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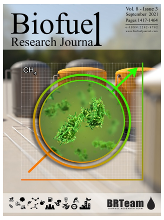

Original Research Paper

Distillery decarbonisation and anaerobic digestion: balancing benefits and drawbacks using a compromise programming approach

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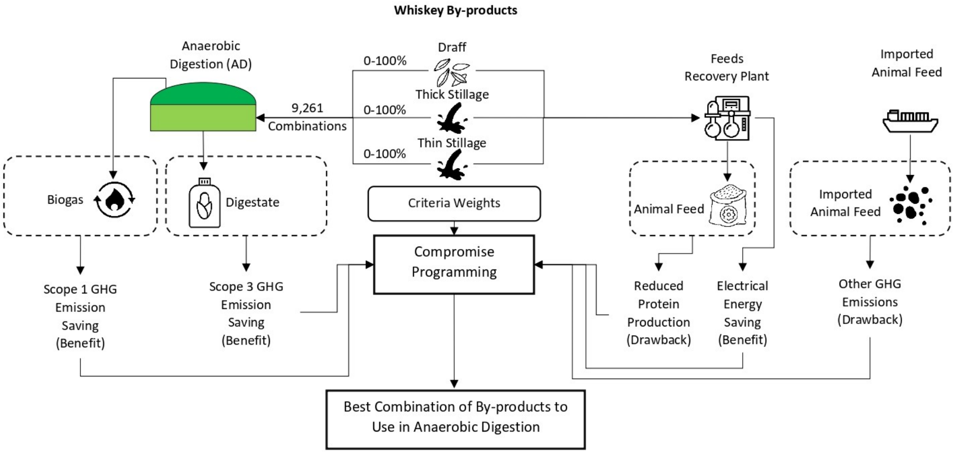
HIGHLIGHTS

- ➢ Maximising the benefits of biogas also maximises the potential drawbacks.
- ➢ Compromise programming (CP) assessed 9,621 scenarios of biogas production.
- ➢ Preferences of distillery management were accounted for in the CP analysis.
- ➢ CP suggests an optimal biogas system uses 100% of thick stillage and 100% of draff.
- ➢ Scope 1 emissions are reduced by 45% when using the optimal biogas system.

GRAPHICAL ABSTRACT



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ABSTRACT

The anaerobic digestion (AD) of distillery by-products presents benefits such as greenhouse gas (GHG) emission savings and electricity savings, as well as drawbacks such as reduced animal feed and protein production and the potential import of animal feeds. This work balances these benefits and drawbacks using compromise programming (CP). The best combination of by-products (from 9,261 scenarios) to use in AD was selected based on criteria chosen by management of a large distillery. The use of all by-products maximises benefits and drawbacks; the contrary also applies. When benefits and drawbacks are equally important, CP recommends using 50% of available draff, 50% of available thick stillage, and 55% of available thin stillage. The best combination when accounting for criteria weights chosen by distillery management is the use of 100% of available draff and 100% of available thick stillage. This could replace 48% of natural gas consumption at the distillery, reduce Scope 1 emissions by 45%, achieve a Scope 3 emissions savings of 22% of current Scope 1 emissions, and reduce electricity consumption in the feeds recovery plant of the distillery by 63%. Protein loss of 9,618 t could require the import of 19.59 kilo-tonne wet weight of material (ktwwt) of distillers grains and 9.15 ktwwt of soybean meal. If different criteria or criteria weights were used, a different result would be recommended. The methodology developed herein can aid in decarbonising the food and beverage industry by allowing decision-makers to balance the benefits and drawbacks of AD while accounting for subjective preferences.

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Contents

Abbreviations		**Abbreviations**	
FB	Food and beverage	CSO	Central Statistics Office
GHG	Greenhouse gas	VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
AD	Anaerobic digestion	TOPSIS	Technique for order of preference by similarity to ideal solution
MCDA	Multi criteria decision analysis	MCDA-1	Multi criteria decision analysis scenario 1
AHP	Analytical hierarch process	MCDA-2	Multi criteria decision analysis scenario 2
ELECTRE	Elimination and choice translating reality	wwt	Wet weight of material
CP	Compromise programming		
FRP	Feeds recovery plant	**Units**	
DDG	Dried distillers' grains	twwt	Tonne wet weight of material
BMP	Biochemical methane potential	ktwwt	Kilo-tonne wet weight of material
STP	Standard temperature and pressure	kt	Kilo-tonne
N	Nitrogen	MWhth	Megawatt hours of thermal energy
P	Phosphorous	GWh	Gigawatt hour
ED	Electoral division	t.km	Tonne-kilometre
UFL	Unité Forragére Lait	UFL	Unité Forragére Lait

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Nomenclature	Description	Unit	Nomenclature	Description	Unit
$SE_{CO2_{Natural\,Gas}}$	CO_2 emissions intensity of natural gas	$kgCO_2/MWh_{th}$	$m_{N_{digestate}}$	Mass of nitrogen contained in digestate	kgN
$mCO_{2_{Electricity}}$	Scope 2 GHG emissions from electricity use	$kgCO_2$	$m_{P_{digestate}}$	Mass of phosphorous contained in digestate	kgP
TS	Total solids content of material	% wwt	$m_{CO2_{Digestate_{Transport}}}$	Mass of CO_2eq emissions associated with digestate transportation	$kgCO_2eq$
VS	Volatile solids content of material	% wwt	d_{ED}	Distance from anaerobic digestion plant to a parcel of land in an electoral division over which digestate is transported	Km
BMP	Biochemical methane potential of material	$LCH_4/kgVS$	$SE_{CO2_{Digestate_{Transport}}}$	Specific CO_2eq emission intensity of digestate transportation	$kgCO_2eq/t.km$
$\eta_{Digestion}$	Efficiency of anaerobic digestion	%	$SE_{CO2_{Digestate_{Spreading}}}$	Specific CO_2eq emission intensity of digestate spreading on land	$kgCO_2eq/twwt$
ρ_{CH_4}	Density of methane	kg/m^3	$m_{CO2\,CAN_{Avoided}}$	Mass of greenhouse gas emissions avoided when replacing calcium ammonia nitrate fertiliser with digestate	$kgCO_2eq$
E_{CH_4}	Energy content of methane	MJ/kg	$m_{CO2\,Phos_{Avoided}}$	Mass of greenhouse gas emissions when replacing triple super phosphate fertiliser with digestate	$kgCO_2eq$
m_i	Mass of by-product 'i'	kgwwt	$m_{CO2\,Digestate_{Use}}$	Mass of greenhouse gas emitted when using digestate as a fertiliser	$kgCO_2eq$
$S_{i_{AD}}$	Share of by-product 'i' used in an anaerobic digestion plant	Fraction of total mass as a decimal	$\Delta GHG_{Digestate}$	Greenhouse gas emission saving when replacing synthetic fertiliser with digestate	$kgCO_2eq$
$E_{Biogas_{Net}}$	Net biogas production from by-products	MWh_{th}	$mCO_{2_{Feed_{Transport}}}$	Greenhouse gas emissions associated with the transportation of animal feed products from the distillery	$kgCO_2eq$
$mCO_{2_{Biogas}}$	CO_2 emissions avoided when replacing natural gas with biogas	$kgCO_2$	m_{Feeds}	Mass of animal feeds produced by the distillery	twwt
$X_{Fugitive}$	Fugitive methane emission from the anaerobic digestion plant	Fraction of total methane produced as a decimal	d_{Feeds}	Average transportation distance of animal feeds produced by the distillery	Km
$mCO_{2_{eq_{Fugitive}}}$	Mass of greenhouse gas emissions associated with fugitive methane emissions	$kgCO_2eq$	$SE_{CO2_{Transport_{Road}}}$	Specific greenhouse gas emissions of road transportation of animal feed by a truck	$kgCO_2eq/t.km$
$m_{digestate_{total}}$	Mass of digestate remaining after anaerobic digestion of by-products	kgwwt	$d_{mode_{AF_j}}$	Transportation distance by mode for alternative imported animal feed 'j'	km
X_{N_i}	Nitrogen content of by-product 'i'	kgN/kgwwt	d_{ideal}	Deviation of result from utopian value	unitless
X_{P_i}	Phosphorous content of by-product 'i'	kgP/kgwwt			

1. Introduction

Globally, the food and beverage (FB) sector emits 0.75% of energy-related greenhouse gas (GHG) emissions (United Nations Framework Convention on Climate Change, 2019), primarily from the combustion of gaseous fossil fuels. Industrial GHG emissions need to reduce by 80% through reduced demand, increased efficiency, electrification, decarbonising remaining non-electric fuels, and carbon capture and sequestration (Rogelj et al., 2018). Certain processes in the FB sector (evaporation, distillation, and drying) are difficult to electrify due to the higher temperatures required in these processes (IEA, 2018); thus, decarbonisation of these processes may benefit from the use of renewable gaseous fuels.

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Anaerobic digestion (AD) of biodegradable by-products can produce biogas, a renewable gaseous fuel that is a mixture of methane and carbon dioxide. A detailed description of the process can be found in (Murphy and Thamsiriroj, 2013). The production of biogas from biodegradable materials has been highlighted as a key component of the circular economy allowing for the recovery of energy and biological nutrients (Ellen MacArthur Foundation, 2013). Globally, biogas is predicted to play a significant role in future energy systems and could contribute up to 20% of modern bioenergy supply in 2040 (IEA, 2020). A plethora of prior work has assessed the energy resource of biogas at a regional level. Examples include the biogas resource derived from organic waste in the EU (Lorenz et al., 2013), the resource associated with agricultural wastes in China (Yan et al., 2021), and the energy resource associated slaughterhouse wastes in the USA (Wang et al., 2018).

