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Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery,

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Abstract:

The need to reduce global greenhouse gas (GHG) emissions may require the use of renewable gaseous fuels in the food and beverage industry to decarbonise processes that are difficult to electrify such as whiskey distillation.

Large companies report their GHG emissions according to the Greenhouse Gas Protocol in terms of direct and indirect GHG emissions.

Anaerobic digestion (AD) of distillery by-products can replace up to 64% of the natural gas consumption of the distillery and could reduce direct GHG emissions by 54% and indirect GHG emissions by 11,389 tCO2eq (41% of direct savings) if digestate replaces synthetic fertiliser used to cultivate barley consumed by the distillery.

The replacement of animal feed produced by the distillery with imported animal feed (distillers' grains from the USA and soybean meal from Argentina) could, in a worst-case scenario, negate a significant portion of direct and indirect GHG emission savings. The decision as to whether the GHG emissions associated with imported animal feed should be included in the calculation is not clear cut and can be subjective.

Digestate management, particularly storage and transportation may pose a significant barrier to the implementation of an AD plant processing distillery by-products. Alternative methods of digestate transportation such as pipelines, and digestate treatment (separation, drying, and evaporation) should be assessed to mitigate logistical issues.

To successfully integrate AD with a distillery future research should conduct multi criteria decision analysis to identify the most suitable share of distillery by-products to use in an AD plant to balance positive and negative attributes of such projects.

Keywords: Biogas; Renewable energy; Emission savings; Energy resource; Digestate management; Energy system

Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery

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Highlights

- Biogas from distillery by-products can replace 64% of natural gas consumption.
- Anaerobic digestion could reduce Scope 1 GHG emissions of the distillery by 54%.
- Spreading digestate on land used for barley production can reduce Scope 3 emissions.
- Emissions from imported animal feeds could negate Scope 1 and Scope 3 savings.
- Use of all by-products could result in significant digestate management challenges.

Abstract

The need to reduce global greenhouse gas (GHG) emissions may require the use of renewable gaseous fuels in the food and beverage industry to decarbonise processes that are difficult to electrify such as whiskey distillation. Large companies report their GHG emissions according to the Greenhouse Gas Protocol in terms of direct and indirect GHG emissions. Anaerobic digestion (AD) of distillery by-products can replace up to 64% of the natural gas consumption of the distillery and could reduce direct GHG emissions by 54% and indirect GHG emissions by 11,389 tCO_2eq (41% of direct savings) if digestate replaces synthetic fertiliser used to cultivate barley consumed by the distillery. The replacement of animal feed produced by the distillery with imported animal feed (distillers' grains from the USA and soybean meal from Argentina) could, in a worst-case scenario, negate a significant portion of direct and indirect GHG emission savings. The decision as to whether the GHG emissions associated with imported animal feed should be included in the calculation is not clear cut and can be subjective. Digestate management, particularly storage and transportation may pose a significant barrier to the implementation of an AD plant processing distillery by-products. Alternative methods of digestate transportation such as pipelines, and digestate treatment (separation, drying, and evaporation) should be assessed to mitigate logistical issues. To successfully integrate AD with a distillery future research should conduct multi criteria decision analysis to identify the most suitable share of distillery by-products to use in an AD plant to balance positive and negative attributes of such projects.

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Keywords

Biogas

Renewable energy

Emission savings

Energy resource

Digestate management

Energy system

1. Introduction

1.1. The need to reduce greenhouse gas emissions

1.1.1. Targets for greenhouse gas emission reduction

In order to mitigate the impact of climate change a limit on the rise in average global temperature below 2 °C above pre-industrial levels has been agreed under the Paris Agreement [1]. Rapid reductions in greenhouse gas (GHG) emissions are required to achieve a balance between the sources of, and sinks for, GHGs in the latter half of the 21st century [1]. Within the EU a reduction in GHG emissions by 40% in 2030, relative to 1990 has been proposed to aid in achieving the goals of the Paris Agreement [2].

1.1.2. Heating and cooling: a significant share of energy use

Heating and cooling in the EU represents a significant share of final energy consumption (ca. 50%) and is a key sector in decarbonisation of the energy system [2]. Member States must ensure an increase of 1.3% in the share of renewable energy in the heating and cooling sector as an annual average from 2021 to 2030 [2]; this would suggest a minimum increase of 10% by 2030 relative to 2020. A significant user of thermal energy (both heating and cooling) is the food processing and beverage (FB) sector.

1.1.3. The need for renewable energy in the food and beverage sector

The remaining carbon budget from 2018 to limit global warming to 1.5 °C above pre-industrial levels with a 50% chance of success is 580 $GtCO_2eq$, this reduces to 420 $GtCO_2eq$ for a 66% chance of success [3]. If current levels of GHG emissions continue (42 $GtCO_2eq/a$ in 2017 [3]) the carbon budget for a 50% chance of success would be “spent” in ca. 14 years (10 years for a 66% chance). Industrial CO_2eq emissions are required to reduce by 80% via; reduced demand, increased efficiency, electrification, decarbonising remaining non-electric fuels, and the implementation of carbon capture and sequestration [3]. Certain industrial sectors, including the FB sector, contain processes (evaporation, distillation, and drying) that may be difficult to electrify, either from a technical perspective owing to the higher temperatures required in these processes [4], or from a financial perspective (high CAPEX and long payback periods). Replacement of fossil fuels in these processes with renewable alternatives is therefore essential. Recent data for Annex 1 countries to the UN Framework Convention on Climate Change, the EU, and

Ireland (the study region of this work) on the contribution of the FB sector to total GHG emissions in 2017 from the UNFCCC [5] are given in Table 1.

Table 1. Annual Annex 1, EU, and Irish GHG Emissions 2017.

	Annex 1 Mt CO_2 equivalent	EU Mt CO_2 equivalent	Ireland kt CO_2 equivalent
Sources of Energy Related GHG Emissions in the Food and Beverage Sector			
Biomass	17.3	7.7	104.9
Gaseous Fuels	62.9	31.1	402.6
Liquid Fuels	11.9	4.1	407.6
Other Fossil Fuels	0.3	0.0	–
Peat	0.0	0.0	3.0
Solid Fuels	25.3	4.7	85.2
Energy Related GHG Emissions from the Food and Beverage Sector	101.0	40.3	900.1
Energy Related GHG Emissions from Manufacturing Industries and Construction	1979.7	499.8	4665.1
Energy Related GHG Emissions	13,424.2	3,367.8	36,762.4
Total GHG emissions	14,818.8	4,065.1	66,741.0

A summary of; total GHG emissions, energy related GHG emissions, GHG emissions from manufacturing and construction, and GHG emissions from the FB sector at; Annex 1, European, and an Irish scale is given in Fig. 1. Replacement of the fossil fuels consumed within the FB sector by renewable and sustainable energy sources is required to effectively decarbonise this sector.

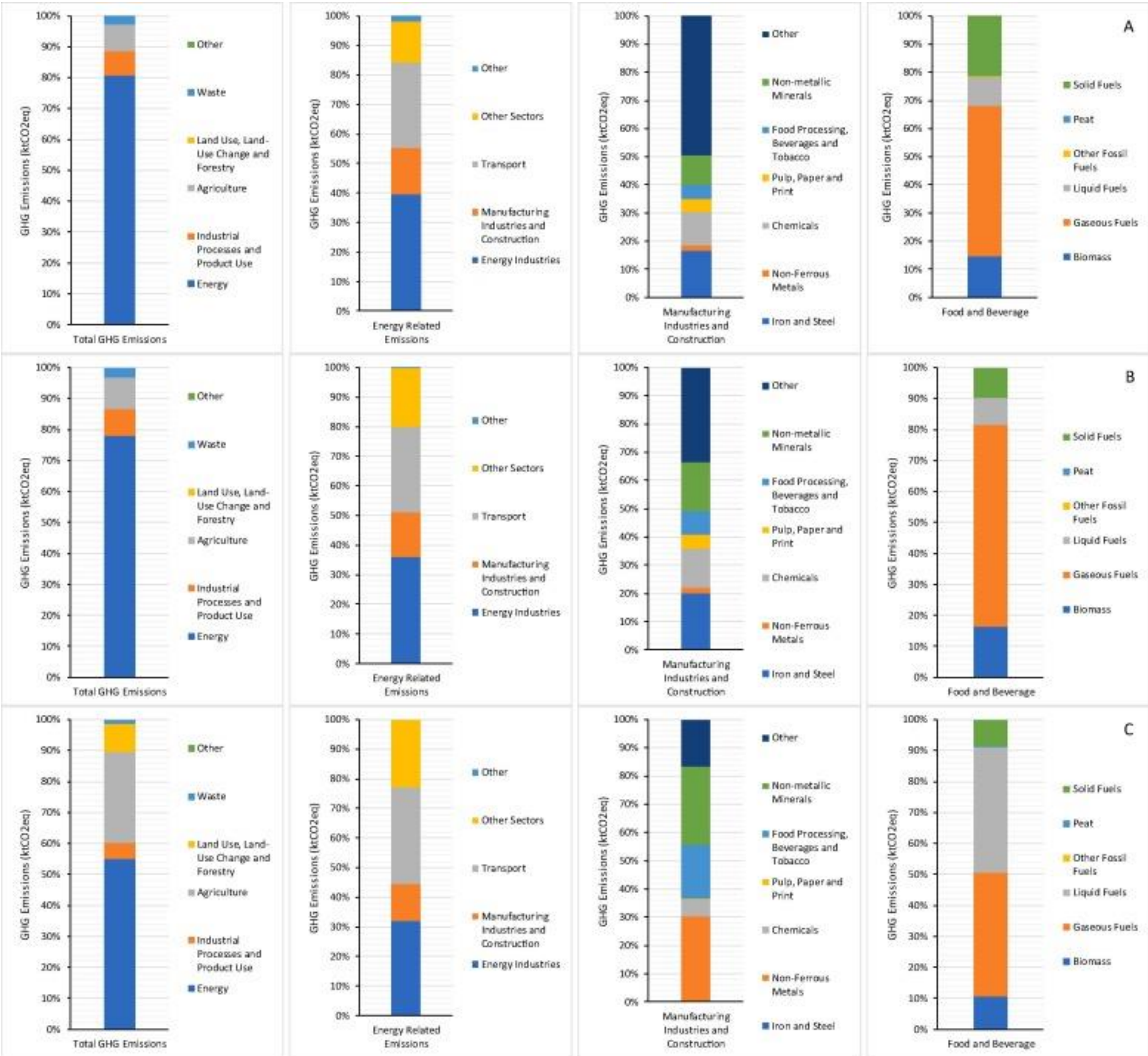

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Fig. 1. Share of Total GHG Emissions and Energy Related GHG Emissions. A: Annex 1 Countries, B: EU, C: Ireland.

In terms of the study region of this work (the Republic of Ireland), energy related GHG emissions are the main source of GHG emissions (55%), lower than the contribution for Annex 1 countries or for the EU owing to a larger contribution of agricultural emissions in Ireland. The contribution of manufacturing and construction to energy related GHG emissions in Ireland is 12.7%, similar to the contribution in Annex 1 countries and at a European scale. The FB sector in Ireland produced 19% of GHG emissions associated with manufacturing and construction, double the contribution in Annex 1 countries and at a European scale. This is a result of the significant agricultural activity in Ireland and the comparatively large value of the FB industry in Ireland. Within the Irish FB sector, the main sources of GHG emissions are liquid fossil fuels (45%) and gaseous fossil fuels (45%). In an Irish context, GHG emissions from the FB sector are higher than the equivalent contributions in Annex 1 countries and at a European level (2.45% of energy related GHG emissions).

1.2. Scope 1, Scope 2, Scope 3 greenhouse gas emission reduction potential

Globally, large companies in multiple sectors including the FB sector account for their GHG emissions using the Greenhouse Gas Protocol developed by the World Resources Institute and the World Business Council for Sustainable Development [6]. GHG emissions within the Greenhouse Gas Protocol are segregated into 3 main areas called "scopes". The Greenhouse Gas Protocol is used by companies across the world to disclose their GHG emissions.

Scope 1 emissions arise from activities under the direct control or ownership of companies such as fuel combustion. Scope 2 GHG emissions are associated with the generation of electricity purchased by companies [6]. Scope 3 emissions are indirect emissions associated with the value chain of companies, but do not arise from sources owned or controlled by the company. Scope 3 emissions are disaggregated into 15 different categories (not all of which are applicable to all companies) and may include indirect emissions from goods and services purchased by the company [7].

