



Original Research Paper

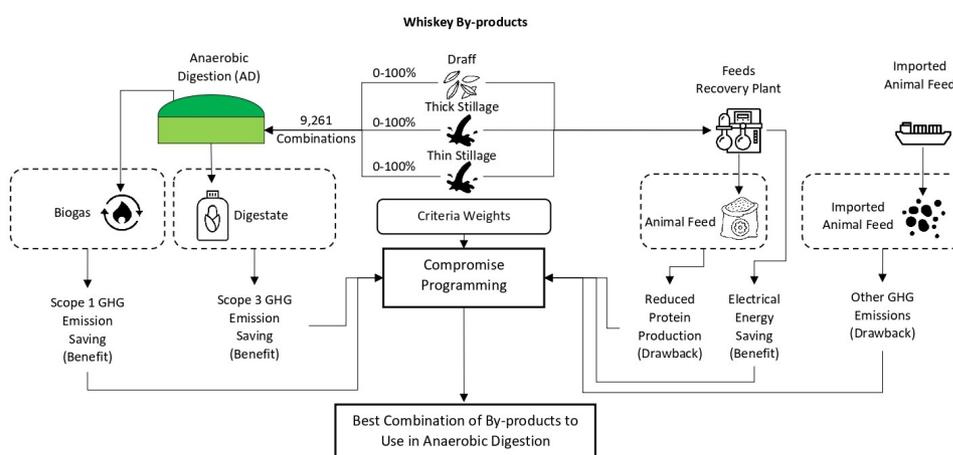
## Distillery decarbonisation and anaerobic digestion: balancing benefits and drawbacks using a compromise programming approach

Richard O'Shea<sup>1,2,\*</sup>, Richen Lin<sup>1,2</sup>, David M. Wall<sup>1,2</sup>, James D. Browne<sup>3</sup>, Jerry D Murphy<sup>1,2</sup><sup>1</sup>MaREI Centre, Environmental Research Institute, University College Cork, Cork, Ireland.<sup>2</sup>Civil, Structural and Environmental Engineering, School of Engineering and Architecture, University College Cork, Cork, Ireland.<sup>3</sup>Irish Distillers Limited, Middleton Distillery, Middleton, Co. Cork, Ireland.

### 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



### ARTICLE INFO

#### Article history:

Received 15 February 2021  
 Received in revised form 22 April 2021  
 Accepted 4 June 2021  
 Available online 1 September 2021

#### Keywords:

Industrial decarbonisation  
 Renewable heat  
 Circular economy  
 Biogas  
 Multi-criteria decision analysis

### 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 9,621 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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\* Corresponding authors at: Tel.: +353 (0)21 490 1971  
 E-mail address: [richard.oshea@ucc.ie](mailto:richard.oshea@ucc.ie)

## Appendix A: Scope 3 GHG Emissions Categories

Scope 3-Category 1 (S3-C1) (Purchased goods and services) includes cradle to gate emissions, this cradle to gate emissions include all emissions that occur in the lifecycle of purchased products up to the point of receipt by the reporting company. S3-C1 emissions are deemed relevant by the distillery. Additionally, these S3-C1 emissions may potentially be influenced by the implementation of an AD project by potentially replacing synthetic fertilizer use in barley cultivation.

Scope 3 Category 2 (S3-C2) emissions from capital goods. Emissions associated with the production of capital goods shall not be amortized, discounted, or depreciated over time, all of the cradle to gate emissions associated with Capital Goods shall be accounted for in the year of acquisition of the capital goods. S3-C2 emissions are deemed relevant by the distillery and will be influenced by the potential construction of an AD plant.

Scope 3 Category 3 (S3-C3) emissions from fuel and energy related emissions not included in Scope 1 and Scope 2 include emissions related to the production of fuels, and energy purchased by the distillery. S3-C3 emissions are deemed relevant by the distillery and will be influenced by the implementation of an AD plant to reduce natural gas consumption.

Scope 3 Category 4 (S3-C4) upstream transportation and distribution includes the emissions from the transportation and distribution of products (excluding fuel and energy products) purchased or acquired by the distillery in vehicles and facilities not owned or operated by the distillery. Other transportation and distribution services purchased by the distillery, such as inbound and outbound logistics are included. S3-C4 emissions are not envisaged to be altered following the implementation of an AD plant as the transportation of digestate (residue remaining after the AD process) will not be paid for by the distillery.

Scope 3 Category 5 (S3-C5) waste generated in operations includes for emissions from third party disposal and treatment of waste that is generated by the distillery. S3-5 emissions are deemed relevant to the distillery in their Scope 3 emission calculations, primarily arising from landfilling of waste and incineration of waste generated in operations. Implementation of an AD project could alter S3-C5 emissions if land spreading of digestate is classified as waste disposal. Inclusion of digestate transportation and application to land in S3-C5 would necessitate that these emissions are not double counted in any other Scope 3 category.

The categories of business travel and employee commuting, and Upstream Leased Assets are not relevant to the current study and will not be influenced by the implementation of an AD plant, further descriptions of these can be found in (WBCSD and WRI, 2013).

Scope 3 Category 8 (S3-C8) upstream leased assets are relevant to the calculation of Scope 3 emissions of the distillery but will not be altered through the implementation of an AD project.

Scope 3 Category 9 (S3-C9) downstream transportation and distribution includes the transportation and distribution of the products sold by the distillery between the distillery and the customer, if the transportation is not paid for by the distillery, and is conducted using vehicles or facilities not controlled or owned by the distillery. S3-C9 emissions are deemed relevant in Scope 3 emissions calculations of the distillery. S3-C9 emissions may be altered by the implementation of an AD plant, specifically in the transportation of feed products from the distillery to customers. Although S3-C9 emissions are not deemed relevant by the distillery, they will be included in this analysis.

Scope 3 Category 10 (S3-C10) Processing of sold products includes emissions associated with the processing of intermediate products sold by the distillery to third parties. S3-C10 emissions are deemed not relevant to total Scope 3 emissions for the distillery and the implementation of an AD plant will not alter S3-C10 emissions.

Scope 3 Category 11 (S3-C11) Use of sold products includes the emissions associated with the use of sold goods. Currently, S3-C11 emissions are deemed not relevant in the calculation of Scope 3 emissions for the distillery. The application (use) of digestate on land following the implementation of an AD plant could potentially result in S3-C11 emissions if the digestate is classified as a product sold to a customer. However, digestate is unlikely to be sold to customers, and as S3-C11 is not deemed relevant to the distillery, they will not be accounted for in this work.

Scope 3 Category 12 (S3-C12) end of life treatment of sold products includes emissions from the waste disposal and treatment of products sold by the distillery. S3-C12 emissions are deemed relevant in the calculation of Scope 3 emissions for the distillery. Implementation of an AD plant could alter S3-C12 if the emissions following the application of digestate on land are classified as an end of life treatment for the digestate, and if the digestate is classified as a product sold by IDL. However, as digestate is not classified as a product in this work S3-C12 emissions will not be assessed.

Scope 3 Category 13 (Downstream Leased Assets), Category 14 (Franchises), and Category 15 (Investments) are not deemed relevant to the distillery Scope 3 calculations and will not be altered if an AD plant is implemented, as such, these Scope 3 categories will not be considered in this work.

In this work, accounting for the impact of an anaerobic digestion system and the implications associated with; the use of biogas, digestate treatment, and feed production, on the GHG emissions arising from the distillery will be split into; Scope 1 emissions, Scope 2 emissions, Scope 3 emissions, and potentially other emissions that do not fall into any of the above scopes.

**Table A-1.** Scope 3 Categories. AD: Anaerobic Digestion.

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
12	End of life treatment of sold products	Y	N
13	Downstream leased assets	N	N
14	Franchises	N	N
15	Investments	N	N

## References

- [1] WBCSD and WRI, 2013. Corporate Value Chain (Scope 3) Accounting and Reporting Standard.