Advantages of integrating AD with installations in the FB sector include: improved management of by-products, reducing Scope 1 GHG emissions by replacing natural gas consumption, producing high temperature renewable heat, increased energy security, and the recycling of nutrients to land in the form of digestate (Fagerström et al., 2018). Nutrient recycling can reduce fertiliser consumption in agriculture, thus reducing the indirect (Scope 3) GHG emissions of facilities in the FB sector. A description of Scope 1 (direct) and Scope 3 (indirect) GHG emissions can be found in (WBCSD and WRI, 2004). Drawbacks of integrating AD into the FB sector include reduced animal feed production as outlined by Lindkvist et al. (2019) and Leinonen et al. (2018), which could be seen as economically or environmentally detrimental and may result in public opposition (Nevzorova and Kutcherov, 2019). AD plant development can be hindered by concerns relating to traffic movements required for digestate management (Capodaglio et al., 2016) which are exasperated as plant size increases. Management costs associated with the application of digestate on land owned by farmers who supply raw materials to the FB sector also increase with the mass of digestate to be managed (Dahlin et al., 2015). Some or all of these drawbacks also apply to AD projects which use other feedstock such as organic wastes, animal manures, and dedicated energy crops.

In the FB sector Lindkvist et al. (2019) assessed the conversion of by-products from the FB sector to biogas which accounted for economic, energy, and environmental performance. Lorenz et al. (2013) assessed the potential energy resource associated with processing biodegradable wastes in the EU, including by-products from the brewing industry. Research into the integration of AD and distilleries has been conducted since the 1970s (Pipyn and Verstraete, 1979). An overview of 28 prior works is provided in O'Shea et al. (2020). Kang et al. (2020) assessed GHG emission reductions as well as the potential replacement of fertilizer using digestate when digesting by-products of whiskey production. Leinonen et al. (2018) considered GHG emission reductions, accounted for the replacement of fertilizer with digestate, and calculated the potential loss of animal feed production. The logistical aspects of digestate use were considered by Drosg et al. (2008 and 2013) and Weber and Stadlbauer (2017). O'Shea et al. (2020) determined that Scope 1 and Scope 3 GHG emissions could be reduced if an AD plant processing all by-products available was integrated into a large distillery. However, GHG emissions from potentially imported animal feeds were found to be substantial. No attempt was made at determining the "optimal" share of by-products to use in an AD plant to balance the positive and negative aspects of AD integration.

Balancing the positive and negative aspects of renewable energy projects can be achieved through the use of multi-criteria decision analysis (MCDA) techniques as outlined by Campos-Guzmán et al. (2019) and Siksnelyte et al. (2018). Several MCDA techniques can be applied such as: Simple Weighted Sum, the Analytical Hierarch Process (AHP), Elimination and Choice Translating Reality (ELECTRE), and Compromise Programming (CP). Reviews of these methods and their application to renewable energy projects can be found in the literature (Kumar et al., 2017; Mardani et al., 2017). The authors have been unable to source any literature which uses MCDA to balance the benefits and drawbacks of integrating AD into a plant in the FB sector by selecting the optimal blend of by-products to use.

This work aims to address this knowledge gap *via* four objectives. Firstly, assess the energy resource and potential Scope 1 GHG emissions saving associated with AD of differing portions of distillery by-products. Simultaneously the production of digestate, potential fertiliser replacement, and Scope 3 GHG emissions saving based on the use of different portions of distillery by-products in an AD plant will be calculated. The reduction in animal feed production, potential imported animal feeds, and associated GHG emissions when different shares of by-products are used in an AD plant will be determined. Finally, MCDA (specifically CP) will be used to assess which combination of distillery by-products should be used in an AD plant to balance the positive and negative aspects of AD integration.

The analysis conducted in this work is applied to a large distillery in the Republic of Ireland, which is a major player in the whiskey and distilled spirits industry globally. The methodology developed herein can be applied to any other facility in the FB sector globally to aid in a more nuanced assessment of AD integration.

2. Materials and Methods

The calculations conducted herein are split across three main areas; biogas production, digestate production, and animal feed production when differing shares of distillery by-products are used in an AD plant. A flowchart outlining the calculation procedure is provided in **Figure 1**.

2.1. Distillery and 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 at the distillery. Draff, thick stillage, and thin stillage are by-products produced by the distillery. The by-products are processed in a feeds recovery plant (FRP) to produce three animal feed products: wet grains, dried distillers' grains (DDG), and syrup. Details are provided in **Table 1**.

The mass of CO_2 emitted from the combustion of natural gas is based on a CO_2 emission intensity of natural gas ($SE_{CO2_{Natural\,Gas}}$) of 201 $kgCO_2/MWh_{th}$ (EPA, 2019). Natural gas combustion accounts for over 99% of Scope 1 GHG emissions arising from the distillery. The distillery currently sources all electricity from renewable sources, as such, the Scope 2 GHG emissions associated with this electricity ($mCO_{2_{Electricity}}$) are zero. Energy consumption is given in **Table 2**.

Scope 3 emissions are classified into 15 categories according to reporting standards (WBCSD and WRI, 2013a), 9 categories are used by the distillery for classifying Scope 3 emissions (See **Appendix A**). The alteration of Scope 3 GHG emissions at the distillery by an AD plant treating by-products will be outlined in the following sections.

2.2. Biogas production from by-products

2.2.1. By-product characteristics

By-product samples were sourced from the distillery and characterised in terms of their total solids content (TS_i), and volatile solids content (VS_i) (Allen et al., 2015). Experimental assays to determine the biochemical methane potential (BMP) were conducted in triplicate following the methods detailed in prior works (Allen et al., 2015; Wall et al., 2013). The TS content, VS content, and BMP values for each by-product are given in **Table 3**.

2.2.2. Biogas production

Gross energy production from AD of by-products (**Eq. 1**) is calculated using the biochemical methane potential of each by-product (BMP_i), an assumed digestion efficiency ($\eta_{Digestion}$) of 80% in continuous operations, methane density (ρ_{CH_4}) of 0.714 kg/m^3 at Standard Temperature and Pressure (STP), an energy content of methane (E_{CH_4}) of 50 MJ/kg, the mass of each by-product available (m_i), the share of each by-product used in an AD plant ($S_{i_{AD}}$), and the volatile solids content of each by-product (VS_i). Division by 3,600 facilitates conversion to MWh_{th}.

$$E_{biogas_{Gross}} = \frac{\left(\frac{\eta_{Digestion}}{100} * \sum_{i=1}^{3} S_{i_{AD}} * m_i * \frac{VS_i}{100} * BMP_i\right)}{1000} * \rho_{CH_4} * E_{CH_4} * \frac{1}{3600} \quad \text{Eq.1}$$

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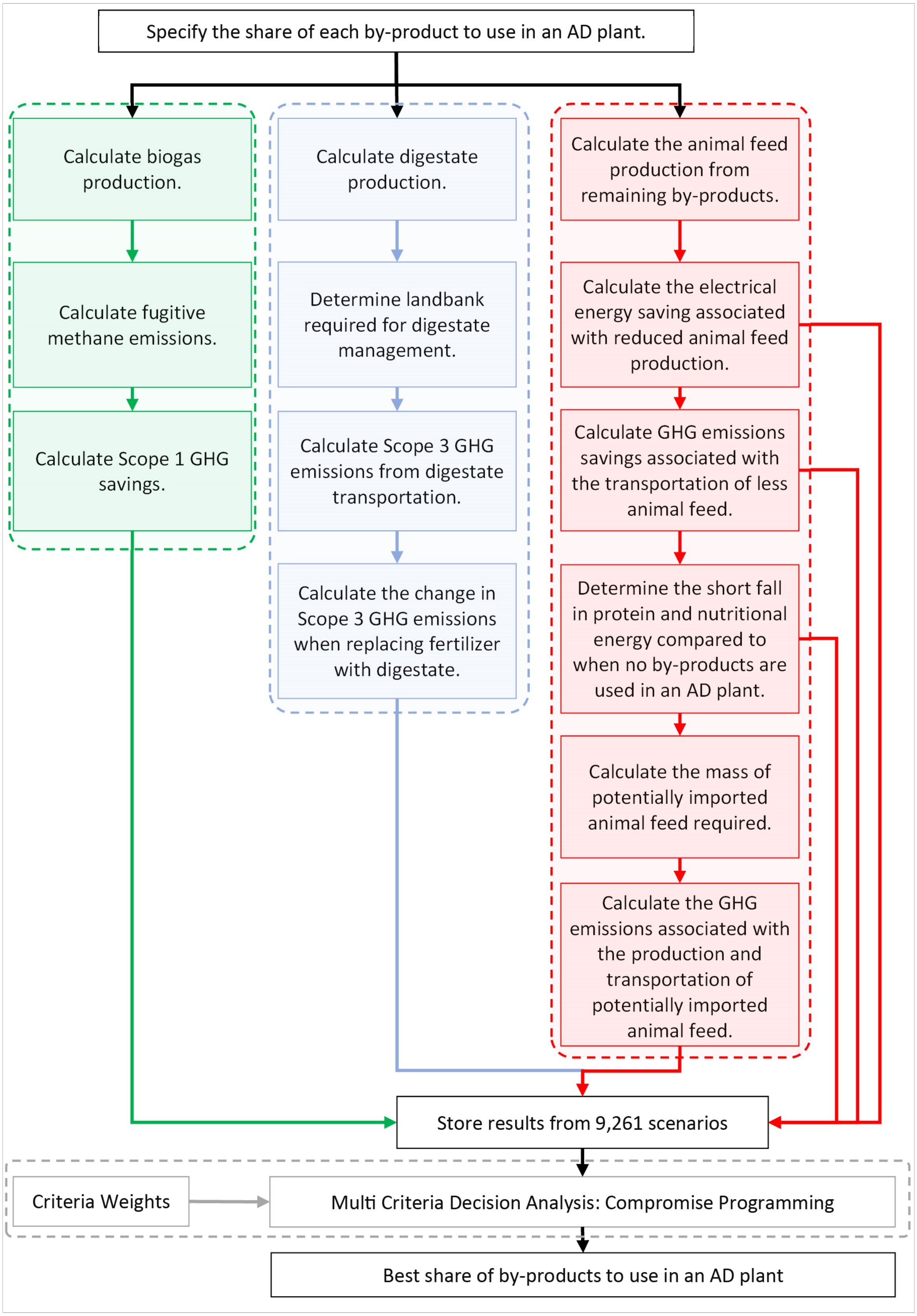

Fig. 1. Calculation flowchart. AD: Anaerobic Digestion. GHG: Greenhouse Gas.