This work will assess a potential method of reducing Scope 1 and Scope 3 GHG emissions from a large distillery in the Republic of Ireland as an example of a facility in the FB sector which currently uses significant quantities of natural gas.

1.3. Potential methods of reducing greenhouse gas emissions in the food and beverage sector

1.3.1. The need for renewable gas

To decarbonise the FB sector the combustion of gaseous fossil fuels (primarily natural gas) must be replaced with renewable alternatives. Renewable gaseous fuels are primarily produced via the process of anaerobic digestion (AD). Production of renewable gas in an AD plant involves the conversion of biodegradable material in the absence of oxygen to biogas (ca. 55%$_{vol}$ CH_4, 45%$_{vol}$ CO_2) and a nutrient rich digestate via a series of microbial processes [8]. Previous work in an Irish context found that a significant portion of industrial natural gas demand could be supplied via AD of residues and grass silage [9], [10], [11], [12]. Biogas produced from residues generated in the FB sector improves resource efficiency, reduces fossil fuel consumption [13], and recycles nutrients [14]. Biogas can be combusted (following drying and H_2S removal) in a gas boiler for the production of thermal energy, or it can be "upgraded" via the removal of $CO_2$to produce biomethane which can be used as a transport fuel [15] or directly injected into the gas network [16]. Globally, the International Energy Agency (IEA) estimates that 20% of current natural gas demand can be met sustainably by biogas [17].

1.3.2. Solid biomass combustion

The combustion of solid biomass can readily supply the high temperature heat required in the FB sector [18]. However, a potentially limited resource base in some regions means that the use of solid biomass to supply industrial heat may compete with solid biomass used in; non-bioenergy uses (e.g. construction), transportation (e.g. advanced biofuel production), and in power generation [18]. This can lead to a reduction in energy security and an increase in costs. Solid biomass combustion as a source of renewable heat is commonplace in the FB sector globally provided that biomass supply logistics are viable. Current use of biomass in the FB sector in Ireland is limited (279 GWh in 2018 [19]), however production of solid biomass for energy production is set to increase substantially in the future [20]. Additional issues arising from the use of solid biomass relate to the vehicle movements required to transport biomass to the user and storage space requirements, both of which are exasperated when end users are in urbanised and built up areas. Combustion of solid biomass is also linked to a deterioration in air quality [21].

1.3.3. Electrification of industrial heat

Electrification of processes in the FB sector can reduce GHG emissions provided that the electricity is renewable. In the IEA "Future is Electric" scenario the growth in electricity consumption in the industrial sector was more constrained than growth in buildings (for space heating and water heating) and in transport, and accounted for only 28% of final energy consumption [4]. Reasons for the lower uptake of electricity in industrial processes include; fuel switching requiring a change in process, the integrated nature of industrial processes results in a change upstream to cause changes downstream, and the long lifetimes and slow turnover of capital stock [4]. According to the IEA, the predominant use of electricity as a heat source in industrial processes is by heat pumps to provide low temperature heat (<100 °C) [4]. However, up to 50% of heat demand in light industry (including textiles, light manufacturing, and the FB sector) require temperatures in excess of 100 °C (for example distillation and evaporation require temperatures of 140–150 °C [18]), and as such the use of heat pumps in these processes is more challenging [4]. Currently some distilleries use mechanical vapour recompression (MVR) technology to produce steam at 120 °C, further integration of this technology may be a viable method of electrifying additional high temperature processes.

1.3.4. Biogas as a source of industrial heat

Owing to the technical maturity of AD, the existing expertise in integrating AD plants with distilleries [22], the ability to use by-products of the FB sector as feedstock for AD plants, and the ability to provide high temperature heat, AD will be the main focus of this work.

1.4. Prior work integrating anaerobic digestion in distilleries

Use of distillery by-products in an AD plant will result in; the production of biogas (a source of renewable energy), GHG emission reductions from the replacement of the incumbent fossil fuel by biogas, the possible replacement of fertiliser by digestate produced by the AD plant, and logistical challenges related to the management of digestate. A review of literature in relation to the integration of AD and distilleries (Table 2) indicates that research has been conducted on the use of distillery waste in AD plants since the 1970s [23]. Most of the work to date is based on the performance of lab scale AD trials treating distillery wastewater and by-products. Of the studies identified; 13 assess the energy resource, 2 consider the potential GHG emission reductions, 3 studies assess the potential for fertiliser replacement using digestate, and 3 consider the logistics associated with digestate use. Issues relating to the replacement of feed products that could be produced from distillery by-products by imported animal feeds were only addressed in one prior study [24].

Table 2. Prior Work Assessing AD and Distillery Wastes and By-products, “Y” Indicates if the Analysis was Conducted in the Study.

Distillery Input Material	AD Feedstock	Study Type	Energy Resource	GHG Reduction	Fertiliser Replacement	Digestate Logistics	Ref
Not Specified	Distillery Wastewater	Pilot Trial					[23]
Barley	Distillery Wastewater	Laboratory Trial					[25]
Molasses	Distillery Wastewater	Laboratory Trial					[26]
Molasses	Vinasse	Laboratory Trial					[27]
Multiple	Multiple	Review					[28]
Barley	Pot Ale	Laboratory Trial					[29]
Not Specified	Distillery Wastewater	Laboratory Trial					[30]
Not Specified	Distillery Waste	Laboratory Trial					[31]
Wine	Vinasse	Review	Y				[32]
Wheat	Stillage	Desktop Analysis	Y				[33]
Maize	Thin Stillage	Laboratory Trial	Y				[34]
Maize and Wheat	Stillage	Laboratory Trial and Analysis	Y		Y	Y	[35]
Several	Stillage	Review	Y				[36]
Several	Spent Wash	Review					[37]
Maize	Thin Stillage	Laboratory Trial and Analysis	Y				[38]
Maize	Stillage	Laboratory Trial					[39]
Maize	Thin Stillage	Laboratory Trial					[40]
Molasses	Spent Wash	Full Scale Trial	Y				[41]
Several	Thin Stillage	Full Scale Plant					[42]
Several	Stillage, wet cake, syrup,	Laboratory Trials and Desktop Analysis	Y			Y	[43]

Distillery Input Material	AD Feedstock	Study Type	Energy Resource	GHG Reduction	Fertiliser Replacement	Digestate Logistics	Ref
Not Specified	Vinasse	Full Scale Commercial Plant Operation					[44]
Several	Vinasse	Review	Y				[45]
Not Specified	Vinasse	Review and Desktop Analysis	Y			Y	[46]
Sugar Cane	Vinasse	Laboratory and Full-Scale Trials	Y				[47]
Sugar Cane	Vinasse	Laboratory Trial					[48]
Sugar Cane	Vinasse	Desktop Analysis		Y			[49]
Barley	Draff and Pot Ale	Desktop Analysis	Y	Y	Y		[24]
Barley	Draff and Pot Ale	Desktop Analysis	Y	Y	Y		[50]

1.5. Gaps in state of the art

There is a clear gap in the state of the art in relation to a combined assessment of; the energy resource, GHG emission reduction, fertiliser replacement, and digestate logistics that arise when integrating an AD plant and a distillery. Furthermore, reductions in Scope 1, Scope 2, and Scope 3 GHG emissions have not been assessed in academic literature. The replacement of feed products manufactured from distillery by-products by imported animal feeds has only been assessed in one prior study [24]. To date, no single study has presented a combined assessment of these parameters.

1.6. Aims and objectives

This work aims to:

1. Assess the energy resource associated with AD of distillery by-products from a large distillery;

2. Quantify fertiliser replacement using digestate produced by the AD plant;

3. Investigate issues arising from the cessation of animal feed production if distillery by-products are used in an AD plant;

4. Determine the impact of AD on Scope 1, Scope 2, and Scope 3 GHG emissions at the distillery;

5. Account for the logistics associated with the use of digestate produced in the AD plant.

This is the first paper to address all of the aforementioned aims in a single piece of work. The methodology developed in this paper is applied to a large distillery in The Republic of Ireland. This distillery is a significant producer of spirits globally and as such the analysis conducted herein can be applied to other facilities in the FB sector within Ireland, the EU, and worldwide.

2. Methodology

2.1. Description of distillery

The distillery studied in this work is the Irish Distillers Ltd. Midleton Distillery, the largest distillery in The Republic of Ireland and a leading global producer of whiskey and spirits. The distillery is located on the outskirts of Midleton Town (population 12,496) in Country Cork. The predominant agricultural land uses in the environs of the distillery are tillage production and pasture for cattle. The distillery produces distilled spirits from a combination of; maize, malted barley, un-malted barley, and smaller quantities of other cereals. All the brewing and distillation processes occur at the one site with some onsite and offsite maturation of whiskey, this centralised production model enables the implementation of large-scale sustainability projects.

Irish Distillers' parent company (Pernod Ricard) aim to reduce total GHG emissions (Scope 1, Scope 2, and Scope 3) associated with all of their subsidiary companies by 50% by 2030 in line with UN sustainable development goal (SDG) 13 “Climate Change” [51]. This goal requires; a reduction in Scope 1 GHG emissions associated with fuel consumption at the distillery, a reduction in Scope 2 GHG emissions through the use of renewable electricity, and a reduction in Scope 3 GHG emissions (responsible for up to 75% of total GHG emissions) through the use of sustainable packaging and improved agricultural practices of suppliers. The Irish Distillers Midleton distillery is one of the largest distilleries owned by Pernod Ricard and as such is also one of the largest emitters of GHGs.

2.2. Distillery operations

The period of production assessed in this work (May 2018 to May 2019) resulted in the production of approximately 61.126 million litres of original alcohol (MOLA). Production of distilled spirits results in three by-products; draff, thick stillage, and thin stillage. Draff () (46.7 ktwwt/a) consists of the residual solids following the brewing of malted and un-malted barley to produce wort. Thin stillage () (277.5 ktwwt/a) is the liquid remaining after the distillation of pot ale (a residual liquid remaining after the initial distillation of fermented wort, also known as wash). Thick stillage () (322.8 ktwwt/a) is the solid–liquid mixture remaining after the distillation of maize in a continuous distillation column (this is similar to the whole stillage by-product fraction found in maize ethanol production). Currently, the by-products are processed in a feeds recovery plant to produce three animal feed products; wet grains () (62,766 twwt/a), dried distillers’ grains also known as DDG, () (12,806 twwt/a), and syrup () (41,794 twwt/a).

Thermal energy used in the distillery for brewing, distillation, and drying of the DDG is provided by the combustion of natural gas () (ca. 254 GWh/a from May 2018 to May 2019) in three large boilers. The main driver of natural gas consumption is steam demand for use in brewing and distilling operations. Thermal energy consumption of the feeds recovery plant () amounts to 8.7 GWh_{th}/a of steam, predominantly used to dry wet grains in the production of DDG. Based on a CO_2 emission intensity of natural gas () of 201 $kgCO_2/MWh_{th}$ [52] the total mass of CO_2emitted from the combustion of natural gas at the distillery () is 51,129 tCO_2eq (May 2018 to May 2019) from the production of 61.216 MOLA. This accounts for >99% of Scope 1 GHG emissions arising from the distillery. Replacing natural gas with biogas from distillery by-products would reduce Scope

1 GHG emissions. Fugitive methane emissions from the operation of an AD plant would contribute to Scope 1 emissions**.**

Electrical energy is primarily consumed by two mechanical vapour recompression (MVR) units used to evaporate water during syrup production. The total electrical energy consumption of the feeds recovery plant () is approximately 7.9 GWh_e/a. Additional consumers of electricity are pumps and motors throughout the distillery. Total electrical energy consumption of the distillery () amounts to ca. 42 GWh_e/a. The distillery currently pays a premium on the electricity purchased to ensure that it comes from renewable sources, as such, the Scope 2 GHG emissions associated with this electricity () are zero.

Scope 3 emissions are classified into 15 categories according to the reporting standards [53] and are mutually exclusive to avoid double counting. Of the 15 categories available, 9 are used by the distillery for classifying Scope 3 emissions, these are detailed in Appendix A. A summary of the Scope 3 categories, their relevance to the distillery, and whether or not they are altered by implementation of a potential AD pant is given in Table 3. The total Scope 3 GHG emissions associated with the distillery activities have not been quantified, however, the potential alteration of Scope 3 GHG emissions following the implementation of an AD system treating by-products will be outlined in the following sections. A flowchart outlining the main aspects of the distillery and the potential role of AD is provided in Fig. 2.

Table 3. Scope 3 Categories and Relevance.