## Appendix B: Thermal Energy Demand of AD Plant

Nomenclature	Description	Unit
$V$	Anaerobic digester volume	$m^3$
$r$	Anaerobic digester radius	m
$h$	Anaerobic digester height	m
$P_{Fabric}$	Fabric heat loss	W
$U_{Wall}$	Tank wall U value	$W/m^2/K$
$A_{Wall}$	Tank wall area	$m^2$
$T_{AD}$	Anaerobic digestion temperature	$^{\circ}C$
$T_{Out}$	External temperature	$^{\circ}C$
$U_{Top}$	Tank top U value	$W/m^2/K$
$A_{Top}$	Tank top area	$m^2$
$U_{Base}$	Tank base U value	$W/m^2/K$
$A_{Base}$	Tank base area	$m^2$
$R_{internal}$	Internal surface heat transfer resistance	$m^2K/W$
$d_{concrete}$	Concrete thickness	m
$\lambda_{concrete}$	Concrete conductivity	$W/(m.K)$
$d_{insulation}$	Insulation thickness	m
$\lambda_{insulation}$	Insulation conductivity	$W/(m.K)$
$R_{external}$	External surface heat transfer resistance	$m^2K/W$
$B'$		
$d_{effective\ floor}$	Effective floor thickness	m
$d_{wall}$	Wall thickness	m
$\lambda_{soil}$	Soil conductivity	$W/(m.K)$
$R_{concrete}$	Concrete heat transfer resistance	$m^2K/W$
$R_{insulation}$	Insulation heat transfer resistance	$m^2K/W$
$U_{floor}$	Floor U value	$W/m^2/K$
$V_{AD\ Daily}$	Anaerobic digester tank volume based on daily available feed	$m^3$
$m_{Feed\ Daily}$	Mass of feedstock added per day	kg
$X_{VS\ Feed}$	Volatile solids content of feedstock	%
$OLR$	Organic loading rate	$kgVS/m^3/day$
$N_{AD}$	Number of anaerobic digesters	No.
$V_{Biogas\ STP}$	Daily volumetric biogas production at standard temperature and pressure	$m^3/day$
$S_{Thin\ AD}$	Share of thin stillage used in an anaerobic digester	%
$m_{Thin}$	Mass of thin stillage available	kg
$X_{VS\ Thin}$	Volatile solids content of thin stillage	%
$BMP_{Thin}$	Biochemical methane potential of thick stillage	$LCH_4/kgVS$
$S_{Thick\ AD}$	Share of thick stillage used in an anaerobic digester	%
$m_{Thick}$	Mass of thick stillage available	kg
$X_{VS\ Thick}$	Volatile solids content of thick stillage	%
$BMP_{Thick}$	Biochemical methane potential of thick stillage	$LCH_4/kgVS$
$S_{Draff\ AD}$	Share of draff stillage used in an anaerobic digester	$LCH_4/kgVS$
$m_{Draff}$	Mass of draff stillage available	%
$X_{VS\ Draff}$	Volatile solids content of draff stillage	kg
$BMP_{Draff}$	Biochemical methane potential of draff stillage	%
$V_{Biogas\ Operational}$	Volume of biogas produced at operational conditions	
$P_{STP}$	Standard pressure	$^{\circ}C$
$T_{STP}$	Standard Temperature	kPa
$T_{Operational}$	Anaerobic digester operational temperature	$^{\circ}C$
$P_{Operational}$	Anaerobic digester operational pressure	kPa
$p_{sat}$	Saturation pressure of water vapour in biogas	kPa
$e$	Exponential	
$T$	Temperature of biogas	K
$m_{water\ Biogas}$	Mass of water vapour contained in biogas	kg
$V_{Biogas\ Daily}$	Daily volume of biogas produced	$m^3$

Nomenclature	Description	Unit
$R_{water}$	Universal gas constant for water vapour	kPa.m <sup>3</sup> /kg.K
$E_{WaterEvap}$	Energy required to evaporate water	kJ
$h_{fg@T_{AD}}$	Specific enthalpy of water evaporation	kJ/kg
$E_{heatfeed}$	Energy required to heat incoming feed to AD plant	kJ
$m_{feed}$	Mass of feedstock added.	kg
$cp_{H_2O@T_{Feed}}$	Specific heat capacity of water	kJ/kg/K
$T_{Feed}$	Feedstock temperature	°C
$E_{biogasNet}$	Net biogas energy production	kJ
$E_{biogasGross}$	Gross biogas energy production	kJ

Fabric heat loss was calculated for an individual tank initially, the volume of each AD reactor tank ( $V$ ) was taken to be 5000 m<sup>3</sup> on the advice of IDL staff. Reactor tanks were assumed to be cylindrical in shape. In order to estimate the surface area of the reactor tanks ( $A$ ), the tank radius ( $r$ ) and height ( $h$ ) were calculated so as to minimize the surface area to volume ratio in an effort to minimize heat loss using Equation B-1.

#### Equation B-1

$$\begin{aligned}
 V &= \pi r^2 h \\
 A &= 2\pi r^2 + 2\pi r h \\
 h &= \frac{V}{\pi r^2} \\
 A &= 2\pi r^2 + \frac{2V}{r} \\
 \frac{d}{dr}(A) &= 4\pi r - \frac{2V}{r^2} = 0 \\
 4\pi r^3 - 2V &= 0 \\
 r &= \left(\frac{2V}{4\pi}\right)^{\frac{1}{3}}
 \end{aligned}$$

The base and wall of each reactor were assumed to be constructed of concrete 300 mm thick and insulation 150 mm thick, the top of each reactor was assumed to be constructed of insulation only with a thickness of 200 mm, see Table B-1.

**Table B-1.** Thermal Properties of AD Tank Structure.

Element	Concrete	Concrete	Insulation	Insulation
	Thickness (m)	Thermal Conductivity (W/(m.K))	Thickness (m)	Thermal Conductivity (W/(m.K))
Wall	0.3	1.33	0.15	0.03 (Jain, 2013)
Base	0.3	1.33	0.15	0.03 (Jain, 2013)
Top			0.15	0.03 (Jain, 2013)

Thermal energy lost through the reactor fabric ( $P_{Fabric}$ ) was calculated based on the temperature of the AD tanks ( $T_{AD}$ ), the external air temperature ( $T_{Out}$ ), the  $U_{value}$  of the tank wall, the tank wall surface area ( $A_{Wall}$ ), the area of the tank top ( $A_{Top}$ ) and its U value ( $U_{Top}$ ), and the area of the tank base ( $A_{Base}$ ) along with the base U value ( $U_{Base}$ ) using Equation B-2:

#### Equation B-2

$$P_{Fabric} = U_{Wall}A_{Wall}(T_{AD} - T_{Out}) + U_{Top}A_{Top}(T_{AD} - T_{Out}) + U_{Base}A_{Base}(T_{AD} - T_{Out})$$

The U value for the reactor wall ( $U_{Wall}$ ) and top ( $U_{Top}$ ) were calculated using based on the thickness of the concrete ( $d_{concrete}$ ) Equations B-3 and B-4.

#### Equation B-3

$$U_{Wall} = \frac{1}{R_{internal} + \frac{d_{concrete}}{\lambda_{concrete}} + \frac{d_{insulation}}{\lambda_{insulation}} + R_{external}}$$

#### Equation B-4

$$U_{Top} = \frac{1}{R_{internal} + \frac{d_{insulation}}{\lambda_{insulation}} + R_{external}}$$

The values of  $R_{internal}$  and  $R_{external}$  refer to the surface heat transfer resistances, these were taken to be 0.17 m<sup>2</sup>K/W and 0.04 m<sup>2</sup>K/W as per CIBSE Guide A Section

## 3.5.2.

The U value calculation for the reactor tank base is based on the methodology used for ground floors in contact with the earth, outlined in CIBSE Guide A, section 3.5.2, as follows.

$$B' = \frac{A_{floor}}{0.5 * p_{floor}} = \frac{\pi r^2}{0.5 * 2 * \pi * (r + d_{wall})}$$

$$d_{effective_{floor}} = d_{wall} + \lambda_{soil}(R_{internal} + R_{concrete} + R_{insulation} + R_{external})$$

$$\text{if } d_{effective_{floor}} < B'$$

$$U_{floor} = 2 \frac{\lambda_{soil}}{\pi B' + d_{effective_{floor}}} \ln \left( \left( \frac{\pi B'}{d_{effective_{floor}}} \right) + 1 \right)$$

$$\text{if } d_{effective_{floor}} \geq B'$$

$$U_{floor} = \frac{\lambda_{soil}}{0.457B' + d_{effective_{wall}}}$$

Soil thermal conductivity was assumed to be 2 W/(m.K) as per Table 3.14, section 3.5.2, CIBSE Guide A.

Thermal energy loss through the reactor tank fabric was calculated for each hour, for each day in a year, based on the minimum external air temperatures ( $T_{out}$ ) recorded at Cork Airport, for each hour over the period 1988-2017 to give a conservative estimate of fabric heat loss.

The total fabric thermal energy loss of all AD tanks requires an estimate of the total number of AD tank to be built. The number of AD tanks was estimated by specifying a given organic loading rate (OLR) in kgVS/m<sup>3</sup>/day for the AD tanks. Based on the mass of feedstock (draff, thin stillage, and thick stillage) available per day, the total volume of all AD tanks can be calculated for each day (Eq. B-5):

**Equation B-5**

$$V_{ADdaily} = \frac{(m_{Feeddaily} * \frac{X_{VSFeed}}{100})}{OLR}$$

As the amount of feed available per day fluctuates, the maximum daily volume required was chosen in order to give a conservative estimate of the total AD tank volume required. The total number of AD tanks required ( $N_{AD}$ ) was then calculated by dividing the total tank volume required by the volume of a single AD tank (5,000 m<sup>3</sup>).

Thermal energy is also required to evaporate water within the AD reactor tanks as the biogas produced is saturated with water vapour. The total daily production of biogas ( $V_{Biogas_{STP}}$ ) at STP (0°C, 101.325kPa) was calculated based on the BMP ( $L_{CH_4}$ /kgVS) of each feedstock type, an assumed methane concentration of 55% vol, and the total mass of volatile solids of each feedstock fed to the AD reactor in a day as per Equation B-6.

