liming (tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0.10	0.08	0.07	0.08	0.08
Total Ag. GHG emissions (tonnes CO2e per ha-1)	1.8	1.3	1.4	1.5	1.5
NH3 emissions kg per hectare	52.0	40.7	39.4	42.3	42.7
Change in GHG vs baseline (tonnes CO2e per ha-1)	-7.9	-3.3	-2.8	-1.5	-4.1
Change in NH3 vs baseline (kg NH3 per ha-1)	3.4	17.3	23.7	27.6	15.4

Effect of supplying slurry as a feedstock for AD

This section outlines a number of sub-scenarios examined around sending livestock slurry as a feedstock for AD and replacing these nutrients with either a) Chemical fertilisers (protected urea, P & K fertilisers); b) Digestate from AD and c) Clover. This again assumes grass yields are held constant as in Table 1. Assumptions under these scenarios are set out below.

Scenario 5: Slurry N applied to land replaced with protected urea N

Scenario 5 is where livestock slurry is used as a feedstock for AD and the nutrients are replaced with chemical fertilisers. Assumptions underpinning the scenario are outlined in Table 7. Under this scenario slurry is assumed to be supplied frequently (fresh) to the AD pant for processing, hence emissions associated with manure storage are no longer applicable. The nutrient content of slurry is assumed to be replaced by chemical N in the form of protected urea and chemical P & K fertilisers. In terms of GHG emissions, results indicate a reduction of between 0.2 to 1.0 tonnes per hectare in emissions depending on the farm system examined. These reductions are associated with the removal of manure management on farm and associated emissions. There is also a significant reduction in NH_3 based emissions as the manure is assumed to be exported fresh, hence, the manure management based emission around housing, storage and land spreading are removed. Remaining emissions are based on chemical N application and emissions associated with outdoor grazing.

Table 8: **Assumption underpinning scenario where livestock slurry is used as an AD feedstock and nutrient are replaced with chemical fertilisers**

	Dairy	Cattle	Sheep	Tillage	All Farms
Tonnes of grass DM yield – Silage baseline	15.6	12.3	11.9	12.8	12.9
Tonnes of slurry applied (m3 ha-1)	0	0	0	0	0
Additional chemical N application required (protected urea kg ha-1)	10.1	6.6	3.2	2.3	6.8
Additional chemical P application required (kg ha-1)	4.5	2.9	1.4	1.0	3.0
Additional chemical K application required (kg ha-1)	31.2	20.3	9.8	7.0	20.7
Organic N land spread in slurry (kg N ha-1)	0	0	0	0	0
3.A Enteric Fermentation (tonnes CO2e per ha-1)	6.7	3.1	3	1.8	3.8
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	1.8	0.9	0.7	0.8	1.0
3.G Liming (tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0.007	0.005	0.002	0.002	0.005
Total Ag. GHG emissions (tonnes CO2e per ha-1)	8.7	4.1	3.9	2.8	5.0
NH3 emissions kg per hectare	15.5	5.5	5.4	5.3	7.6
Change in GHG vs baseline (tonnes CO2e per ha-1)	-1.0	-0.5	-0.3	-0.2	-0.6
Change in NH3 vs baseline (kg NH3 per ha-1)	-33.1	-17.9	-10.3	-9.4	-19.7

Scenario 6: Slurry N applied to land replaced with Digestate

Scenario 6 is where slurry is used as a feedstock for AD and the nutrients are replaced with digestate. Assumptions underpinning the scenario are outlined in Table 8. Under this scenario slurry is again assumed to be supplied frequently (fresh) to the AD plant for processing, hence emissions associated with manure storage are no longer applicable. The nutrient content of slurry is assumed to be replaced by digestate and shortfalls in P and K are assumed to be met by chemical fertilizers supplementation. GHG emissions results indicate a reduction of between 0.2

to 1.0 tonnes per hectare in emissions depending on the farm system examined. These reductions are again associated with the removal of manure management on farm and associated emissions. There is also a significant reduction in NH_3 based emissions as the manure is assumed to be exported fresh, hence, the manure management based emission around housing, storage and land spreading are removed. Remaining emissions are based on those associated with outdoor livestock grazing and land spreading of digestate.

Table 9: Assumption underpinning scenario where slurry is used as an AD feedstock and nutrient are replaced with digestate

	Dairy	Cattle	Sheep	Tillage	All Farms
Tonnes of grass DM yield – Silage baseline	15.6	12.3	11.9	12.8	12.9
Slurry applied per ha	0	0	0	0	0
Digestate applied (tonnes per hectare)	6.1	4.0	1.9	1.4	4.0
Digestate (N kg ha-1)	15.6	10.2	4.9	3.5	10.3
Chemical N application (kg ha-1)	0	0	0	0	0
Digestate P application (kg ha-1)	3.8	2.5	1.2	0.9	2.5
Digestate K application (kg ha-1)	28.3	18.5	8.9	6.4	18.8
Additional Chemical P application (kg ha-1)	0.6	0.4	0.2	0.1	0.4
Additional Chemical K application (kg ha-1)	2.8	1.8	0.9	0.6	1.9
Organic N land spread in slurry (kg N ha-1)	0	0	0	0	0
N landspread in Digestate (kg N ha-1)	15.6	10.2	4.9	3.5	10.3
3.A Enteric Fermentation (tonnes CO2e per ha-1)	6.7	3.1	3	1.8	3.8
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	1.8	0.9	0.7	0.8	1.0
3.G Liming (tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0	0	0	0	0
Total Ag. GHG emissions (tonnes CO2e per ha-1)	8.7	4.1	3.9	2.8	5.0
NH3 emissions kg per hectare	19.1	7.8	6.6	6.1	10.0
Change in GHG vs baseline (tonnes CO2e per ha-1)	-1.0	-0.5	-0.3	-0.2	-0.6
Change in NH3 vs baseline (kg NH3 per ha-1)	-29.5	-15.6	-9.1	-8.6	-17.3

Scenario 7: Slurry N applied to land replaced with clover and chemical P & K

Scenario 7 is where slurry is used as a feedstock for AD and the nutrients are replaced with N from biological fixation and chemical P & K fertilisers. Assumptions underpinning the scenario are outlined in Table 9. Under this scenario slurry is again assumed to be supplied frequently (fresh) to the AD plant for processing, hence emissions associated with manure storage are no longer applicable. GHG emissions results indicate a reduction of between 0.2 to 1.1 tonnes per hectare in emissions depending on the farm system examined. These reductions are again associated with the removal of manure management on farm and associated emissions. There is also a significant reduction in NH_3 based emissions as the manure is assumed to be exported fresh, hence, the manure management based emission around housing, storage and land spreading are removed. Remaining emissions are based on those associated with outdoor livestock grazing. NH_3 emissions have been reduced by between 9.5 to 33.5 kg per hectare depending on the farm system.

Table 10: **Assumption underpinning scenario where slurry is used as an AD feedstock and nutrient are replaced with N from biological fixation and chemical P & K fertilisers.**

	Dairy	Cattle	Sheep	Tillage	All Farms
Tonnes of grass DM yield – Silage baseline	15.6	12.3	11.9	12.8	12.9
Slurry exported per ha	8.9	5.8	2.8	2.0	5.9
Chemical N application (kg ha-1)	0	0	0	0	0
Additional chemical P application (kg ha-1)	4.5	2.9	1.4	1.0	3.0
Additional Chemical K application in protected urea (kg ha-1)	31.2	20.3	9.8	7.0	20.7
Organic N land spread in slurry (kg N ha-1)	0	0	0	0	0
N landspread in Digestate (kg N ha-1)	0	0	0	0	0
Biological Nitrogen (kg N ha-1)	10.1	6.6	3.2	2.3	6.7
3.A Enteric Fermentation (tonnes CO2e per ha-1)	6.7	3.1	3	1.8	3.8
3.B Manure management (tonnes CO2e per ha-1)	0	0	0	0	0
3.D Agricultural Soils (tonnes CO2e per ha-1)	1.7	0.9	0.7	0.8	1.0
3.G Liming (tonnes CO2e per ha-1)	0.2	0.1	0.2	0.2	0.2
3.D Urea (tonnes CO2e per ha-1)	0	0	0	0	0
Total Ag. GHG emissions(tonnes CO2e per ha-1)	8.6	4.1	3.9	2.8	5.0
NH3 emissions kg per hectare	15.1	5.2	5.3	5.2	7.3
Change in GHG vs baseline (tonnes CO2e per ha-1)	-1.1	-0.5	-0.3	-0.2	-0.6
Change in NH3 vs baseline (kg NH3 per ha-1)	-33.5	-18.2	-10.4	-9.5	-20.0

Summary of gaseous emissions results

Table 11 below presents a summary of GHG emission changes under the different scenarios versus the baseline. The scenarios (1 to 4) that involved replacing current actively levels with supplying grass as a feed stock indicate between a 50-98% reduction in GHG emissions depending on the farm system and scenario examined on a stylised per hectare basis. These reductions are primarily driven by the removal of livestock from the activity levels under the different scenarios, which eliminate all Enteric Fermentation (CH4), and manure management (CH_4 & N2O) based emissions. The scenario where biological N is the main supply for crop growth shows the largest reductions.

In the scenarios (5-7) where slurry was used as a feedstock, the emission reductions were significantly less than the grass feedstock scenarios. This was because the livestock were assumed to remain on the farm and only slurry based emissions were excluded, hence this excluded emissions around the storage and landspreading of slurry. Land spreading of digestate or protected urea attracted some additional emissions under the different scenarios. Results indicate between a 6.5-11.6% reduction in GHG emission depending on the scenarios and farm system type. The scenarios with biological N replacing slurry indicates the highest level of reduction followed by protected urea then digestate.

Table 11: Summary of GHG emissions changes on different scenario versus the baseline

Farm System	Dairy	Cattle	Sheep	Tillage	All Farms
% Changes in GHG Emissions vs Baseline					
Scenario 1 - PRG-RC with 0% Digestate	-98%	-98%	-95%	-93%	-96%
Scenario 2 - PRG-RC with 42% Digestate	-93%	-90%	-87%	-81%	-90%
Scenario 3 - PRG-RC with 100% Digestate	-87%	-79%	-76%	-64%	-81%
Scenario 4 - PRG-RC with Digestate + protected urea	-81%	-71%	-67%	-50%	-73%
Scenario 5 - Slurry N replaced with protected urea N	-10.7%	-11.4%	-7.4%	-6.9%	-11.1%
Scenario 6 - Slurry N replaced with Digestate	-10.1%	-10.6%	-7.0%	-6.5%	-10.5%
Scenario 7 - Slurry N replaced with clover	-11.1%	-11.9%	-7.7%	-7.2%	-11.6%

Table 12 below presents a summary of NH_3 emissions changes under the different scenarios versus the baseline. Scenario 1, where the entire N is provided by biological N eliminates, NH_3 emissions entirely. The 42% digestate scenario reduces NH_3 emissions on Dairy (-60%), Cattle (-34%) and Sheep (-5%) but increases them on tillage farms (+9%). Reductions on the more livestock orientated are due to the removal of manure housing, storage and land spreading based emissions. Tillage farms had the lowest baseline NH_3 levels and digestate is associated with higher level of NH_3 emissions. Scenario 4 elucidates this as under the digestate and protected urea scenario, NH_3 emissions increase significantly across all farm systems. The increase was largest across non-dairy system (dairying had the highest baseline level of emissions).

In the scenarios (5-7) where slurry was used as a feedstock, the emission reductions were also significant, between 58-78% depending on the scenario and farm system. Again as all livestock manure housing, storage and land spreading emissions are assumed to be avoided, this drives these reductions, as under these scenarios just emissions associated with the land spreading of protected urea and digestate apply.

Table 12: Summary of NH_3 emission changes in different scenarios versus the baseline

Farm System	Dairy	Cattle	Sheep	Tillage	All Farms
% Changes in NH3 Emissions vs Baseline					
Scenario 1 - PRG-RC with 0% Digestate	-100%	-100%	-100%	-100%	-100%
Scenario 2 - PRG-RC with 42% Digestate	-60%	-34%	-5%	9%	-41%
Scenario 3 - PRG-RC with 100% Digestate	-5%	55%	124%	157%	40%
Scenario 4 - PRG-RC with 100% Digestate + protected urea	7%	74%	151%	188%	56%
Scenario 5 - Slurry N replaced with protected urea N	-68%	-77%	-65%	-64%	-72%
Scenario 6 - Slurry N replaced with Digestate	-61%	-67%	-58%	-58%	-63%
Scenario 7 - Slurry N replaced with clover	-69%	-78%	-66%	-64%	-73%

Effect on nutrient balances of supplying biomass & organic manures for AD

Following the approach of Buckley et al., (2016) and Buckley & Donnellan (2024) baseline level of N balances and use efficiency by farm system for the sample are reported in Table 13. The N balances and use efficiencies are reported at the farm gate level (tracks imports and exports that go through the farm gate) and does not account for N deposition or biological fixation that is considered here under scenarios 1-4 and 7. Hence, a direct comparison is not possible where biological N is prevalent.

Table 13: Baseline level of average farm gate level N surplus

	Dairy	Cattle	Sheep	Tillage	All Farms
Nitrogen inputs (kg ha-1)	**217.0**	**72.6**	**62.3**	**126.1**	**104.2**
Nitrogen offtakes (kg ha-1)	**57.1**	**17.0**	**15.7**	**80.6**	**27.8**
N balance (kg ha-1)	**159.9**	**55.5**	**46.6**	**45.5**	**76.3**
Nitrogen use efficiency	**26.2%**	**23.5%**	**25.7%**	**63.9%**	**25.9%**

However, scenarios 5 and 6 can be compared at a farm gate level as nitrogen inputs in these scenarios cross the farm gate. Table 13 indicated a reduction of between 2.6 to 11.2 kg in N ha_{-1} balances (surpluses) when substituting organic N in slurry for protected urea depending on the farm system. Nitrogen use efficiency increased by between 1.0-2.6% again depending on the farm system under scenario 5.

Table 14: **Changes in Nitrogen balance and use efficiencies under scenario 5 (Slurry N replaced with protected urea N)**

Farm System	Dairy	Cattle	Sheep	Tillage	All Farms
Scenario 5 - Slurry N replaced with protected urea N					
Changes in Chemical N application (kg ha-1)	10.1	6.6	3.2	2.3	6.8
Changes in Organic N slurry (kg ha-1)	-21.3	-14.0	-6.8	-4.9	-14.3
Changes in Organic N Digestate (kg ha-1)	0	0	0.0	0.0	0.0
Changes in Nitrogen inputs (kg ha-1)	-11.2	-7.4	-3.6	-2.6	-7.5
N balance (kg ha-1) under scenario 5	149	48	43	43	69
Changes in N Balance (kg ha-1)	-11.2	-7.4	-3.6	-2.6	-7.5
Nitrogen use efficiency under scenario 5	28%	26%	27%	65%	29%
Changes in Nitrogen use efficiency	+1.5%	+2.6%	+1.0%	+1.3%	+2.9%

Table 15 reports results for scenario 6 where the organic N applied in slurry is substituted for Digestate. Depending on the farm system, the N balance (surplus) declined by between 1.4 and 5.7 kg N ha_{-1}. The reduction was highest across dairy farms on average. The nitrogen use efficiency increased by between 0.3% to 1.2% as seen in Table 14.