Scope 3 Category	Category Description	Relevant to Distillery	Altered by AD Plant
1	Purchased goods and services	Y	Y
2	Emissions from capital goods	Y	Y
3	Emissions from fuel and energy	Y	Y
4	Upstream transportation and distribution	Y	N
5	Waste generated in operations	Y	Y
6	Business commuting	Y	N
7	Employee commuting,	Y	N
8	Upstream Leased Assets	Y	N
9	Downstream transportation and distribution	N	N
10	Processing of sold products	N	N
11	Use of sold products	N	N

Scope 3 Category	Category Description	Relevant to Distillery	Altered by AD Plant
12	End of life treatment of sold products	Y	N
13	Downstream leased assets	N	N
14	Franchises	N	N
15	Investments	N	N

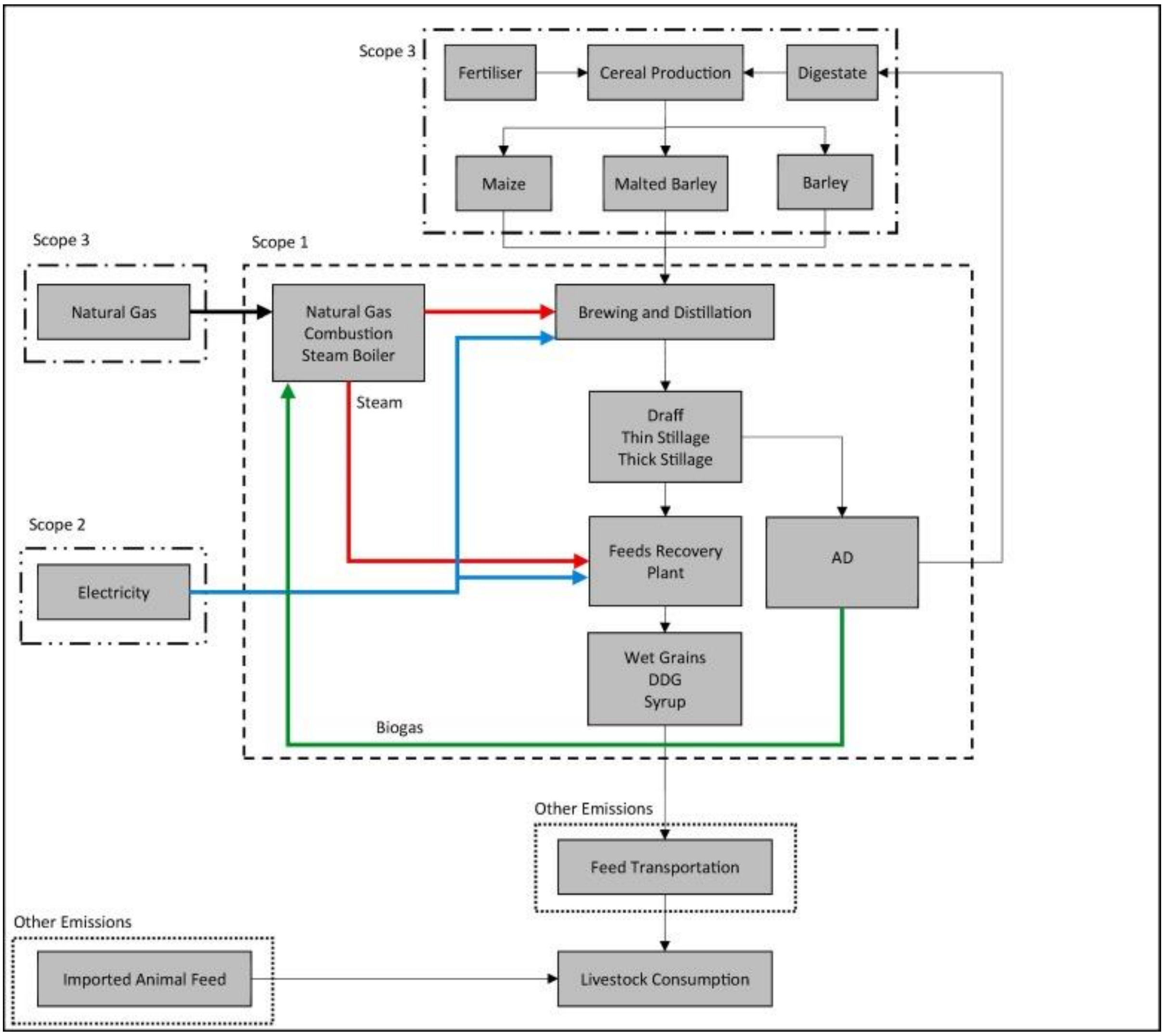

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Fig. 2. Distillery AD Flowchart.

Transportation of the feed products (wet grain, DDG, and syrup) results in the emission of GHG. The total CO_2eq emissions associated with feed product transportation () are calculated based on the total mass of feed products produced (), an average transportation distance () of 98 km, and a specific CO_2eq emission of 0.225 kgCO_2eq/t.km for goods transportation by truck () as per Equation (1).

Equation (1) Feed Transportation CO2 Emissions(1)

Transportation of feed products is conducted by customers who purchase feed products, as such, the GHG emissions emitted during feed product transport are not accounted for in Scope 1, Scope 2, or Scope 3, and will be dubbed "other emissions" in this work.

2.3. Reduction in distillery energy consumption

Using distillery by-products in an AD plant will shut down the feeds recovery plant and will eliminate the total thermal and electrical energy consumption of the feeds recovery plant (8713.6 MWh_{th} and 7.9 GWh_e). The avoided natural gas consumption when the feeds recovery plant no longer operates () is calculated using a total steam system efficiency () of 73.4% based on data from the distillery (Equation (2)).
Equation (2) Avoided Natural Gas in Feeds Recovery Plant(2)
The reduction in GHG emissions associated with avoided natural gas consumption in the feeds recovery plant is calculated using the specific CO_2eq emission factor for natural gas (Equation (3)). This will reduce Scope 1 GHG emissions.
Equation (3) Avoided CO_2 Emissions from Feed Recovery Plant(3)
Additionally, as feed products are no longer being produced, the GHG emissions associated with feed transportation are no longer generated, the mass of CO_2 avoided is calculated as per Equation (1).

2.4. Biogas production from by-products

2.4.1. By-product characteristics

Samples of the by-products were sourced from the distillery and characterised in terms of their total solids content () by drying in an oven at 105 °C for 24 h, and volatile solids content () by combustion at 550 °C for 2 h. Additional data from the quality control lab of the distillery was also sourced to characterise the total solids and volatile solids content of the by-products.
Experimental assays to determine the biochemical methane potential (BMP) were conducted in triplicate using glass fermenters (a working volume of 400 ml for each fermenter). The goal of the BMP assay is to determine the methane production from each by-product in controlled laboratory conditions. Inoculum was sourced from an operational mesophilic AD plant processing a mixture of source separated food waste and slaughterhouse waste. The inoculum to substrate

ratio used was 2:1 on a volatile solid basis. A positive control (cellulose) and blank (inoculum only) were also included in the assay. A detailed description of the BMP assay procedure can be found in previous studies [54], [55]. Using the volatile solid content, the BMP can be used to obtain the methane yield per t_{wwt} of each by-product. Total solids (TS) content, volatile solids (VS) content, and BMP yield for each by-product are shown in Table 4.

Table 4. By-product properties.

By-product	Annual Production	TS	VS	BMP	Methane Yield
	twwt/a	%wwt	%wwt	LCH_4/kgVS	LCH_4/kgwwt
Draff	31,251	27.6	26.5	330 ± 2.2	87.4 ± 0.58
Thin Stillage	277,503	3.9	3.5	494.6 ± 41	17.4 ± 1.44
Thick Stillage	322,846	8.8	8.2	502.6 ± 42.7	41.4 ± 3.52

2.4.2. Gross biogas production

The gross energy production from AD of distillery by-products is calculated using; the BMP of each by-product (), a digestion efficiency () of 80% in practical operation, methane density () of 0.714 kg/m^3 at Standard Temperature and Pressure (STP), an energy content of methane () of 50 MJ/kg, the mass of each by-product available (), and the volatile solids content of each by-product (). Division by 3,600 facilitates conversion to MWh_{th} (Equation (4)).

Equation (4) Gross biogas production (MWh_{th})(4)

It assumed that all of the by-products are combined and processed in a continuously stirred tank reactor (CSTR) system owing to the simplicity of operation of such systems, ease of construction, and significant operational experience. The TS content of the combined by-products when fed to the AD plant is ca. 7.7% which is within the recommended operation TS content of CSTR reactors [56].

2.4.3. Net biogas production

The net energy () production of the AD plant was determined by subtracting the total thermal energy demand of the AD plant comprising of; fabric heat loss through the AD tank structures, heat lost via the evaporation of water within the AD tanks, and heat required to bring the incoming by-products to the temperature of the AD system. Detailed calculations of the thermal energy losses are contained in Appendix B. The biogas produced by the AD plant will be used in the existing gas boilers at the distillery to produce steam for use in distillery operations. The total mass of CO_2eq avoided by using biogas to replace natural gas was () calculated assuming a carbon intensity of natural gas of 201kgCO_2/MWh is based on Equation (5).

Equation (5) Mass of CO_2 Avoided by Replacing Natural Gas with Biogas(5)

Replacement of natural gas with biogas would reduce Scope 1 GHG emissions at the distillery site. Replacement of natural gas will also reduce the Scope 3 Category 3 GHG emissions associated with the upstream production and transportation of natural gas. Scope 3 Category 3 GHG emissions associated with natural gas use at the distillery are calculated using a Scope 3 emissions intensity of 0.02391kgCO_2eq/kWh$_{GCV}$ for natural gas [57].

2.4.4. Fugitive methane emissions

The operation of an AD plant will result in fugitive methane emissions. The calculation of fugitive methane emissions, expressed in terms of the total methane production at biogas plants sourced from literature, are detailed in Appendix C. Mean and median fugitive methane emissions of the total methane produced at AD plants from data contained in Appendix C are ca. 2.65% and 2.6% respectively. This work will assume that fugitive methane emissions () associated with the operation of an AD plant at the distillery site will be 2% of the gross methane production as the plant will be newly built, significant in scale, and will incorporate covered digestate storage and off gas treatment in order to minimise fugitive emissions [58], [59]. The total mass of CO_2eq emitted as a result of fugitive emissions () is calculated using a global warming potential of 25 [60] as per Equation (6).

Equation (6) Fugitive methane emissions(6)

Fugitive methane emissions from an AD plant at the distillery will contribute to the Scope 1 GHG emissions of the distillery, minimisation of such emissions will ensure greater Scope 1 GHG emission reductions.

2.5. Anaerobic digestion plant size

The working volume () of an AD plant processing all distillery by-products is calculated based on an organic loading rate () of 2.5kgVS/m^3/day and is calculated as per Equation (7).

Equation (7) Anaerobic Digester Working Volume(7)

The total number of tanks () required for such the AD plant is based on a tank working volume of 5000 m^3 as per discussions with distillery staff. The dimensions of each tank were calculated so as to minimise the ratio of surface area to volume (to minimise conductive and convective heat losses) as per Appendix B. The diameter of each tank () was chosen to be 18.5 m. Tanks were assumed to be 10 m apart from one another () to facilitate the passage of 2 articulated lorries between them, the tanks were assumed to be arranged in a single line. The land area for the AD tanks is calculated as per Equation (8).

Equation (8) Land Area for AD Tanks(8)

The capital cost of the AD plant () is calculated using Equation (9) based on work by Browne [61].

Equation (9) AD Plant Capital Cost(9)

The electrical energy consumption of the AD plant is calculated based on a figure of 8.26 kWhe/twwt of feedstock processed, as outlined in Appendix B. The cost of electricity used in the operation of the AD plant is 100 €/MWhe based on the average cost of electricity paid for by the distillery.

2.6. Digestate production

AD results in the production of digestate, a mixture of liquid and solids remaining following the digestion process. The digestate can be used as a biofertiliser on agricultural land. The total mass of digestate that is produced can be calculated as per Equation (10).

Equation (10) Mass of digestate produced(10)

The digestate produced can be spread on agricultural land in the vicinity of the AD plant (assumed to be located adjacent to the distillery). The total content of nitrogen and phosphorous entering a biogas plant in the feedstock is contained in the digestate leaving the plant. Based on the protein content of the draff, thin stillage, and thick stillage, the nitrogen content (crude protein divided by 6.25) of each by-product () was found to be; 13.76 gN/kgwwt for draff, 1.6 gN/kgwwt for thin stillage, and 3.68 gN/kgwwt for thick stillage. The phosphorous content of each by-product () is; draff 1.76 g/kgwwt, thin stillage 0.33 g/kgwwt, and thick stillage 0.91 g/kgwwt, based on analysis conducted by an external laboratory.