**Equation B-6**

$$V_{Biogas_{STP}} = \frac{(S_{ThinAD} m_{Thin} X_{VS_{Thin}} BMP_{Thin} + S_{ThickAD} m_{Thick} X_{VS_{Thick}} BMP_{Thick} + S_{DraffAD} m_{Draff} X_{VS_{Draff}} BMP_{Draff})}{1000 * 0.55}$$

The volume of biogas at an operating condition ( $V_{Biogas_{Operational}}$ ) of 37 °C and 2 kPa above atmospheric pressure (103.325 kPa) was then calculated (Eq. B-7):

**Equation B-7**

$$V_{Biogas_{Operational}} = \frac{P_{STP} V_{Biogas_{STP}}}{T_{STP}} * \frac{T_{Operational}}{P_{Operational}}$$

As the biogas produced in the reactor is a saturated mixture of biogas and water vapour, the saturation pressure ( $p_{sat}$ ) of the water vapour was calculated as per ASHRAE Fundamentals, Section 1.8, Equation 6, using the temperature of the digester (K) as outlined in Equation B-8:

**Equation B-8**

$$p_{sat} = e^{\left(\frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln(T)\right)}$$

The values of coefficients used in Equation B-8 are shown in Table B-2.

**Table B-2.** Coefficients used in saturation vapour pressure of water.

C <sub>1</sub>	-5.8002206E+03
C <sub>2</sub>	1.3914993E+00
C <sub>3</sub>	-4.8640239E-02
C <sub>4</sub>	4.1764768E-05
C <sub>5</sub>	-1.4452093E-08
C <sub>6</sub>	6.5459673E+00

The total mass of water vapour contained in the biogas produced per day ( $m_{Water_{biogas}}$ ) was calculated using **Equation B-9** under the assumption that water vapour behaves as an ideal gas:

**Equation B-9**

$$m_{Water_{Biogas}} = p_{sat} \cdot \frac{V_{Biogas_{Daily}}}{R_{water} * (T_{AD} + 273.15)} \quad (kg)$$

Within **Equation B-9**,  $R_{water}$  is the universal gas constant for water (0.461 kPa.m<sup>3</sup>/kg.K).

The energy required to evaporate the water contained in the saturate biogas was calculated using the specific enthalpy of water evaporation at the AD reactor temperature as per **Equation B-10**. Values for the specific enthalpy of water evaporation ( $E_{Water_{Evap}}$ ) were sourced from ASHRAE Fundamentals 2017.

**Equation B-10**

$$E_{Water_{Evap}} = m_{water_{biogas}} * h_{fg@T_{AD}} \quad (kJ)$$

The thermal energy required to heat the incoming feed ( $E_{Heat_{Feed}}$ ) was calculated for each feed stream (Draff, thin stillage, and thick stillage) individually using **Equation B-11**:

**Equation B-11**

$$E_{heat_{feed}} = m_{feed} * cp_{H_2O@T_{Feed}} * (T_{AD} - T_{Feed}) \quad (kJ)$$

The specific heat capacity of each feed stream was assumed to be that of water at the given temperature of the feed stream, sourced from CIBSE Guide: A Concise Guide to Building Services Engineering. The temperature of each feed stream was based on data sourced from the distillery SCADA system. As an initial estimate, the temperature of draff was assumed to be 78 °C, thin stillage was assumed to be at a temperature of 80 °C, and thick stillage was assumed to be at a temperature of 90 °C.

The total annual thermal energy demand of the AD plant was assumed to be met through the combustion of some of the biogas produced, the boiler efficiency was assumed to be 80%. Based on this, the total annual net energy production of the AD plant ( $E_{biogas_{NET}}$ ) was calculated (**Eq. B-12**).

**Equation B-12**

$$E_{biogas_{Net}} = E_{biogas_{Gross}} - \frac{N_{AD} * E_{Fabric} + E_{Water_{Evap}} + E_{Heat_{Feed}}}{0.8}$$

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**Appendix C: Fugitive Methane Emissions****Table C-1.** Fugitive Methane Emissions.

Fugitive methane emissions (% Total CH <sub>4</sub> Production)	Digestate Storage	Source
2.9	Open	(Delre et al., 2014)
3.1	Not Specified	(Flesch et al., 2011)
1.8	Not Specified	(Dieterich et al., 2014)
1.0	Not Specified	(Adams and McManus, 2019)
3.8	Not Specified	(Groth et al., 2015)
3.4	Not Specified	(Hrad et al., 2015)
1.4	Closed	(Fredenslund et al., 2018)
1.9	Closed	(Fredenslund et al., 2018)
8.3	Open	(Fredenslund et al., 2018)
3.3	Closed	(Fredenslund et al., 2018)
1	Not Specified	(Poeschl et al., 2012)
0.4	Closed	(Scheutz and Fredenslund, 2019)
1.8	Closed	(Scheutz and Fredenslund, 2019)
2.6	Closed	(Scheutz and Fredenslund, 2019)
0.7	Closed	(Scheutz and Fredenslund, 2019)
0.6	Closed	(Scheutz and Fredenslund, 2019)
2.6	Closed	(Scheutz and Fredenslund, 2019)
1.6	Closed	(Scheutz and Fredenslund, 2019)
0.6	Closed	(Scheutz and Fredenslund, 2019)
4.5	Closed	(Scheutz and Fredenslund, 2019)
2.6	Closed	(Scheutz and Fredenslund, 2019)
8.6	Closed	(Scheutz and Fredenslund, 2019)
2.1	Open	(Scheutz and Fredenslund, 2019)
2.6	Open	(Scheutz and Fredenslund, 2019)
3.1	Not Specified	(Mathieu Dumont et al., 2013)

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## Appendix D: Land Bank Calculation

Nomenclature	Description	Unit
$m_{N_{EDj}}$	Mass of nitrogen (N) application allowed in electoral division (ED) “j”	kg
$m_{P_{EDj}}$	Mass of phosphorous (P) application allowed in electoral division (ED) “j”	kg
$X_{FRV_P}$	Fertiliser replacement value of phosphorous (P)	%
$X_{FRV_N}$	Fertiliser replacement value of nitrogen (N)	%
$m_{digestate}$	Mass of digestate produced	kg
$X_{N_{digestate}}$	Nitrogen (N) content of digestate	%
$X_{P_{digestate}}$	Phosphorous (P) content of digestate	%
$m_{digestate,j}$	Mass of digestate sent to electoral division (ED) “j”	kg
$d_j$	Distance from anaerobic digestion plant to electoral division (ED) “j”	km
$m_{CO_2_{digestate,transport}}$	Mass of CO <sub>2</sub> eq emissions associated with digestate transportation	kg

The total land area required for the spreading of digestate was calculated in accordance with S.I. 605 of 2017 (Government of Ireland, 2017) using the methodology outlined in (Department of Agriculture Food and the Marine and Department of Housing Planning and Local Government, 2017) 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 (Central Statistics Office, 2012).

The maximum allowable mass of biologically available phosphorous to be spread on arable land is based on a soil P index of 3 for as per S.I 605 of 2017 (Government of Ireland, 2017) 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 (Government of Ireland, 2017).

The total amount of nitrogen ( $m_{N_{EDj}}$ ) and phosphorous ( $m_{P_{EDj}}$ ) that can be spread on land within each electoral division (j) is found by the 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 ( $X_{FRV_P}$ ) was taken to be 100% (Government of Ireland, 2017). No default availability of N is available for digestate in Ireland, values of bioavailable N content in digestate (also termed fertiliser replacement value  $X_{FRV_N}$ ) found in the literature range from 24-90% of N content in digestate (Table D-1). The average fertiliser replacement value of digestate found in literature is 61.7%, as no definitive values for the fertilizer replacement value of digestate ( $X_{FRV_N}$ ) exist for Irish conditions a value of 60% based on values assessed in literature will be used.

Knowing the mass of digestate produced ( $m_{digestate}$ ) and nitrogen ( $X_{N_{digestate}}$ ) and phosphorous ( $X_{P_{digestate}}$ ) 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 ( $m_{digestate,j}$ ) to be hauled to each ED (Eq. D-1). 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 ( $d_j$ ) 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 D-1

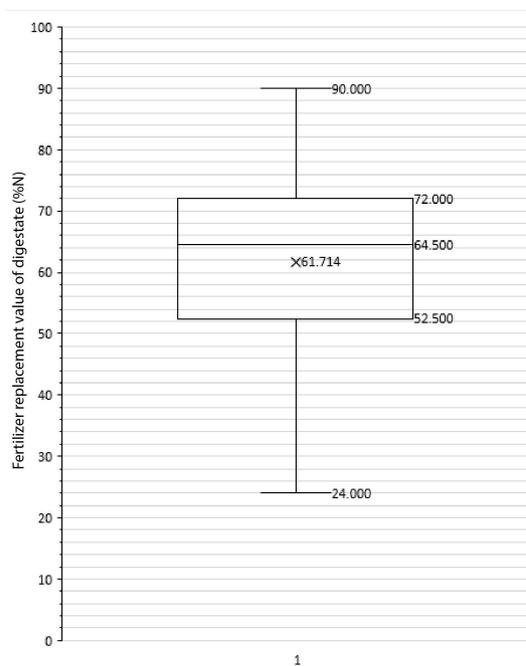
$$\min : t.km_{digestate} = \sum_{j=1}^n m_{digestate,j} \cdot d_j$$

$$s. t. \begin{cases} \sum_{j=1}^n m_{digestate,j} = m_{digestate_{total}} \\ \sum_{j=1}^n m_{digestate,j} \cdot X_{N_{digestate}} = m_{N_{digestate}} \\ \sum_{j=1}^n m_{digestate,j} \cdot X_{P_{digestate}} = m_{P_{digestate}} \\ m_{digestate,j} \cdot X_{N_{digestate}} \leq m_{N_{EDj}} \\ m_{digestate,j} \cdot X_{P_{digestate}} \leq m_{P_{EDj}} \\ m_{digestate,j} \geq 0 \end{cases}$$

The CO<sub>2</sub>eq emissions associated with the transportation of digestate ( $m_{CO_2_{digestate,transport}}$ ) to each ED was calculated 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.