Table 15: **Changes in Nitrogen balance and use efficiencies under scenario 6 (Slurry N replaced with Digestate)**

Farm System	Dairy	Cattle	Sheep	Tillage	All Farms
Scenario 6 - Slurry N replaced with Digestate					
Changes in Chemical N application (kg ha-1)	0.0	0.0	0.0	0.0	0.0
Changes in Organic N slurry (kg ha-1)	-21.3	-14.0	-6.8	-4.9	-14.3
Changes in Organic N Digestate (kg ha-1)	15.6	10.2	4.9	3.5	10.3
Changes in Nitrogen inputs (kg ha-1)	-5.7	-3.8	-1.9	-1.4	-4.0
N balance (kg ha-1) under scenario 6	154.2	51.7	44.7	44.1	72.3
Changes in N Balance (kg ha-1)	-5.7	-3.8	-1.9	-1.4	-4.0
Nitrogen use efficiency under scenario 6	27%	25%	26%	65%	28%
Changes in Nitrogen use efficiency	0.8%	1.2%	0.3%	0.7%	1.8%

Potential Biodiversity Impacts

This section outlines the results from the qualitative focus group discussion regarding particpants opinions on the two biodiversity components: species and ecosystem. Table 16 and 17 outline the themes identified from the qualitative assessment of biodiversity species and ecosystem related impacts respectively associated with S1: impact of a shift from slurry application to digestate application. Similarly, Table 18 and 19 outline the themes identified from the qualitative assessment of biodiversity species and ecosystem related impacts respectively associated with S2: grass silage production for AD feedstock compared to a status quo Business as Usual (BaU) farm system.

In general, there tended to be discussion points entered for positives and negatives associated with S1. However, the discussion time tended to be slightly more weighted to the discussion of possible negative outcomes for species related biodiversity impacts, whereas there was more time devoted to positive related outcomes on the ecosystem related biodiversity impacts of a shift to digestate compared to slurry spreading.

Likewise for S2, there tended to be discussion points entered for potential positive and negative biodiversity impacts. The identified biodiversity positive impacts with S2 were caveated with the understanding that the impacts would be largely influenced by what the AD silage feedstock was replacing, in particular, the existing positive biodiversity impacts of old permanent pastures should not be compromised. There was an identified need for the role of education in preserving existing biodiversity rich swards.

Finally, it must be noted that this was a very general discussion in a structured focus group setting, with a lot of risks and unknowns identified in both S1 and S2. In particular, there were significant caveats discussed relating to how biodiversity impacts on species and ecosystems would differ depending on the region and the superseded enterprise. This scoping study on potential biodiversity impacts was of a very high level nature, with first round impacts identified. In future research a more in depth study focused on achieving a consensus amongst a wider set of experts would be useful on the potential biodiversity impacts of AD feedstock supply.

Table 16: Themes identified from qualitative assessment of biodiversity species related impacts associated with S1: Impact of a shift from slurry application to digestate application

	Positives	**Negatives**
Microbes	• Potentially lower pathogenic load in digestate vs slurry due to heating/ pasteurisation • Solid types of digestate may also increase Arbuscular Mycorrhiza Fungi (AMF) and soil mycelia over the longer term. AMF are soil-borne fungi, which help plants take up water, nutrients, and also overcome abiotic stresses.	• Use of digestate with high ammonium content could potentially decrease soil fauna (and their associated soil functions). • It was assumed that application rate could potentially impact on the negatives of soil fauna, but a trade off on traffic impacts on soil must to be considered. For example, if soils are waterlogged and digestate is applied using a fully loaded tanker, the cost of trafficking on soil structure and content must be taken into account.
Plants	• Use of digestate has the potential to increase sward production due to higher N, P and K input, compared to slurry.	• The slightly higher N content of digestate returning to the land may impact sward persistency of clovers, at high application rates. There may be a need to reduce the quantity of digestate applied to offset the high N content.
Animals	• No positives associated with a animals in a biodiversity context were identified	• Possible risks associated with the use of liquid digestate include a possible reduction in the number of soil macrofauna (nematodes, earthworms), due to high ammonium content • Possible compaction: leading to a reduced number of nematodes, earthworms, etc, associated with high traffic on ground.

Table 17: Themes identified from qualitative assessment of biodiversity ecosystem related impacts associated with S1: Impact of a shift from slurry application to digestate application

	Positives	Negatives	Neutral
Water	• The difference in nutrient content and dry matter of the digestate in comparison to cattle slurry, has the potential to positively impact on water quality, if appropriate management techniques are applied. • Reducing livestock from land in some areas might be beneficial for water quality. • Reducing chemical fertiliser use might be beneficial for water quality.	• Is there a risk of increasing stocking rate in one block of land to allow another block of land to be used to supply AD plants, which could have a negative impact on water quality? • Do we know what the potential effect of digestate on water quality is? There was uncertainty regarding the current research in this area. • The potential impact at a regional level may differ, due to soil conditions and risk to water quality.	
Soil	• Higher nutrient value in digestate has the potential to displace chemical fertilisers • Solid digestate (with higher fibre and recalcitrant C) can enhance soil structure and potentially C sequestration • Potential for better information on nutrients available in digestate (NPK), therefore improved/ targeted application to be considered a positive for soil health	• The liquid component of digestate (with high N ammonium) may potentially increase N priming effects on SOC mineralization • If ploughing of old permanent pasture were to occur to establish grass/red clover swards, this could have a negative on soil health.	• The beneficial / detrimental effects of digestate on soil health and living organisms depends on its type and quality (organic matter content & quality, solid vs. liquid form, labile vs. recalcitrant C, ammonium, etc). • Particular unknowns were identified relating to the potential impact of digestate versus slurry on carbon sequestration • Particular unknowns were identified relating to the difference
Air	• Biogas from digestate replaces fossil fuels, which can contribute to decreases in GHG emissions	• Potential for a risk of increased ammonia emissions from AD was questioned.	• Particular unknowns were identified relating to the difference in N2O emissions in slurry versus digestate. vs slurry.

Table 18: Themes identified from qualitative assessment of biodiversity species related impacts associated with S2: grass silage production for AD feedstock compared to a status quo Business as Usual (BaU) farm system

	Positives	Negatives
Microbes	• The growing of multispecies (MSS) was generally agreed to improve soil structure and thus soil microbes. However, the benefit was caveated with what the MSS was replacing. If MSS is to replace Perennial Rye Grass (PRG) then soil microbes should benefit, but the impact on well established long term pasture was not as well know.	• The only negative identified for microbes associated with the switch to silage production from existing farm systems was a possible negative for the dung bettle.
Plants	• MSS enhance biodiversity compared to permanent pastures dominated by perennial ryegrass • The growing of MSS was also identified as potentially improving the nutritional value of silage, if used for part of the year for dry stock system fodder.	• If MSS replace old permanent pasture this could be viewed as having a negative impact on plant diversity. • Continued long term silage production was viewed as having a potentially negative impact on sward persistency even in a PRG sward due to the requirement for more regular reseeding. • Whilst there was no known history of disease with red clover in Ireland, it was stated that there is an issue in UK and EU. Red clover requires a break crop between subsequent sowings of 3 to 4 years, to avoid the incidence of eel worms.
Animals	• If MSS are used (vs clover-grass mix) the potential to benefit pollinators/ birds was discussed. • The potential for improved daily gain from grass/clover silage compared to PRG, which has the potential to reduce concentrate feed requirements on livestock enterprises.	• In an existing arable system, a switch to reduced arable area in favour of silage for AD could result in less cover crops and potentially less winter food supply for wildlife.

Table 19: Themes identified from qualitative assessment of biodiversity ecosystem related impacts associated with S2: grass silage production for AD feedstock compared to a status quo Business as Usual (BaU) farm system

	Positives	**Negatives**
Water	• A potential for reduced nutrient run off was cited as a possibility with the scenario of silage feedstock production, compared to the baseline of existing farm systems. • A reduction in livestock, may be beneficial in some areas, for water quality.	• Uncertainty regarding the benefits, costs and regional nature of the benefits and costs for water quality was discussed. Uncertainty was deemed to have a potential negative impact on uptake of feedstock production in the early stages of development. • Potentials for water quality improvements associated with changing farming system may be impacted by farmers attitude to change. Changing farm system was viewed as difficult for farmers that have invested in their current system and have knowledge/skills in their current farming system. • At a spatial level, the areas that have the potential to grow the significant volumes of silage feedstock are typically areas most profitable in the current scenario. Hence, the potential for water quality improvements associated with the system change will be limited by existing farm level economics.
Soil	• Returning a fraction of organic matter and nutrients back to soil was viewed as having a potentially beneficial impact on soil health, compared to the use of chemical fertilizers. • Diversification of sward was cited as having a potentially positive impact on resilience to drought. • MSS was cited as having a potential to sequester organic carbon deeper in the soil profile relative to shallow rooting grasses •	• There was some concern that even if silage production for AD comes from more productive land and not old permanent pasture (which would be a loss to biodiversity), this could put extra pressure on other farmers to take land and improve land, which will increase demand for land generally and a concern regarding impacts on old permanent pasture. • Harvesting three to four cuts of high quality silage in a narrow window could lead to significant land damage.
Air	• MSS were cited as beneficial in terms of lower nitrous oxide emissions compared to the use case of chemical fertiliser application on traditional agricultural enterprises.	• No negatives associated with air in a biodiversity context were identified.

5 Transport Modelling of Alternative Feedstock Solutions for a Regional AD Plant

This work package explores the application of Geographic Information System (GIS) methods to provide an updated comprehensive spatial analysis of the key locations of enterprises with biomass and manure production and their relative proximity to target users. Due to the cost of hauling various biomass products and organic manures, proximity of supply is a key issue for exploration in the context of various scenarios investigated. A thorough economic assessment of the most appropriate regimes for biomass and manure usage needs to account for the distance/transport cost variable. This spatial assessment of the source/target relationship provides a key input in to the formal assessment of the nature of the distance-cost equation.

The development of this analysis also provides a new high resolution method and an updated approach to develop baseline datasets and which could be used to model the economic impacts of different biomass and manure management strategies under various policy initiatives.

5.1 Introduction

The National Biomethane Strategy (Government of Ireland, 2024) sets out national policy on the development of biomethane industry in Ireland. It describes twenty-five actions with the ambitions of scaling the production of indigenously produced biomethane by up to 5.7 TWh by 2030. Three scenarios for the deployment of Biomethane were assessed by the National Biomethane Working Group and are addressed in the strategy document. These range from widespread deployment with a larger number of smaller plants, through to what is termed an economic deployment, which envisages a smaller number of larger plants. The strategy acknowledges that while a combination of both the widespread and economic approaches should be followed, larger plants will be generally favoured by private developers due to the arising economies of scale.

Spatial assessment of Anaerobic Digestion resources

Understanding how variations in feedstock ratios can affect the performance of AD facilities is pivotal for optimizing their location, operational efficiency and sustainability. A considerable amount of research has been conducted in recent years on various aspects of the development of a rural based Anaerobic Digestion industry producing biogas and ultimately biomethane. Much of the work has focussed on the supply potential for feedstocks derived from agriculture. These are principally expected to be comprised of animal manures, which optimally would be co-digested with plant material. In Ireland, due to the nature of its dominant agriculture industry with an extensive pasture based system, grass is perceived as the feedstock with the strongest potential for co-digestion with animal manures.

The availability of feedstocks such as grass silage and animal slurry spatially vary in their availability across regions due to varying agricultural practices. Studies utilizing GIS tools for spatial analysis highlight regions with excess feedstocks that could feasibly support new anaerobic digestion facilities. O'Shea et al. (2016) investigated the potential extent and geography of a renewable gas industry based on waste digestion of wastes in Ireland. They sought to provide comprehensive assessment of the potential Biomethane resource derived from bio-based waste stream and identify the spatial distribution of these waste resources. The geographic unit of their analysis of feedstock supply was the Electoral Division (ED).

Singlitico et al. (2018) conducted an evaluation of the potential for and possible spatial distribution of target feedstocks for bio-SNG (sustainable natural gas) production in Ireland. They used Electoral Divisions as their minimum geographical unit for assessment and reporting. Beausang et al. (2021) highlighted the biomethane resource associated with surplus grass and cattle slurry for a region in Ireland and provide mapping, also using the ED as a base geographic unit.

The National Heat Study (SEAI 2022) conducted a detailed analysis of the availability and national spatial distribution of potential feedstock. Using detailed data on land parcel and land use and data on animal numbers and their associated locations enabled a detailed geographical analysis to be performed. The potential availability of cattle slurry and areas where surplus grass could be best redirected towards AD were presented as 5 km grid square maps. Importantly, the study notes that the economic assessment of the costs arising from the transportation of feedstock to potential AD plants will depend on the road network and the actual distance travelled and not just straight line distances between plants and supply locations.

O'Shea et al. (2016) account for this issue of straight-line compared to real, along-road transport distance when assessing the transport cost component in optimally siting modelled plants and the injection of biomethane into the Irish gas network. After Smyth et al. (2011) they apply a tortuosity factor of $\sqrt{2}$ to their Euclidean distances in order to account for the winding nature of rural roads.

Network Analysis and location-allocation

Fischer (2004) noted that although conceptually simple, network location-allocation problems involving routing are among the most difficult to solve due to their inherent complexity. The aim of the current research is to provide a network-based analysis of the location of large pig-producing enterprises in relation to potential arable land. Allocation-modelling, which is considered to be the most useful for this research, is the modelling of supply and demand through a network system. Supply represents a quantity of some resource or quantified service that is located at a facility. Demand is the potential for the use of the resource or commodity. Allocation is the process bringing together demand and supply at one or more locations in space.

Until recently location-allocation algorithms were not routinely implemented in most available GIS software packages, largely due to their inherent complexity. Deployment of location-allocation routines was traditionally very difficult due to both hardware and software limitations. With improvements in both hardware and GIS software, application of location-allocation modelling, though still computer-resource intensive, is considerably more amenable to general use. Although the method tends to have an initially steep learning overhead, implementation of the approach is now sufficiently robust and has been used successfully in the roads-AD enterprise analysis we present here.

5.2 Data

A number of key datasets were required to enable a high-resolution analysis to be performed and to ensure that the design of our scenario analysis conformed as closely as possible to existing or emerging policy guidance in the area of anaerobic digestion in Ireland. These datasets are outlined here and are further discussed where applicable in the Methods section.

Land Parcel Identification Scheme (LPIS)

The LPIS dataset is a geospatial database established under Article 17 of Council Regulation 73 (European Commission, 2009) and originally developed as a key element of the Integrated Administration and Control System (IACS).

The database contains high spatial and temporal resolution information on agricultural activity (Zimmermann et al., 2016). The LPIS datasets are managed within each member state by its respective paying agency, which in Ireland is the Department of Agriculture, Food and the Marine (DAFM). For the LPIS implementation in Ireland, a parcel is an area of land owned by a farmer and can either be made up of multiple nearby fields/paddocks or more commonly comprise subdivisions of a field into multiple parcels.

Parcel boundaries are either defined by physical features or by the boundaries of differing crop types for the year in question or property boundaries. The datasets cover the entire Republic of Ireland and in each case of issue, represents a single year, dating back to January 1996. However, the dataset is only considered complete from 2000 onwards. The parcels range in size from < 0.01 ha to > 65000ha with an average size of 10.23 ha (Zimmermann et al., 2016).