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Table 1.
By-product and feed product mass. 'ktwwt': Kilo-tonne of Wet Weight of Material. 'DDG': Dried Distillers' Grains.

Parameter	Symbol	Mass (ktwwt/a)	Description
Draff	m_{Draff}	46.7	Residual solids following the brewing of malted and un-malted barley to produce wort.
Thick Stillage	m_{Thick}	277.5	Liquid remaining after the distillation of pot ale (a residual liquid remaining after the initial distillation of fermented wort)
Thin Stillage	m_{Thin}	322.8	Solid-liquid mixture remaining after the distillation of maize in a continuous distillation column.
Wet Grain	$m_{Wet\ Grain}$	62.776	A mixture of draff, the solid portion of thick stillage, and syrup
DDG	m_{DDG}	12.806	A mixture of wet grains and syrup which is dried
Syrup	m_{Syrup}	41.794	Produced from the evaporation of water from thin stillage and the liquid portion of thick stillage

Table 2.
Distillery annual energy consumption. subscript 'th' corresponds to thermal energy. Subscript 'e' corresponds to electrical energy.

Parameter	Symbol	Unit	Value
Total Natural Gas Demand	$E_{Natural\ Gas}$	GWh_{th}/a	229
Steam Demand of Feeds Recovery Plant	$E_{Thermal_{Feeds}}$	GWh_{th}/a	8.7
CO_2eq from Natural Gas Combustion	$mCO_{2_{Natrual\ Gas}}$	tCO_2eq/a	45,975
Total Electricity Consumption	$E_{Electrical_{Distillery}}$	GWh_e/a	42
Electricity Demand of Feeds Recovery Plant	$E_{Electrical_{Feeds}}$	GWh_e/a	7.9

Table 3.
By-product properties. 'TS': Total Solids Content. 'VS': Volatile Solids Content. 'BMP': Biochemical Methane Potential. 'N': Nitrogen. 'P': Phosphorous. '%wwt': Percentage of Wet Weight of Material

By-product	TS %wwt	VS %wwt	BMP $LCH_4/kgVS$	Methane Yield $LCH_4/kgwwt$	Nitrogen (gN/kgwwt)	Phosphorous (gP/kgwwt)
Draff	27.6	26.5	330±2.2	87.4±0.6	13.76	1.76
Thin Stillage	3.9	3.5	494.6±41.0	17.4±1.4	1.60	0.33
Tick Stillage	8.8	8.2	502.6±42.7	41.4±3.5	3.68	0.91

The net energy ($E_{Biogas_{Net}}$) production of the AD plant was determined by subtracting the total thermal energy demand of the AD plant as outlined by the authors (O'Shea et al., 2020) and are contained in **Appendix B**.

The mass of CO_2eq avoided by using biogas to replace natural gas ($mCO_{2_{Biogas}}$) is calculated assuming a carbon intensity of natural gas of ($SE_{CO2_{Natural\ Gas}}$) 201 $kgCO_2/MWh$ as per **Equation 2**.

$$m_{CO_{2_{Biogas}}} = E_{Biogas_{Net}} * SE_{CO2_{Natural\ Gas}} \qquad \text{Eq.2}$$

Using biogas would reduce Scope 1 GHG emissions at the distillery site and would also reduce the Scope 3 GHG emissions associated with the upstream production and transportation of natural gas outlined (O'Shea et al., 2020).

2.2.3. Fugitive methane emissions

This work assumes fugitive methane emissions ($X_{Fugitive}$) from the AD plant of 2% (see **Appendix C** for details). The total mass of CO_2eq emitted as a result of fugitive emissions ($mCO_{2_{eq_{Fugitive}}}$) is calculated using **Equation 3** and a global warming potential of 25 for methane (O'Shea et al., 2020). Fugitive emissions will contribute to Scope 1 GHG emissions of the distillery, minimisation of fugitive emissions will ensure greater Scope 1 GHG emissions saving.

$$mCO_{2_{eq_{Fugitive}}} = \left(\eta_{Digestion} * \sum_{i=1}^{3} S_{i_{AD}} * m_i * VS_i * BMP_i\right) * \rho_{CH_4} * X_{Fugitive} * 25 \qquad \text{Eq.3}$$

2.3. Digestate production

The total mass of digestate ($m_{digestate_{total}}$) produced can be calculated as per **Equation 4**.

$$m_{digestate_{total}} = \sum_{i=1}^{3} S_{i_{AD}} * m_i * \left(1 - \eta_{Digestion} * VS_i\right) \qquad \text{Eq.4}$$

The nitrogen (N) and phosphorous (P) content of the digestate was estimated based on feedstock N (X_{N_i}) and P (X_{P_i}) content (**Table 3**). The total mass of nitrogen ($m_{N_{digestate}}$) and phosphorous ($m_{P_{digestate}}$) leaving the AD plant in digestate are assumed to be equal to the total mass of nitrogen and phosphorous contained in the by-products added to the AD plant calculated according to **Equation 5** and **Equation 6**, respectively.

$$m_{N_{digestate}} = \sum_{i=1}^{3} S_{i_{AD}} * m_i . X_{N_i} \qquad \text{Eq.5}$$

$$m_{P_{digestate}} = \sum_{i=1}^{3} S_{i_{AD}} * m_i . X_{P_i} \qquad \text{Eq.6}$$

2.3.1. Calculating the landbank required for spreading of digestate

The land area required for digestate spreading was calculated in accordance with S.I. 605 of 2017 as outlined in prior work by the authors (O'Shea et al., 2020) and is provided in **Appendix D** for completeness. The CO_2eq emissions associated with the transportation of digestate ($m_{CO2_{Digestate_{Transport}}}$) to each Electoral Division (ED) was calculated based on the mass of digestate sent to each ED ($m_{Digestate_{ED}}$) and the distance to each ED (d_{ED}) as per **Equation 7**. The specific CO_2eq emissions associated with the transportation of digestate ($SE_{CO2_{Digestate_{Transport}}}$) to farmland was taken to be 0.19 $kgCO_2eq/t.km$ based on prior work by the authors (O'Shea et al., 2020).

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$$mCO_{2_{Digestate_{Tranport}}} = m_{Digestate_{ED}} * d_{ED} * SE_{CO2_{Digestate_{Transport}}} \qquad \text{Eq.7}$$

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 ($SE_{CO2_{Digestate_{Spreading}}}$) used in this work is 1.15 $kgCO_2eq/t_{wwt}$ based on a review of work by (Berglund and Börjesson, 2006; Nemecek and Kagi, 2007; Korres et al., 2010; Pöschl et al., 2010; Foley et al., 2011; Nguyen et al., 2011; Rehl and Müller, 2011; Dieterich et al., 2014; Lijó et al., 2014; McAuliffe et al., 2017).

As indicated in prior work by the authors (O’Shea et al., 2020), the potential land bank, truck movements, and storage volumes required for digestate management may be substantial. Therefore, the use of digestate processing is considered a mandatory element of the AD project. However, this work does not consider the impact of digestate processing techniques as the processing technique to be used has not yet been decided. The landbank, transportation energy consumption, and associated GHG emissions resulting from the management of the whole digestate will be considered in this work.

2.3.2. Calculating the impact of digestate use on GHG emissions associated with barley cultivation

Digestate can be applied to land used for the cultivation of barley that is subsequently used in the distillery and could reduce Scope 3 GHG emissions of the distillery. The mass of synthetic nitrogen and phosphorous fertiliser that can be replaced by digestate is outlined in **Appendix E**.

Direct and indirect N_2O emissions associated with the application of nitrogen fertiliser to agricultural land are calculated according to the report by Duffy et al. (2020) in line with IPCC guidelines (Dong et al., 2006; Hergoualc’h et al., 2019). A detailed description of these calculations is given in **Appendix F**. An example of the calculation to determine the mass of synthetic phosphorous fertiliser replaced by digestate and the avoided GHGs is given **Appendix E** and in **Appendix F**, respectively. 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**.

Replacing calcium ammonia nitrate (CAN) commonly used nitrogen fertiliser with digestate results in GHG emissions savings ($m_{CO2_{CAN_{Avoided}}}$). Replacing triple super phosphate, a commonly used source of phosphorous, with digestate also results in GHG emission savings ($m_{CO2_{Phos_{Avoided}}}$). Using digestate as a fertiliser to cultivate barley will result in the emission of some GHGs ($m_{CO2_{Digestate_{Use}}}$). Combining the GHG emissions avoided when replacing CAN and triple super phosphate, with the emissions arising from the use of digestate allows for the potential change in GHG emissions ($\Delta GHG_{Digestate}$) to be calculated *via* **Equation 8**. This will impact the Scope 3 GHG emissions of the distillery (if the barley grown is used in the distillery).

$$\Delta GHG_{Digestate} = m_{CO2_{CAN_{Avoided}}} + m_{CO2_{Phos_{Avoided}}} - m_{CO2_{Digestate_{Use}}} \qquad \text{Eq.8}$$

2.4. Production of animal feed

The production of animal feed was calculated based on a mass balance of the FRP, an indicative flowchart of the FRP is shown in **Figure 2**. Altering the mass of each by-product used in the FRP will alter the mass