**Table D-1.** Fertiliser Replacement Value of Digestate.

Material	Fertilizer Replacement Value of N (%)	Source
Digestate	65	(Leinonen et al., 2018)
Cattle Slurry	40	(Wall and Plunkett, 2016)
Digestate	80	(Dieterich et al., 2014)
Digestate	80	(Lukehurst et al., 2010)
Digestate	65	(De Vries et al., 2012b)
Digestate	75	(De Vries et al., 2012b)
Digestate	62	(De Vries et al., 2012a)
Digestate	45	(De Vries et al., 2012a)
Digestate	59	(Rigby and Smith, 2014)
Digestate	76	(Rigby and Smith, 2014)
Digestate	68	(Rigby and Smith, 2014)
Digestate	85	(Rigby and Smith, 2014)
Digestate	60	(Baral et al., 2017)
Digestate	64	(I. Sigurnjak et al., 2017)
Digestate	71	(I. Sigurnjak et al., 2017)
Digestate	69	(Ivona Sigurnjak et al., 2017)
Digestate	55	(De Notaris et al., 2018)
Digestate	41	(De Notaris et al., 2018)
Digestate	24	(De Notaris et al., 2018)
Digestate	86	(De Notaris et al., 2018)
Digestate	65	(De Notaris et al., 2018)
Digestate	39	(De Notaris et al., 2018)
Digestate	65	(De Notaris et al., 2018)
Digestate	40	(Cavalli et al., 2016)
Digestate	37	(Cavalli et al., 2016)
Digestate	62	(Cavalli et al., 2016)
Digestate	60	(Jensen, 2013)
Digestate	90	(Jensen, 2013)

**Figure D-1.** Fertilizer Replacement Value of Digestate.

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## Appendix E: Replacement of Synthetic Fertiliser

Nomenclature	Description	Unit
$mN_{CANReplaced}$	Mass of nitrogen (N) contained in calcium ammonia nitrate (CAN) which is replaced by digestate	kg
$mN_{Digestate}$	Mass of nitrogen (N) contained in digestate	Kg
$X_{NFRV}$	Nitrogen (N) fertiliser replacement value of digestate	%
$SE_{CANCO_2}$	Specific CO <sub>2</sub> eq emissions associated with the production of calcium ammonia nitrate (CAN)	kgCO <sub>2</sub> eq/kgN
$mP_{TripleSuperReplaced}$	Mass of phosphorous contained in triple super phosphate that can be replaced by digestate	kg
$mP_{Digestate}$	Mass of phosphorous contained in digestate	kg
$SE_{TripleSuperCO_2}$	Specific CO <sub>2</sub> eq emissions associated with the production of triple super phosphate	kgCO <sub>2</sub> eq/kgP <sub>2</sub> O <sub>5</sub>
$SE_{P_{CO_2}}$	Specific CO <sub>2</sub> eq emissions associated with the production of synthetic phosphorous	kgCO <sub>2</sub> eq/kgP

The total mass of nitrogen contained in CAN could be replaced by using digestate ( $mN_{CANReplaced}$ ) was calculated according to Equation E-1:

## Equation E-1

$$mN_{CANReplaced} = mN_{Digestate} * X_{NFRV}$$

The mass of CAN replaced is calculated based on the nitrogen content of CAN of 27.5%. The CAN used in Ireland is assumed to be produced in Europe, the GHG emissions associated with the production of CAN in Europe ( $SE_{CANCO_2}$ ) was taken to be 8.03 kgCO<sub>2</sub>eq/kgN (Kool et al., 2012). The emissions of GHGs associated with the production of CAN used in other literature are outlined in Table E-1.

The main source of phosphorous in Ireland is 18-6-12 (N-P-K) fertiliser (Dillon et al., 2018). The phosphorous is assumed to be present in the form of triple super phosphate. The total mass of phosphorous that can be replaced by digestate produced in an AD plant processing whiskey by-product was calculated assuming that 100% of the phosphorous present in the digestate was bioavailable, as outlined in S.I 605 (Government of Ireland, 2017). The total mass of synthetic phosphorous that can be replaced by digestate ( $mP_{Triple SuperReplaced}$ ) from the AD plant was calculated as per Equation E-2:

## Equation E-2

$$mP_{Triple SuperReplaced} = mP_{Digestate}$$

The triple super phosphate used in Ireland was also assumed to be sourced from mainland Europe, GHG emissions associated with the production of triple super phosphorous ( $SE_{Triple SuperCO_2}$ ) were found to be 0.36 kgCO<sub>2</sub>eq/kgP<sub>2</sub>O<sub>5</sub> (Kool et al., 2012). Conversion of 1 kgP<sub>2</sub>O<sub>5</sub> to 1 kgP was done through multiplication by 0.436 (Wall and Plunkett, 2016), thus the GHG emissions associated with the production of synthetic phosphorous ( $SE_{P_{CO_2}}$ ) were 0.15696 kgCO<sub>2</sub>eq/kgP. Alternative GHG emissions associated with the production of triple super phosphate are shown in Table E-1.

Table E-1. GHG emissions associated with synthetic fertiliser production.

Fertiliser	Unit	CO <sub>2</sub> (kg)	CH <sub>4</sub> (kg)	N <sub>2</sub> O (kg)	CO <sub>2</sub> eq (kg)	Reference
CAN	kgN	2.66	0.00174	0.0134	6.697	(O'Brien et al., 2012)
CAN	kgN	-	-	-	7.11	(Donal O'Brien et al., 2014)
CAN	kgN	-	-	-	5.164	(D. O'Brien et al., 2014)
Triple Superphosphate	kgP <sub>2</sub> O <sub>5</sub>	1.67	0.00245	0.00003	1.740	(O'Brien et al., 2012)
Triple Superphosphate	kgP <sub>2</sub> O <sub>5</sub>	-	-	-	1.86	(Donal O'Brien et al., 2014)
Triple Superphosphate	kgP <sub>2</sub> O <sub>5</sub>	-	-	-	1.926	(D. O'Brien et al., 2014)

In the case of synthetic fertiliser, transportation from production facilities in mainland Europe was assumed to consist of the following stages; transportation from a production facility to a port, sea transport from a port to Ringaskiddy Port Co. Cork (Ireland), land transportation within Ireland. Synthetic fertilizers were assumed to be produced in The Netherlands, internal transportation within The Netherlands is outlined in Table E-2, consisting of 56km of road transportation, 2 km of rail transportation, and 19 km of maritime transportation.

Table E-2. Transportation distances for fertiliser.

Origin	Destination	Truck (km)	Train (km)	Inland Ship (km)	Maritime Ship (km)	Reference
NL	NL	56	2	19	-	(Durlinger et al., 2017)

Synthetic fertilizers are then assumed to be transported to Ringaskiddy by bulk carriers, the sea voyage was assumed to be over a distance of 1163 km. The specific CO<sub>2</sub>eq emissions of each transportation phase in terms of kgCO<sub>2</sub>eq/t.km are; 0.1878 kgCO<sub>2</sub>eq/t.km for road transportation, 0.0304 kgCO<sub>2</sub>eq/t.km for rail transportation, 0.0188 kgCO<sub>2</sub>eq/t.km for water-based transportation with the Netherlands, and 0.00544 kgCO<sub>2</sub>eq for maritime transportation between The Netherlands and Ireland.

Average transportation distance of goods when carried as road freight within Ireland was taken to be 56 km in 2017 based on data from (Durlinger et al., 2017).