The high spatial and temporal resolution of LPIS provides an excellent opportunity to improve the resolution of spatial research undertaken in various fields of environmental research. However, as LPIS was developed specifically for grant administrative purposes i.e. grant payments and management, there are important limitations that need to be taken into account when using the database for scientific research and in other application areas.

Distribution of the LPIS dataset is normally limited due to concerns around confidentiality, and until relatively recently was not generally available for use other than its intended purpose of managing agricultural subsidy payments, in addition to some limited research applications permitted on a case by case basis. More recently, however, the DAFM has made a relatively comprehensive version of the dataset available publically. This has been made possible while maintaining confidentiality through the anonymization of the details of herd ownership. This is done to protect original LPIS applicant farm stakeholders. The dataset *Anonymised LPIS and N&P (Nitrates and Phosphorus) for 2022* was downloaded from the Department of Agriculture Food and Marine open data site.

Soils

The Teagasc EPA Indicative Soils Map was produced in 1998, in response to European legislation (Fealy et al, 2009). Arising from the fact that 56% of the country remained unmapped, Teagasc was tasked with producing the national Indicative Soils Map of Ireland (IFS). The map used data from the previous soil survey, along with novel remote sensing and Geographical Information Systems (GIS) techniques to develop a predictive model of soil types for previously unmapped areas.

Teagasc developed the national indicative soils map to a standardised methodology. The map classifies the soils of Ireland on a categorically simplified but cartographically detailed basis into 25 classes, using an expert rule based methodology. The soils map has a nominal working scale of 1:100,000-1:150,000.

National Parks and Wildlife Service (NPWS)

The NPWS estimates that approximately 13.79% of the national territory of Ireland is currently protected for nature conservation. (Department of Housing, Local Government and Heritage, 2021). The land under statutory protection includes six National Parks and 80 Statutory Nature Reserves. Approximately 10% of terrestrial designated sites are owned by the Irish State, with the remaining 90% privately owned.

Central Statistics Office reporting (2024) for the area of Ireland under agriculture in 2023 indicate that approximately 66% of the Irish land area is used for agricultural production (excluding commonage land). NPWS estimates that in total approximately 60% of the area of designated nature conservation sites is being farmed.

Stout and Ó Cinnéide, (2021) outline the various designations and detail the amount of land apportioned to these in Ireland Table 20. Knowledge of the extent and location of these protected areas is very relevant to the assessment of feedstock availability, primarily due to the conservation obligations effective on these land areas under national regulations but also in light of RED II sustainability obligations (European Commission, 2019b).

Table 20: Protected Areas designated by the NPWS

Type of Protection	Number of sites	Total area
Special Areas of Conservation (SAC)	439	16,944 km2
Special Protection Areas (SPA)	154	5,971 km2
Natural Heritage Areas	148	603 km2
National Parks	6	687 km2
Nature reserves	74	189 km2

Source: Adapted from Stout and Ó Cinnéide (2021)

NHAs

The basic designation for wildlife in the Irish state is the Natural Heritage Area (NHA). This is an area considered important for the habitats present or which holds species of plants and animals whose habitat needs protection.

pNHAs

In addition to the designated NHAs, there are 630 proposed NHAs (pNHAs), which were published on a non-statutory basis in 1995, but have not since been statutorily proposed or designated. These sites are of significance for wildlife and habitats. The pNHAs cover approximately 65,000ha and designation will proceed on a phased basis over the coming years.

Special Areas of Conservation

Special Area of Conservation are prime wildlife conservation areas in the country, considered to be important on a European as well as Irish level. Most Special Areas of Conservation (SACs) are in the countryside, although a few sites reach into town or city landscapes, such as Dublin Bay and Cork Harbour. The areas designated as SAC in Ireland cover an area of approximately 13,500 sq. km. Roughly 53% is land, the remainder being marine or large lakes.

Special Protection Areas

The EU Birds Directive (79/409/EEC) requires designation of SPAs for listed rare and vulnerable species, regularly occurring migratory species, such as ducks, geese and waders and wetlands, especially those of international importance, which attract large numbers of migratory birds each year.

National Parks

There are currently 7 National Parks, originally designated under the guiding criteria and standards for National Parks set by the International Union for the Conservation of Nature (IUCN).

Official data in GIS format from the NPWS were downloaded from NPWS. All boundary datasets were downloaded for designated areas comprising Special Protection Areas, Proposed Natural Heritage Areas, Natural Heritage Areas and Special Areas of Conservation and National Parks.

Topography

To represent the land surface and derive both slope and elevation thresholds for land suitability assessment, we used a 20m Digital Terrain Model (Preston & Mills, 2002). This was originally developed using national 1:50,000 Ordnance Survey Ireland data.

Admin Boundaries

We used the Townland boundary dataset from Tailte Eireann, the Irish national mapping agency (previously Ordnance Survey Ireland). The Townland is the smallest administrative division in the country and varies in size from approximately 1 acre to 7000 acres. All other territorial delineations are collections of townlands. There are approximately 51,000 townlands in the Republic of Ireland. (Tailte Eireann, 2019). We also used the Electoral Divisions (EDs) data generated from the 2019 National Statutory Boundary dataset. There are 3,440 EDs, which are the smallest, legally defined administrative areas in the State. (Tailte Eireann, 2019).

Urban

In order to exclude national urban areas from consideration in our analysis, CSO Urban and Built Up Area boundaries were acquired from Tailte Eireann. This a new dataset that has been jointly developed by CSO and Tailte Eireann and is hosted for download from Tailte Eireann (CSO/Tailte Eireann, 2022)

Road network

We use a roads dataset provided by Tailte Eireann. Tailte Eireann holds the roads data in an authoritative digital referencing framework known as PRIME2 and which acts as the primary database for Tailte Eireann national geospatial data. DLM Core is a digital landscape model that presents normalised PRIME 2 data (OSI, 2016). Within DLM Core, roads and other routes are presented as 'Ways'. Ways are made up of *WayNetWorksgements* and *WayNetwrokNodes*. These essentially describe the line and point junction geometry of the national route network. Using this data model and the information it contains on how lines and point junctions relate to each other allows topologically connected networks to be built within a GIS framework and which underpin our location-allocation analysis

Gas network

Gas Networks Ireland (GNI) have outlined that by 2028 in the region of 15 to 20 Centralised Grid Injection facilities could be developed across the country at locations in close proximity to the existing gas grid. They state that "*Renewable gas producers within 50km of the existing gas grid will be able to avail of these facilities, using high capacity gas storage trailers to transport their gas via road, and inject into the national gas grid.* " (GNI, 2018, pg13)

The Biomethane Catchment Map (GNI, 2018) highlights all geographical regions within a 50km radius of the existing gas transmission network. This map indicates to biogas plant developers and operators whether their planned facilities are likely to be within the catchment zone.

While GIS based datasets on the national gas network of Biomethane catchment zones were not easily accessible, we used publically available information from GNI to assist in our assessment. In the absence of digital GIS data, we imported the published map image of 50 km catchment zones to our GIS and using standard GIS tools georeferenced it to ensure a good approximation to spatial location of the contained map elements. Having assigned geographic referencing to the map, we were able to spatially capture the catchment zones. This provided a working version of the spatial information delineating GNI's suggested areas for consideration for siting AD plants. This spatial dataset was then used as a constraint parameter for locating facilities in our location-allocation modelling.

5.3 Methods

Location-Allocation analysis

The Location-Allocation routine was run in an ArcGIS Pro GIS software environment. The solver routine is essentially based on matching demand with supply. To match demand with supply, and to assess the time or distance cost arising, transportation or movement through a network must be modelled. The demand is brought-or allocated-to the supply, or the supply is brought-or allocated- to the demand through the network. In our case, the network analysis is run in a form analogous to a population demand for a centrally available service where each of a set of demand points is assigned to the supply centre or facility for the purposes of appropriate resource allocation. Key terms used in the location-allocation routine are 'facility', 'demand', 'weight' and 'impedance'.

A demand weight is assigned to a set of demand points that notionally seek to consume goods and services from a set of facilities. An impedance value provides a distance or time threshold beyond which demand will not be allocated. The goal of the location-allocation solver is to locate the facilities in a way that supplies the demand points most efficiently. As the name suggests, location-allocation is a twofold problem that simultaneously locates facilities and allocates demand points to the facilities The algorithm seeks to locate facilities such that as many demand points as possible and that are required are allocated to chosen facility locations within a chosen impedance cut-off. Impedance can be set as a travel time or a distance parameter. In effect it ceases allocation of demand point to a solution facility when that travel time or distance from the facility to demand points is reached. The demand allocated to a facility cannot exceed the facility's capacity which is chosen as part of the model set up (ESRI Inc.).

For our model implementation, we applied the Maximize Capacitated Coverage problem type. This solver chooses facilities such that all, or the greatest amount, of demand can be served without exceeding the capacity of any facility. When an impedance cut-off is specified, any demand point outside all the facilities' impedance cut-offs is not allocated. An allocated demand point has all or none of its demand weight assigned to a facility; demand isn't apportioned with this problem type. If the total demand within the impedance cut-off range of a facility is greater than the capacity of that facility, only the demand points that maximize total captured demand and minimize total weighted impedance are allocated (ESRI Inc.).

In applying the above, potential AD plants enterprises are considered as facilities and have a capacity term associated with them. We assign the facility capacity as the size of the AD plant in GWh. This capacity term of 40 GWh is chosen based on the criterion for model design and primarily driven by the National Biomethane Strategy (Government of Ireland, 2024). We then assign a GWh potential to demand locations based on their feedstock resource, and assessed on a land parcel basis. GWh potential is based on modelled grass production and cattle manure produced by a herd as indicated by the LPIS dataset.

The available grass and slurry are amalgamated, summed and assigned to townland centroids (broadly similar to the geometric midpoints) and their biomethane potential calculated. In the location-allocation processing, these points are associated with the closest network segments representing the road network based on a minimum distance method. These 'snapped' parcel centroids which carry the calculated demand term are then able to participate in the network analysis. As townlands are relatively small in area, they serve as excellent spatial units for representing feedstock from contained parcels. Their small size leads to a relatively lower level of error in distance calculations compared to other approaches.

The Location-allocation routine was run using distance from a facility as an impedance constraint ensuring that demand points representing parcel groupings with a 'demand' for AD feedstock processing would be allocated on a minimised distance basis. In this way, selected parcels which were accumulated to local townland level on the network were allocated to a potential AD facility which minimised distance while seeking to maximise the potential capacity served by the facility. The allocation of parcels to a particular facility continued until the capacity term of the facility – GWH size of the facility was fully assigned.

When the chosen number of national facilities was reached, allocation assignment ceased. The result of the operation produces a number of attributes appended to the input spatial data table. These contain the ID number of the AD facilities and the associated demand centroids which were allocated to that facility. A straight-line segment layer is also created which shows the linkage between each facility and its allocated demand points. While these are depicted as straight lines for simplicity, the actual along-road journey length for each connection is calculated and stored by the algorithm.

Criteria for demand (feedstock) locations

We followed guidance provided in the National Heat Study (SEAI, 2022) and applied exclusion criteria to select areas of agricultural land that were deemed appropriate for feedstock supply. The datasets used in the exclusion assessment have been described above in the *Data* section and are outlined in Table 21. Exclusions were applied as described in the table and as implemented in the National Heat Study to ensure consistency in our approach to previous studies.

Table 21 Exclusion criteria used to identify

Exclusion Criteria	Exclusion Criteria	Note
Protected areas	Special Areas of Conservation, Special Protected Areas, Natural Heritage Areas, proposed Natural Heritage Areas	Data on the location of areas from NPWS
Environmentally sensitive areas	Land parcels classified as traditional Hay Meadow or Low Input Pasture	Data on the location of areas from LPIS dataset
Soil types not suitable for productivity improvement measures	Soils with peaty topsoil, or potentially peaty topsoils, peats;(IFS codes 41 to 46 and 61 to 66	As these are high carbon soils, their disturbance should be avoided as it may lead to carbon loss and release of CO2. Improvement might also affect biodiversity on these soils
Slope	>15%	Limit for machinery needed to carry out required operations
Elevation	250m	Expert judgement; higher areas likely to be wetter
Soil types not suitable for cultivation of silage for AD or other bioenergy crops	Soils with peaty topsoil, or potentially peaty topsoils, peats;(IFS codes 41 to 46 and 61 to 66	Poorly draining soils are excluded based on expert judgement related to the use of machinery for soil cultivation

Source: Adopted from the National Heat Study SEAI, 2022

Criteria for supply facilities (AD plants)

While our demand points were calculated on highly spatially resolved townland centroid points, for our location-allocation analysis we use electoral division centroid points as candidate facilities. This ensures that candidate facilities are available from a broad spatial distribution nationally while not being overly constrained to narrow local locations. Resulting facilities are therefore indicative of locations that are broadly suitable from a feedstock supply perspective. Actual plant locations would need to be subjected to normal site suitability analysis and planning.

Gas Networks Ireland has indicated that a 50 km distance from the gas network as optimal for plant locations. We use our derived national gas network catchment map to select potential facility locations that fall with that delineated catchment area.

We also use the urban and built up area data to develop an additional exclusion criterion for potential AD plant locations. We buffered a 1 km area around each mapped urban centre to ensure facilities weren't located within urban areas as part of the location-allocation analysis.

Model set up

We based our model set largely on the recommendations and assumptions contained in the National Biomethane Strategy (Government of Ireland, 2024). We specifically designed aspects of the model to reflect as closely as possible the modelling assumptions and parameters used by recent researchers in the field and specifically in Ireland. We chose to do so in order that our modelling approach, which is novel in an Irish setting, could be tested in the context of previous work and importantly to explore its role in integrating with that previous research and providing additional tools to expand on it. We used Tisocco et al's (2021) underlying concept of a model farm to frame our approach to implementing feedstock availability from individual herds and a number of their assumptions are applied in our work (table 22).

Table 22 Model parameters

Model Parameters		Unit
Facilities		
Facility capacity	40	GWh
Number of AD facilities	140	
Distance cut-off	10,15	km
Feedstock		
Grass yield	11	t DM/ha
Volatile Solids (VS) grass	92	% of DM
Biomethane potential grass	339	m3 CH4/t VS
Nitrogen per animal (suckler cow)	65	kg/year
Slurry production	0.29	m3/week
Annual storage period	16,18,20,22	weeks
Dry matter slurry	6.3	% fresh matter
Volatile solids (VS) slurry	77.7	% of DM
Biomethane potential slurry	186	m3 CH4/t VS
Ratio grass to silage	4:1	VS basis
Grass feed requirement	5	t DM/ha

Grass availability

We selected *Permanent Pasture* and *Permanent Pasture (MSS)* parcels from the LPIS dataset. The design of the LPIS dataset allows for shared parcels as in Commonage lands. This can result in area of the commonage bee assigned multiple times to the Commonage participants. In addition, LPIS parcels may be comprised of one geometric area (or polygon) which is subdivided into multiple subareas with different crop types apportioned to these subdivisions. Areas derived within the GIS processing environment will lead to over-estimation of the true Permanent Pasture areas that are attached to each herd. To avoid these errors we deselected Commonage areas. For subdivided parcel areas, we extracted the true pasture area and used that in our calculations.

To provide a general estimate of grass availability, we applied a grass yield figure of 11 tonnes (t) dry matter (DM) per hectare per annum. This was multiplied by the corrected permanent pasture areas to derive a grass supply value. Grass production and yields can vary substantially across area and enterprise but this value was chosen as a relatively conservative estimate while allowing scope for the model to show what may be achievable from a supply point of view.