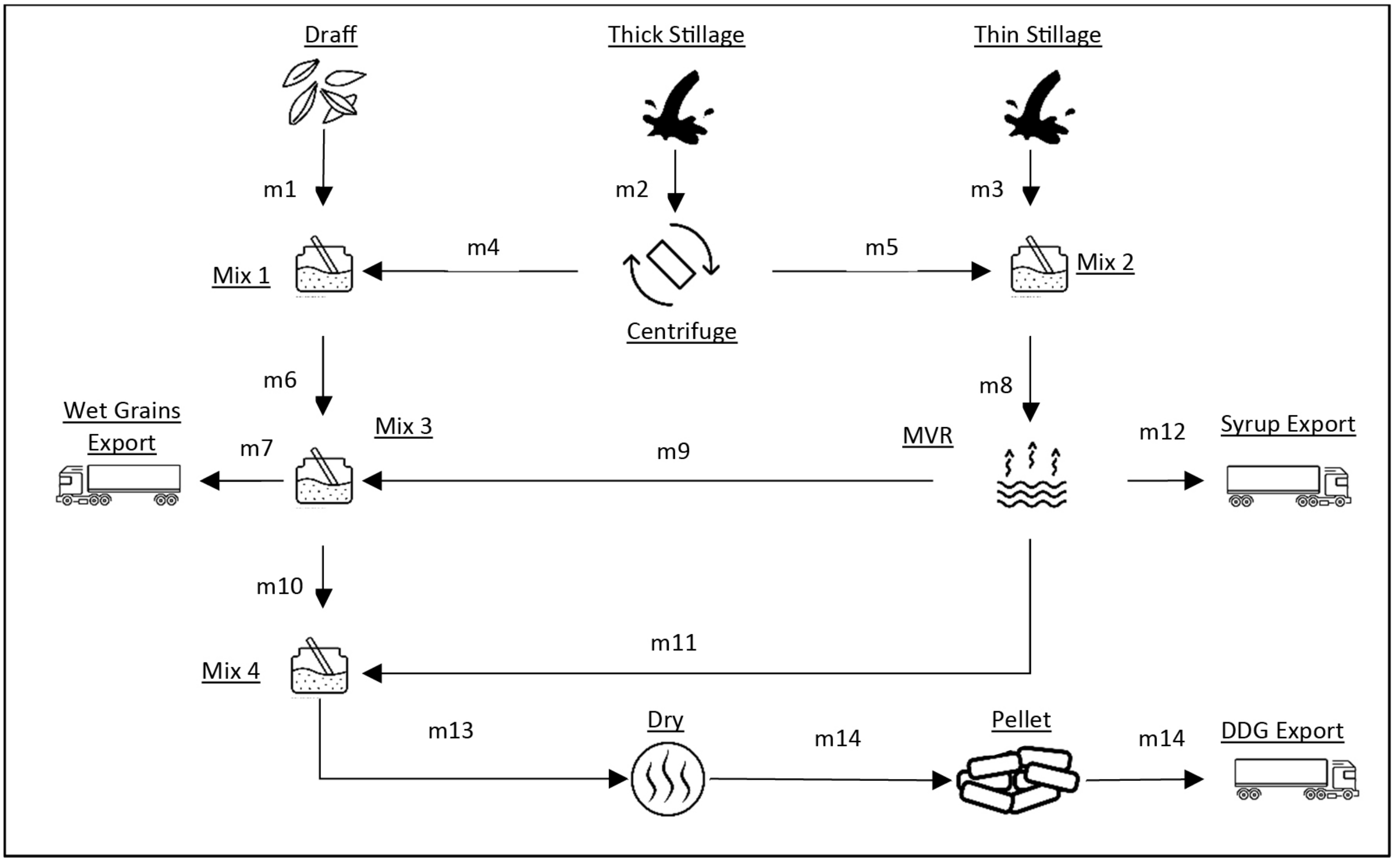

Fig. 2. Feeds recovery plant layout. ‘DDG’: Dried Distillers’ Grains. ‘MVR’: Mechanical Vapour Recompression. ‘m1’: Draff. ‘m2’: Thick Stillage. ‘m3’: Thin Stillage. ‘m4’: Cake Maize from Centrifuge. ‘m5’: Centrate from Centrifuge. ‘m6’: Draff and Cake Maize Mixture. ‘m7’: Wet Grains Exported from Site. ‘m8’: Thin Stillage and Centrate Sent to Mechanical Vapour Recompression (MVR) Evaporator. ‘m9’: Syrup Added to Wet Grains. ‘m10’: Wet Grains Sent to Dried Distillers’ Grains Mixer. ‘M11’: Syrup Sent to Dried Distillers Grains Mixer. ‘m12’: Syrup Exported from Site. ‘m13’: Wet Grains and Syrup Sent to Dryer. ‘m14’: Dried Distillers’ Grains Exported from Site.

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and composition of the resulting feed products (wet grains, DDG, and syrup). A detailed description of the equations governing the feeds recovery plant is given in **Appendix G**. Based on the share of by-products sent to a potential AD plant the mass of; wet grains ($m7$), DDG ($m14$), and syrup ($m12$), along with their respective nutritional energy content (Unité Forragére Lait (UFL)) and protein content can be calculated by solving the mass balances outlined in **Appendix G**.

2.5. Feeds recovery plant energy consumption

Using by-products in an AD plant will alter the thermal and electrical energy consumption of the FRP. The energy consumption of the FRP is calculated using models detailed in **Appendix H**. Reduced output of the FRP will lower natural gas consumption at the distillery and will reduce Scope 1 GHG emissions as outlined in **Appendix I**. Reduced throughput of distillery by-products in the FRP will also lower electrical energy consumption; calculation of the electrical energy savings associated with reduced FRP throughput are is detailed in **Appendix I**.

2.5.1. Transportation of feed products

The CO_2eq emissions from animal feed product transportation ($mCO_{2_{Feed_{Transport}}}$) are calculated based on the total mass of feed products produced (m_{Feeds}), an average transportation distance (d_{Feeds}) of 98 km, and a specific CO_2eq emission of 225 gCO_2eq/t.km for goods transportation by truck ($SE_{CO2_{Transport_{Road}}}$) as per **Equation 9** adapted from (WBCSD and WRI, 2013b).

$$mCO_{2_{Feed_{Tranport}}} = m_{Feeds} * d_{Feeds} * SE_{CO2_{Transport_{Road}}} \qquad \text{Eq.9}$$

Transportation of feed products is not within the value chain of the distillery, and as such these emissions do not fall within Scope 1, Scope 2, or Scope 3 and are classified as "other emissions".

2.6. Replacement of animal feed

Based on the mass, UFL content, and protein content of each feed product currently produced and the feed products produced when by-products are used in an AD plant, it is possible to calculate the difference in total UFL and protein produced. The mass of alternative feeds required to replace this difference can thus be calculated. Replacement of animal feeds produced at the distillery with imported animal feeds was assessed as this is seen as a "worst case" scenario which would result in the highest GHG emissions. Data that compared indigenously grown animal feed to imported animal feed indicates that from 2014-2018 2,332 kt (39%) of feed was grown in Ireland, compared to 3,707 kt (62%) of imported feed during the same period from (Wallace, 2020).

Imported replacement feeds assessed (distillers grains, maize gluten feed, soybean meal, and soyhulls), each has their own UFL and protein content as per **Table 4**. An optimisation model with the goal of calculating the minimum required mass of each alternative replacement feed to make up the difference in energy (UFL) and protein was developed. A description of the model is given in **Appendix J**.

2.6.1. GHG emissions associated with imported replacement animal feed production

Source countries of imported animal feeds were based on data acquired from the Irish Central Statistics Office (CSO), a detailed description is provided in **Appendix K**. GHG emissions associated with the production of imported animal feed are based on the mass of each feed required and the associated production emissions intensities sourced from the Global Feed Lifecycle Institute database of animal feed production (Blonk and Paassen, 2018). Details on the calculation method are also provided in **Appendix K**. The GHG emissions associated with potentially imported animal feed are not within the boundary of Scope 1, Scope 2, or Scope 3 emissions, as such they are classified as "other emissions".

Table 4.
Composition of replacement feeds. 'UFL': Unité Forragére Lait. 'wwt': Wet Weight of Material.

Feed	**Crude Protein** g/kgwwt	**Energy** UFL/kgwwt	**Imported Feed**
Distillers Grains	266.1	1.0324	Brewing or distilling dregs and waste
Maize Gluten Feed	203.3	0.8996	Residues from the manufacture of starch from maize of a kind used in animal feeding
Soya Bean Meal	481.2	1.0195	Oilcake and other solid residues resulting from the extraction of soya-bean oil
Soya Hulls	104.6	0.8878	Oilcake and other solid residues resulting from the extraction of soya-bean oil

2.6.2. GHG emissions associated with transportation of imported replacement animal feed

Transportation emissions of imported animal feeds are based on distances of each imported feed by mode of transportation ($d_{mode_{AF_j}}$), as outlined in **Appendix L**. The emissions arising from the transportation of potentially imported animal feed are also classified as "other emissions".

2.7. Digestate logistics

Digestate must be stored until it can be spread at the optimal times for crop uptake, as outlined by Plana and Noche (2016) and Logan and Visvanathan (2019). Digestate is to be used on land to cultivate barley that will then be used by the distillery to mitigate Scope 3 GHG emissions. In prior work by the authors, the volume of digestate storage required could be substantial if using a large portion of distillery by-products in an AD plant (O'Shea et al., 2020). The use of digestate processing to reduce storage volume and transportation requirements is seen as a necessary component of an AD plant processing distillery by-products by distillery management. Therefore, the storage volumes and truck movements required for digestate management are not considered in this work as the optimum digestate processing method has not been finalised.