The total mass of nitrogen () and phosphorous () leaving the AD plant in the digestate is calculated according to Equation (11) and Equation (12).

Equation (11) Total Mass of Nitrogen Leaving the AD Plant(11)

Equation (12) Total Mass of Phosphorous Leaving the AD Plant(12)

2.6.1. Calculation of landbank required for spreading of raw digestate

The total land area required for the spreading of digestate was calculated in accordance with S.I. 605 of 2017 [62] using the methodology outlined in [63]applied to each parcel of land in the vicinity of the AD plant. For the purpose of this work data on total livestock population and land use in electoral divisions (EDs) in Ireland was sourced from the Census of Agriculture [64].
The maximum allowable mass of biologically available phosphorous to be spread on arable land is based on a soil P index of 3 as per S.I 605 of 2017 [62]and will result in a conservative estimate of the mass of phosphorous that could be applied to each ED. The amount of nitrogen that can be applied to arable land is based on a soil N-Index of 1 for the cultivation of barley [62].
The total amount of nitrogen () and phosphorous () that can be spread on land within each electoral division (ED) () is found by division of the total mass of N and P allowed by the biologically available share of nitrogen and phosphorous in the digestate. The phosphorous availability () was taken to be 100% [62]. No default availability of N is available for digestate in Ireland, values of bioavailable N content in digestate (also termed fertiliser replacement value) found in the literature range from 24 to 90% of N content in digestate (Appendix D). The average fertiliser replacement value of digestate found in literature is 61.7%, as no definitive values for the fertilizer replacement value of digestate () exist for Irish conditions a value of 60% based on values assessed in literature will be used.
Knowing the mass of digestate produced () and nitrogen () and phosphorous () content of the digestate, the location of where to spread the digestate can be determined. The problem can be formulated as a linear optimisation model with the goal of minimising total tonne-kilometres of digestate hauled with the decision variables being the mass of digestate () to be hauled to each ED (Equation (13)).
Minimising the total tonne-kilometres hauled will minimise the energy consumption and GHG emissions associated with road transportation of the digestate. The distance from each ED to the AD plant () was calculated using road network data from Open Street Maps using QGIS software. The optimisation problem was solved in the software package GNU Octave.
Equation (13) Linear Optimisation Model to Minimise Digestate Haulage(13)

The CO_2eq emissions associated with the transportation of digestate () to each ED was calculated using Equation (1) based on the mass of digestate sent to each ED and the distance to each ED. The GHG emissions associated with the transportation of digestate will contribute to Scope 3 GHG emissions. The specific CO_2eq emissions associated with the spreading of digestate () used in this work is 1.15kgCO_2eq/twwt based on previous literature [65], [66], [67], [68], [69], [70], [71], [72], [73], [74]. The specific CO_2eq emissions associated with the spreading of synthetic fertilizer () used in this work is 0.03kgCO_2eq/$kg_{fertilizer}$ [75].

The specific cost of digestate transportation to a given ED in €/m^3 () is calculated using Equation (14) based on work by Nolan [76].

Equation (14) Specific Transportation Cost of Digestate(14)

The total cost of digestate transportation () is calculated based on the mass of digestate sent to each ED, the distance from each ED to the AD plant, and the specific transportation cost of digestate, according to Equation (15).

Equation (15) Total Cost of Digestate Transportation(15)

2.6.2. Calculating the impact of digestate use on greenhouse gas emissions associated with barley cultivation

Digestate can be applied to all available agricultural lands in the environs of the AD plant, or, the digestate can be applied to land only used for the cultivation of barley that is then used in the distillery (this would also include for barley used in the production of malted barley). The implications on the total global GHG emissions from digestate utilisation will not vary whether the digestate is spread on pastureland, tillage land, or a combination of both, as these differences are not captured in the UNFCCC Tier 1 calculation method used here [77], [78]. However, the use of digestate on land used to cultivate barley for use in the distillery impacts the Scope 3 GHG emissions of the distillery. The total emissions of GHG associated with the use of synthetic nitrogen fertiliser for the cultivation of barley are calculated for the following stages (as outlined in Fig. 3), these will contribute to Scope 3 GHG emissions:

- Fertiliser production;
-

Fertiliser transportation from the factory in mainland Europe to fields in Ireland for application;

•

Fertiliser application;

•

N_2O emissions associated with the application of the synthetic nitrogen fertiliser.

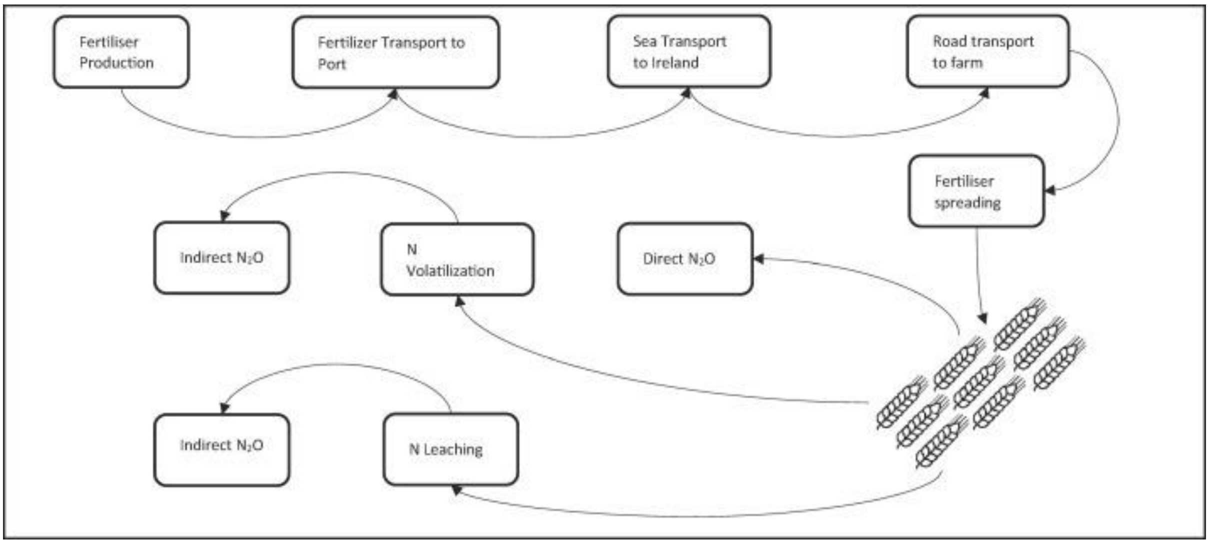

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Fig. 3. N_2O emissions arising from synthetic nitrogen fertiliser use.

The total mass of synthetic nitrogen and phosphorous fertiliser that can be replaced by digestate was calculated based on the total mass of nitrogen and phosphorous contained in the digestate produced. The digestate is assumed to replace calcium ammonium nitrate (CAN) as this is the most common form of synthetic nitrogen fertiliser used in Ireland [79], and is also assumed to replace phosphorous fertiliser. The mass of synthetic nitrogen fertiliser and phosphorous fertiliser replaced by digestate is calculated based on the methodology in Appendix E. The use of digestate to replace synthetic fertiliser will alter the direct and indirect emissions of nitrous oxide (N_2O) from land following the application of nitrogen fertiliser. Direct and indirect N_2O emissions associated with the application of nitrogen fertiliser to agricultural land are calculated according to Duffy [80] in line with the Tier 1 emission calculation procedure outlined by the IPCC [77], [78]. A detailed description of these calculations is given in Appendix F, an example calculation of the GHG emissions that can be avoided by replacing CAN with digestate is given in Box F-1 (Appendix F).

In addition to the use of CAN fertiliser for the cultivation of barley, super-triple phosphate was assumed to be the predominant form of phosphorous used in the cultivation of barley. The P_2O_5 content of TSP is approximately 45%, therefore, the cultivation of barley would require $20.4kg_{TSP}/kg_{Barley}$. An example of the calculation to determine the mass of GHGs associated with synthetic phosphorous fertiliser replaced by digestate is contained in Box F-2 (Appendix F).

When fertiliser, either synthetic or organic, is transported to and spread on agricultural land, energy is consumed in the machinery used predominantly in the form of diesel used by tractors. Following a literature review of data contained in [70], [72], [73], [74], [81], [82], [83] as well as data sourced from BioGrace-II and Bilans GES online data query portal [84] the specific CO_2eq emissions associated with the transportation of digestate () to farm land was calculated to be $0.19kgCO_2eq/t.km$.

Use of digestate as a fertiliser will result in GHG emissions. The GHG emissions associated with the use of digestate is calculated using; emission factors, volatilisation factors, and leaching factors for organic fertilisers as outlined in Appendix F. The GHG emissions associated with the transportation of digestate from the AD plant to each electoral division are based on the total tonne kilometres required for digestate transportation as calculated according to Equation (13). An example calculation of the GHG emissions associated with the use of digestate as a source of nitrogen fertiliser on land used for barley cultivation is shown in Box F-3**.**

Comparison of the GHG emissions associated with using synthetic fertiliser only, to the GHG emissions associated with using digestate allows for the potential change in GHG emissions resulting from digestate use () to be calculated via Equation (16). This change in GHG emissions will impact the Scope 3 GHG emissions of the distillery (if the barley grown is used in the distillery).

Equation (16) GHG Saving Associated with Digestate Use as a Fertiliser(16)

Replacement of synthetic fertiliser by digestate will reduce the Scope 3 GHG emissions of the distillery if and only if the digestate replaces fertiliser used in the production of cereals consumed by the distillery. If the digestate is spread on land used for the cultivation of cereals that are not consumed by the distillery it will not reduce Scope 3 emissions.

2.7. Replacement of animal feed

Processing of the distillery by-products in an AD plant would result in the current feed production at the distillery ceasing. The average composition of the feed products () (dry matter, ash, crude protein, crude fibre, and fat) produced at the distillery is shown in Table 5. These animal feeds are sold within Ireland and are used widely in the dairy, beef, and pork production sectors.

Table 5. Composition of Feed Products.

Feed Product	Dry Matter (DM)	Ash	Crude Protein	Crude Fibre	Fat
	%wwt	%DM	%DM	%DM	%DM
Wet Grains	28.163	3.584	27.591	12.892	10.366
Syrup	32.315	10.039	22.626	1.246	13.555
DDG	89.673	4.115	29.330	11.401	10.426

2.7.1. Sources of imported animal feed

Expanding the boundaries of the analysis outside scope 1, 2 & 3 emissions leads to considerations that the wet grains, DDG, and syrup may be replaced by imported feed () which could have a negative impact on global GHG emissions. Imported animal feeds are considered here as a worst-case scenario in terms of potential GHG emissions. Imported feeds are assumed to be used in the dairy farming sector as this is a profitable sector within the Irish livestock industry. To assess what sort of imported feed is used in Ireland data was sourced from the International Trade in Goods Section of the Irish Central Statistics Office (CSO) (Personal Communication with CSO Staff, 2019). A discussion on the data sourced is given in Appendix G.

In order to estimate the origin from which each type of alternative feed would be imported, a pro-rata allocation of the total mass of each alternative feed to each respective country of origin was conducted based on data from 2014-2018. Table 6 outlines the country of origin for each imported animal feed ().

Table 6. Share of Imported Feed from Origin Countries.

Brewing or distilling dregs and waste		Oilcake and other solid residues resulting from the extraction of soybean oil		Residues from the manufacture of starch from maize used in animal feeding	
Country	Share %	Country	Share %	Country	Share %
United States	60.049	Argentina	78.123	United States	100
Canada	12.034	Canada	7.929		

Brewing or distilling dregs and waste		Oilcake and other solid residues resulting from the extraction of soybean oil		Residues from the manufacture of starch from maize used in animal feeding	
Country	**Share %**	**Country**	**Share %**	**Country**	**Share %**
Northern Ireland	7.713	Northern Ireland	5.839		
Sweden	7.193	Paraguay	5.699		
Great Britain	6.313	United States	2.410		
Vietnam	3.377				
Netherlands	3.322				

2.7.2. Mass of imported animal feed to replace distillery feed products

For the purpose of this analysis the alternative feeds () that are assumed to take the place of wet grains, DDG, and syrup in dairy farming are; maize distillers' grains, maize gluten feed, soybean meal and soyhulls. The crude protein () and energy content () of these feed types were sourced from Teagasc (The Irish Agriculture Research Centre) [85], [86] and are shown in Table 7 along with the imported feed that they represent. In order to estimate the mass of each alternative feed that would be used in place of the wet grains, DDG, and syrup, the energy content of each distillery feed product () was calculated. In Ireland the energy content of animal feed is expressed in terms of "Unité Fourragére Lait" (UFL) when fodder is used for dairy cows [85], [86]. Calculation of the UFL of the wet grains, DDG, and syrup was based on the methodology in [87] and is outlined in Appendix G. The crude protein () and energy content for the wet grains, DDG, and syrup are shown in Table 7.