Grass surplus was determined by subtracting the total feed grass requirement per herd from the total grass DM yield per herd. Grass feed requirement was initially set to 5t DM per animal per year. This was multiplied by the modelled number of animals to provide a general estimate of the potential feed requirement for modelling purposes.

For the current model implementation, we assume that grass supply will be in the main only available from beef enterprises. The LPIS dataset does not have an indicator to differentiate between what the farm enterprise types. To extract beef enterprises for modelling purposes we selected herds with an indicated organic nitrogen per hectare of <= 135 kg Organic N. National Farm Survey data suggests this as a reasonable value to se as it excludes c. 85% of dairy farms and includes c. 80% of beef farms.

Manure availability

To estimate farm level slurry volumes as a feedstock resource, an estimate of animal numbers per herd is required. Unlike the National Heat Study (SEAI, 2002), the Animal Identification and Movement System (AIMS) dataset was not available to us for this work. To provide an estimate of animal's numbers at herd level we used the recorded bovine organic nitrogen per herd per annum (Bovine Org N) in the LPIS dataset. We applied standard statutory values for annual nutrient excretion rates for suckler cows (65 kg N year) to determine a modelled value for number of animals per herd (Government of Ireland, 2022).

To determine potential available slurry per herd, we used the statutory slurry storage capacity requirement value for suckler cows of 0.29 m3 per week (Government of Ireland, 2022). We spatially assigned the mandated storage period requirements to our working parcel dataset which enabled us to determine an estimate for the amount of slurry that should be potentially available per herd across the country.

Ratios of grass to manure for feedstock mix

Previously published research has looked in detail at various ranges of the relative proportions of grass and slurry in order to determine optimum ratios for use in AD, including Himanshu et al. (2019), Wall et al. (2013), Ó Céileachair et al. (2022), Beausang et al. (2021) among others. In general, results of these and other studies tends to show that a 4:1 ratio in volatile solids (VS) terms of grass to slurry is economically optimal. Beausang et al. (2021) observed that notwithstanding an economically optimal mix, an environmental optimum was observed at a VS ratio of 0.4:0.6 grass silage to slurry mix.

As we are broadly following Tisocco et al. (2024) in their model set up we have used a 4:1 grass to slurry ratio on a VS basis for our evaluation.

Scenarios examined

We ran our location-allocation model for four variations around our demand point model. We applied two distance parameters to define the impedance or cut-off value for distance travelled from any potential AD facility. For feedstock supply we implemented a 'Strict' and a 'Surplus' scenario control. In the 'Strict' control, we allowed each of the demand points to only have available 15% of the total grass from the aggregate modelled grass grown term for that demand point. This was to reflect recent work showing that only 15% of farmers were willing to supply feedstock to AD plants. In the 'Surplus' scenario, we allowed all grass surplus to animal feed requirements to be available as a feedstock. In both cases, slurry availability was determined based on the chosen grass availability on a 4:1 VS ratio basis of grass to slurry.

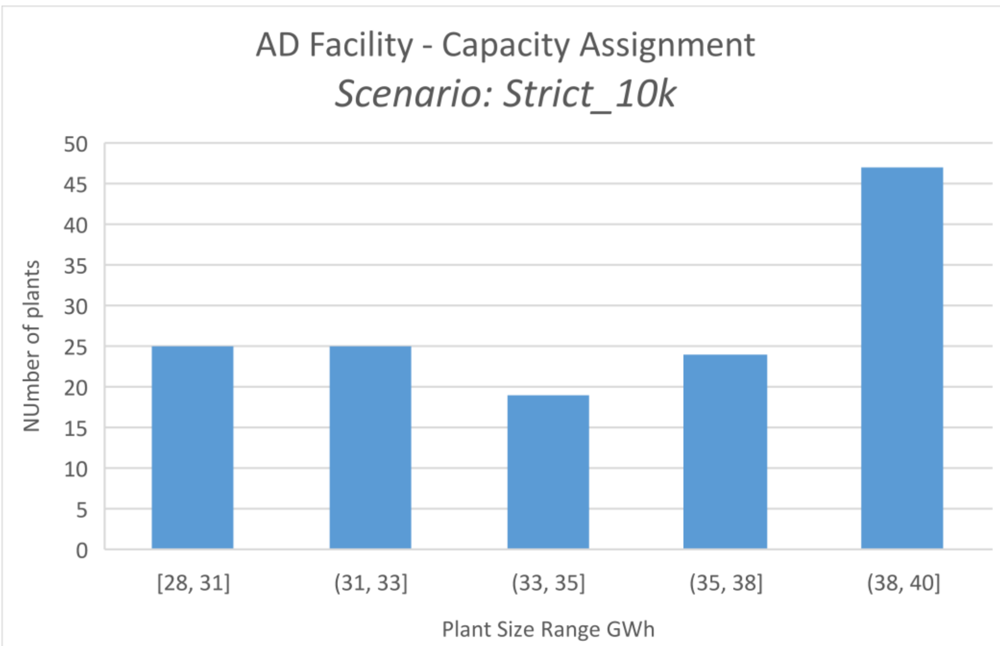
Table 23 **Scenario used for location-allocation model runs**

Scenario	Grass available	Distance from AD facility	AD Facility capacity	Number of facilities
Strict_10k	15% of grass grown per parcel	10 km	40 GWh	40
Surplus_10k	Surplus above animal feed requirement	10 km	40 GWh	40
Strict_15k	15% of grass grown per parcel	15 km	40 GWh	40
Surplus_15k	Surplus above animal feed requirement	15km	40 GWh	40

5.4 Results

We successfully ran the location –allocation solver for our model setup with four scenarios. Three scenarios filled the assigned 40 GWh capacity within the allocated impedance/distance cut-off. The Strict_10k scenario allocated available feedstock within the 10 km area for each facility but this was insufficient to meet the assigned feedstock requirements of all 40 GWh plants. Only 40 out of 140 plants were assigned sufficient feedstock to the 40 GWh capacity (Figure 6)

Figure 6 Distribution of AD plants by capacity assigned under the Strict_10k. Only 40 plants were assigned sufficient feedstock to reach full 40 GWh capacity



Mean/Max capacity assigned by scenario

Assignment of capacity and resolution of the model generally followed an expected trend. The scenarios allowing surplus grass to be assigned provided full resolution with all 140 plants attaining 40 GWh potential capacity (figs 7-8). Transport distances were least for the surplus grass scenario at 10km and greatest for the strict grass scenario with a 15 km allowable catchment area (bearing in mind that his latter scenario did reach the 40 GWh plant size target).

Figure 7: Mean of total transport distance for AD facilities in modelled scenarios

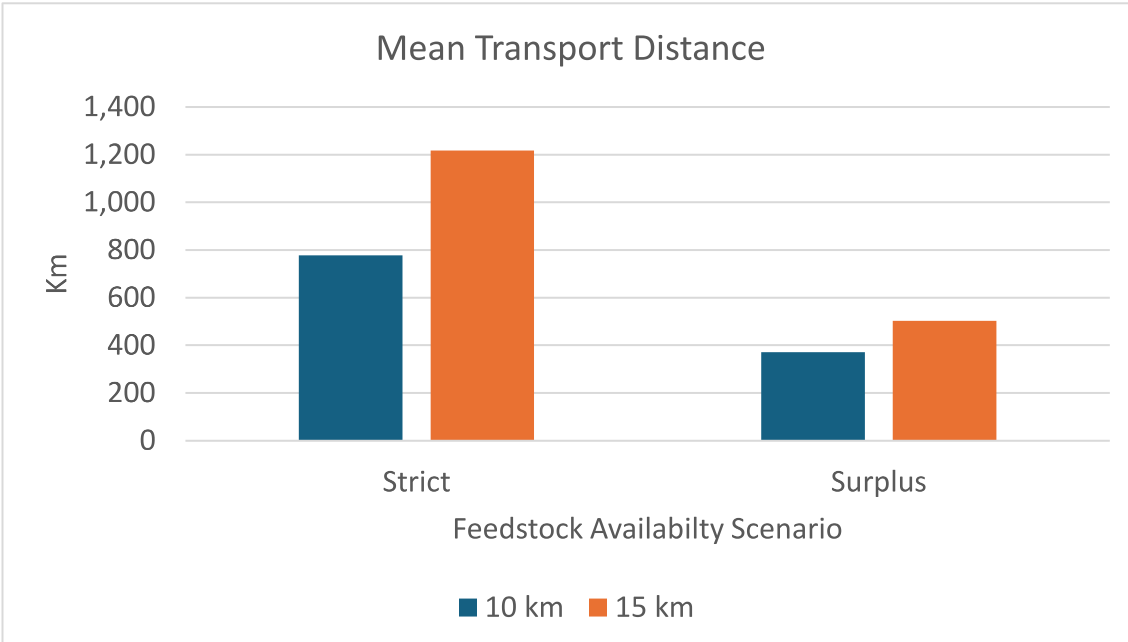
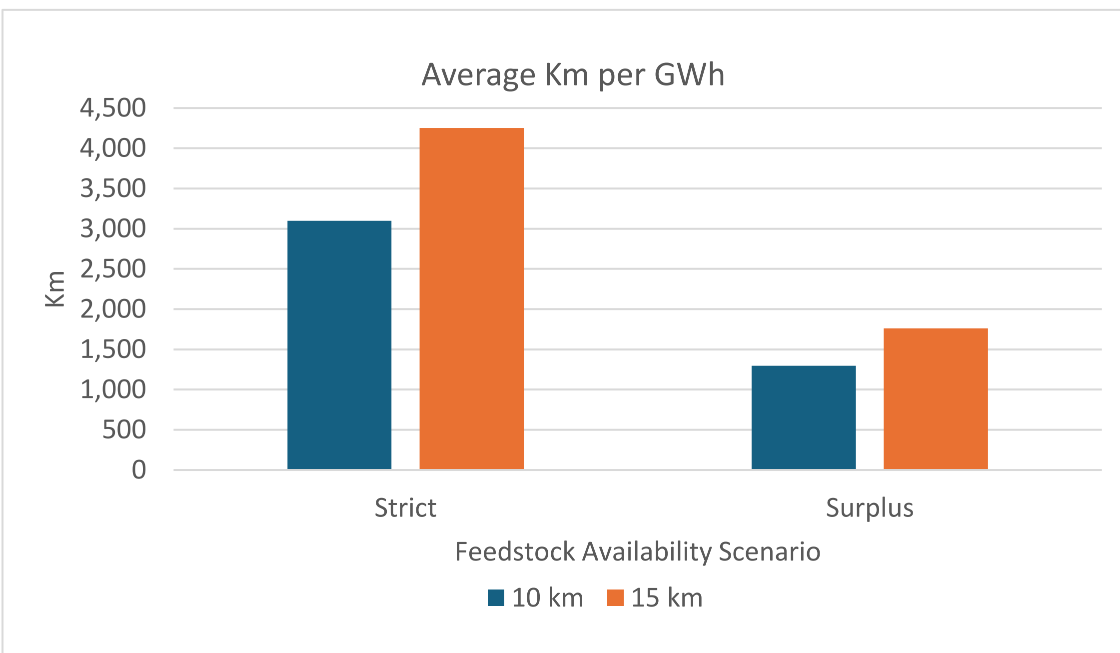


Figure 8: Average km per GWh for modelled scenarios



Figures 9 to 12 show the facility locations chosen by the location-allocation model to optimise capacity assignment from feedstock locations.