2.8. Multi criteria decision analysis (MCDA)

2.8.1. Compromise programming

The MCDA technique used in this work is CP, developed by Zelany (1974) and Zeleny (1976). CP is based on the identification of an "ideal" solution that is generally infeasible, the identification of a "nadir" solution, and uses these to aid in the selection of a feasible "optimal" solution that is closest to the ideal. The CP method was used in this work as it is the basis for MCDA techniques such as VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The concept of determining which solution is closest to an ideal is relatively simple to understand and has been used by scholars since the early days of MCDA (Yu, 1985). CP has been used extensively in a range of fields, including agricultural planning (Romero et al., 1987), river basin development (Duckstein and Opricovic, 1980), the improvement of building energy efficiency (Diakaki et al., 2008), energy management in microgrids (Panwar et al., 2017; Sandgani and Sirouspour, 2018), forest management (de Sousa Xavier et al., 2015), the interaction between variable renewable generation technologies (Canales et al., 2020), and sustainability assessment (Dorini et al., 2011) amongst others. A detailed description of the CP methodology used in this work is given in **Appendix M**. There is technically an infinite number of by-product combinations that could be used in an AD plant. In order to present real world results, different scenarios are generated by varying the share of each by-product used in an AD plant from 0 to 100% (in increments

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Table 5.
Justification for criteria selection. 'MCDA': Multi Criteria Decision Analysis. 'GHG': Greenhouse Gas. 'FRP': Feeds Recovery Plant. 'AD': Anaerobic Digestion.

Criterion	Objective	Include MCDA	Weight	Justification
Scope 1 Savings	Maximise	Yes	0.3213	Reducing Scope 1 GHG emissions is a key priority of distillery management.
Scope 3 Savings	Maximise	Yes	0.3213	Reducing Scope 3 GHG emissions is a high-level target of distillery management. Using digestate as a fertiliser for the cultivation of barley that is consumed by the distillery can reduce Scope 3 GHG emission.
Other GHG Emissions	Minimise	Yes	0.1325	Emissions associated with the production and transportation of potentially imported animal feed were selected owing to concerns regarding the potential global impact of reducing animal feed production when by-products are used in an AD plant.
Loss of Protein Production	Minimise	Yes	0.1953	Included owing to concerns in relation to the potential negative impact that an AD plant could have on the supply of high-quality plant derived animal feeds to the local agricultural sector.
Electricity Savings in FRP	Maximise	Yes	0.0296	Electrical energy savings in the feed recovery plant (FRP) were selected as the FRP is one of the largest consumers of electricity in the distillery.
Digestate Production	Minimise	No	N/A	The mass of digestate produced by the anaerobic digestion of distillery by-products can potentially be large. As a result, the use of digestate processing is seen as a mandatory element of any AD project at the distillery. This will reduce the logistical issues of storage and transportation associated with digestate management. As such, the production of digestate is not considered in this analysis.
Total GHG Emissions	Maximise	No	N/A	Total GHG emissions savings (summation of Scope 1, Scope 3, and other GHG emissions) is not included in the MCDA as these emissions are not strictly additive as companies have control over which of categories of emissions are to be included in the reporting of Scope 3 GHG emissions.
Loss of Nutritional Energy	Minimise	No	N/A	The loss of nutritional energy is not included in the MCDA as distillery management indicated a greater concern in relation to the loss of protein.
Financial Performance	N/A	No	N/A	The financial performance of an AD plant processing by-products was not included in the MCDA owing to a lack of reliable data on the costs associated with construction of an AD plant at numerous different scales depending on the share of by-product use.

of 5%) resulting in a total of 9,261 different solutions generated in this work.

2.8.2. Selection of criteria included in multi criteria decision analysis

Criteria included in the CP analysis were determined following discussions with distillery management (**Table 5**). The results of the analysis in this work will be assessed with respect to each of these criteria individually to ascertain the differences that arise when choosing different criteria. The distillery management determined that the following criteria should be included in the analysis: Scope 1 GHG emissions, Scope 3 GHG emissions, other GHG emissions (from potentially imported animal feed), loss of protein production, and electricity savings in the feeds recovery plant. Initial CP analysis was conducted assuming equal importance for all criteria selected (MCDA-1), this would result in each criterion receiving a "weight" of 0.2 (five criteria were considered in MCDA-1).

A workshop was held with distillery management to ascertain the relative degree of importance ("Weights") of each criterion selected using the AHP method (Saaty, 1990). The relative degrees of importance of the selected criteria are included in **Table 5**. The consistency ratio obtained during the AHP process was 0.09, which indicates that the pairwise comparisons made by distillery management were consistent (Saaty, 1990). A further CP analysis was conducted using these criteria weights was conducted (MCDA-2).

3. Results and Discussion

The following sections outline the results obtained when: criteria included in the MCDA are considered individually, multiple criteria are considered simultaneously with equal weights (MCDA-1), and multiple criteria are considered simultaneously with weights ascertained by distillery management (MCDA-2).

3.1. Consideration of individual criteria

3.1.1. Scope 1 GHG emissions

When the only relevant criterion is Scope 1 GHG emissions, the MCDA results indicate that all by-products should be used in an AD plant. A summary of results is presented in **Table 6**, **Figures 3** and **4**.

3.1.2. Scope 3 GHG emissions

The results obtained when only Scope 3 GHG emissions are the same as the results obtained when only Scope 1 GHG emissions are considered.

3.1.3. Other GHG emissions (imported animal feed)

When the goal is to minimise the GHG emissions associated with the production and transport of potentially imported animal feed no by-products should be used in an AD plant. Feed production at the distillery using all of the available by-products should continue. No Scope 1 or Scope 3 emissions savings would be achieved. This result is trivial and corresponds to a "do nothing" scenario.

3.1.4. Loss of protein

When the loss of protein is the only criteria considered, the MCDA analysis indicates that no by-products should be used in an AD plant as this minimises the loss of protein. In this case, no Scope 1 or Scope 3 emissions savings would be achieved, and no biogas would be produced. Distillery operations continue unchanged. This is also a "do nothing" scenario.

3.1.5. Electrical energy savings in feed recovery plant

Maximum electrical energy savings in the feed recovery plant would occur if all of the by-products were used in an AD plant. Results are identical to those obtained when Scope 1 savings or Scope 3 savings are the only criteria included.

3.2. Impact of considering only Scope 1 savings, Scope 3 savings, and electrical energy savings

When the only criterion assessed is either Scope 1 emissions savings, Scope 3 emissions savings, or electrical energy savings, the use of 100% of each by-product in an AD plant and enables all of these criteria to achieve their ideal values (distance to ideal value (d_{ideal}) =0, **Fig. 3b**). Use of all by-products maximises the production of biogas (154 GWh/a, equivalent to 67% of current gas consumption) which yields maximum Scope 1

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Table 6.
Multi criteria decision analysis (MCDA) results. 'GHG': Greenhouse Gas. 'N': Nitrogen. 'P': Phosphorous. 'DDG': Dried Distillers' Grains. 'ktwwt': Kilo-tonne Wet Weight of Material.

Scenario	Unit	Maximise: Scope 1 Saving, Scope 3 Saving, Electrical Energy Saving	Minimise: Other GHG Emissions, Protein Loss	MCDA-1	MCDA-2
Net Biogas Production	GWh/a	154	0	79	110
Share of Distillery Energy Use from Biogas	%	67	0	34	48
Scope 1 GHG Savings from Biogas	ktCO2eq	30.99	0	15.94	22.20
Scope 1 GHG Savings from Feed Recovery Plant	ktCO2eq	2.42	0	2.42	2.42
Fugitive Methane Emissions	ktCO2eq	5.66	0	2.91	4.06
Scope 3 Category 3 Emissions Saving (Natural Gas)	ktCO2eq	3.97	0	2.18	2.93
Digestate GHG Emissions (Scope 3)	ktCO2eq	11.15	0	4.96	6.40
Synthetic N Fertiliser: Mass N Replaced	tN	1,181	0	606	841
Synthetic N Fertiliser GHG Savings (Scope 3)	ktCO2eq	18.04	0	9.26	13.31
Synthetic P Fertiliser: Mass P Replaced	tP	456	0	239	239
Synthetic P Fertiliser GHG Savings (Scope 3)	ktCO2eq	0.52	0	0.273	0.272
Wet Grain Production	ktwwt	0	62.77	43.67	0
DDG Production	ktwwt	0	12.81	0	0
Syrup Production	ktwwt	0	41.79	29.68	38.98
Feed Product Transport GHG Emission Saving	ktCO$_2$eq	2.77	0	1.15	1.91
Distillers Grain Import	ktwwt	30.06	0	15.47	19.59
Soymeal Import	ktwwt	11.54	0	5.93	9.15
Distiller Grain GHG Emissions	kgCO$_2$eq	32.65	0	16.80	21.27
Soymeal GHG Emissions	kgCO$_2$eq	8.77	0	4.51	6.95
Landbank Area	ha	18,257	0	9,564	9,541

emissions savings (27,748 tCO$_2$eq, equivalent to 60% of current Scope 1 emissions). Processing all by-products in an AD plant maximises digestate production and Scope 3 emissions savings (11,389 tCO$_2$eq). Electrical energy savings are maximised (8,541 MWh/a) as the FRP does not operate when all by-products are used in the AD plant.

However, using all by-products in an AD plant maximises the loss of protein (13,544 t) and nutritional energy (42,802x10^3 UFL), and would maximise other emissions associated with potentially imported animal feed (38,642 tCO$_2$eq), all of which attain their nadir value (d_{ideal}=1, **Fig. 3b**). Maximum loss of protein and nutritional energy production is undesirable as the distillery is seen as an essential source of high protein animal feed in the local agricultural sector. The mass of distillers' grains (30.06 ktwwt) and soybean meal (11.54 ktwwt) to be imported is equivalent to 5% and 2% of their respective imports into Ireland in 2018. Emissions associated with potentially imported animal feed may be substantial (41.42 ktCO$_2$eq). Maximum digestate production (597,545 twwt/a) may thwart the implementation of an AD plant at the distillery owing to digestate management issues if digestate is not processed further. If the whole digestate was to be applied to land used for barley cultivation, a total of 18,257 ha of land would be required. Digestate transportation up to 50 km from the AD plant would be required, which could be unviable from an economic and social acceptance standpoint. The transportation of this mass of digestate would require a substantial number of truck movements (O'Shea et al., 2020). Recent objections to the construction of large AD plants in Ireland on the basis of increased vehicle movements may render such a plant unviable. The use of digestate processing techniques is currently under investigation in order to minimise truck movements and storage volumes required.