Table 7. Composition and Energy Content of Replacement Feeds.

	Crude Protein	**Energy**	**Imported Feed Name**
Feed	**kg/kgwwt**	**UFL/kgwwt**	**NA**
Replacement Feed			
Maize Distillers	0.2661	1.0324	Brewing or distilling dregs and waste
Maize Gluten Feed	0.2033	0.8996	Residues from the manufacture of starch from maize of a kind used in animal feeding
Soybean Meal	0.4812	1.0195	Oilcake and other solid residues resulting from the extraction of soybean oil

	Crude Protein	Energy	Imported Feed Name
Feed	**kg/kgwwt**	**UFL/kgwwt**	**NA**
Soyhulls	0.1046	0.8878	Oilcake and other solid residues resulting from the extraction of soybean oil
Distillery Feed Product			
Wet grains	0.0789	0.272	**N/A**
DDG	0.2630	0.892	**N/A**
Syrup	0.0731	0.424	**N/A**

To calculate the required mass of alternative feeds () (maize distillers, maize gluten feed, soybean meal, and soyhulls) to replace 1kgwwt of distillery feed products () (wet grains, DDG, or syrup) a linear optimisation model was developed. The goal of the optimisation model was to determine the minimum mass of alternative feed required to provide the same mass of crude protein and the same amount of energy (UFL) that would be contained in 1 kg of distillery feed product (). A mathematical description of the model is given in Equation (17). This model was solved in GNU Octave.

Equation (17) Feed Optimisation Model(17)

2.7.3. Greenhouse gas emissions associated with of imported replacement animal feed production

The GHG emissions () associated with the production of each imported animal feed () in a given country () was sourced from the Global Feed Lifecycle Institute (GFLI) database of animal feed production [88]. The allocation of environmental burdens associated with the production of the imported animal feeds was based on an economic allocation, as per prior literature [66], [89], [90]. Prior work used values of 0.929kgCO_2/kgDM of dried distillers grains, 1.472kgCO_2/kgDM of South American soybean meal, and 0.299kgCO_2/kgDM of soybean meal from the USA for the GHG emissions associated with the production of imported feed products [91]. The GHG emission values associated with the production of imported feeds used in this work are shown in Table 8.

Table 8. GHG emissions associated with imported feed production.

Imported Feed	Country	kgCO_2eq/kg Product
Brewing or distilling dregs and waste	EUR	1.010
Brewing or distilling dregs and waste	USA	0.949

Imported Feed	Country	$kgCO_2eq$/kg Product
Solid residues resulting from the extraction of soybean oil – Soybean hulls	AR	0.285
Solid residues resulting from the extraction of soybean oil – Soybean hulls	GLO	0.287
Solid residues resulting from the extraction of soybean oil – Soybean hulls	UK	0.325
Solid residues resulting from the extraction of soybean oil – Soybean Meal	AR	0.568
Solid residues resulting from the extraction of soybean oil – Soybean Meal	GLO	0.570
Solid residues resulting from the extraction of soybean oil – Soybean Meal	UK	0.647
Residues from the manufacture of starch from maize of a kind used in animal feeding	GLO	1.660

*AR: Argentina, EUR: Europe, USA: United States of America, GLO: Global, UK: United Kingdom.

The GHG emissions associated with the production of imported animal feeds are calculated excluding the GHG emissions associated with land use change owing to the large degree of uncertainty associated with land use change emissions. The total GHG emissions associated with the production of imported animal feeds () are calculated as per Equation (18).

Equation (18) GHG Emissions Associated with Imported Animal Feed Production(18)

2.7.4. Greenhouse gas emissions associated with the transportation of imported replacement animal feed

Transportation distances of each imported feed by mode of transportation () were based on data from literature [66], [83], [89] and are outlined in Table 9.

Table 9. Transportation distances for imported feed.

Origin	Destination	Road (km)	Rail (km)	Barge (km)	Maritime Ship (km)	Ref.
IE	IE	58	1		0	[89], [83]
AR	IE				16,147	[66]
CA	IE				4578	
NL	IE				1163	[89]
SE	IE				2719	This work
UK	IE				441	[83]

Origin	Destination	Road (km)	Rail (km)	Barge (km)	Maritime Ship (km)	Ref.
US	IE				5700	[83]
VN	IE				17,455	This work
PY	IE				16,147	This work
AR	AR	410	80		10	[83]
BR	BR	867	477		101	[83]
US	US	182	619	1019		[83]
NL	NL	56	2	19		[83]
SE	SE	92	39			[89]
UK	UK	84	11			[83]
CA	CA	1096	0			This work
VN	VN					
PY	PY			1637		This work

When data was unavailable from literature the transportation distances were calculated according to the methodology outlined by The FAO [90]. This was conducted for the transportation of; brewing and distilling by products from Canada (CA) to Ireland (IE), brewing and distilling by products from Sweden (SE) to Ireland, soybean by-products from Paraguay (Py) to Ireland, and brewing and distilling by-products from Vietnam (VN) to Ireland. Details are contained in Appendix H.

Emission data was sourced from Bilans GES data query portal [84] and was assessed for road transportation of freight. For the purposes of this project, the CO_2eq emissions associated with the road transportation of freight () will be 0.2kgCO_2qe/t.km. Emissions associated with empty return journeys shall be equal to 20% of the total emissions associated with the transportation of freight by road. Data on the specific CO_2eq emissions associated with the maritime transportation of goods in bulk carriers was sourced from Bilans GES data query portal [84]. Following a review of the data the CO_2eq emissions associated with sea transportation of goods () used in this work will be 0.005kgCO_2eq/t.km.

The CO_2eq emissions associated with the transportation of goods by inland vessels () are also based on data from Bilans Carbone, resulting in the emission of 0.0188kgCO_2eq/t.km. Rail transportation () was assumed to result in the emission of 0.0304kgCO_2eq/t.km in The Netherlands.

The GHG emissions associated with the transportation () of imported feed products is calculated based on the origin of each feed product, the distance over which each feed product is transported, and the mode of transportation used (Equation (19)). Equation (19) GHG Emissions from Imported Animal Feed(19)

2.8. Digestate management

The use of digestate as a fertiliser returns nutrients to the land and offsets the use of synthetic fertilisers. Digestate must be stored until it can be spread at the optimal times for nutrient uptake by plants [92], [93]. This also minimises the run-off and leaching of nitrogen and phosphorous into surface and ground waters. The specific time frames for application dictates the period of storage and storage volumes needed. This work assumes that digestate is to be used on land to cultivate barley that will then be used by the distillery to reduce Scope 3 category 1 GHG emissions. In Ireland the ideal dates for the application of nitrogen fertiliser to land for barley cultivation are mid-March (30% of required nitrogen) and mid-April (70% of required nitrogen) [94], therefore digestate should be stored until it can be utilised at these times.

The volume of digestate to be stored can be calculated knowing the daily production of digestate and the desired application times. For the purpose of this analysis it is assumed that the daily production of digestate by the AD, the nitrogen content, and the phosphorous content of the digestate is constant. The maximum storage requirement of digestate can be calculated knowing the number of days between the second application of digestate () and the first application of digestate to land the following year (). Two options exist for the storage of digestate are available as outlined in [92] and include:

1. Storage of digestate at a large centralised digestate storage tank adjacent to the AD plant;

2. Storage of digestate at distributed storage tanks in the vicinity of land used for barley cultivation.

The transportation of digestate from a storage facility to the point of use can be achieved using tractors, trucks, or pipelines, the most common method of which is truck based transportation [92].

2.8.1. Centralised digestate storage

For centralised digestate storage the maximum mass of digestate to be stored () is calculated using the daily digestate production and the time required for storage as per Equation (20).

Equation (20) Centralised Digestate Storage Volume(20)

The maximum volume of digestate that would require storage can be calculated assuming the density of digestate is 1000 kg/m^3 as an initial approximation.

Following the storage of digestate at a centralised location the digestate needs to be transported to the ED and used for the cultivation of barley. The mass of digestate to be transported to an ED for the initial application of digestate () in mid-March is calculated as per Equation (21);

Equation (21) Mass of Digestate to a Given ED for the First Application of Fertiliser(21)

: Annual mass of digestate spread in a given ED

: Share of total mass of nitrogen applied during first application.

The same calculation holds for the mass of digestate to be sent to a given ED for the second application of digestate in mid-April (Equation (22))

Equation (22) Mass of Digestate to a Given ED for the Second Application of Fertiliser(22)

: Share of total mass of nitrogen applied during second application.

The number of trucks required to transport the digestate to a given ED for the first (Equation (23)) or second (Equation (24)) application of digestate is based on a carrying capacity of 20 m^3 in this work.

Equation (23) Truck Movements Required for first digestate application(23)

Equation (24) Truck Movements Required for second digestate application(24)

The time period over which the digestate needs to be transported from a possible centralised storage location to each ED in order to be available at the correct times for application is assumed to be 3 days (36 h) in order to apply nitrogen at the optimal time. Hourly truck movements for the first and second applications are based on this 36-h period as per Equation (25).

Equation (25) Centralised Digestate Storage Hourly Truck Movements(25)

2.8.2. Decentralised digestate storage

An alternative option to the centralised storage of digestate is the distributed storage of digestate at individual storage tanks located within each ED in the landbank required. The maximum mass of digestate storage required at each individual ED is calculated based on the annual mass of digestate to be sent to the ED in question () and the number of days of storage required between the second application of fertiliser in a year and the first application of fertiliser in the following year as per Equation (26). The total mass of digestate to be sent to each ED () is calculated using the digestate optimisation model to ensure that the nitrogen and phosphorous limits of each ED are not exceeded.

Equation (26) Maximum mass of decentralised digestate storage in a given ED(26)

The number of vehicle movements to transport digestate to each ED is based on a carrying capacity per truck of 20 m^3. During decentralised digestate storage it is assumed that transportation of the digestate produced at the AD plant to the decentralised digestate storage tanks occurs constantly throughout the year. A best-case scenario would involve the transportation of digestate for 365 days a year (8760 h per year). The advantage of decentralised digestate storage is that the number of truck movements per hour is lower than the number of truck movements per hour in a centralised storage system as the transportation is spread out over an entire year for decentralised digestate storage. The total number of truck movements in a year to each given ED will remain the same in a centralised or decentralised storage system. The volume of digestate storage required within each ED in a decentralised digestate storage model could be provided by; the distillery, individual farmers, or a third party who is responsible for the transportation, storage, and spreading of digestate.

3. Results

A combined summary of results in relation to; energy production, digestate production, feed imports, and GHG emissions (Scope 1, Scope 3, and Other) is given in Table 10.

Table 10. Combined Results.

	Energy (MWh_{th})	Mass (twwt)	Scope 1 (tCO_2eq)	Scope 3 (tCO_2eq)	Other (tCO_2eq)
Biogas	154,000		−30,993	−3686	
Feed Plant Energy Consumption	−11.6		−2418	−288	
Fugitive Emissions			5663		
Digestate Production		597,545			
Digestate Transport				3456	

	Energy (MWh_{th})	Mass (twwt)	Scope 1 (tCO_2eq)	Scope 3 (tCO_2eq)	Other (tCO_2eq)
Digestate Spreading				687	
Digestate Application – Direct Emissions				5529	
Digestate Application – Indirect Emissions				1474	
Avoided CAN – Production				−9480	
Avoided CAN – Transport				−139	
Avoided CAN – Spreading				−127	
Avoided CAN Application – Direct Emissions				−7740	
Avoided CAN Application – Indirect Emissions				−553	
Avoided Phosphorous – Production				−376	
Avoided Phosphorous – Transport				−75	
Avoided Phosphorous – Spreading				−69	
Feed Product Transportation					−2773
Imported Distillers' Grains - Production		30,062			29,047
Imported Distillers' Grains - Transport					3599
Imported Soybean Meal - Production		11,541			6610
Imported Soybean Meal - Transport					2157
Total			**−27,748**	**−11,389**	**38,642**

The use of all distillery by-products in an AD plant would require the construction of 7 no. 5000 m^3 tanks occupying an area of 8107 m^2 (0.811 ha) at a capital cost of ca. 41.914 M€. The annual electricity consumption of the AD plant is approximately 5217 MWhe/a at an annual cost of 521,666€/a.