Figure 9: Network location-allocation solution for Surplus_10k scenario

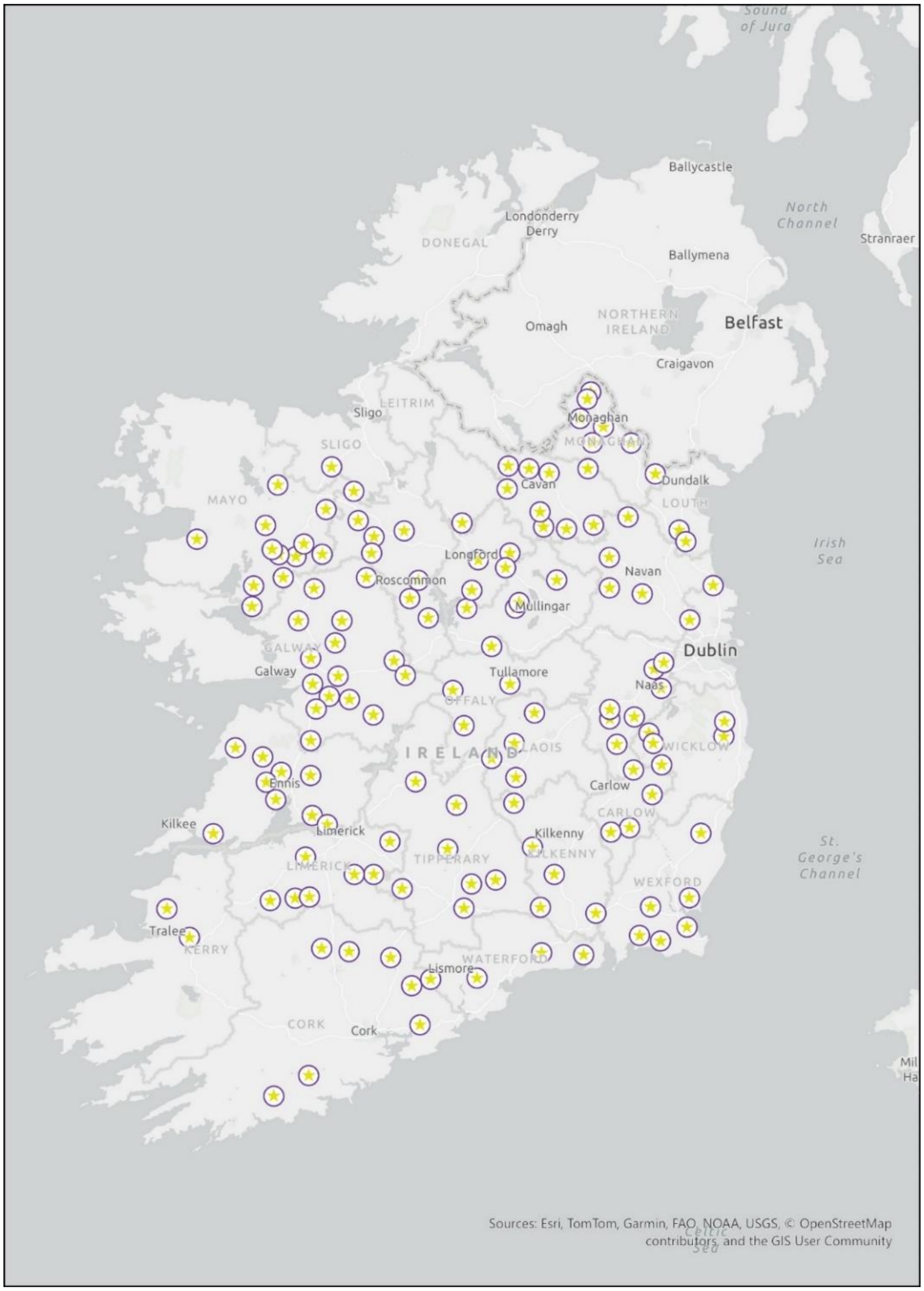


Figure 10: Network location-allocation solution for Strict_10k scenario

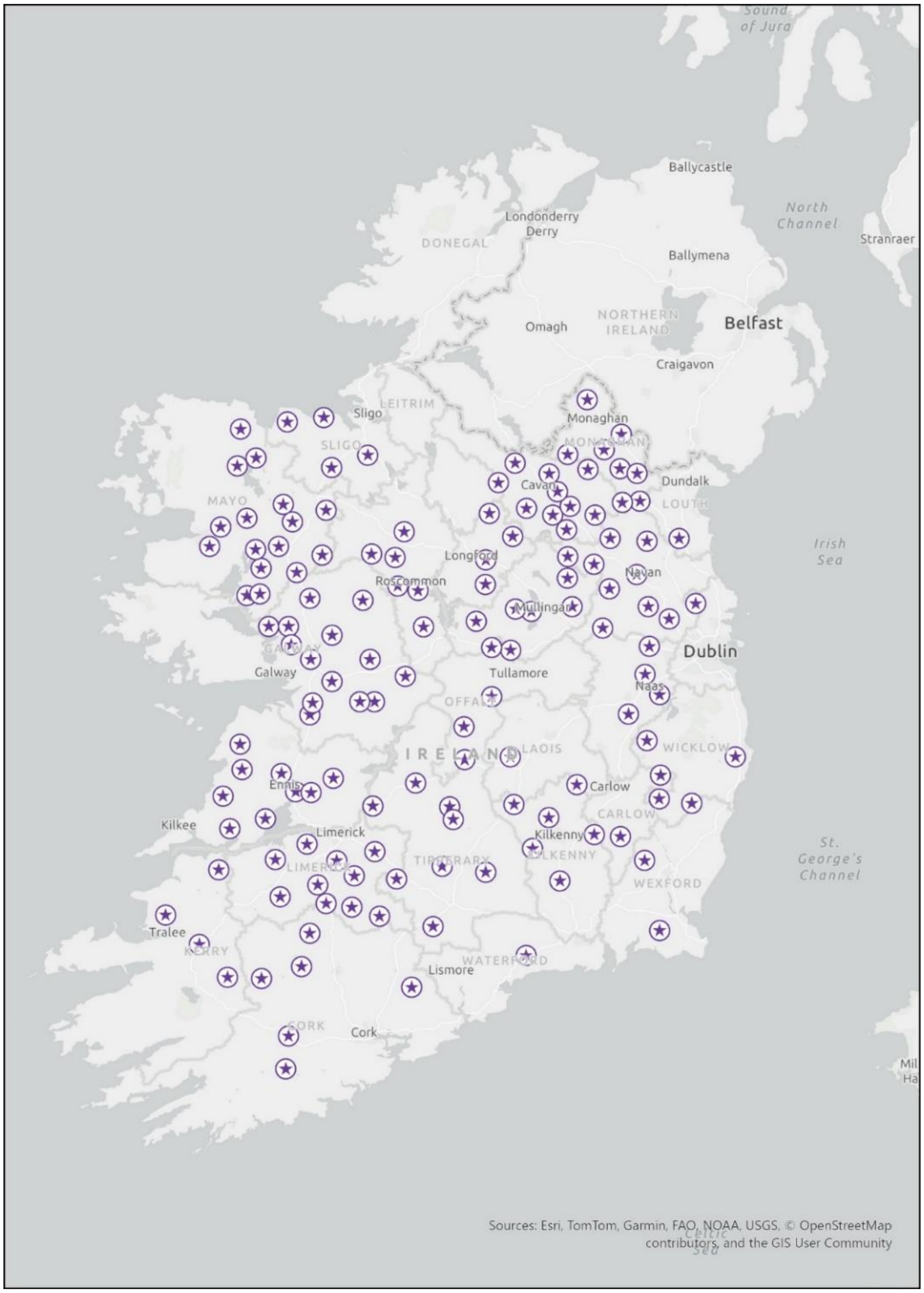


Figure 11: Network location-allocation solution for Surplus_15k scenario

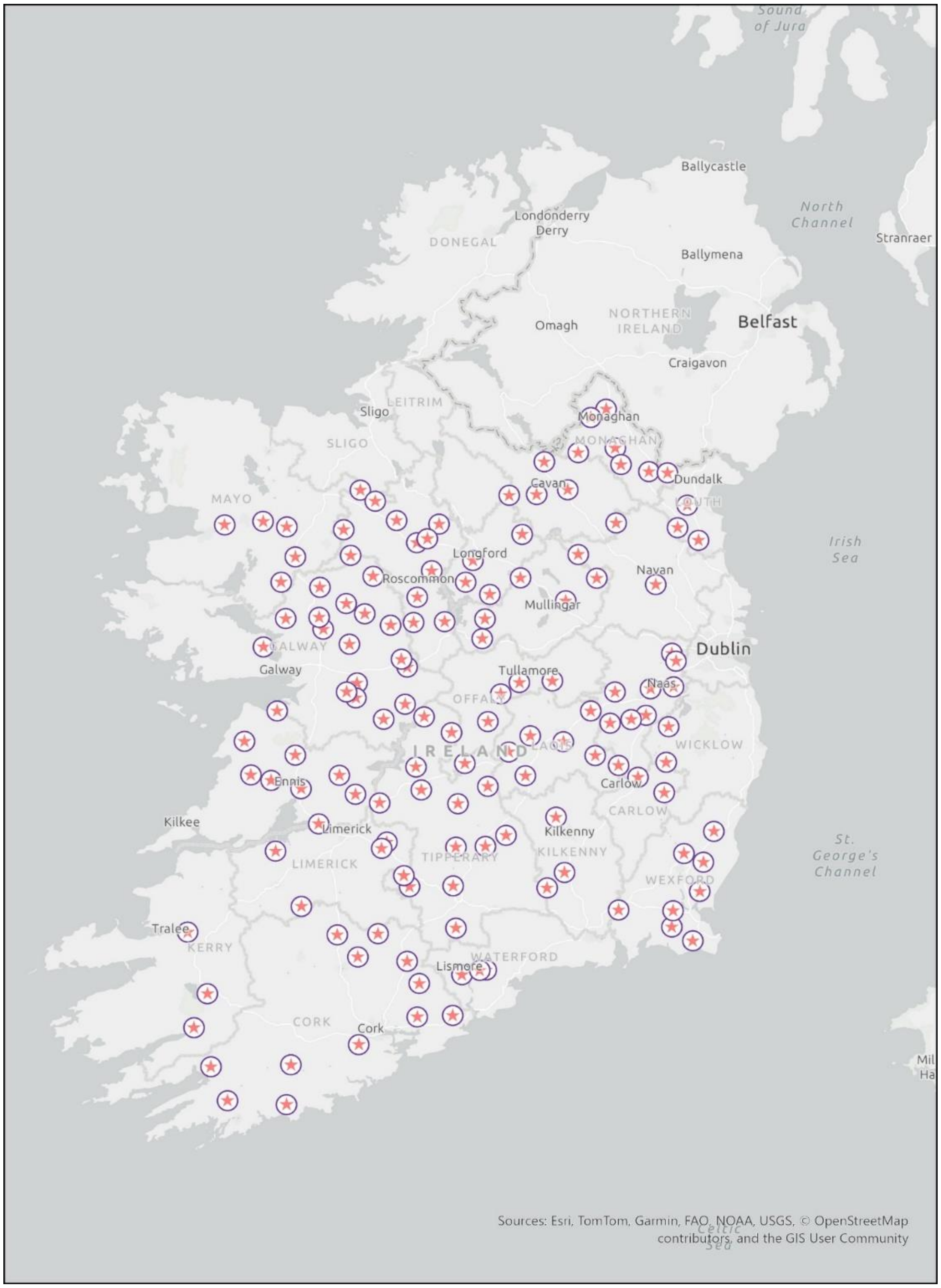


Figure 12: Network location-allocation solution for Strict_15k scenario

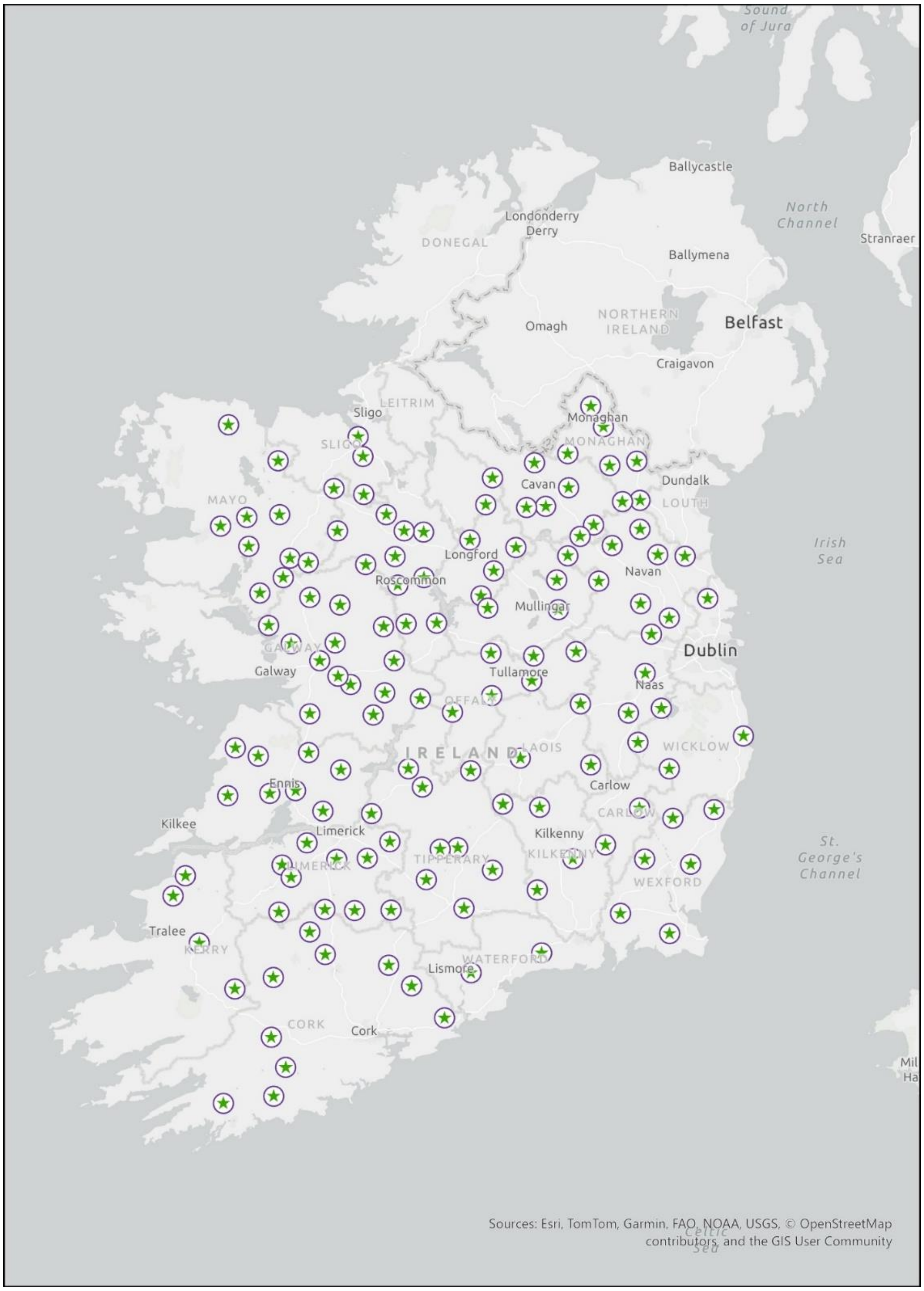
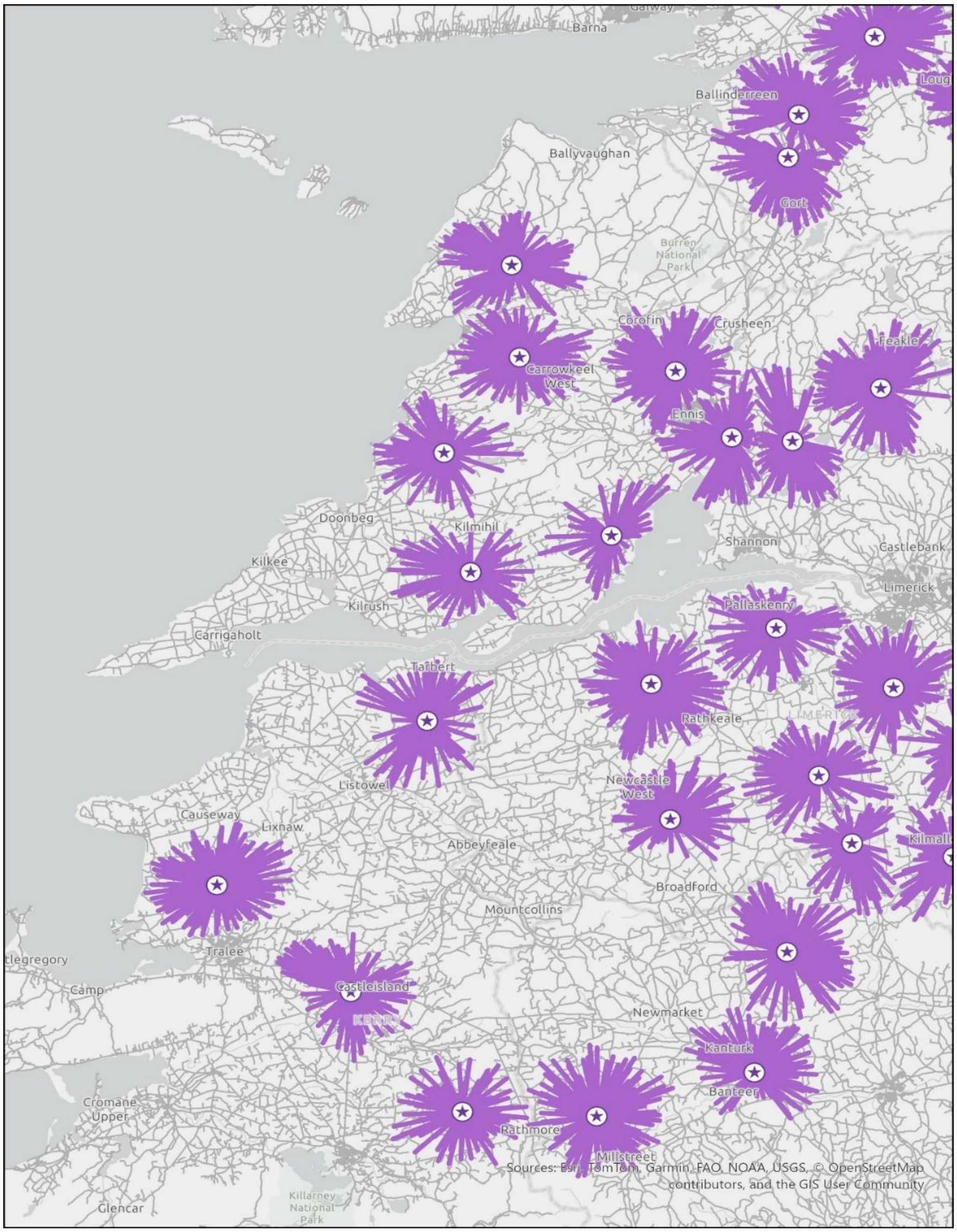


Figure 13 shows how the model outputs connectivity lines linking the chosen facility locations with their assigned input demand locations. Although these are depicted in model map output as straight lines, the model uses along road distance for both its allocation calculations and tabular outputs showing results.