**References**

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## Appendix F: GHG Emissions Associated with Fertiliser Replacement and Digestate Use

Nomenclature	Description	Unit
$m_{N_2O-N_{FertiliserDirect}}$	Mass of direct N <sub>2</sub> O-N emissions from synthetic fertiliser application	kgN <sub>2</sub> O-N
$m_{N_{FertiliserSynthetic}}$	Mass of nitrogen from synthetic fertiliser applied to land	kg
$m_{N_{FertiliserOrganic}}$	Mass of nitrogen from organic fertiliser applied to land	kg
$EF_{1Synthetic}$	Direct N <sub>2</sub> O-N emission factor for synthetic nitrogen fertiliser	kgN <sub>2</sub> O-N/kgN
$EF_{1Organic}$	Direct N <sub>2</sub> O-N emission factor for organic nitrogen fertiliser	kgN <sub>2</sub> O-N/kgN
$m_{N_{Volatilised}}$	Mass of nitrogen applied which is volatilised	kgN
$Frac_{GASF}$	Volatilisation factor for nitrogen from synthetic fertiliser	kgN/kgN
$Frac_{GASO}$	Volatilisation factor for nitrogen from organic fertiliser	kgN/kgN
$m_{N_2O-N_{FertiliserIndirectVolatilised}}$	Mass of indirect N <sub>2</sub> O-N emissions form volatilised nitrogen	kgN <sub>2</sub> O-N
$EF_4$	Emission factor for the conversion of volatilised N to N <sub>2</sub> O-N	kgN <sub>2</sub> O-N/kgN
$m_{N_{LeachFertiliser}}$	Amount of nitrogen fertiliser applied to land that is lost via leaving and run off.	kgN
$Frac_{Leach}$	The fraction of applied nitrogen that is lost via leaching and run off.	kgN/kgN
$m_{N_2O-N_{FertiliserIndirectLeach}}$	Mass of indirect N <sub>2</sub> O-N emissions associated with nitrogen	kgN <sub>2</sub> O-N
$EF_5$	Emission factor for N <sub>2</sub> O-N arising from leached nitrogen	gN <sub>2</sub> O-N/kgN
$m_{N_2O-N}$	Mass of N <sub>2</sub> O expressed as the mass of nitrogen	kgN
$m_{N_2O}$	Mass of N <sub>2</sub> O	kgN <sub>2</sub> O
$X_{N_{Digestate}}$	Nitrogen content of digestate	kgN/kgwwt
$m_{DigestateTotal}$	Total mass of digestate	kgwwt
$m_{N_{Replacement}}$	Mass of nitrogen in synthetic fertilizer replaced by digestate	kgN
$X_{FRV_N}$	Nitrogen (N) fertiliser replacement value of digestate	%
$X_{N_{CAN}}$	Nitrogen (N) content of calcium ammonia nitrate (CAN) fertiliser	%
$m_{CAN_{Total}}$	Total mass of calcium ammonia nitrate (CAN) replaced	kg
$m_{CO_2_{CAN_{Production}}}$	Mass of CO <sub>2</sub> eq from CAN production	kgCO <sub>2</sub> eq
$m_{CO_2_{CAN_{Road(NL)}}$	Mass of CO <sub>2</sub> eq from CAN transportation via road in the Netherlands	kgCO <sub>2</sub> eq
$d_{road(NL)}$	Road transportation in the Netherlands	km
$m_{CO_2_{CAN_{Rail(NL)}}$	Mass of CO <sub>2</sub> eq from CAN transportation via rail in the Netherlands	kgCO <sub>2</sub> eq
$d_{rail(NL)}$	Rail transportation in the Netherlands	km
$m_{CO_2_{CAN_{Barge(NL)}}$	Mass of CO <sub>2</sub> eq from CAN transportation via barge in the Netherlands	kgCO <sub>2</sub> eq
$d_{barge(NL)}$	Barge transportation in the Netherlands	km
$m_{CO_2_{CAN_{Sea(NL)}}$	Mass of CO <sub>2</sub> eq from CAN transportation via sea from the Netherlands	kgCO <sub>2</sub> eq
$d_{sea(NL)}$	Sea transportation from the Netherlands	km
$m_{CO_2_{CAN_{Road(IRL)}}$	Mass of CO <sub>2</sub> eq from CAN transportation via road in Ireland	kgCO <sub>2</sub> eq
$d_{road(IRL)}$	Road transportation in Ireland	km
$m_{CO_2_{FertiliserSpreading}}$	Mass of CO <sub>2</sub> eq from CAN spreading	kgCO <sub>2</sub> eq
$GW_{P_{N_2O}}$	Global warming potential of N <sub>2</sub> O	kgCO <sub>2</sub> eq/kgN <sub>2</sub> O
$X_{P_{Digestate}}$	Phosphorous (P) content of digestate	%
$X_{FRV_P}$	Fertiliser replacement value of phosphorous (P)	%
$m_{P_{Replacement}}$	Mass of phosphorous (P) replaced	kgP
$m_{P_2O_5_{Replacement}}$	Mass of P <sub>2</sub> O <sub>5</sub> replaced	kgP <sub>2</sub> O <sub>5</sub>
$m_{TSP_{Replaced}}$	Mass of triple super phosphate (TSP) replaced	kg
$m_{CO_2_{PhosphorousProduction}}$	Mass of CO <sub>2</sub> eq from phosphorous production	kgCO <sub>2</sub> eq
$m_{CO_2_{TSP_{Road(NL)}}$	Mass of CO <sub>2</sub> eq from triple super phosphate from road transportation in the Netherlands	kgCO <sub>2</sub> eq
$m_{CO_2_{TSP_{Rail(NL)}}$	Mass of CO <sub>2</sub> eq from triple super phosphate from rail transportation in the Netherlands	kgCO <sub>2</sub> eq
$m_{CO_2_{TSP_{Barge(NL)}}$	Mass of CO <sub>2</sub> eq from triple super phosphate from barge transportation in the Netherlands	kgCO <sub>2</sub> eq

Nomenclature	Description	Unit
$mCO_{2TSP_{Sea}}(NL)$	Mass of CO <sub>2</sub> eq from triple super phosphate from sea transportation from the Netherlands	kgCO <sub>2</sub> eq
$mCO_{2TSP_{Road}}(IRL)$	Mass of CO <sub>2</sub> eq from triple super phosphate from road transportation in Ireland	kgCO <sub>2</sub> eq
$mCO_{2DigestateUse}$	Mass of CO <sub>2</sub> eq arising from digestate use	kgCO <sub>2</sub> eq
$mCO_{2DigestateTransport}$	Mass of CO <sub>2</sub> eq arising from digestate transportation	kgCO <sub>2</sub> eq
$mCO_{2DigestateSpreading}$	Mass of CO <sub>2</sub> eq arising from digestate spreading	kgCO <sub>2</sub> eq
$mCO_{2DigestateDirect}$	Mass of CO <sub>2</sub> eq from direct N <sub>2</sub> O emissions associated with digestate use	kgCO <sub>2</sub> eq
$mCO_{2DigestateIndirectVolatilisation}$	Mass of CO <sub>2</sub> eq from indirect N <sub>2</sub> O emissions from volatilization associated with digestate use	kgCO <sub>2</sub> eq
$mCO_{2DigestateIndirectLeaching}$	Mass of CO <sub>2</sub> eq from indirect N <sub>2</sub> O emissions from leaching associated with digestate use	kgCO <sub>2</sub> eq

Direct N<sub>2</sub>O emissions arise from, amongst other sources, the application of synthetic or organic fertiliser on managed agricultural soils. The total direct N<sub>2</sub>O-N emission from agricultural land ( $m_{N_2O-N_{FertiliserDirect}}$ ) following the application of a mass of synthetic nitrogen fertiliser ( $m_{N_{FertiliserSynthetic}}$ ) and/or organic nitrogen fertiliser ( $m_{N_{FertiliserOrganic}}$ ) application is calculated as per **Equation F-1**:

**Equation F-1**

$$m_{N_2O-N_{FertiliserDirect}} = (m_{N_{FertiliserSynthetic}} \cdot EF_{1Synthetic} + m_{N_{FertiliserOrganic}} \cdot EF_{1Organic})$$

The specific emission factor for N<sub>2</sub>O-N for synthetic fertiliser ( $EF_{1Synthetic}$ ) is taken to be 0.014 kgN<sub>2</sub>O-N/kgN<sub>Applied</sub> (Duffy et al., 2019) when calculating N<sub>2</sub>O-N emissions from the application of Calcium Ammonium Nitrate (CAN) as it is the predominant synthetic nitrogen fertiliser used in Ireland (Dillon et al., 2018). The specific emission factor for N<sub>2</sub>O-N for organic fertiliser ( $EF_{1Organic}$ ) is taken to be 0.006 kgN<sub>2</sub>O-N/kgN<sub>Applied</sub> based on updates to the 2006 IPCC methodology published in 2019. For the purpose of this calculation, organic fertiliser is digestate produced in the AD plant that is spread on agricultural land.