3.1. Biogas production

The net biogas production (154 GWh) is primarily from thick stillage (89 GWh_{th}/a) followed by thin stillage (44 GWh_{th}/a), and then draff (21 GWh_{th}/a). The biogas

produced could replace 61% of the current natural gas consumption of the distillery (254 GWth/a). As the feeds recovery plant will no longer operate the biogas produced could meet up to 64% of the remaining natural gas demand of the distillery. Combined CO_2eq savings associated with biogas use and a reduction in natural gas consumption would reduce the Scope 1 GHG emissions from the distillery by 33,411 tCO_2eq/a (64%). The current steam boiler infrastructure at the distillery may be upgraded in the near future, this would increase steam generation efficiency to ca. 80% and reduce natural gas demand to 233 GWh/a (222 GWh/a without feeds recovery plant operation). If the steam boiler is upgraded biogas could supply between 66% and 69% of natural gas demand of the distillery.
The Scope 3 Category 3 GHG emission reduction achieved by replacing natural gas with biogas and reduced natural gas consumption by the feed recovery plant is 3973 tCO_2eq/a.

3.2. Fugitive methane emissions

Fugitive methane emissions amount to 5663 tCO_2eq/a, these would negate the Scope 1 savings associated with reduced natural gas consumption. Minimisation of fugitive methane emissions is therefore a key priority through; high quality construction, the proper monitoring of pressure release valves, and covered digestate storage.

3.3. Digestate production and utilisation

The total GHG emissions associated with the transportation and use of digestate as a replacement for synthetic fertiliser is 11,146 tCO_2eq/a, this will contribute to the Scope 3 GHG emissions of the distillery.

3.4. Synthetic fertiliser replacement

Use of digestate on agricultural land to replace CAN fertiliser would reduce Scope 3 GHG emissions by 18,040 tCO_2eq/a. The total GHG emissions that are saved following the replacement of synthetic phosphorous fertiliser with digestate amounts to 520 tCO_2eq/a. The digestate produced could replace 1180 t of synthetic nitrogen (equivalent to 1180 t/a of CAN) and 456 t of synthetic phosphorous.

3.5. Replacement of animal feed

Replacement of animal feed produced in the distillery would require the import of distillers' grains and soybean meal. The mass of imported distillers' grains is equivalent to 5% of the total mass of maize distillers grains imported into Ireland in 2018, and the mass of soybean meal is equivalent to 2% of the total mass of soybean meal imported into Ireland in 2018. No other imported animal feeds were required to provide the same mass of protein and nutritional energy (UFL). Total GHG emissions associated with the production and transportation of distillers' grains to Ireland amounted to 32,646 tCO_2eq/a. The total GHG emissions associated with the production and transportation of soybean meal amounts to 8767 tCO_2/a. Feed products no longer produced at the distillery would reduce feed product transportation emissions by 2773tCO_2eq/a.

3.6. Summary of greenhouse gas emissions and savings

The GHG emissions and savings associated with the implementation of an AD plant processing distillery by-products are summarised graphically in Fig. 4. Scope 1 GHG emissions associated with the replacement of natural gas with biogas, reduced energy consumption of the feeds recovery plant, and fugitive methane emissions combined result in GHG emissions savings of 27,748 tCO_2eq/a.

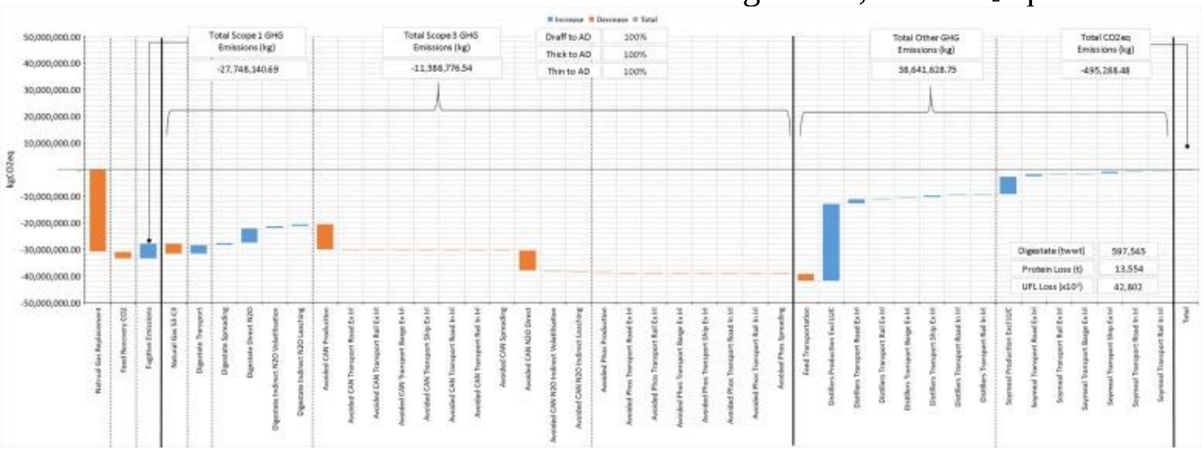

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Fig. 4. Summary of GHG Emissions and Savings. Thick black lines delineate between Scope 1, Scope 3, and other GHG emissions associated with imported feed production.

The distillery sources all the electricity consumed onsite from renewable sources; the electricity required for the operation of the AD plant is also envisaged to be sourced from renewable sources. The implementation of an AD plant processing distillery by-products will not alter Scope 2 GHG emissions at the distillery.

The use of digestate to replace synthetic fertiliser result in a reduction in GHG emissions of 7414 tCO_2eq/a. The GHG emission reduction associated with the replacement of synthetic fertiliser used to cultivate barley consumed by the distillery will reduce Scope 3 GHG emissions of the distillery. Replacement of natural gas with biogas and a reduction in gas consumption would also reduce Scope 3 GHG emissions associated with the extraction and transportation of natural gas by 3973 tCO_2eq/a. Total potential Scope 3 GHG emissions reductions amount to 11,389 tCO_2eq/a.

The mass of GHG emissions avoided from feed product transportation amount to 2773 tCO_2eq/a. The total GHG emissions associated with the production and transportation of imported animal feed required to supply the same quantity of protein and nutritional energy that would no longer be produced by the feeds' recovery plant amount to an increase of 41,414 tCO_2eq/a. The GHG emissions associated with the production and transportation of imported animal feed do not form part of the Scope 1, Scope 2, or Scope 3 GHG emissions of the distillery. The total increase in "other emissions" amounts to 38,642 tCO_2eq/a.

Summation of the total GHG emissions and savings (Scope 1 and Scope 3) associated with the implementation of an AD plant at the distillery are a reduction of 39,137 tCO_2eq/a. However including imported animal feeds (which are not part of Scope 1, 2 or 3 emissions) reduces this to 495 tCO_2eq/a.

3.7. Digestate logistics

Whole digestate is transported over a maximum distance (by road) of 45–50 km. The share of the total mass of whole digestate applied to EDs in the landbank shows 2 peaks, one at 5–10 km, and another at 35–40 km. Approximately 50% of the total mass of whole digestate is applied to EDs within 25 km of the potential AD plant, and the remaining 50% is applied to EDs between 25 and 50 km of the potential AD plant (Fig. 5a). An illustrative example of the ED's in which digestate could be spread on land used for barley cultivation is illustrated in Fig. 5b. The share of the total mass of nitrogen and phosphorous contained within the whole digestate that is applied to ED's within a given distance of the potential AD plant is outlined in Fig. 5c & d. The total cost of digestate transportation to the required landbank is approximately €3.373 M€/a.

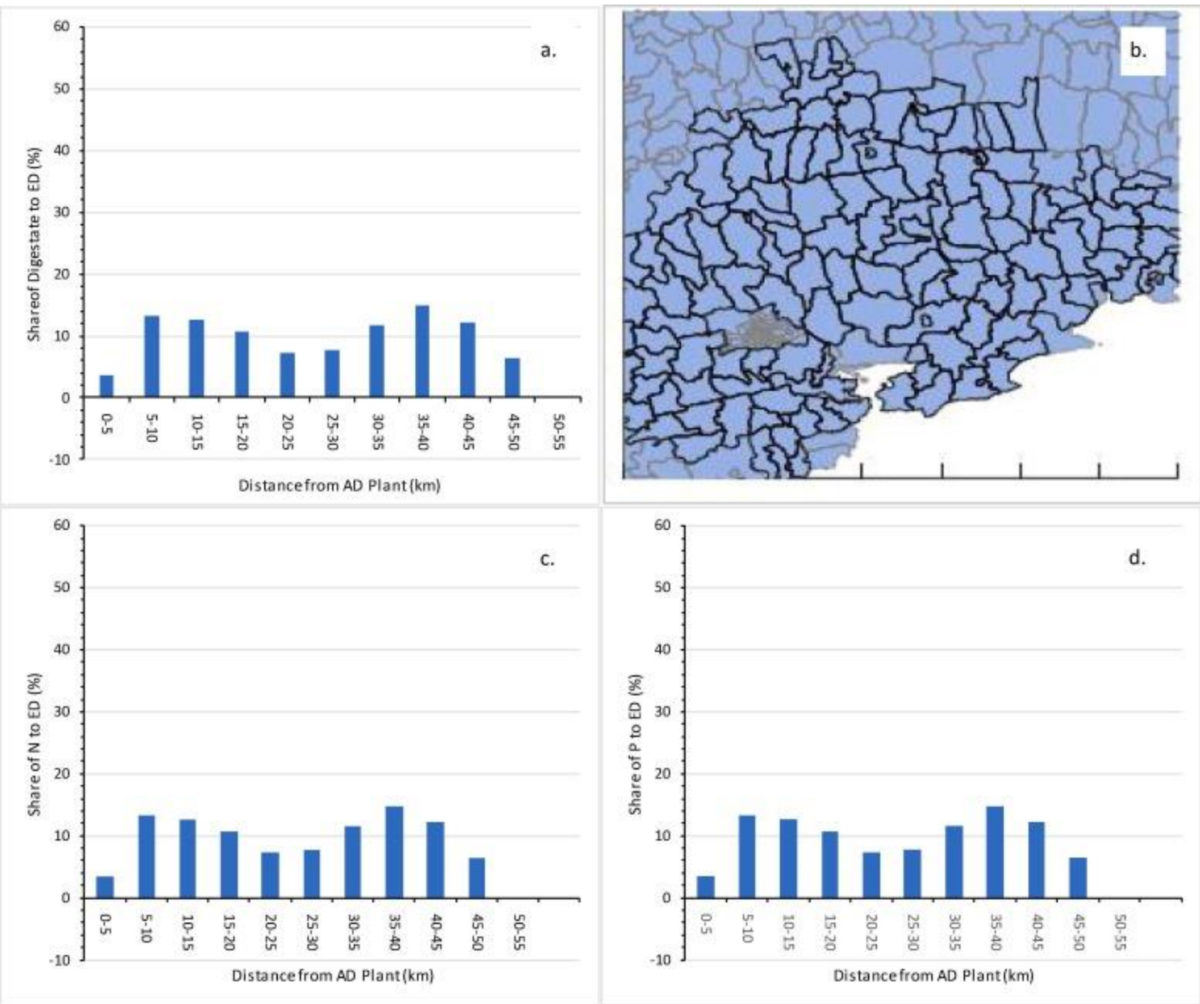

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Fig. 5. Share of a. Total digestate, b. Landbank, c. Nitrogen and d. Phosphorous Applied to Landbank.

The share of the maximum allowable mass of nitrogen and phosphorous applied to EDs within the landbank is approximately 31% and 100% respectively (Fig. 6). The application of digestate to agricultural land used for barley cultivation in the vicinity of the potential AD plant is limited by the mass of phosphorous that can be applied.