Figure 13 Model output showing connectivity lines between solution facilities and feedstock locations



5.5 Discussion

The spatial distribution of feedstocks is crucial in determining optimal locations for anaerobic digestion facilities. Research has indicates that regions with high livestock density and extensive grasslands can supply sufficient quantities of feedstock necessary for economically viable AD operations. Beausang et al. (2021) demonstrated how regional patterns of grass production and cattle farming influence the placement of AD facilities to optimize transportation logistics and reduce costs.

Studies also highlight the importance of the location of local biomass resources in minimizing transportation distances. Facilities that are located closer to feedstock sources benefit from reduced operational costs associated with transport, leading to more favourable economic outcomes. Importantly, optimal siting of AD facilities to ensure proximity to sufficient feedstock supply will also both reduce the environment impact of developing and running those facilities, along with the cost per unit of methane produced, making AD a potentially more financially and politically attractive solution for agribusinesses and governments transitioning towards renewable energy sources.

We have shown that due to the increased availability of high-resolution national datasets and enhanced hardware and software and notwithstanding the fact that the undertaking is not trivial, it is now feasible to not alone set up and run high computer resource intensive models but to conduct multiple runs for scenario assessment. Conducting a location-allocation analysis with c. 50,000 demand points and c. 3,400 potential facilities would have taken hours if not days a number of years ago. Now, these model runs can be completed in less than an hour, thus allowing multiple scenario assessments to be undertaken.

As in any modelling task, we have had to make some processing choices along the way in order that our location-allocation would run efficiently. The assignment of parcel centroids to their local townland centroid in order to deal with the issue of farm fragmentation will result in the distribution of some slurry from the true farm holding location to the townland in which the parcels an out farm might be located. While this is artificial and unrealistic, the effect is judged to be relatively minor in the overall assessment of the national distribution and supply of slurry.

A further analysis of farm fragmentation may lead to improvements in this aspect of the calculations. A spatial outlier analysis may allow for an approximate location of the centroid for the actual farm holding to be used rather than aggregating the parcels to a townland level. While this would enhance the spatial accuracy, in real terms the gains in assessing the aggregate along-road distance would likely be very minor and may not warrant the additional work.

Using the suckler cow excretion rate for slurry volume estimation likely overestimates slurry production, at least to some degree at herd level. In the absence of access to AIMS data, this could be resolved by using a coefficient to reduce slurry proportionally. Application of NFS values may also help in this regard and could be investigated as part of future work.

However, in general grass availability rather than slurry is the limiting constraint in the analysis. Balancing grass with slurry at each individual farm level leads to a reduction in potential available slurry. Selecting farm where <= 135 kg Org N ha-1 means that slurry is not deemed as being available from farms with higher stocking densities. While this may seem a challenging limitation, it does reflect a likely supply real challenge that will have to be worked out by AD plant developers relating to the supply of grass to match slurry feedstock intakes. It has been well demonstrated that co-digestion of silage and slurry provides optimal AD solutions compared to mono-digesting approaches. Therefore, even if there is a significant surplus slurry supply in a geographic area, if a co-digestion approach is preferred, grass silage will need to be sourced from other farms or even localities. O'Shea, Kilgallon, et al. (2016) found similarly when considering grass silage and slurry supply in southern, dairy intensive areas of Ireland. Where the grass silage biomethane resource was lowest, these acres typically contained the highest cattle slurry resource and reduced grass silage availability.

It is also worth noting that in our current location –allocation scenario analysis we used a 4:1 grass silage to slurry on a VS basis. Other ratios have been considered in the literature with Beausang et al. (2021) noting a 0.4:0.6 VS ratio and Wall et al. (2013) considering a 1:1 on a VS basis. This essentially means that within the bounds of our assessment, should other grass silage to slurry mix ratios be considered, additional slurry volume could be integrated into the feedstock mix. A 1:1 VS basis grass silage to slurry mix would enable an additional 300% of slurry to be considered for intake and utilisation over the value used by our current modelling of AD facilities.

5.6 Conclusion

There is now a significant amount of high resolution spatial data available nationally to facilitate very detailed location analysis for feedstock and facilities siting for AD development. Our analysis shows that in our 'middle optimistic' (surplus grass) scenario, the National Biomethane Strategy target of 140 40 GWh plants could be relatively easily accommodated spatially, and with feedstocks supplying these plants largely coming from within a 10 km along road travel distance. However our 'pessimistic' scenario with 15% of grass being made available suggests that travel distance must increase on average to 15 km and potentially greater. This would obviously have a negative economic and environmental impact Hardware and software resources have advanced considerably in the last decade and, though not trivial, high end network analysis can now be conducted on local desktop GIS workstations.

6 Sector Level Modelling of Alternative Feedstock Solutions for a Regional AD Plant

6.1 Introduction

Whereas earlier chapters in this study have examined impacts at a farm and landscape level, this section of the report models the aggregate economic and environmental implication at a national scale. The FAPRI-Ireland partial equilibrium model of Irish agriculture (Behan and McQuinn, 2003, Binfield et al., 2002, Donnellan et al., 2014, Donnellan et al., 2019), which has been in used to model a range of economic and environmental questions for the last 25 years, has been used to do this.

6.2 Methodology

This chapter addresses a number of environmental and economic questions using the FAPRI-Ireland aggregate sector model that has been used extensively in the analysis of the impact of interventions to reduced GHG emissions from Irish agriculture (Lanigan et al., 2023 and Lanigan et al. 2024) and the outlook for the future development of GHG emissions in Irish agriculture (EPA, 2024).

Firstly this chapter examines the impact on agricultural activity, agricultural output value and associated sectoral measures of economic activity of reducing land use for bovine agriculture activities and diverting this land to use in growing grass as a feedstock for AD. The use of pasture land as a resource for AD feedstock production leads to a reduction in animal numbers (cattle) and an associated reduction in animal emissions and emissions from animal waste. Second, in this paper we assesses the reduction in GHG emissions associated with the diversion of animal slurries from use in agriculture to use as a feedstock in the AD industry. Thirdly, it estimates the reduction in synthetic nitrogen fertiliser use and associated emissions due to the associated reduction in livestock activity. Ultimately, this allows the calculation of the aggregate reduction in agricultural emissions associated with the transition of agricultural land from animal production activities to use as a resource to produce feedstocks for AD.

The chapter also addresses a number of economic questions. Firstly, it examines the implications for agricultural output value of the shift in land use from cattle production (a decline in the value of cattle output), and estimates the output value of grass grown for use in AD. This then allows the net change in output value in the agriculture sector to be determined. On the input side there would be changes also. Lower cattle numbers lead to a decrease in expenditure on inputs used by the cattle sector. The aggregate decline in expenditure in agriculture is determined.

Ultimately, this allows the calculation of a change in agricultural income associated with the transition to AD. This can be expressed in aggregate absolute terms, as a percentage of aggregate sectoral income or on a per hectare equivalent basis for the land used for AD.

6.3 Economic Impact Analysis

Slurry Feedstock Assumptions: It is assumed that the use of animal slurry as an AD feedstock increases linearly over the period 2025 to 2030 to reach the amount required to meet the 5.7 TWh target. By 2020, all pig slurry is used as an AD feedstock and 8% of cattle slurry from the housing period is used as an AD feedstock.

It is assumed that the farmer supplying slurry as an AD feedstock receives no payment. Equally, it is assumed that farmers paying to receive the AD digestate. It is recognised these are simplifying assumptions. For the purposes of this aggregate modelling task it was considered that too little information was available to make assumptions about the price of slurry and the prices of digestate, since this would depend on supply and demand considerations and transport distances which were beyond the scope of this task.

Grass Feedstock Assumptions: For the purposes of the analysis, under the baseline it is assumed that no grassland is used for AD over the period between 2025 and 2030. This represents the baseline assumption in the model. There will be relatively minor changes in grassland area in the coming years, even in the baseline, since we typically observe a reduction in available agricultural land, due to demand for non-agricultural uses (residential, business, public buildings, roads etc).

It is assumed that the area of land required for grass for AD increases linearly from 2025 to 2030 to achieve the 5.7 TWh target. Given the uncertainty about the amount of DM that could be produced on the average hectare used for AD, it was decided to run three different land area scenarios to meet the required level of grass feedstock production required to produce the national biomethane target.

Table 24 therefore shows the assumed diversion of grassland from pasture area to grass production for AD under three scenarios:

- 110,000 ha for grass production for AD (AD_110),
- 120,000 ha for grass production for AD (AD_120)
- 130,000 ha for grass production for AD (AD_130).

Pasture area is diverted to AD use from 2025 onwards, with the target area in each scenario reached in 6 equal steps.

Table 24: Assumed pasture area required to achieve 5.7 TWh target in 2030

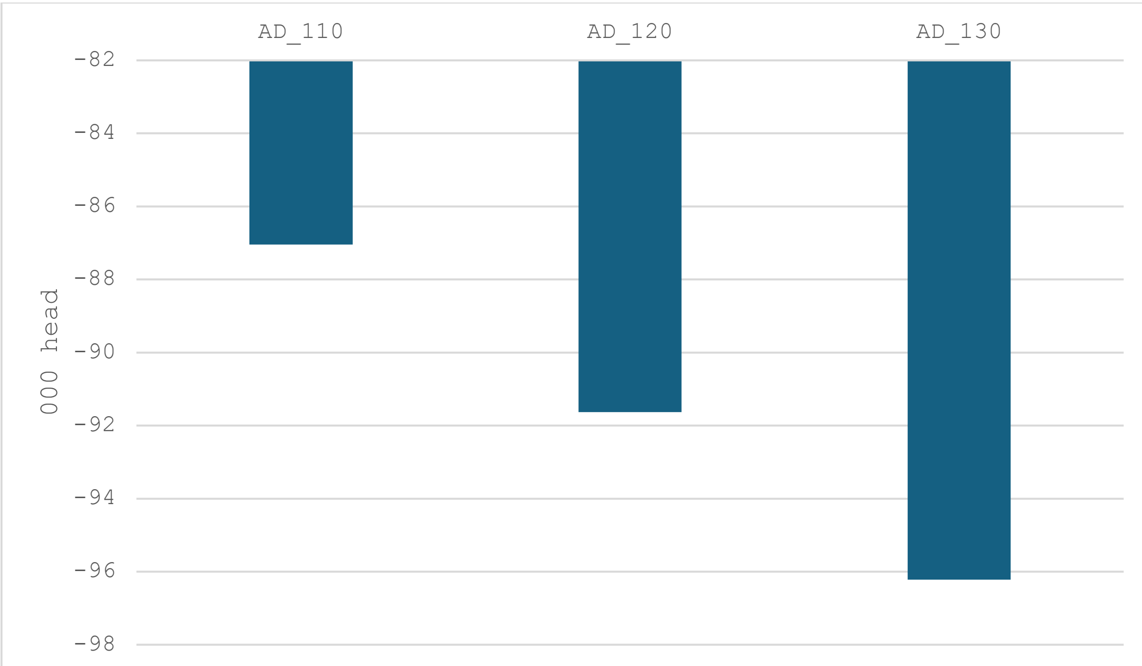
	2025	2026	2027	2028	2029	2030
AD_110	18.33	36.67	55.00	73.33	91.67	110
AD_120	20	40	60	80	100	120
AD_130	21.67	43.33	65.00	86.67	108.33	130
Baseline Pasture Area	2,288	2,285	2,283	2,281	2,279	2,278
AD_110 Pasture Area	2,270	2,249	2,228	2,208	2,189	2,169
AD_120 Pasture Area	2,268	2,245	2,223	2,201	2,180	2,159
AD_130 Pasture Area	2,266	2,242	2,218	2,194	2,171	2,149

The value of grass sold as an AD feedstock is assumed to be the same for each of the area diverted scenarios, since they reflect uncertainty about the volume of grass dry matter (DM) likely to be yielded per ha from each unit of pasture area used to grow feedstocks for the AD industry.

There are two key variable in determining the value per ha to the farmer growing grass for AD these are

- the price per tonne of grass DM paid by the AD industry and
- the yield of DM per ha of grassland.

Figure 14: Decrease in suckler cows by 2030 under each land area scenario



Source: FAPRI-IReland Model 2024

For the purposes of the scenarios, it is assumed that dairy and tillage farmers would be uninterested in grass production for AD and that the grassland diverted to AD would be on cattle farms only. Furthermore, it is assumed that the stocking rate nationally remains unchanged despite the reduction in available area. In other words there is no intensification of cattle production elsewhere, in response to the reduction in pasture area used to raise cattle for beef.

Accordingly, with the decline in pasture area, there is an associated reduction in the number of suckler cows and associated followers (other cattle), so as to ensure that the stocking rate per average hectare of grassland does not increase relative to the baseline. The projected reduction (relative to the baseline in suckler cow numbers is shown in Figure 11. the greater the area of pasture land diverted to producing grass for AD the larger is the projected reduction in animal numbers.

The decline in cattle numbers also leads to a reduction in synthetic fertiliser use, given that land used for AD cannot use synthetic fertilisers to ensure that the biogas from AD is RED II compliant. By 2030 under the AD_120 scenario aggregate use of chemical N fertiliser is projected to be 2% lower than under the Baseline.

Grassland FeedStock Results

AD _120 Scenario

Decline in Cattle population: By 2030, under the AD_120 scenario, suckler cows numbers are projected to be 13% lower than under the baseline. By 2023, the total cattle inventory is 2% lower than under the baseline. The smaller decline in total cattle numbers, reflects the declining share of suckler cows in overall bovine breeding numbers under the baseline and the AD scenarios analysed. With lower suckler cow numbers the importance of dairy cow progeny in the overall cattle population increases and the impact on aggregate cattle numbers and beef production of a given reduction in suckler cows is reduced.

Value of Beef Output: Total beef production under the AD_120 scenario declines relative to the baseline and with cattle prices assumed to be largely unaffected by the reduced level of bovine activity in Ireland, the value of cattle output declines relative to the baseline. By 2030, the reduced suckler cow numbers and reduced overall volumes of cattle slaughtered are reflected in a 3% (€82m) decline in the value of cattle output, relative to the baseline 2030 level.

Input Expenditure: Lower cattle activity levels are reflected in reduced expenditure on inputs, with total intermediate consumption projected to decline by almost 1% (€44m). The projected decline in intermediate consumption is dominated by reductions in expenditure on synthetic fertiliser (due to reduction in the pasture area farmed), reduced expenditure on animal feed and veterinary services (all due to reduced cattle numbers).

Value of Grass as AD Feedstock: Without consideration of the value of the grass grown and sold to the AD industry, the value added by the agricultural sector would decline by €38m. However, because the grass produced on pasture land diverted to use for AD produces a marketed output, the value of the grass grown for AD on the 120,000 ha needs to be added to the other items of output currently counted in the agricultural sector accounts (reference to the OII release CSO, 2023). Under the AD_120 scenario we have assumed that the yield of grass per ha is 13.5 tonnes/ha and that the price per tonne of DM paid to the farmers is €55/tonne DM. By 2030 the additional value of grass sold by the agricultural sector is assumed to amount to €89.1m euro.

There is uncertainty as to what price the AD industry will pay farmers for grass DM delivered to their plants. A lower price assumption would reduced the simulated value of grass output in our modelling of the economic impact of the achievement of the national biomethane target through the use of grass and animal slurries.