Indirect N<sub>2</sub>O emissions arise from the volatilisation of applied N to the air and the subsequent deposition of this volatilised N, along with N that is leached from the ground following fertiliser application. Indirect N<sub>2</sub>O emissions are calculated in Ireland using the IPCC Tier 1 methodology (Duffy et al., 2019). The mass of volatilised N ( $m_{N_{Volatilised}}$ ) following the application of nitrogen fertiliser to land is calculated according to **Equation F-2**:

**Equation F-2**

$$m_{N_{Volatilised}} = (m_{N_{FertiliserSynthetic}} \cdot Frac_{GASF} + m_{N_{FertiliserOrganic}} \cdot Frac_{GASO})$$

The volatilisation factor for synthetic fertiliser ( $Frac_{GASF}$ ) in Ireland is 0.025 kgN<sub>Volatilised</sub>/kgN<sub>Applied</sub> (Duffy et al., 2019). In the calculations done by (Duffy et al., 2019) for Ireland, indirect N<sub>2</sub>O emissions from the application of organic fertiliser are assumed to arise from the application of animal manure and the application of sewage sludge. There are different volatilisation factors used in Ireland for manure ( $Frac_{GASO}$ ) (0.085 kgN<sub>Volatilised</sub>/kgN<sub>Applied</sub>) and sewage sludge (0.13 kgN<sub>Volatilised</sub>/kgN<sub>Applied</sub>), the value of 0.085 kgN<sub>Volatilised</sub>/kgN<sub>Applied</sub> will be used for digestate in this analysis. The emissions of N<sub>2</sub>O-N associated with volatilised N from fertiliser application ( $m_{N_2O-N_{FertiliserIndirectVolatilised}}$ ) is calculated as per **Equation F-3**:

**Equation F-3**

$$m_{N_2O-N_{FertiliserIndirectVolatilised}} = m_{N_{Volatilised}} \cdot EF_4$$

The emission factor for the conversion of volatilised N to N<sub>2</sub>O-N ( $EF_4$ ) is taken to be 0.01 kgN<sub>2</sub>O-N/kgN<sub>Volatilised</sub> (Duffy et al., 2019).

Indirect N<sub>2</sub>O emissions also arise from the fraction of N applied in fertiliser that is lost through leaching and runoff. The amount of nitrogen fertiliser applied to land that is lost via leaching and run off ( $m_{N_{LeachFertiliser}}$ ) is calculated according to **Equation F-4**:

**Equation F-4**

$$m_{N_{LeachFertiliser}} = (m_{N_{FertiliserSynthetic}} + m_{N_{FertiliserOrganic}}) \cdot Frac_{Leach}$$

The fraction of applied nitrogen that is lost via leaching and run off ( $Frac_{Leach}$ ) is taken to be 0.1 kgN<sub>Leached</sub>/kgN<sub>Applied</sub> as used for nitrogen fertiliser, per (Duffy et al., 2019). The emission of N<sub>2</sub>O-N arising from nitrogen lost via leaching and runoff ( $m_{N_2O-N_{FertiliserIndirectLeach}}$ ) is calculated as per **Equation F-5**:

**Equation F-5**

$$m_{N_2O-N_{FertiliserIndirectLeach}} = m_{N_{Leach}} \cdot EF_5$$

The emission factor for N<sub>2</sub>O-N arising from leached nitrogen ( $EF_5$ ) is taken to be 0.0075 gN<sub>2</sub>O-N/kgN<sub>Leached</sub> (Duffy et al., 2019).

Conversion from the mass of N<sub>2</sub>O-N to the mass of N<sub>2</sub>O emitted is achieved using the following equation (**Eq. F-6**):

**Equation F-6**

$$m_{N_2O} = (m_{N_2O-N} - N) \cdot \frac{44}{28}$$

The global warming potential of N<sub>2</sub>O (GWP<sub>N2O</sub>) used in the most recent submission from Ireland to the IPCC was 298 kgCO<sub>2</sub>eq (Duffy et al., 2019), this value will be used in calculations in this work. The GWP of CH<sub>4</sub> used in this work is 25, also used in the most recent submission from Ireland to the IPCC was 298 kgCO<sub>2</sub>eq (Duffy et al., 2019).

Total Mass of Digestate (kg<sub>wwt</sub>):  $m_{DigestateTotal}$   
 Nitrogen content of digestate (kgN/kg<sub>wwt</sub>):  $X_{NDigestate}$   
 Mineral N replacement (kgN<sub>min</sub>):  $m_{NReplacement} = m_{DigestateTotal} * X_{NDigestate} * X_{FRVn}$   
 N content in CAN (%):  $X_{NCAN}$   
 Total mass of CAN replaced (kg):  $m_{CANTotal} = \frac{m_{NReplacement}}{X_{NCAN}}$

#### **Fertiliser Production**

Specific emissions form fertiliser production: 8.03 kgCO<sub>2</sub>eq/kgN

Emissions associated with CAN production (kgCO<sub>2</sub>eq):  $mCO_{2CANProduction} = m_{CANTotal} * \frac{X_{NCAN}}{100} * 8.03$

#### **Fertiliser transportation from factory to port**

Road Transportation NL (km):  $d_{road(NL)} = 56$

Specific CO<sub>2</sub>eq emissions: 0.1878 kgCO<sub>2</sub>eq/t.km

Total road transportation CO<sub>2</sub>eq emissions for CAN (kgCO<sub>2</sub>eq):  $mCO_{2CANRoad(NL)} = \frac{m_{CANTotal}}{1000} * d_{road(NL)} * 0.1878$

Rail Transportation NL (km):  $d_{rail(NL)} = 2$

Specific CO<sub>2</sub>eq emissions: 0.0304 kgCO<sub>2</sub>eq/t.km

Total rail transportation CO<sub>2</sub>eq emissions for CAN (kgCO<sub>2</sub>eq):  $mCO_{2CANrail(NL)} = \frac{m_{CANTotal}}{1000} * d_{rail(NL)} * 0.0304$

Inland water way NL (km):  $d_{barge(NL)} = 19$

Specific CO<sub>2</sub>eq emissions: 0.0188 kgCO<sub>2</sub>eq/t.km

Total inland water transportation CO<sub>2</sub>eq emissions for CAN (kgCO<sub>2</sub>eq):  $mCO_{2CANbarge(NL)} = \frac{m_{CANTotal}}{1000} * d_{barge(NL)} * 0.0188$

#### **Fertiliser transportation from port to port**

Oversea water NL (km):  $d_{sea(NL)} = 1163$

Specific CO<sub>2</sub>eq emissions: 0.00544kgCO<sub>2</sub>/t.km

Total oversea water transportation CO<sub>2</sub>eq for CAN (kgCO<sub>2</sub>eq):  $mCO_{2CANSea(NL)} = \frac{m_{CANTotal}}{1000} * d_{sea(NL)} * 0.00544$

#### **Fertiliser transportation from port to farm**

Road transportation IRL (km):  $d_{road(IRL)} = 81$

Specific CO<sub>2</sub>eq emissions of road transportation: 0.1878 kgCO<sub>2</sub>eq/t.km

Total road transportation CO<sub>2</sub>eq emission for CAN (kgCO<sub>2</sub>eq):  $mCO_{2CANRoad(IRL)} = \frac{m_{CANTotal}}{1000} * d_{road(IRL)} * 0.1878$

#### **Fertiliser Spreading on farmland**

Specific CO<sub>2</sub>eq emissions of fertiliser spreading: 0.029676 kgCO<sub>2</sub>eq/kg<sub>fertiliser</sub>

Total CO<sub>2</sub>eq emissions from fertiliser spreading (kgCO<sub>2</sub>eq) :  $mCO_{2FertiliserSpreading} = m_{CANTotal} * \frac{X_{NCAN}}{100} * 0.029676$

#### **Fertiliser application to farmland**

##### **Direct N<sub>2</sub>O emissions**

Total N<sub>2</sub>O emitted from CAN application (kgN<sub>2</sub>O):  $mN_2OFertiliserSyntheticDirect = m_{CANTotal} * \frac{X_{NCAN}}{100} * EF_{1Synthetic} * \frac{44}{28}$

Direct emission of GHG from CAN application (kgCO<sub>2</sub>eq):

$mCO_{2FertiliserSyntheticDirect} = mN_2OFertiliserSyntheticDirect * GWP_{N_2O}$

##### **Indirect N<sub>2</sub>O emissions**

Total N<sub>2</sub>O emissions emitted from volatilisation associated with the application of CAN fertiliser (kgN<sub>2</sub>O):

$mN_2OFertiliserIndirect,volatilisation = m_{CANTotal} * \frac{X_{NCAN}}{100} * Frac_{GASF} * EF_4 * \frac{44}{28}$

Indirect emissions of GHG from volatilisation of CAN (kgCO<sub>2</sub>eq):

$mCO_{2FertiliserSyntheticIndirect,volatilisation} = mN_2OFertiliserIndirect,volatilisation * GWP_{N_2O}$

Total N<sub>2</sub>O emissions emitted from leaching associated with the application of CAN (kgN<sub>2</sub>O):

$mN_2OFertiliserIndirect,leaching = m_{CANTotal} * \frac{X_{NCAN}}{100} * Frac_{Leach} * EF_5 * \frac{44}{28}$

Indirect emissions of GHG from leaching of synthetic fertiliser (kgCO<sub>2</sub>eq):

$mCO_{2FertiliserSyntheticIndirect,leaching} = mN_2OFertiliserIndirect,leaching * GWP_{N_2O}$

**Box F-1.** Calculation of the Avoided GHG Emissions Associated with CAN Replacement.

The mass of GHGs that would be emitted by CAN replaced by digestate is calculated as per [Equation F-6](#).