At a global level, the total change in GHG emissions achieved is a saving of 495 tCO$_2$eq/a, when Scope 1 emission savings, Scope 3 emission savings, and other emissions from potentially imported animal feed are combined. The summation of Scope 1 emission savings, Scope 3 emission savings, and other emissions may not be additive, and therefore, this "total" value should be treated with caution. However, it is encouraging to see that when the only criteria included in the analysis were Scope 1 emission savings, Scope 3 emission savings, or electrical energy savings, there is the potential for an overall total GHG emission saving at a global level.

Focusing solely on achieving maximum possible savings in Scope 1 emissions and Scope 3 emissions is not recommended as this also maximises the undesirable impacts of integrating an AD plant with the distillery. The loss of protein production especially could be seen as a significant hurdle for the implementation of an AD plant using distillery by-products.

3.3. Impact of considering only other GHG emissions or the loss of protein

When the only relevant criterion considered is; other GHG emissions (potentially imported animal feed), or loss of protein, the MCDA suggests that no by-products should be used in an AD plant. This result is a "do nothing" scenario for the distillery, none of the drawbacks of AD plant integration at the distillery occur as no AD plant built. The elimination of the drawbacks associated with an AD plant also eliminates any of the benefits arising from the use of by-products in an AD plant. The need to reduce Scope 1 GHG emissions and Scope 3 emissions at the distillery makes this course of action undesirable unless other methods of reducing Scope 1 emissions and Scope 3 emissions can be identified.

3.4. Multiple criteria selected by distillery management

Results from MCDA-1 (equal criteria weights) indicate that 50% of thick stillage, 55% of thin stillage, and 50% of draff should be used in an AD plant, with the remaining by-products used to produce animal feed. Results are summarised in **Figure 5**. The application of digestate to the required landbank is summarised in **Figure 6**.

Results from MCDA-2 suggest that 100% of thick stillage, 0% of thin stillage, and 100% of draff should be used in an AD plant. The remaining thin stillage should be used to produce animal feed (syrup) in the feeds recovery plant. Results of MCDA-2 are summarised in **Figure 7**. The application of the whole digestate to the required landbank is summarised in **Figure 8**.

3.5. Impact of considering multiple criteria selected by distillery management

3.5.1. Equal criteria weights (MCDA-1)

In MCDA-1 the CP analysis indicates that 50% of thick stillage, 55% of thin stillage, and 50% of draff should be used in the AD plant yielding 79

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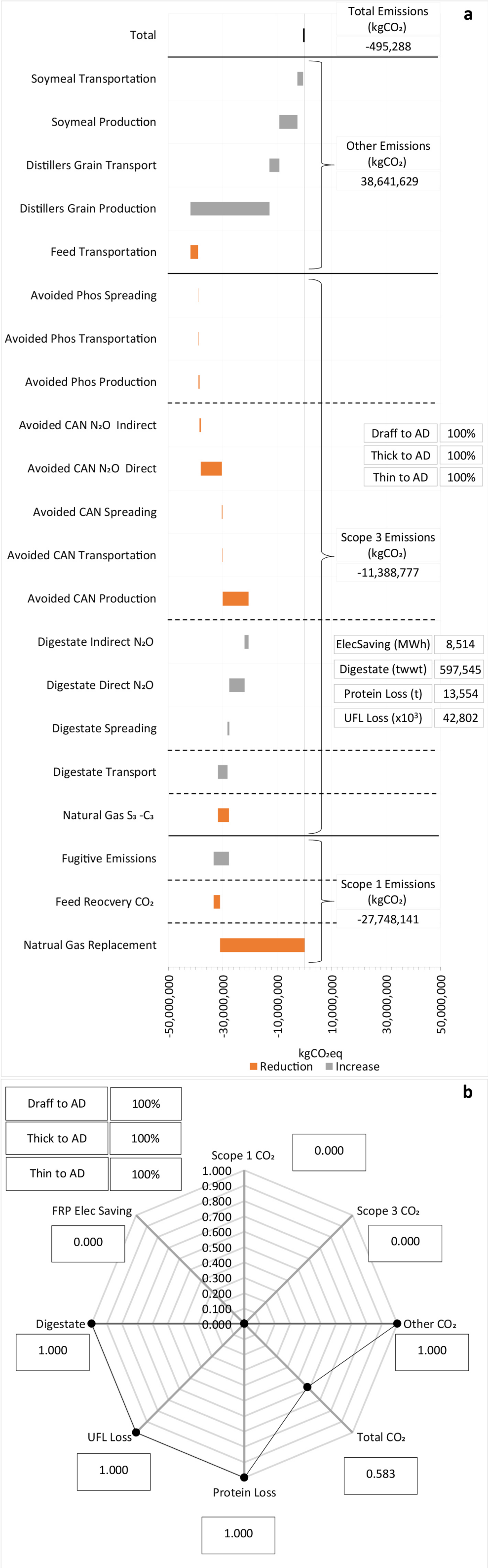

Fig. 3. Result when only considering Scope 1, Scope 3, or electricity savings. **(a)** Summary of results. **(b)** Deviation from Utopian value. 'CAN': Calcium Ammonia Nitrate. 'Phos': Phosphorous Fertiliser. 'Elec Saving': Electrical Energy Saving. 'UFL': Unité Forragére Lait. 'twwt': Tonne Wet Weight of Material. 'AD': Anaerobic Digestion. 'FRP': Feeds Recovery Plant. 'Thick': Thick Stillage. 'Thin': Thin Stillage.

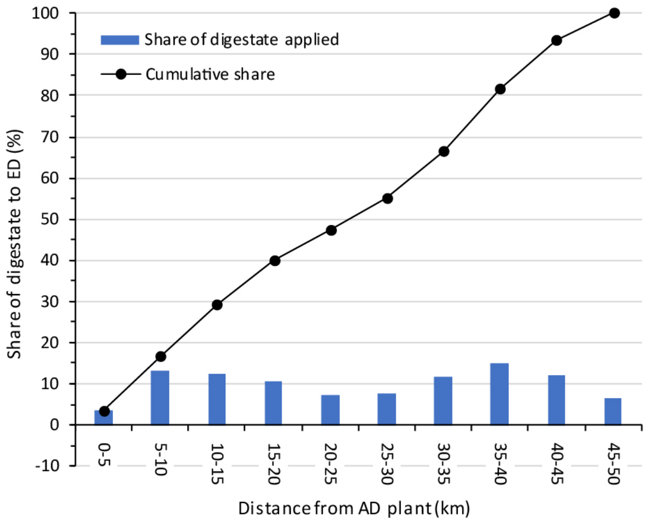

Fig. 4. Digestate management: Scope 1, Scope 3, or electricity savings only criteria considered. Share of digestate applied to landbank at a given distance. 'AD': Anaerobic Digestion. 'ED': Electoral Division.

GWh/a of biogas, equivalent to 34% of current gas consumption. This is 51% of the biogas production achieved when all of the by-products are used in an AD plant. Scope 1 GHG savings of 15,442 tCO_2eq (d_{ideal}=0.443) are equivalent to 33% of current Scope 1 GHG emissions from the distillery, this is lower than Scope 1 emission savings when only benefits of AD were to be maximised. Scope 3 emissions savings of 6,748 tCO_2eq (d_{ideal}=0.407) could arise from the replacement of synthetic fertilisers used for barley cultivation by digestate. These Scope 3 emission savings are equivalent to 15% of the current Scope 1 emissions from the distillery. Scope 3 GHG savings are lower when multiple criteria are considered compared to when only Scope 3 savings is the criterion selected. Electrical energy savings of 6,086 MWh (d_{ideal}=0.285) result from lower electricity consumption in the FRP. Electrical energy saving is lower when considering multiple criteria than when electrical energy saving is the only criteria considered.

Protein loss of 6,974 t (d_{ideal}=0.515) and the loss of nutritional energy of 22,026x10^3 UFL (d_{ideal}=0.515) would require the importation of 15.47 ktwwt of distillers' grains and 5.93 ktwwt of soybean meal resulting in other emissions of 20,166 tCO_2eq (d_{ideal}=0.522). These values are lower than those obtained when the goal was to maximise only the benefits of AD. The whole digestate produced amounted to 314.458 ktwwt (d_{ideal}=0.526), which is 52.6% of the mass of digestate that would be produced if all by-products were used in an AD plant. A landbank of 9,564 ha could be required for the whole digestate application. This is 52% of the land area required if all by-products were to be used in an AD plant. The whole digestate could require transportation to land up to 30 km from the AD plant, with the majority of digestate (70%) applied to land between 5-20 km from the AD plant. Further processing of digestate *via*; separation, evaporation, pyrolysis, or gasification could digestate management issues. The specific impact of these digestate processing methods will be assessed in future work.