Sectoral Income: In the economic accounts for the agricultural sector compiled by the CSO, grass grown for used in AD does not exist currently exist as an element of output value. However, in this analysis it will be ascribed a value. Thus, by 2030, under the AD_120 scenario, the value to the agricultural sector of grass output sold to the AD industry is assumed to be €89.1m. The €89m of grass output value is additional output value relative to the baseline. Thus the net change in agricultural sector output value is €8m (addition of €89m in AD grass output value less the reduction of €82m in cattle output value).

When this small change in output value is added to the saving in reduced intermediate consumption of €44m, thus the change in sectoral Gross Value Added (GVA) is in 2030 is projected to be €52m, which equates to a roughly 1% increase in sectoral GVA and a 1.3% increase in sectoral Operating Surplus (income). Under the AD_12 the increase in sectoral income when expressed relative to the volume of land diverted to AD is equivalent to sectoral income per ha used to produced AD of circa €425.

AD _110 Scenario and AD_130 Scenario

Relative to the AD_120 scenario, the other two scenarios involve slightly different land allocations to AD (due to differing assumption about the amount of DM per ha diverted from pasture use to use in growing grass for AD), but we assume that the aggregate volume of grass DM delivered to the AD is unchanged from that assumed under the AD_120 scenario. They do however produce different results, since the number of cattle displaced differs from the AD_120 scenario. Hence, the AD_110 and AD_130 scenarios result in different outcomes in terms of the impact on cattle output and input use and ultimately sectoral income.

In economic terms, the results of these three land area scenarios, in terms of cattle activity levels, input usage and sectoral income are summarised in Table X.

Table 25: Economic implications of diversion of land from cattle to AD

	2023	2030	2030	2030	2030
		Baseline	Scenarios		
			AD110	AD120	AD130
Output Value		euro m			
Total Agricultural Output	11,311	12,259	12,270	12,266	12,262
Of which					
Cattle Output	3,013	2,922	2,844	2,840	2,836
Grass for AD Output	0	0	89	89	89
Total Intermediate Consumption	7,758	7,313	7,271	7,269	7,268
Of which					
Feedingstuffs	2,264	2,062	2,043	2,043	2,042
Fertilisers	817	658	644	644	643
Veterinary Expenses	390	457	448	447	447
Gross Value Added at Basic Prices	3,553	4,946	4,999	4,997	4,994
Operating Surplus	2,964	4,038	4,092	4,089	4,087

6.4 Environmental Impact Analysis

Reduced levels of bovine agricultural activity are reflected in reduced emissions to air (GHG and Ammonia) and, depending on where spatially reductions in activity occur, may result in less environmental pressures on water. In this section we focus on the impact of simulated changes in agricultural activity on GHG emissions. Given that the FAPRI-Ireland model is an aspatial partial equilibrium model of the Irish agricultural economy, it does not have the capacity to analyse the impact of agricultural activity on water pollution.

Under the Baseline with relatively stable levels of aggregate agricultural activity, agricultural GHG emissions are also projected to remain at close to recently reported levels over the next ten years. Under this Baseline, the suite of mitigations measures evaluated in Teagasc Marginal Abatement Cost Curve (MACC) analyses are not assumed to be implemented. In the most recent MACC (Lanigan et al., 2023) and in work for the Climate Change Advisory Council (Lanigan et al., 2024), the impact of MACC measures on agricultural GHG emissions has been evaluated. In this analysis, we quantify the mitigation of agricultural GHG emissions arising from AD using grass and animal slurry feedstocks. In so doing we focus on the impact on GHG emissions of a sub-element of the diversification measures of the 2023 Teagac MACC (Lanigan et al., 2023) - the achievement of the national biomethane generation target.

As outlined in our assessment of the economic impact of the scenarios modelled, the diversion of land from grazing use to use as a resource to grow grass for AD, leads to reduced numbers of cattle, reduced cattle output value, increased output value from the sale of grass DM to the AD industry and reduced intermediate consumption (input expenditure) in agriculture on items such as animal feed, chemical fertiliser and veterinary services, whose usage volumes are driven by animal activity levels.

A reduction in cattle numbers and in fertiliser use will be reflected in reduced emissions of both methane and nitrous oxide. GHG emissions from animals are reduced due to reductions (relative to the baseline) in cattle being farmed over the projection period under all of the scenarios analysed. Emissions of Methane and Nitrous Oxide are reduced, not only due to the reduced numbers of animals being farmed, but also because of reductions in applications of chemical fertiliser and because of the diversion of slurries from storage (housing) and subsequent application to farmland to use instead as a feedstock with grass in AD plants.

In our analysis, the proportion of cattle slurry diverted for use in AD increases linearly from 2025 to 2030 to reach 8% in 2030. The proportion of pig slurry diverted for use in AD increases linearly over the same period to 100% by 2030.

Our analysis of the impact of using grass and animal slurries to achieve the national biomethane target takes no account of the mitigation of GHG emissions arising from increasing use of biomethane and reduced use of fossil based fuels (so called offsetting of fossil based emissions).

This is because within the GHG accounting process the reductions in energy emissions are credited to the energy sector rather than the agriculture sector.

GHG Emissions Reduction Potential:

Under the AD_120 scenario, as a consequence of the reduction in animal numbers, emissions of methane, both from both enteric fermentation and manure management, are reduced relative to the baseline. By 2030 under the AD_120 scenario, emissions of methane are projected to be 1.8% lower than under the baseline. The path of methane emissions in CO_2 eq under the baseline and each of the scenarios are shown in Figure 15. Given the very minor differences in agricultural activity levels under AD_110, AD_120 and AD_130 scenarios, the differences in the levels of methane emissions are also very small. Due to higher (lower) cattle numbers in AD_110 (AD_130) as compared to AD_120 methane emissions are also higher (lower).

Figure 15: Decline in GHG Emission (in CO2 Eq) by 2030 under the three scenarios

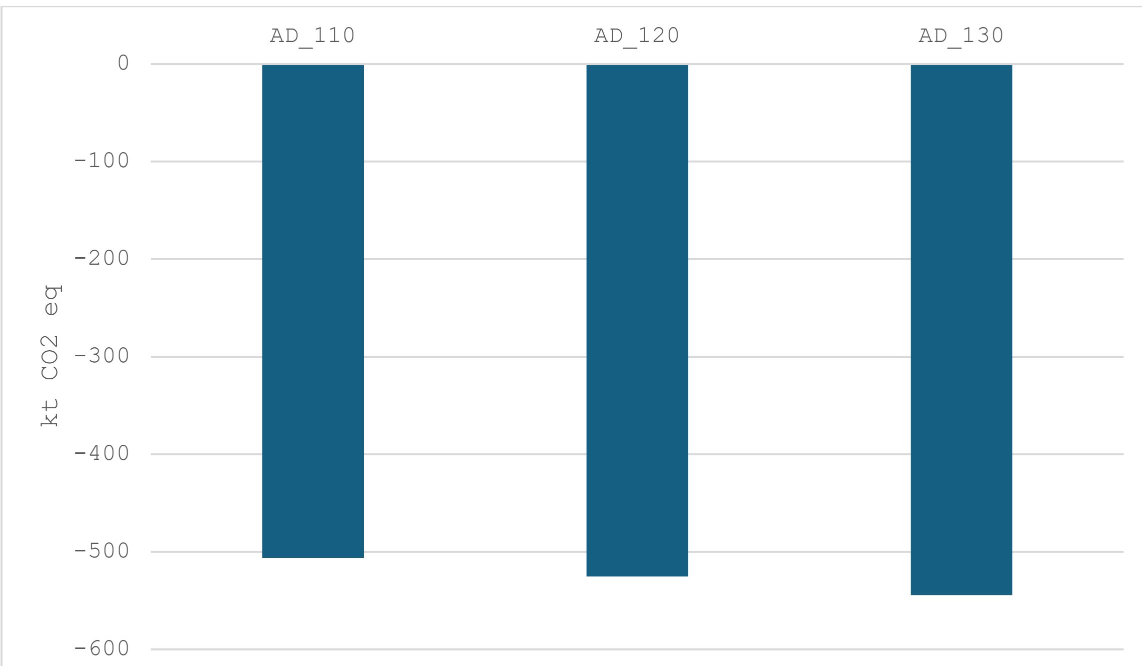
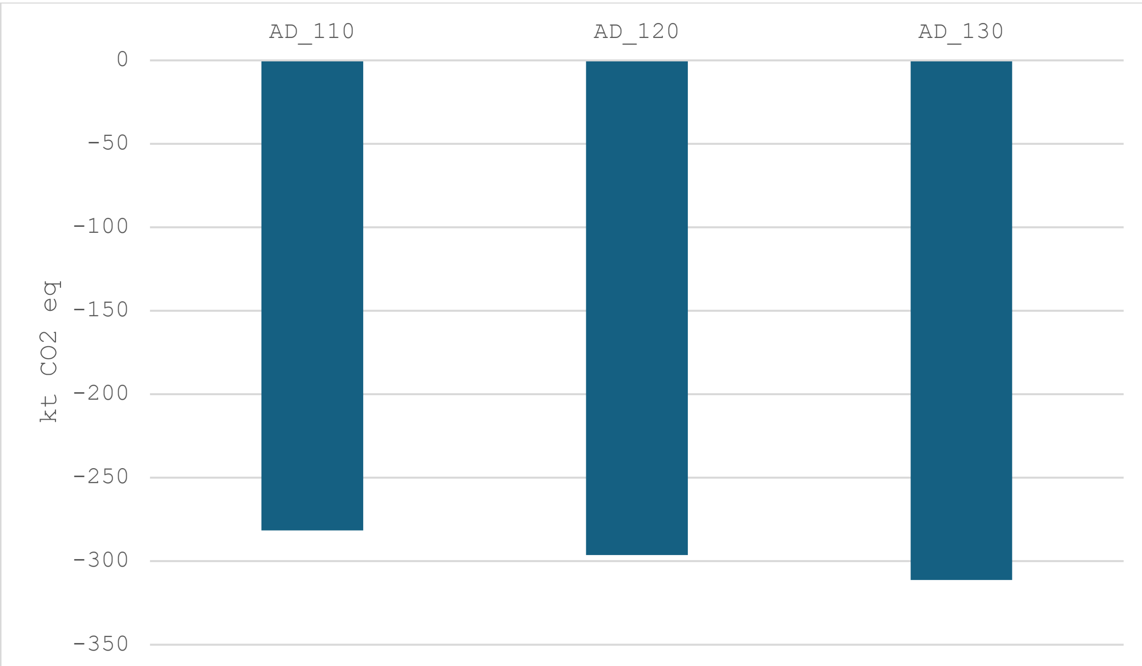
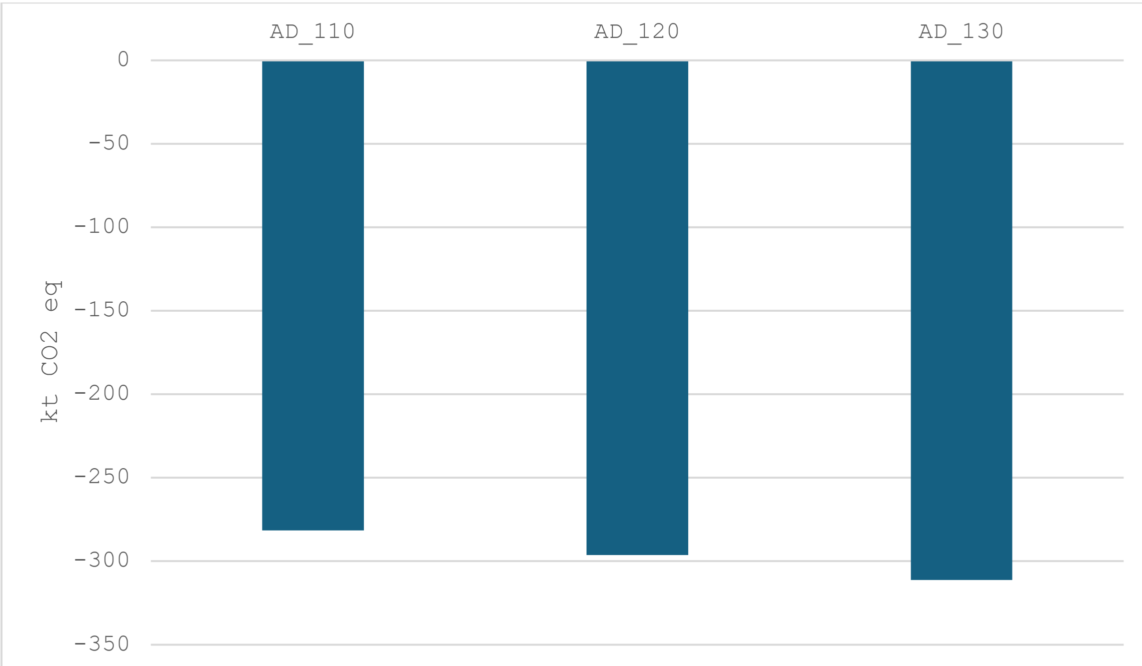


Figure 16: Decline in CH4 Emission (in CO2 Eq) by 2030 under the three scenarios



Under each of the scenarios analysed, cattle numbers are lower than under the Baseline and animal slurries are diverted from storage and application to farmland to use in the AD industry. In addition, the aggregate application of chemical fertiliser is reduced because of the reduced area of pasture in each of the scenarios. Lower animal numbers, use of animal slurries in AD and lower aggregate use of chemical fertilisers are all reflected in reduced emissions of nitrous oxide from agriculture.

Figure 17: Decline in N2O Emission (in CO2 Eq) by 2030 under the three scenarios



Under scenario AD_120 nitrous oxide emissions from agriculture in 2030 are projected to be 4% lower than under the baseline. The larger percentage reduction in emissions of nitrous oxide as compared to methane reflects the fact that nitrous emissions reduction occur not only from lower animal numbers, but also due to lower chemical N use (2% lower than under the baseline) and from the diversion of animal slurry from storage and application to farmland to use in AD.

As was the case with methane, the differences in the level of nitrous oxide emissions from agriculture under each of the three AD scenarios AD_110, AD_120 and AD_130 are relatively minor. Emissions are lowest under scenario AD_130 as changes in pasture area and animal numbers are largest, and emission reductions are smallest under scenario AD_110.

In aggregate under each of the AD scenarios agricultural GHG emissions are lower than under the Baseline. The projected reductions in Agricultural emissions relative to the baseline are relatively small. By 2030 under AD_120 agricultural GHGs are 2.3% lower than under the Baseline. This finding is consistent with the analysis in Teagasc MACC published in 2023 (Lanigan et al., 223) and the updated MACC analysis published in 2024 (Lanigan et al., 2024).

The development of an AD industry based on the use of grass and animal slurry that increases incrementally to reach the national biomethane target of 5.7 TWh in 2030 can make a small but positive contribution to the decarbonisation of agriculture and the Irish energy system, but cannot, in and of itself, significantly reduce Ireland agricultural GHG emissions.

However, a key conclusions of Teagasc's MACC analysis is that no one measure can deliver a sizable chunk of the reductions in agricultural emissions required to live within the sectoral ceilings allocated to agriculture under Ireland's GHG emissions reductions strategy (Lanigan et al., 2023 and 2024). It follows that the successful implementation of a wide range of mitigation measures across all of Irish agriculture will be necessary to achieve the reductions in GHG emissions required. AD can make a contribution to this decarbonisation effort, but like most other MACC measures, AD itself makes a relatively small contribution.