**Equation F-6** GHG Emissions of CAN Replaced by Digestate.

$$m_{CO_2CAN\text{Avoided}} = m_{CO_2CAN\text{Production}} + m_{CO_2CAN\text{Road}(NL)} + m_{CO_2CAN\text{rail}(NL)} + m_{CO_2CAN\text{barge}(NL)} + m_{CO_2CAN\text{sea}(NL)} + m_{CO_2CAN\text{Road}(IRL)} + m_{CO_2Fertiliser\text{Spreading}} + m_{CO_2Fertiliser\text{SyntheticDirect}} + m_{CO_2Fertiliser\text{SyntheticIndirect,volatilsation}} + m_{CO_2Fertiliser\text{SyntheticIndirect,leaching}}$$

Total Mass of Digestate (kg<sub>wwt</sub>):  $m_{Digestate\text{Total}}$

Phosphorous content of digestate (kgP/kg<sub>wwt</sub>):  $X_{P\text{Digestate}}$

Mineral P replacement (kgP<sub>min</sub>):  $m_{P\text{Replacement}} = m_{Digestate\text{Total}} * X_{P\text{Digestate}} * X_{FRVP}$

Mass of P<sub>2</sub>O<sub>5</sub> Replaced (kgP<sub>2</sub>O<sub>5</sub>):  $m_{P_2O_5\text{Replacement}} = m_{P\text{Replaced}} * 2.291$

Mass of Triple Super Phosphorous Replaced (kgTSP):  $m_{TSP\text{Replaced}} = m_{P_2O_5\text{Replacement}} * \frac{1}{0.45}$

#### **Fertiliser Production**

Specific emissions form fertiliser production: 0.15696 kgCO<sub>2</sub>eq/kgP

Emissions associated with phosphorous production (kgCO<sub>2</sub>eq):  $m_{CO_2\text{PhosphorousProduction}} = m_{P\text{Replaced}} * 1.5696$

#### **Fertiliser transportation from factory to port**

Road Transportation NL (km):  $d_{road(NL)} = 56$

Specific CO<sub>2</sub>eq emissions: 0.1878 kgCO<sub>2</sub>eq/t.km

Total road transportation CO<sub>2</sub>eq emissions for TSP (kgCO<sub>2</sub>eq):  $m_{CO_2\text{TSPRoad}(NL)} = \frac{m_{TSP\text{Replaced}}}{1000} * d_{road(NL)} * 0.1878$

Rail Transportation NL (km):  $d_{rail(NL)} = 2$

Specific CO<sub>2</sub>eq emissions: 0.0304 kgCO<sub>2</sub>eq/t.km

Total rail transportation CO<sub>2</sub>eq emissions for TSP (kgCO<sub>2</sub>eq):  $m_{CO_2\text{TSPrail}(NL)} = \frac{m_{TSP\text{Replaced}}}{1000} * d_{rail(NL)} * 0.0304$

Inland water way NL (km):  $d_{barge(NL)} = 19$

Specific CO<sub>2</sub>eq emissions: 0.0188 kgCO<sub>2</sub>eq/t.km

Total inland water transportation CO<sub>2</sub>eq emissions for TSP (kgCO<sub>2</sub>eq):  $m_{CO_2\text{TSPbarge}(NL)} = \frac{m_{TSP\text{Replaced}}}{1000} * d_{barge(NL)} * 0.0188$

#### **Fertiliser transportation from port to port**

Oversea water NL (km):  $d_{sea(NL)} = 1163$

Specific CO<sub>2</sub>eq emissions: 0.00544 kgCO<sub>2</sub>eq/t.km

Total oversea water transportation CO<sub>2</sub>eq for TSP (kgCO<sub>2</sub>eq):  $m_{CO_2\text{TSPSea}(NL)} = \frac{m_{TSP\text{Replaced}}}{1000} * d_{sea(NL)} * 0.00544$

#### **Fertiliser transportation from port to farm**

Road transportation IRL (km):  $d_{road(IRL)} = 81$

Specific CO<sub>2</sub>eq emissions of road transportation: 0.1878 kgCO<sub>2</sub>eq/t.km

Total rod transportation CO<sub>2</sub>eq emission for TSP (kgCO<sub>2</sub>eq):  $m_{CO_2\text{TSPRoad}(IRL)} = \frac{m_{TSP\text{Total}}}{1000} * d_{road(IRL)} * 0.1878$

#### **Fertiliser Spreading on farmland**

Specific CO<sub>2</sub>eq emissions of fertiliser spreading: 0.029676 kgCO<sub>2</sub>eq/kg<sub>fertiliser</sub>

Total CO<sub>2</sub>eq emissions from fertiliser spreading (kgCO<sub>2</sub>eq):  $m_{CO_2\text{FertiliserSpreading}} = m_{TSP\text{Replaced}} * 0.029676$

### **Box F-2.** Calculation of GHG Emissions Associated with Phosphorous Replacement.

The mass of GHGs that would be emitted by phosphorous replaced by digestate is calculated as per [Equation F-7](#):

**Equation F-7**

$$m_{CO_2\text{PhosphorousAvoided}} = m_{CO_2\text{PhosphorousProduction}} + m_{CO_2\text{TSPRoad}(NL)} + m_{CO_2\text{TSPrail}(NL)} + m_{CO_2\text{TSPbarge}(NL)} + m_{CO_2\text{TSPSea}(NL)} + m_{CO_2\text{TSPRoad}(IRL)} + m_{CO_2\text{FertiliserSpreading}}$$

Total Mass of Digestate (kg<sub>wwt</sub>):  $m_{DigestateTotal}$   
 Nitrogen content of digestate (kgN/kg<sub>wwt</sub>):  $X_{NDigestate}$   
 Mineral N replacement (kgN<sub>min</sub>):  $m_{NReplacement} = m_{DigestateTotal} * X_{NDigestate}$

### **DIGESTATE**

#### **GHG Emissions from Digestate Transport to Land**

Transportation of digestate to farmland (t.km) :  $t.km_{Digestate}$   
 Specific CO<sub>2</sub>eq emissions of road transportation: 0.1878 kgCO<sub>2</sub>eq/t.km  
 Mass of CO<sub>2</sub>eq from digestate haulage to land (kgCO<sub>2</sub>eq):  $m_{CO2DigestateTransport} = t.km_{Digestate} * 0.1878$

#### **GHG Emissions from Digestate Spreading on Land**

Specific CO<sub>2</sub>eq emissions of fertiliser spreading: 1.1492 kgCO<sub>2</sub>eq/kg<sub>Digestate</sub>  
 Mass of CO<sub>2</sub>eq from spreading of digestate (kgCO<sub>2</sub>eq):  $m_{CO2DigestateSpreading} = m_{DigestateTotal} * 1.1492$

### **Digestate Application to Farmland**

#### **Direct N<sub>2</sub>O Emissions**

Total N<sub>2</sub>O emitted from of digestate application (kgN<sub>2</sub>O):  $m_{N2ODigestateDirect} = m_{DigestateTotal} * X_{NDigestate} * EF_{1Organic} * \frac{44}{28}$   
 Direct emission of GHG from digestate application (kgCO<sub>2</sub>eq):  $m_{CO2DigestateDirect} = m_{N2ODigestateDirect} * GWP_{N2O}$

#### **Indirect N<sub>2</sub>O emissions**

Total N<sub>2</sub>O emissions emitted from volatilisation associated with the application of digestate (kgN<sub>2</sub>O):

$$m_{N2ODigestateIndirect,volatilisation} = m_{DigestateTotal} * X_{NDigestate} * Frac_{GASO} * EF_4 * \frac{44}{28}$$

Indirect emissions of GHG from volatilisation of digestate (kgCO<sub>2</sub>eq):

$$m_{CO2DigestateIndirect,volatilisation} = m_{N2ODigestateIndirect,volatilisation} * GWP_{N2O}$$

Total N<sub>2</sub>O emissions emitted from leaching associated with the application of digestate (kgN<sub>2</sub>O):

$$m_{N2ODigestateIndirect,leaching} = m_{DigestateTotal} * X_{NDigestate} * Frac_{Leach} * EF_5 * \frac{44}{28}$$

Indirect emissions of GHG from leaching of digestate (kgCO<sub>2</sub>eq):

$$m_{CO2DigestateIndirect,Leaching} = m_{N2ODigestateIndirect,leaching} * GWP_{N2O}$$

**Box F-3.** Calculation of the GHG Emissions Associated with Digestate Use.

The GHG emissions arising from the use of digestate on land ( $m_{CO2DigestateUse}$ ) for barley cultivation are calculated according to [Equation F-8](#).