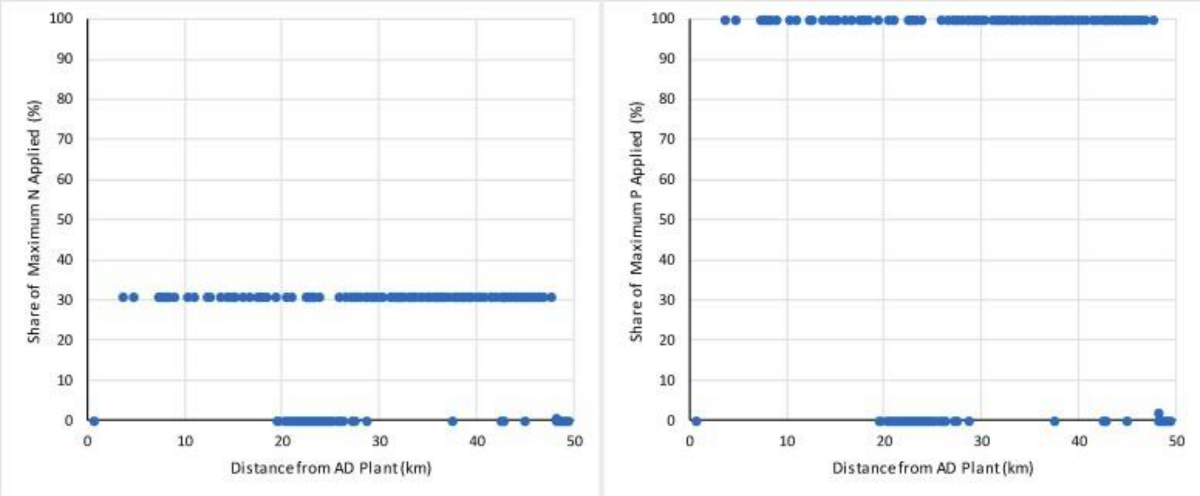

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Fig. 6. Share of Maximum Allowable N and P Applied to EDs.

The required volume of centralised digestate storage amounts to 541,884 m^{3}when all the by-products are used in a potential AD plant. To put the volume of centralised digestate storage into perspective, the largest above ground ADI-BVF® anaerobic digester (a type of large scale AD plant used in food processing facilities manufactured by Evoqua) in the world is located at the Dairygold site in Mitchelstown, Co. Cork has a volume of 45,000 m^{3}corresponding to a diameter of 75 m and a height of 10.2 m. The volume of centralised digestate storage (541,884 m^3) would require 12 such tanks. If a single tank with a height of 10 m was to be constructed, the required diameter would be 263 m.

The total number of truck movements required to transport digestate from a centralised digestate storage facility to each of the required EDs within the landbank for the first and second application of digestate are 8963 and 20,914 respectively. This equates to 249 and 581 trucks per hour respectively.

Decentralised digestate storage would require the construction of decentralised storage tanks for digestate in each of the EDs within the landbank. The maximum volume of decentralised digestate storage required within a single ED is 28,029 m^3. The number of storage tanks within a given range of volumes required in each ED at a given range of distance from the AD plant are given in Table 11.

Table 11. Decentralised Digestate Storage Volume (m^3).

	Decentralised Digestate Storage Volume Required (m^3)							
Distance from AD Plant (km)	**0–500**	**500–1000**	**1000–5000**	**5000–10,000**	**10,000–15000**	**15,000–20,000**	**20,000–25,000**	**>25,000**
0–5	0	0	1	0	0	1	0	0

	Decentralised Digestate Storage Volume Required (m³)							
Distance from AD Plant (km)	**0–500**	**500–1000**	**1000–5000**	**5000–10,000**	**10,000–15000**	**15,000–20,000**	**20,000–25,000**	**>25,000**
5–10	0	0	0	4	0	1	0	1
10–15	1	0	3	1	3	1	0	0
15–20	1	0	5	3	0	1	0	0
20–25	0	0	7	3	0	0	0	0
25–30	1	1	10	2	0	0	0	0
30–35	1	1	11	4	0	0	0	0
35–40	4	1	11	4	2	0	0	0
40–45	7	3	9	3	0	1	0	0
45–50	1	2	8	2	0	0	0	0
>50	0	0	0	0	0	0	0	0

The total annual truck movements required to transport digestate from a potential AD plant to decentralised storage tanks within each ED in the required landbank is 29,878. Assuming constant digestate production and transportation of digestate to decentralised storage sites over 365 days, the daily truck movements required are 82.

Explanatory note: At a distance of between 40 and 45 km from the AD plant decentralised digestate storage would require; 7 tanks with a volume of 0–500 m^3, 3 tanks with a volume of 500–1000 m^3, 9 tanks with a volume of 1000–5000 m^3, 3 tanks with a volume of 5000–10,000 m^3, and one tank with a volume of 15,000–20,000 m^3. Each tank would be in a separate ED. Each row of Table 11 shows the number of tanks required of a given size, at a give distance from the AD plant.

4. Discussion

4.1. Energy supply

The biogas produced from an AD plant could provide up to 61% of the natural gas demand of the distillery. The potential annual cost saving associated with the replacement of natural gas by biogas could amount to 3.256 M€/a based on current natural gas prices. Use of distillery by-products in a potential AD plant could supply a significant share of the natural gas demand of the distillery and increase the energy security of the distillery. Operation of an AD plant processing all of the by-products produced at the distillery would further reduce natural gas consumption of the distillery by approximately 4.7% when the feeds recovery plant shuts down. This would result in a further reduction in CO_2 emissions of 2384 tCO_2eq and a cost reduction of 250,355 €/a (based on a natural gas price of 0.0211 €/kWh from distillery data). Biogas could supply 64% of the remaining natural gas demand of the distillery. The capital cost of the distillery (41.914 M€) represents a significant capital outlay, this cost is indicative, a detailed design of such a system would be required to provide an accurate cost estimate to account for; planning applications, environmental impact assessments, civil engineering works, installation costs, insurance and contingency amongst others. The annual electricity cost for operation of the AD plant (521,666 t€/a) results in a net annual saving of 2.985 M€/a which would yield a simple payback period of 14 years. A simple payback period of 14 years is quite long and assumes that the cost of digestate transportation is not borne by the distillery. New technologies to reduce the capital cost of AD plants should be assessed such as high rate anaerobic digestion of the thick stillage and thin stillage which could allow for lower capital costs owing to smaller AD plant volumes required.

The mass of woodchips required to supply an equivalent amount of energy as biogas from distillery by-products (154 GWh/a) is 48,125 twwt/a at a cost of 4.84 M€ (0.0314 €/kWh, personal communication with Coillte, Irish Forestry Service) to 6.25 M€/a (3.2 kWh/kgwwt for wood chips, 0.0406 €/kWh [95]). If the distillery were to source 154GWh from solid biomass combustion it would represent an increase of 55% in biomass used by the entire FB sector in Ireland (279 GWh in 2018 [19]). Securing a cost competitive source of solid biomass and mitigating logistical issues regarding biomass storage and transportation may not be possible.

The production of biogas from distillery by-products is a potential method of replacing natural gas consumed by the distillery. The desire to use renewable gaseous fuels within the FB sector in Ireland is growing, Diageo and Danone have publicly called for government support in order to enable the development of a renewable gas industry in Ireland [96]. It is clear that there is demand for renewable gaseous fuels from other large companies in the FB sector in Ireland, as such, the production of biogas from distillery by-products is a secure method for the distillery to replace natural gas consumption with a source of renewable energy.

Most of the biogas produced by distillery by-products originates from the thick stillage, followed by thin stillage and then by draff. It may therefore be possible to utilise only a portion of each distillery by-product to produce biogas, with the remaining by-products used in animal feed production. An analysis of the use of differing portions of by-products for biogas production should be conducted in future work.

4.2. Digestate utilisation

The re-use of nutrients contained in digestate by farmers in the distillery supply chain minimises the production of "waste" which is a key principle of circular economies. The use of digestate on agricultural land for the cultivation of barley will replace the use of 1180 t of synthetic nitrogen and 500 t of synthetic phosphorous fertiliser, allowing for the recycling of nutrients and progression toward a circular bioeconomy (Aligned with the European Bioeconomy Strategy [97]) and a reduction in nutrient dependency from third countries [98].

4.3. Imported animal feed

Animal feed production at the distillery will cease if all by-products are used in an AD plant. In a worst-case scenario the predominant alternative imported feeds that may be needed to replace distillery feed products were imported distillers' grains and soybean meal. The total mass of alternative feed required represented an increase of 5% and 2% of the imported mass of each feed in 2018 respectively, and an increase of 0.5% of total imported feed products in 2018. The imported alternative feeds were primarily from the United States (distillers' grains) and Argentina (soybean meal).

The imported animal feeds are by-products of food processing activities, distillers' grains are a by-product of the ethanol production industry in the USA, soybean meal is a by-product of soybean oil extraction in Argentina. It could be argued that the production of these imported feeds is not dictated by demand for these feeds as they are by-products, as such, an increase in demand for these feeds in Ireland will probably not result in an increase in global production.

Common concerns regarding the production of soybean in Amazonian rain forests and the associated environmental damage [99] do not apply in this instance as the

major share of imported soybean derived feeds (75%) are produced in Argentina, not Brazil or other countries within the Amazonian basin.
The mass of imported distillers' grains and soybean meal required is between 2% and 5% of national imports in 2018 which is a small portion of total imports. However, at a local and regional scale, the production of animal feed at the distillery is seen as being a strategically important part of the fodder supply chain. The use of imported animal feeds to replace feed products from the distillery assumes that a demand for these feeds will exist in Ireland. There is an opinion that the size of the bovine herd in Ireland may need to reduce in the coming years to facilitate a reduction in agricultural GHG emissions [100], this could result in a reduction in demand for imported animal feeds.

4.4. Greenhouse gas emissions

4.4.1. Scope 1, Scope 2, Scope 3

Following the implementation of an AD plant processing distillery by-products Scope 1 emissions reduce by 27,748 tCO_2eq, (54% of Scope 1 GHG emissions). This would also reduce GHG emissions of the distillery within the EU Emissions Trading System (ETS) by 27,748 tCO_2eq as biogas is assigned a fuel emission factor of 0 tCO_2/TJ [101]. Internal cost guidelines from the distillery envisage a future cost of CO_2 in the EU-ETS of 50 €/tCO_2, as such a reduction of 27,748 tCO_2eq could result in a cost saving of 1.4 M€/a.
Scope 2 GHG emissions are those associated with the generation of electricity purchased by the distillery. As outlined previously, no alteration to the Scope 2 GHG emissions of the distillery will result from the implementation of an AD plant.

Scope 3 emissions associated with the implementation of an AD plant at the distillery depends greatly on where the Scope 3 boundary is drawn and which Scope 3 Categories the emissions associated with digestate transportation, spreading, and application are allocated to.

Scope 3 – Category 1 (S3-C1) GHG emission reduction associated with the replacement of synthetic fertiliser used in the cultivation of barley amounts to 7414 tCO_2eq/a. The GHG emissions alterations to S3-C1 stated above are valid if all the GHG emissions arising from digestate transport, spreading, and application are allocated to S3-C1. In this work, the transportation, spreading, and application of digestate is considered waste disposal and therefore should be allocated to Scope 3 Category 5 (S3-C5). In this case, the GHG emissions savings in S3-C1 are 18,560 tCO_2eq. The GHG emissions associated with S3-C5 (Digestate transportation, application, and spreading) would amount to 11,146 tCO_2eq. The total net alteration to Scope 3 emissions as a result of digestate use is 7414 tCO_2eq, the same result that would occur if all GHG emissions were allocated to S3-C1.

S3-C1 emissions associated with barley used in the distillery will only be altered if the digestate is used in barley cultivation (for the distillery) as a fertiliser, if the digestate is not used in barley cultivation then no alteration of the S3-C1 emissions associated with barley will occur. Potential emissions savings associated with the replacement of synthetic fertilisers in other agricultural sectors shall not be used as a credit to reduce Scope 3 emissions of the distillery as these sectors are not within the supply chain of the distillery. Regardless of whether the digestate is spread on land used for cultivation of barley consumed by the distillery or on other agricultural land, S3-C5 GHG emissions of the distillery associated with the transportation, spreading, and application of digestate will be increased by 11,146 tCO_2eq. As such, if the distillery is to effectively reduce Scope 3 GHG emissions as a result of digestate use on agricultural land then the digestate must be spread on land used for the cultivation of barley consumed by the distillery. Further discussion on scope 3 emissions is included in Box 1.

Scope 3 – Category 2 (S3-C2) emissions will be increased by the construction of an AD plant. Calculation of S3-C2 emissions will be carried out in future works.

Scope 3 – Category 3 (S3-C3) emissions would be reduced by 3,973 tCO_2eq/a following the replacement of natural gas with biogas and a reduction in total gas consumption.

Scope 3 – Category 4 (S3-C4) emissions would increase if the transportation of digestate to land or to storage sites for further collection by farmers is paid for by the distillery. In this work, the transportation, spreading, and application of digestate on agricultural land is assumed to be accounted for in S3-C5 (Waste disposal) therefore no alteration to S3-C4 emissions will occur following the implementation of an AD plant.