The reductions in agricultural GHG emissions associated with the diversification of agricultural activity away from bovine agriculture towards the production of feedstocks for AD is associated with an increase in agricultural sector income. Losses in cattle output value, in our analysis, are more than offset by gains in output value from grass sold to the AD industry and from savings in expenditure on farm input items (feed, fertiliser and veterinary services) that are directly related to the raising of cattle for beef production.

The analysis indicates a positive impact of the scenarios on agricultural sector income, but takes no account of the negative impact of reduced animal output on upstream and downstream sectors. Reduced input purchases and reduced throughput of cattle in meat factories would have a negative impact on aggregate economic activity. However, at least some of this negative impact would be offset by the positive impact of new economic activity associated with the AD industry. Assessment of the economy wide effects of the development of the AD industry would require analysis beyond the scope of the FAPRI-Ireland model.

6.5 Conclusion and Key Findings

1. **Agricultural diversification supports GHG reduction, but at a modest scale:** The development of an AD industry using grass and animal slurry contributes to the decarbonization of Irish agriculture. However, the overall reduction in agricultural greenhouse gas (GHG) emissions is modest, estimated at 2.3% by 2030 under the AD_120 scenario. This underscores the need for a multi-faceted mitigation approach, combining AD with other measures outlined in the Teagasc MACC (Lanigan et al., 2023).
2. **Economic gains in agriculture, but a negative impact on beef supply:** The shift from cattle farming to grass production for AD results in a net gain in sectoral income, primarily due to increased output from grass sales and lower input expenditure (e.g., feed, fertiliser, and veterinary expenses). By 2030, the projected increase in sectoral income is 1.3%, with per-hectare income from AD estimated at €425. However, reduced cattle output would negatively impact the beef processing sector.
3. **Implications for land use and stocking rates:** Achieving the national biomethane target requires diverting between 110,000 and 130,000 hectares from pasture to AD feedstock production. This results in lower suckler cow numbers, and a requirement that there is no intensification of stocking rates elsewhere.

4. **Reduced input use and environmental co-benefits:** Lower cattle numbers reduce demand for chemical nitrogen fertilisers, with usage projected to be 2% lower under AD_120. This also contributes to lower nitrous oxide emissions and potential water quality benefits.
5. **Beyond agriculture: economy-wide considerations:** While the development of AD benefits the agricultural sector, reduced cattle production would negatively impact the meat processing and feed supply industries. Conversely, the expansion of AD presents new economic opportunities in energy production, infrastructure development and rural employment. A more comprehensive economy-wide assessment would be needed to evaluate these trade-offs.
6. **Integration with Ireland's energy and climate policy:** A clear policy framework on AD incentives, feedstock pricing, and GHG accounting (to reflect environmental benefits that accrue beyond the agriculture sector) is required.

7 Conclusions

Currently the cost of on-farm Anaerobic Digestion (AD) technology in the Irish context is considered prohibitive for the typical Irish farm size. This means for most projects, animal manures and crops would have to be transported from farms to a central regional AD unit. This would add to the cost of energy production from this system.

FLEET, **F**arm **l**evel **e**conomic, **e**nvironmental and **t**ransport modelling of alternative feedstocks for regional Anaerobic Digestion, was co-ordinated by Teagasc and funded by the Sustainable Energy Authority of Ireland (SEAI) and Gas Networks Ireland (GNI). The project has made extensive use of the Teagasc National Farm Survey (NFS) to assess the feasibility of the export of feedstock from farms to support biomethane generation through Anaerobic Digestion (AD).

The microeconomic and environmental modelling carried out in the project used micro data from the Teagasc National Farm Survey (NFS). While some sectors such as dairying exhibit consistent strong economic performance, other sectors are more economically vulnerable. The economic viability of some enterprises are low, thus a rationale exists for examining alternative enterprises which complement or replace existing systems.

An existing data gap relating to the economic case for the production of silage for AD in Ireland, was addressed by an analysis of the potential costs and returns at farm level, of supplying silage as a feedstock for a regional AD facility. The analysis was based on farm level data for the period 2018-2020. Whilst there has been significant volatility in costs and output in the intervening years, the methodology for establishing competitiveness of feedstock supply has been established and will be updated in future research.

Economic analysis has shown that excluding capital cost of land and silage storage facility, while including the nutrient opportunity costs, the new enterprise of supplying silage to an AD plant could be competitive with existing farm enterprises such as specialist cattle rearing, specialist cattle other and specialist sheep when the price of silage is above €35 per tonne. However, during the 2018-2020 time period, traded silage prices of €30 per tonne were recorded and these would be below the average cost of production.

The Teagasc, NFS, was also used to determine farmers willingness to engage in feedstock supply for an AD facility. The results indicated of those farmers willing to supply silage, they would be willing to supply a total weighted silage area of approximately 420,000 acres (175,000 hectares). The total amount of grassland area that is needed to reach the biomethane target of 5.7 TWh is estimated to be in the range of 110,000 to 130,000 ha,

Environmental models were used to examine the environmental sustainability of alternative farm scale feedstock solutions supplied to the regional AD plants. This analysis has shown that the GHG emissions reduction on a stylised hectares basis are very high (50 to 98%) for the scenarios where grass is grown and used as a feedstock for AD. Furthermore, in the scenarios where slurry iss used as a feedstock, the emissions reduction were significantly less than the grass feedstock scenarios. This was because the livestock were assumed to remain on the farm and only slurry based emissions were excluded. The same logic generally applied to NH3 emissions. The larger reductions are due to animal based emission being taken out. However in a couple of scenario emissions actually increase versus the baseline as Digestate is heavily applied (which is high in NH3).

Transport models were used to identify possible feedstock volumes at a landscape level, which was enabled by the significant amount of high resolution spatial data available nationally to facilitate very detailed location analysis for feedstock and facilities siting for AD development. The analysis shows that in our ‘middle optimistic’ (surplus grass) scenario, the National Biomethane Strategy target of 140 40 GWh plants could be relatively easily accommodated spatially, and with feedstocks supplying these plants largely coming from within a 10 km along road travel distance. However, the ‘pessimistic’ scenario with 15% of grass being made available suggests that travel distance must increase on average to 15 km and potentially greater.

The aforementioned, farm scale economic, environmental and transport models were used to inform aggregate sector modelling to evaluate potential national economic and environmental trade-offs of alternative feed stock solutions. The aggregate sector modelling carried out indicated that the development of an AD industry that uses grass DM and animal slurries to achieve the national biomethane target of 5.7 TWh by 2030 is projected to lead to an increase in agricultural sector income and a decrease in agriculture sector GHG emissions relative to a baseline where the use of grass and slurry feedstocks for AD does not occur.

By 2030 agricultural sector income, where the AD industry meets that national biomethane target by using grass dry matter and animal slurry as feedstocks, is projected to be between 1.2% and 1.3% higher (€49 - €53m) than under the Baseline. This is equivalent to an income of €425 per ha for the land used for AD.

The projected changes to agricultural activity levels, input usage and the diversion of animal slurries from use as nutrients in agriculture to use as feedstocks in AD is also reflected in reduced agricultural GHG emissions. By 2030 agricultural GHG emissions are projected to be 2.3% lower than under the baseline.

FLEET is the first of its kind research which identified economic and environmental impacts at farm, landscape and national levels associated with different farm scale feedstock solutions for supply to regional AD plants. The research results have the potential to provide a range of economic, energy, climate, environmental, social and economic benefits to a wide range of stakeholders.

Next Steps

The baseline sustainability of a grass silage feedstock supply to a regional AD facility was established during the FLEET project. Whilst the economic and environmental sustainability of silage production for AD purposes competed favourably with average drystock systems of production, during the period 2018-2020, there is a need for ongoing research on updated competitiveness of feedstock supply in a changing agricultural and energy market environment. Furthermore, the feedstocks examined as part of FLEET were limited to grass silage and slurry. With the publication of the Biomethane Strategy and the Biomethane Capital Grant announced in 2024, there is growing interest in a potentially wider range of feedstock supply and business models, not limited to the feedstocks and business model examined as part of FLEET. Hence, next steps in the research would benefit from an updated range of feedstock sustainability and business model assessment, from an economic, environmental, transport and aggregate sector modelling perspective.

Appendix I: AD development in select European countries

Germany

Germany is by far the largest biogas producer in Europe. The first AD facilities were installed in the early 1990s, reaching 3 gigawatts by 2006 (Auer, 2017). In 2018, 91% of biogas was used in the form of Combined Heat and Power (CHP), whereby the heat is used for heating, industrial or district heating, while also producing electricity.

The feedstock for these AD plants are primarily energy crops such as maize, grass silage and whole crop, while liquid manure and solid manure are also used (Auer, 2017). In 2011, Germany shifted its policy to discourage the production of large AD plants in favour of smaller ones, imposing maximum limits on energy crops of 60%. This high usage of energy crops is controversial, as the AD plants rely on government supports, while competing for land with food production. This led to the abolition of the substrate bonus for energy crops in 2014 (Eyl-Mazzega et al., 2019).

In 2015, further price changes were made to reduce the feed-in tariffs for new large AD plants, while increasing the subsidy for AD plants smaller than 75kW utilizing manure substrates. With expiring subsides for existing biogas plants, many operators were faced with new requirements and challenges to continue operating economically.

There was a shift in 2017 from a guaranteed feed-in tariff to a tendering system based on auctions, an outcome of political arguments about reducing the cost, favouring market integration and establishing competitive renewables (Eyl-Mazzega wt al., 2019).

Flexible operation is a requirement for existing biogas plants in a bid to enhance power grid stability. This means it is necessary to install at least twice the capacity of the average rated power output, allowing electricity to be supplied at peak periods of the day or week in response to demand. So far neither the maximum auctioned volume or substantial cost reductions have been achieved.

There is an additional tariff depending on the type of substrate, with food not eligible for additional payments. Energy crops are categorized as; maize (wholecrop), cereals (whole crop), cereal grain, corn, grass and sugar beet, which were entitled to a bonus payment of 4-6€ ct/kWh. Feedstock category 2 was entitled to a bonus of 6-8 € ct/kWh which included; clover grass (as catch crop), lucerne grass (as catch crop), horse manure, cattle slurry, sheep manure, solid manure from pigs, straw (Fulton et al., 2012). The importance of the differentiation between the use of main crops, such as wholecrop and catch crops, can be seen as a bonus payment. The use of catch crops reduces the ecological footprint of main crops, reduced erosion, nitrate leaching and application of mineral fertiliser, while improving soil humus content due to use of digestate (Maier et al., 2017).

Italy

In Italy the AD industry was stimulated by the introduction of advantageous feed-in tariffs that guaranteed the price for small biogas plants based on agricultural feedstock, including energy crops, in 2008 (Eyl-Mazzega, 2019). The sector is the second largest producer in Europe by number of plants. There is availability of agricultural biomass, with 80% using it as a feedstock, combined with strong usage of gas in transportation, which has favoured the upgrading of biogas to biomethane (Eyl, Mazzega et al., 2019).

Italy has the largest natural gas vehicle fleet (in the EU?) and since 2018 has seen a shift towards generation for biomethane. Fuel retailers are required to provide consumers with an amount of biofuels or purchase Certificates of Release to Consumption of Biofuels (CIC) (McCabe et al., 2020) Biomethane injected into the natural gas grid to be used in the transport sector can have access to the support mechanisms (Eyl, Mazzega et al., 2019) and is seen as an important step towards the usage of biomethane in agricultural transportation and heavy good vehicles.

Italy changed its supports towards small size plants based on by-products and agricultural waste over energy crops which has reduced the growth considerably (Torrijos, 2016). Additional support was given for projects capturing heat as well as reducing the nitrogen content of the digestate.

An interesting case study in Italy is Biogasdoneright (BDR) in the Po valley which combines energy crop production for biogas with crop production, by use of sequential cropping or integration crops (Dale et al., 2020). These crops are like cover crops and do not cause land use change, improve soil fertility and carbon sequestration by having a living root in the soil, cycling carbon throughout the season, which otherwise would be left partially fallow (Chapagain et al., 2020). When these crops are combined with the application of manures, they can help reduce the synthetic fertiliser need of the subsequent crop Cottney et al., 2020).

Denmark

In 2009 the Danish government set a target for the agricultural sector to be a supplier of green energy, with the goal that 50% of livestock manure would be used for green energy production by 2020. Up until that point the typical biogas plant in Denmark was jointly owned and operated by farmers, with the biogas used in CHP to supply heat to the local town . With the introduction of the feed-in subsidy for injection of biomethane into the gas grid, this enabled the construction of large centralised facilities which were largely credited with achieving the goal of digesting 50% of animal manures by 2020 (Eyl-Mazzega et al., 2019).

The policies governing AD in Denmark have imposed limits on the use of energy crops to 12% of feedstock mass, with an exception for ryegrass and clovers from land that has not been cultivated in the previous 5 years (Al Seadi et al., 2018).

In 2029 , production of biogas was 8% of the annual domestic gas consumption and a target was set of becoming a net CO2 neutral society in 2050 (Eyl-Mazzefa, 2019). While wind and solar are variable, biogas production is stable and storable and is recognised as part of the solution involving power grid, gas grid and district heating systems in the country.

Since the cost of the biogas subsidy scheme reached €215 million in 2017, the Danish parliament reacted to curb the cost of the biogas subsidy, by introducing a new subsidy with a fixed annual pool of €32 million (Eyl-Mazzega et al., 2019).

While biogas is often cited as best utilised in the transport sector, particularly of heavy good vehicles, the taxation system in Denmark does not allow for the differentiation between biomethane and natural gas once it has entered the gas grid. Thus, it is taxed as natural gas resulting in primary use of biogas for heat and power (Eyl-Mazzega et al., 2019).

France

The biogas sector in France underwent significant development from 2006, with lower feed in tariffs, with feedstocks primarily based on livestock waste and limited use of energy crops (André et al., 2018). The feed in tariffs are based on co-generation systems (CHP) and are dependent on the size of the installed capacity, substrate type and heat use. An extra premium applies if 60% livestock waste is used. A tender system has been used to support large scale above 500kWe plants.

Biomethane was granted grid access in 2011 and since 2015 has seen a sharp increase in the number of plants, with expectations that France will become a leader in the European biomethane sector (Eba et al., 2020). Originally biomethane plants of any size qualified for a feed in tariff, however, the French government announced in 2019 plans to end the feed in tariff for the large scale biomethane plants, without specifying the threshold between the feed in tariff and the tender system which has no size based limit.

UK

Anaerobic Digestion has operated in the UK on a farm scale since the 1970's, typically focused on manure management. The benefits include providing storage, reducing odours and reducing pollution of water courses .

In 1996 landfill taxes were introduced in the UK with differing rates for inert and non-inert waste which was taxed at £96.7/tonne as of 1st April 2021, rising from an original rate of £7/tonne (Elliot, 2016). The landfill tax significantly reduced the quantity of waste sent to landfill and provided biogas plants with an opportunity to charge gate fees (McCabe et al., 2020).

Feed-in-Tariffs were introduced in 2011 along with Renewable Obligations (ROC) and Renewable Heat Incentive (RHI) leading to a rapid expansion in non-sewage based AD plants in the UK (McCabe et al., 2020). In the UK context, the digestion of food waste and manures are cited as providing maximum potential for GHG emissions reductions compared to possible carbon leakage associated with use of crops and wastes that could be used as animal feed [46]. ROCs can be traded, with AD eligible for two ROCs per MWh generated.

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