The use of by-products in MCDA-1 is approximately half of that used when the goal was to maximise the benefits of AD. The reduction in by-product use in an AD plant is a direct result of a compromise between maximising the benefits of by-product use in an AD plant and minimising the associated drawbacks. Figure 5b indicates that the values achieved by the criteria considered in MCDA-1 fall between a normalised distance of 0.285 to 0.522 from their respective ideal values (d_{ideal}). Figure 5b also shows that criteria not included in the analysis for MCDA-1 (Total GHG emission savings, UFL loss, and digestate production) achieve values that fall between a normalised distance of 0.356 to 0.526 from their respective

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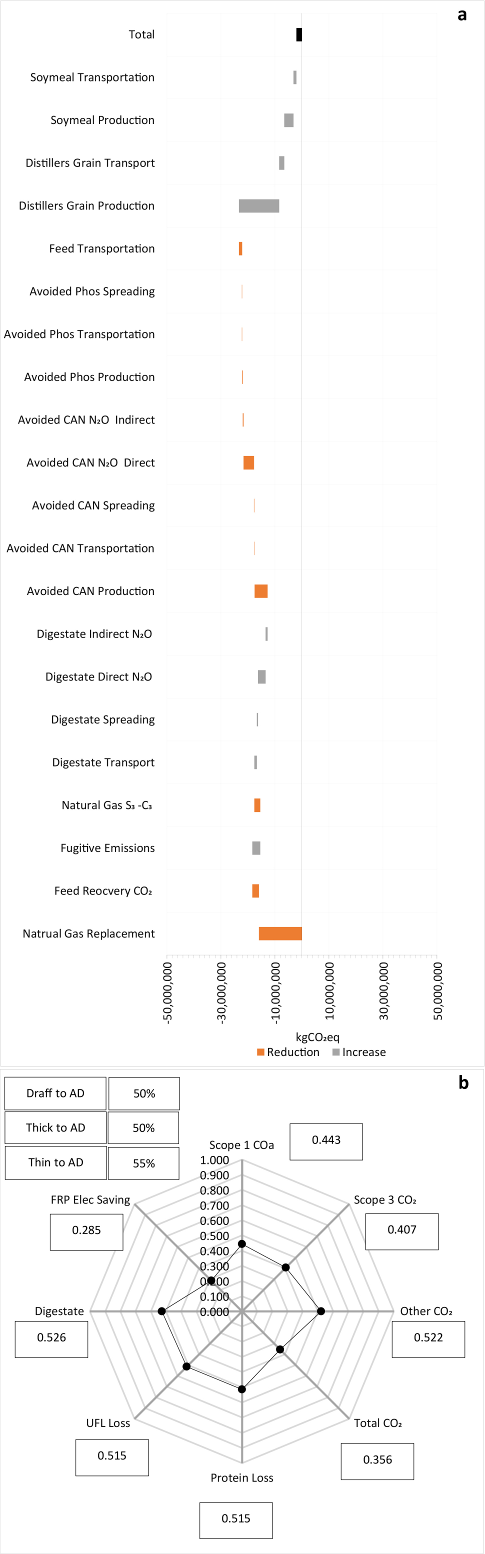

Fig. 5. MCDA-1: Scope 1, Scope 3, and electricity savings, protein loss, and other GHG emissions. Equal criteria weights. **(a)** Summary of results. **(b)** Deviation from Utopian value. 'CAN': Calcium Ammonia Nitrate. 'Phos': Phosphorous Fertiliser. 'Elec Saving': Electrical Energy Saving. 'UFL': Unité Forragére Lait. 'twwt': Tonne Wet Weight of Material. 'AD': Anaerobic Digestion. 'FRP': Feeds Recovery Plant. 'Thick': Thick Stillage. 'Thin': Thin Stillage. 'MCDA': Multi Criteria Decision Analysis. 'GHG': Greenhouse Gas.

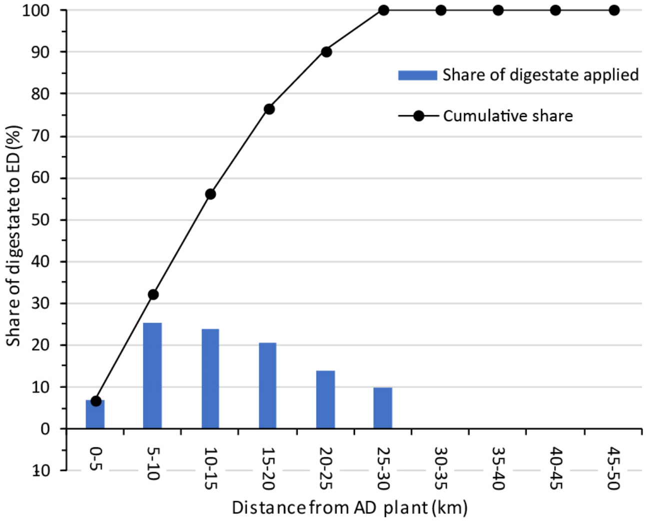

Fig. 6. Digestate management: results from MCDA-1. Share of digestate applied to landbank at a given distance. 'AD': Anaerobic Digestion. 'ED': Electoral Division. 'MCDA': Multi Criteria Decision Analysis.

ideals values. This indicates that in MCDA-1, neither the criteria considered in the analysis or the criteria not considered approach their nadir values.

The recommended use of ca. 50% of by-products in MCDA-1 appears to be trivial, this however, is not the case owing to the different properties of each by-product and the complex calculation procedures used herein. Recommending the use of ca. 50% of by-products to balance the benefits and drawbacks of AD in the absence of any MCDA would simply be a lucky guess.

Results of MCDA-1 assume all criteria are equally important, which is a common approach to take as it removes the subjective nature of applying weights of importance to criteria. This can be beneficial as the relative degrees of importance of each criterion may change over time.

3.5.2. Criteria weights specified by distillery management (MCDA-2)

Based on the criteria weights obtained from distillery management (**Table 5**) greater emphasis is placed on Scope 1 and Scope 3 GHG emission savings, followed by protein loss, other GHG emissions from potentially imported animal feed, and finally, electrical energy savings. The assumption of equal criteria weights in MCDA-1 does not reflect the actual criteria weights obtained from distillery management for use in MCDA-2. MCDA-2 suggests the use of 100% of thick stillage, 0% of thin stillage, and 100% of draff in an AD plant. This would yield 110 GWh of biogas, equivalent to 48% of the natural gas consumption of the distillery. Biogas production is ca. 71% of the total biogas production if the goal was to maximise the benefits of AD. Biogas production in MCDA-2 (110 GWh/a) is 39% higher than in MCDA-1 (79 GWh/a) as a result of higher weighting being placed on Scope 1 emission savings and Scope 3 emission savings.

Scope 1 GHG savings of 20,564 tCO$_2$eq (d_{ideal}=0.259) are 45% of current Scope 1 GHG emissions from the distillery. Scope 1 emission savings in MCDA-2 are 26% lower than when only Scope 1 savings is the only criterion selected; however, they are 33% greater than Scope 1 emission savings in MCDA-1. This is a direct result of the increased weight applied to Scope 1 emission savings in MCDA-2 compared to MCDA-1. Scope 3 emissions savings of 10,105tCO$_2$eq (d_{ideal}=0.113) are equivalent to 22% of current Scope 1 GHG emissions. Scope 3 emission savings are 11% lower in MCDA-2 when compared to results obtained when Scope 3 emission savings is the only criterion considered. The Scope 3 emission savings obtained in MCDA-2 are 50% higher than Scope 3 emission savings obtained in MCDA-1 as a result of the higher emphasis on Scope 3 emission savings in MCDA-2. Electrical energy savings of 5,442 MWh (d_{ideal}=0.361) are obtained in MCDA-2; these savings are 36% lower

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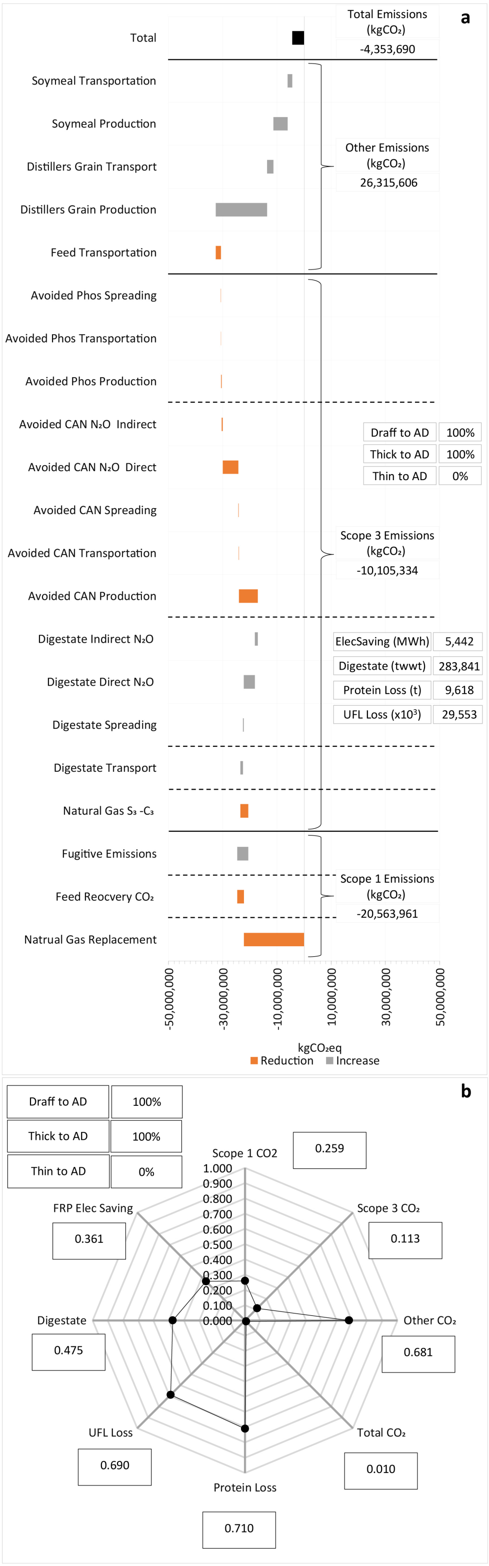

Fig. 7. MCDA-2: Scope 1, Scope 3, and electricity savings, protein loss, and other GHG emissions. Criteria weights from AHP. A) Summary of results. B) Deviation from Utopian value. 'CAN': Calcium Ammonia Nitrate. 'Phos': Phosphorous Fertiliser. 'Elec Saving': Electrical Energy Saving. 'UFL': Unité Forragére Lait. 'twwt': Tonne Wet Weight of Material. 'AD': Anaerobic Digestion. 'FRP': Feeds Recovery Plant. 'Thick': Thick Stillage. 'Thin': Thin Stillage. 'MCDA': Multi Criteria Decision Analysis. 'GHG': Greenhouse Gas.