Scope 3 – Category 5 (S3-C5) emissions arising from the disposal and treatment of waste generated at the distillery will increase if the use of digestate as a fertiliser is accounted for under S3-C5. The total increase in S3-C5 GHG emissions associated with digestate transportation, spreading, and application would be 11,146 tCO_2eq/a. The major contributor to S3-C5 emissions are direct and indirect N_2O emissions associated with digestate application on land.

Scope 3 – Category 6, Category 7, Category 8, Category 9, and Category 10 emissions will not be altered following the implementation of an AD project.

Scope 3 - Category 11 (S3-C11) emissions could potentially increase if the GHG emissions associated with the application of digestate on land is considered use of a sold product. As GHG emissions associated with the use of digestate on land is allocated to S3-C5 in this study no alteration to S3-C11 emissions will occur.

Scope 3 – Category 12, Category 13, Category 14, and Category 15 will not be influenced by the implementation of an AD project.

Box 1. Detailed assessment of Scope 3 emissions.

Regardless of the specific Scope 3 Category to which the GHG emissions associated with the transportation, spreading, and application of digestate are allocated to, the total Scope 3 emissions of the distillery will be altered by the same amount, provided the digestate is spread on land used for barley cultivation. The total change in Scope 3 emissions that could result from the implementation of an AD plant processing distillery by-products, with digestate spreading on land used for the cultivation of consumed by the distillery, would be a reduction of 11,289 tCO_2eq/a.

From the perspective of reducing Scope 3 GHG emissions, it is recommended to use digestate on land that is used for the cultivation of barley consumed at the distillery. The technical and logistical feasibility of this will be discussed in the following sections.

4.4.2. Greenhouse gas emissions associated with animal feed production

The GHG emissions associated with animal feed production is not included in Scope 1, 2 or 3 emissions of the distillery and the distillery will not have any control over them following the implementation of an AD plant. Therefore, the emissions associated with the production and transportation of these imported animal feeds are classified as “other emissions” in this work. In a worst-case scenario, the inclusion of GHG emissions arising from the production and transportation of imported animal feeds (38,642 tCO_2eq) to the total GHG calculation results will convert a very large potential GHG saving of 39,137 tCO_2eq (77% of Scope 1 emissions) to a reduced net reduction in total GHG emissions of 495 tCO_2eq (1% Scope 1 emissions). There are no international regulations that oblige the distillery to report on the emissions associated with products that are not contained within their value chain. The choice to include the emissions associated with potentially imported animal feed is therefore subjective and at the discretion of the distillery but may have a significant impact on whether the system is seen as sustainable or not.

4.4.3. Relevant greenhouse gas emissions to the distillery

The question as to which GHG emissions are of relevance to the distillery is inherently subjective and will also produce different results in relation to the suitability of a potential AD plant to reduce GHG emissions. If only Scope 1 emissions are considered relevant, a maximum reduction in Scope 1 GHG emissions of 27,748 tCO_2eq (54% of Scope 1 emissions) occurs when all by-products are used in an AD plant. Reduction of Scope 1 GHG emissions would result in simultaneous reduction in the emission of GHGs counted in the ETS and could represent a cost saving of 1.4 M€ per annum to the facility. It can also be argued that as Scope 1 GHG emissions are under the direct control of the distillery, the replacement of natural gas with biogas from an AD plant processing distillery by-products is a tangible, tactile, and definitive action that the distillery can take to reduce Scope 1 GHG emissions.

If the system boundary is extended to include Scope 1 and Scope 3 emissions as required by the GHG reporting method used by the distillery [6], the implementation of an AD plant could result in a reduction in total GHG emissions of 39,137 tCO_2eq (equivalent to 77% of Scope 1 emissions). The reduction in Scope 1 emissions remains the same, as such ETS emissions would also remain the same as in this case ETS emissions are the same as Scope 1 emissions. The potential reduction in Scope 3 emissions (11,389 tCO_2) could arise from; avoided emissions associated with extraction and transportation of natural gas and the replacement of synthetic fertilisers used for the cultivation of barley by digestate produced in an AD plant (only if the digestate is spread on land used for the cultivation of barley used by the distillery). If only Scope 1 and Scope 3 emissions are deemed relevant, then the implementation of an AD plant would be an attractive option as it results in a simultaneous net reduction in both Scope 1 (and associated ETS emissions) and Scope 3 GHG emissions (not included in the ETS). Alternative methods of reducing Scope 1 GHG emissions such as the combustion of biomass or electrification of processes, or the use of bio-LPG would not result in a reduction in Scope 3 emissions associated with barley cultivation. Likewise, potential methods of reducing Scope 3 emissions associated with barley cultivation (improved farming practices and optimal supply chains) would not result in a reduction in Scope 1 GHG emissions.

Further expansion of the system boundary to include the production and transportation of replacement animal feed products results in GHG emissions of 38,642 tCO_2eq/a, which if included in the analysis (though not part of Scope 1,2 or 3) leads to in a net reduction in total GHG emissions of 495 tCO_2eq in a worst-case scenario. Inclusion of the GHG emissions associated with the production and transportation of imported animal feed could lead to the conclusion that the implementation of an AD plant at the distillery is less attractive than when considering Scope 1 emissions only, or Scope 1 and Scope 3 emissions only. The potential need to reduce the size of the cattle herd in Ireland to reduce GHG emissions [100] may remove the need for this imported feed in the future.

The decision as to which GHG emissions are of relevance, and the relative importance of each of the relevant GHG emissions is at the discretion of the distillery, as is the case for any large industrial user of energy in the FB sector. A potential method of elucidating the relevant GHG emissions, and the importance of these relevant GHG emissions is the Analytical Hierarchy Process [102]. Knowledge of the relevant GHG emissions and their relative importance can be used in a multi criteria decision analysis to gain a better insight into the suitability of a potential AD plant at the distillery or any other plant in the FB sector.

4.5. Digestate logistics

Transportation of large shares of whole digestate over long distances to the required landbank is unlikely to be viable from an economic or traffic management standpoint. The annual cost of digestate transportation was calculated as 3.373 M€/a, if this transportation cost is paid for by the distillery, it will negate the annual net saving of 2.985 M€/a and could render the project unviable. Ideally the asset value of the nutrients in the digestate and the replacement of fossil mineral fertiliser should be realised to such an extent as to at a minimum cover the transportation cost of this digestate.

Whole digestate must be transported a significant distance from the potential AD plant owing to the limitation on the mass of phosphorous that can be spread on agricultural land. The application of nitrogen to EDs in the landbank reaches ca. 31% of the maximum allowable application rate, and the application of phosphorous reaches 100% of the maximum allowable application rate (Fig. 6), therefore digestate must be transported further away from the potential AD plant to avoid breaching S.I. No. 605 [62]. A potential solution could be the separation of whole digestate into a solid and liquid fraction, thereby separating the nitrogen and phosphorous contained in the digestate [103]. This could allow for application of more nitrogen to land closer to the potential AD plant without breaching the phosphorous application limit which would result in a reduction in the distance over which digestate must be transported.

The large storage volume required if centralised digestate storage is used (541,884 m^3) would make the successful development of an AD plant extremely difficult. The land area required for such a large storage volume is not available at the distillery site, additionally, the cost associated with the construction of 12 no. 45,000 m^3 tanks with a diameter of 75 m and a height of 10.2 m. would be prohibitively high. Further concerns in relation to public perception and the granting of planning permission (required for any construction project in Ireland) for the construction of such a large storage volume are also seen as severe hurdles to the development of an AD plant at the distillery.

Centralised digestate storage may be un-viable in the absence of appropriate methods of digestate treatment to reduce the volume of digestate to be transported to land, or alternative digestate use options owing to the large storage volumes required and the high number of truck movements needed.

If decentralised digestate storage is used, the majority of digestate storage tanks would be smaller than 25,000 m^3 in volume, predominantly within the 1000–5000 m^3 range, and would be located between 25 km and 40 km from the AD plant. The total number of decentralised storage tanks required for decentralised digestate storage is 126. This represents a significant construction of digestate storage infrastructure within each electoral division. Ownership of these storage tanks is also not clear, they could be owned and maintained by the distillery, however this would result in a significant capital expenditure for the distillery. If the storage tanks within each electoral division are owned by farmers within each area, negotiation with these parties would be required to ensure that sufficient decentralised digestate storage facilities are constructed and are available for use each year.

The daily number of truck movements is significantly lower when decentralised digestate storage is used compared to centralised digestate storage, however, 82 truck movements per day, 365 days per year still represents a substantial number of truck movements. Owing to the large daily number of truck movements required and the potentially large number of decentralized digestate storage facilities required in each ED, decentralised digestate storage may still be unviable.

4.5.1. Alternative methods for digestate management

There are other options available for the processing of whole digestate that are technically viable such as; solid–liquid separation, evaporation and drying, struvite precipitation, and ammonia stripping [104], [105]. The potential advantages of these existing technologies are their ability to isolate plant nutrients and reduce the mass of digestate to be transported. Additional options for the processing of digestate which are promising but less technically mature include; gasification [106], pyrolysis [107], and low temperature hydrothermal treatment [108]. These additional digestate processing options can facilitate additional energy production in the form of syngas and bio-oil [106], [107]. An additional benefit is the ability to produce biochar and hydro-char which can be used to enhance the AD process by-facilitating direct interspecies electron transfer, or which can be applied to land to increase soil organic carbon levels [108]. These advanced methods of digestate treatment can also reduce the mass of digestate to be transported from the distillery. Other options for the transportation of digestate include the use of pipelines, as is the case at the Maabjerg biogas plant in Denmark which transports digestate to decentralised collection points using a pipeline network to reduce traffic movements [109].

The issues with storage and use of digestate could be alleviated if less distillery by-products, or a fraction of each distillery by-product were used in the potential AD plant. This would reduce the total mass of digestate produced and could potentially allow for the continued operation of the feeds recovery plant, thereby reducing the requirement for imported animal feeds. Further processing of whole digestate, via solid–liquid separation and further treatment of the solid and liquid fraction (e.g. solid fraction combustion and liquid fraction evaporation [104]) could further reduce the volume of storage required and the number of truck movements needed.

5. Conclusion

The use of distillery by-products in an AD pant could replace up to 64% of the natural gas demand of the distillery assessed. The replacement of natural gas by biogas derived from distiller by-products can substantially reduce the Scope 1 GHG emissions of the distillery (54%), and also reduce the ETS emissions of the facility. Digestate produced in an AD plant processing distillery by-product could be used to replace synthetic fertiliser used in the cultivation of barley consumed by the distillery, this could result in a net reduction in Scope 3 GHG emissions of the distillery (equivalent to 22% of Scope 1 emissions). Use of distillery by-products in an AD plant could, in a worst-case scenario, result in the need to import animal feed. Although the GHG emissions associated with the production and transportation of these imported animal feeds are not included in Scope 1 or Scope 3, they could partially negate the GHG emission reductions associated with the replacement of natural gas and synthetic fertiliser. Processing all of the distillery by-products available in an AD plant would create significant issues in relation to the storage and transportation of the digestate produced. The significant volume of storage required as well as the large number of truck movements needed could render such a project unviable.

Processing of all distillery by-products in an AD plant could have a simple payback of 14 years based on savings from the replacement of natural gas with biogas. However, the project may be unviable if digestate management is paid for by the AD plant operator. Agreements with farmers who could use the digestate as a replacement for synthetic fertiliser to cover the cost of digestate transportation may be one method of alleviating the issue of digestate transportation cost. The CAPEX calculated in this work is substantial, future work on high rate AD systems which are smaller in size may result in reduced CAPEX. Additional work assessing the economic performance of using distillery by-products in an AD plant could determine areas (e.g. CAPEX, operating cost, and digestate transportation cost) which have the greatest impact on financial performance and could focus future research by industries and academia. Additionally, the impact of different forms of financial support (e.g. capital grants or feed in tariffs) could be assessed. Life cycle assessments and in-depth techno-economic assessments should also be conducted when assessing the use of distillery by-products in an AD plant when more detailed design data become available. Future work must also assess; digestate treatment (such as separation and evaporation), the use of only a fraction of each distillery by-product, or the use of dewatered by-products in an AD plant using a multi criteria decision analysis cognisant of the benefits and drawbacks in order to determine the potential of a realistic AD plant.

CRediT authorship contribution statement

Richard O'Shea: Conceptualization, Investigation, Methodology, Writing - original draft, Visualization. **Richen Lin:** Writing - review & editing. **David M. Wall:** Writing - review & editing. **James D. Browne:** Writing - review & editing. **Jerry D Murphy:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

The following are the Supplementary data to this article: Download
: **Download Word document (137KB)**
Supplementary data 1.

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