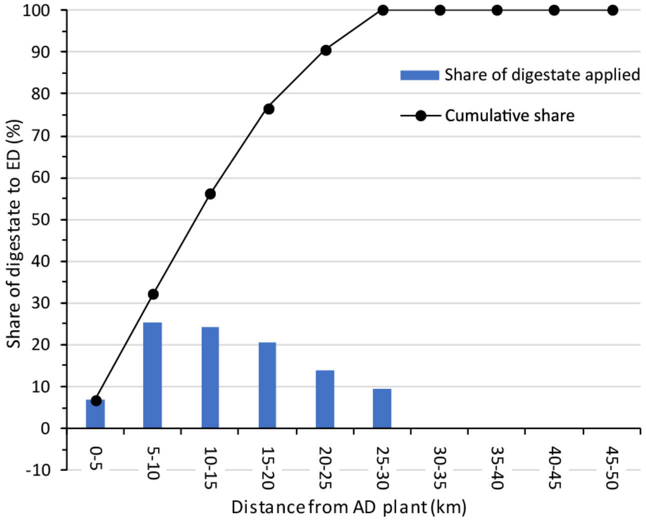

Fig. 8. Digestate management: results from MCDA-2. Share of digestate applied to landbank at a given distance. 'AD': Anaerobic Digestion. 'ED': Electoral Division. 'MCDA': Multi Criteria Decision Analysis.

compared to electrical energy savings when electrical energy saving is the only criterion considered. The electrical energy saving obtained in MCDA-2 is 10% lower than that obtained in MCDA-1 as a result of the lower weight applied to the electrical energy saving criterion in MCDA-2 (0.0296) compared to MCDA-1 (0.2).

Protein loss of 9,618 t (d_{ideal}=0.710) and the loss of nutritional energy of (29,553,026x10^3 UFL) d_{ideal}=0.69 would require the import of 19.59 ktwwt of distillers' grains and 9.15 ktwwt of soybean meal resulting in other emissions of 26,316 tCO$_2$eq (d_{ideal}=0.681). These values are lower than those obtained when the goal was to maximise only the benefits of AD. Protein loss in MCDA-2 is 38% higher than protein loss in MCDA-1, other emissions associated with potentially imported animal feed in MCDA-2 are 30% higher compared to other emissions in MCDA-1. These are a result of the increased mass of distillers grains and soybean meal which may need to be imported in MCDA-2 based on the lower weight associated with the protein loss criteria in MCDA-2, and the higher weight associated with Scope 1 and Scope 3 emission savings in MCDA-2 compared to MCDA-1 respectively.

Whole digestate produced in MCDA-2 amounted to 283,841 twwt (d_{ideal}=0.475), which is 47.5% of the mass of digestate that would be produced if all by-products were used in an AD plant. The mass of whole digestate produced in MCDA-2 is 10% lower than the mass of whole digestate produced in MCDA-1 owing to the reduced use of thin stillage by the AD plant in MCDA-2. The use of thick stillage and draff is favoured in MCDA-2 in order to maximise Scope 1 and Scope 3 emission savings. A landbank of 9,541 ha could be required in MCDA-2, this is 52% of the land area required if all by-products were to be used in an AD plant and 99.8% of the land area required in MCDA-1. Despite the lower mass of digestate produced in MCDA-2 compared to MCDA-1 a similar land area is required for the application of whole digestate. The similar landbank area is a result of the total mass of phosphorous contained in the digestate (239 t) in MCDA-1 and MCDA-2 being the same. Phosphorous is the rate limiting nutrient for land application of fertilisers, and therefore a similar land area would be required for the application of digestate. Transportation of digestate up to 30km from the AD plant would be required, with the majority of digestate (70%) applied to land within 5-20 km of the AD plant. In reality, digestate processing will be required to mitigate the number of truck movements and storage volumes required for digestate management. These processing techniques such as: separation, evaporation, combustion, pyrolysis, and gasification will be assessed in future work.

The compromise solution achieved in MCDA-2 is substantially different to the compromise solution achieved in MCDA-1. The increased use of thick stillage and draff in MCDA-2 is a result of the higher weights applied to Scope 1 emission savings and Scope 3 emission savings in MCDA-2 compared to MCDA-1. Increased use of thick stillage and draff directly increases Scope 1 emission savings owing to increased biogas production and increases Scope 3 emission savings owing to the higher nitrogen and phosphorous content of these by-products compared to thin stillage, thereby replacing more synthetic fertilisers. Electricity savings achieved in MCDA-2 are lower than those obtained in MCDA-1 as the weight associated with this criterion in MCDA-2 is lower than in MCDA-1. Drawbacks associated with the use of by-products in an AD plant, such as the loss of protein production and the GHG emissions associated with potentially imported animal feed are greater in MCDA-2 compared to MCDA-1. This is a direct result of the lower weights applied to these criteria in MCDA-2.

Comparison of **Figure 5b** and **Figure 7b** shows that criteria with a higher weight in MCDA-2 compared to MCDA-1 achieve values that are closer to their ideal values. Criteria with lower weights in MCDA-2 compared to MCDA-1 attain values which are further from their ideal value. This is to be expected as criteria with higher weights in MCDA-2 are seen as being more important. The values achieved by the criteria considered in MCDA-2 fall between a normalised distance of 0.113 to 0.710 from their respective ideal values therefore, none of the criteria considered in MCDA-2 approach their nadir values. The alteration of criteria weights in MCDA-2 results in a compromise solution that favours the criteria assigned higher weights at the expense of criteria with lower weights.

Figure 7b also shows that the criteria which are not included in the analysis for MCDA-2 (Total emission savings, UFL loss, and digestate production) achieve values which fall between a normalised distance of 0.010 to 0.690 from their respective ideal values. None of the criteria which are not considered in MCDA-2 approach their nadir value. It is worth noting that the "Total emission savings" criteria, although not considered in MCDA-2, approaches its ideal value in MCDA-2, despite the increased emissions arising from potentially imported animal feed. This is because the increased Scope 1 and Scope 3 emission savings outweigh the increase in other emissions in MCDA-2.

The compromise solution achieved in MCDA-2 is based on criteria weights obtained from a single workshop with distillery management using the AHP method. These criteria weights and the criteria themselves may be altered or updated by distillery management in the future to arrive at a more refined reflection of their preferences. The results given in this work do not represent a conclusive and definite measure of the criteria selected by distillery management or the relative weighting of these criteria. The results presented are a snapshot in time of an iterative process which can incorporate changing opinions and priorities.

3.6. The need for compromise

AD of distillery by-products can result in major reductions to Scope 1 GHG emissions by replacing natural gas with biogas. Electrical energy savings in the FRP by reducing by-product processing in the FRP can also be realised. The use of digestate as a fertiliser on land used for the cultivation of barley consumed by the distillery could reduce Scope 3 GHG emissions. However, the use of distillery by-products in an AD plant will reduce animal feed production and result in a loss of protein supplied to the livestock sector by the distillery. Imported replacement animal feed could result in significant GHG emissions associated with the production and transportation of these feeds.

There is a multitude of by-product combinations that can be used in an AD plant which results in confusion when trying to ascertain what the best combination is. Maximum benefits and maximum drawbacks occur when all of the by-products are used in an AD plant. Minimum benefits and minimum drawbacks occur when no by-products are used in an AD plant, neither of these extreme solutions are viable. To balance the positive and negative aspects of using distillery by-products in an AD plant a compromise must be made. This compromise mitigates the negative impacts of by-product use in an AD plant but also partially negates the positive impacts.

Selection of the share of each by-product to use in an AD plant in to balance these benefits and drawbacks is not trivial owing to the conflicting nature of the criteria considered and the vast number of potential by-product combinations to choose from (9,261 in this analysis). The use of the CP approach allows for systematic selection of an appropriate share of by-products to use in an AD plant so as to achieve a holistic and balanced result based on the relevant criteria selected.

The need to find a compromise between benefits and drawbacks in the implementation of AD within the wider FB sector is paramount to ensure that these renewable energy projects can be developed in an informed manner. The integration of AD with facilities in the FB sector is a potential way to reduce GHG emissions, especially in processes that require high temperature heat which are difficult to decarbonise. However, all AD projects will have beneficial and detrimental impacts on a range of often conflicting criteria. Many projects integrating AD into the FB sector will need to consider some of, and potentially more than, the criteria considered in this work. The use of MCDA techniques, such as CP, can aid in the identification of possible project designs that maximise beneficial results while minimising detrimental impacts.

4. Conclusions

From 9,261 scenarios assessed, the use of 50% of thick stillage, 55% of thin stillage, and 50% of draff in an AD plant is recommended based on criteria selected by distillery management, assuming equal criteria importance. This combination of by-product use could: reduce Scope 1 GHG emissions by 33%; reduce Scope 3 GHG emissions by 6,748 tCO_2eq; reduce electrical energy consumption in the feeds recovery plant by 71%; maintain 48% of current protein production; and limit the GHG emissions from potentially imported animal feed to 52% of the maximum amount of GHG emissions from potentially imported animal feed when all by-products are used in an AD plant.

Based on criteria selected by distillery management and accounting for relative levels of importance the use of 100% of thick stillage and 100% of draff in an AD plant is recommended. This combination of by-products could: reduce Scope 1 GHG emissions by 45%; reduce Scope 3 GHG emissions by 10,105 tCO_2eq; reduce electrical energy consumption in the feeds recovery plant by 63%; maintain 29% of current protein production; and limit the GHG emissions from potentially imported animal feed to 68% of the maximum amount of GHG emissions from potentially imported animal feed when all by-products are used in an AD plant. Considering different criteria or applying different degrees of relative importance would result in a different compromise solution being recommended. The thesis presented in this work can be applied to other facilities in the FB sector to aid the design of AD projects whilst balancing potential benefits and drawbacks.

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