#### **Equation F-8**

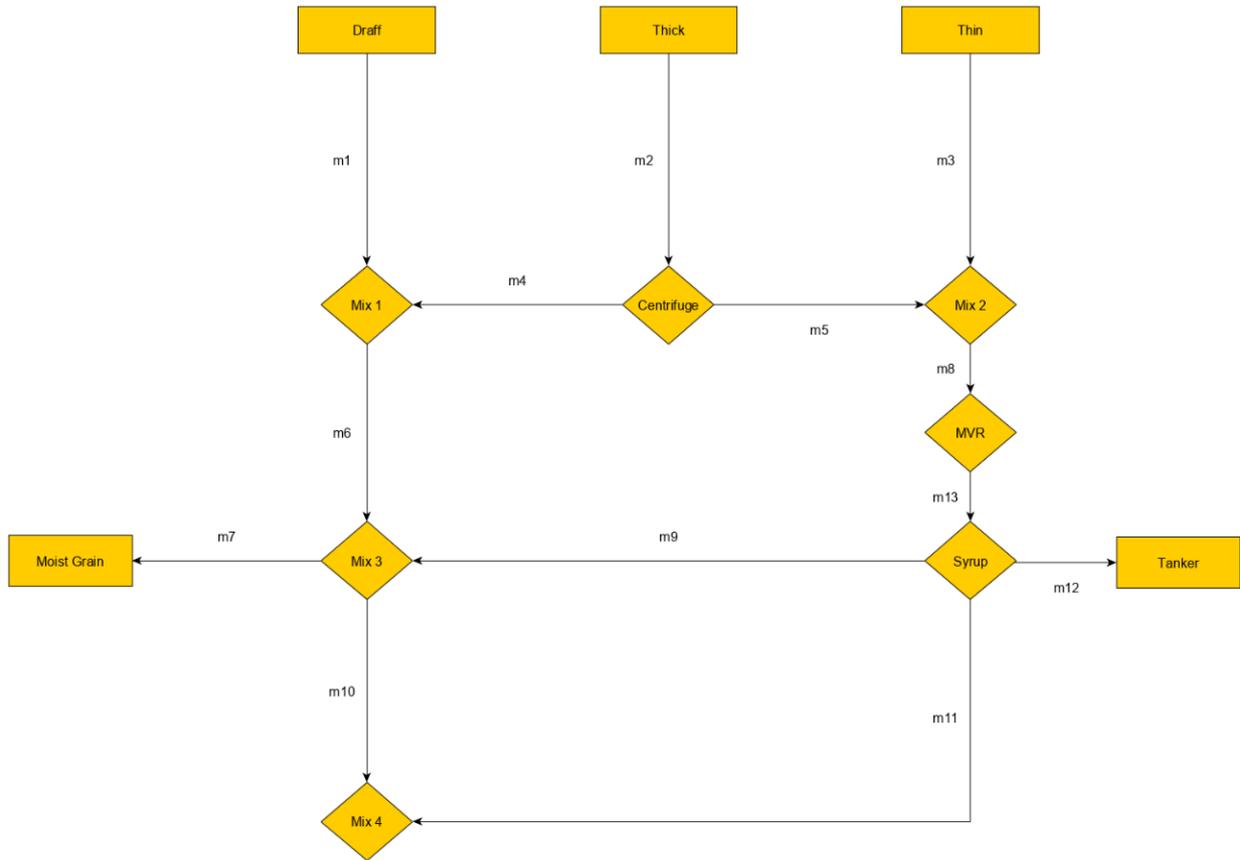
$$m_{CO2DigestateUse} = m_{CO2DigestateTransport} + m_{CO2DigestateSpreading} + m_{CO2DigestateDirect} + m_{CO2DigestateIndirect,volatilisation} + m_{CO2DigestateIndirect,Leaching}$$

#### **References**

- [1] Duffy P, Black K, Hyde B, Ryan A, Ponzi J, Alam S. Ireland's National Inventory Report. Johnstown Castle, Wexford: 2019.

## Appendix G: Animal Feed Production

Nomenclature	Description	Unit
$X_{DM_i}$	Dry matter content of material "i"	% wwt
$X_{MC_i}$	Moisture content of material "i"	% wwt
$X_{CP_i}$	Crude protein content of material "i"	%DM
$X_{CF_i}$	Crude fat content of material "i"	%DM
$X_{F_i}$	Fibre content of material "i"	%DM
$m_{Syrup\ to\ wet\ grain}$	Syrup addition to wet grain	kgwwt
$m_{6daily}$	Daily production of draff and cake maize mixture	kgwwt/day
$R_{SyrupMoist\ Grain}$	Ratio of syrup addition to moist grains	Na
$m_{Moist\ Grain\ Total}$	Total mass of moist grain produced	kgwwt
$GE_{m_i}$	Gross energy of material "m <sub>i</sub> "	MJ/kg
$OMd_i$	Organic matter digestibility of stream "i"	%
$ED_i$	Energy digestibility of stream "i"	%
$DE_i$	Digestible energy of stream "i"	MJ/kg
$ME_i$	Metabolizable energy of stream "i"	MJ/kg
$q_i$	Quotient of metabolizable energy to gross energy of stream "i"	Na
$kl_i$	Milk production energy use efficiency	%
$km_i$	Maintenance energy use efficiency	%
$kf_i$	Fate energy use efficiency	%
$kmf_i$	Combined maintenance and fat energy use efficiency	%
$UFL_i$	Energy content of feed product "i". Unite forragere lait	Na
$R_{SyrupDDG}$	Ratio of syrup sent to dried distillers grains (DDG)	Na



**Figure G-1.** Feeds recovery plant flowchart.

(‘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’: Syrup production from MVR)

Information regarding the composition of the distillery by-products and the distillery feed products are outlined in **Table G-1**.

**Table G-1.** By-product Parameters.

Parameter	Symbol	Unit
Dry Matter Content	$X_{DM}$	% wwt
Moisture Content	$X_{MC}$	% wwt
Ash Content	$X_A$	% DM
Crude Protein Content	$X_{CP}$	% DM
Crude Fibre Content	$X_{CF}$	% DM
Fat Content	$X_F$	% DM

**G.1. Centrifuge processing of thick stillage**

Thick stillage is centrifuged to produce cake maize and centrate. The cake maize is mixed with draff in the production of moist grains, the centrate is mixed with thin stillage and is sent for processing in the MVR units for the production of syrup. Conservation of; total mass, dry matter, and water are assumed as per **Equation G-1**.

**Equation G-1**

$$m4 + m5 = m2$$

$$m4 \cdot \frac{X_{DM4}}{100} + m5 \cdot \frac{X_{DM5}}{100} = m2 \cdot \frac{X_{DM2}}{100}$$

$$m4 \cdot \frac{X_{MC4}}{100} + m5 \cdot \frac{X_{MC5}}{100} = m2 \cdot \frac{X_{MC2}}{100}$$

The mass of maize cake produced was calculated as per [Equation G-2](#).

**Equation G-2**

$$m_4 = m_2 - \frac{\left( \frac{X_{DM_2}}{100} \cdot m_2 - \frac{\frac{X_{DM_4} \cdot X_{MC_2}}{100} \cdot m_2}{\frac{X_{MC_4}}{100}} \right)}{\left( \frac{X_{DM_5}}{100} - \frac{\frac{X_{DM_4} \cdot X_{MC_5}}{100}}{\frac{X_{MC_4}}{100}} \right)}$$

The dry matter content of maize cake ( $X_{DM_4}$ ) was taken to be 29.103% wwt based on data from the onsite laboratory at the distillery. No direct information on the volatile solid, ash, protein, fibre, or fat composition of the maize cake was available. The percentage of dry matter comprised of volatile solids, ash, protein, fibre, and fat were assumed to be the same as the dry matter composition of thick stillage.

The mass of ash, protein, fibre, and fat in the Cake Maize ( $m_4$ ) were calculated as per [Equation G-3](#).

**Equation G-3**

$$\begin{aligned} \text{Cake Maize Ash} &= m_4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{A_4}}{100} \\ \text{Cake Maize Protein} &= m_4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{CP_4}}{100} \\ \text{Cake Maize Crude Fibre} &= m_4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{CF_4}}{100} \\ \text{Cake Maize Fat} &= m_4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{F_4}}{100} \end{aligned}$$

The mass of centrate ( $m_5$ ) exiting the centrifuge was calculated as per [Equation G-4](#).

**Equation G-4**

$$m_5 = \frac{\left( \frac{X_{DM_2}}{100} \cdot m_2 - \frac{\frac{X_{DM_4} \cdot X_{MC_2}}{100} \cdot m_2}{\frac{X_{MC_4}}{100}} \right)}{\left( \frac{X_{DM_5}}{100} - \frac{\frac{X_{DM_4} \cdot X_{MC_5}}{100}}{\frac{X_{MC_4}}{100}} \right)}$$

The dry matter content of centrate ( $X_{DM_5}$ ) was taken to be 4.0417% wwt based on data from the onsite laboratory at the IDL facility. No direct information on the volatile solid, ash, protein, fibre, or fat composition of the centrate was available. The percentage of dry matter comprised of volatile solids, ash, protein, fibre, and fat were assumed to be the same as the dry matter composition of thick stillage.

The mass of ash, protein, fibre, and fat in the centrate were calculated as per [Equation G-5](#).

**Equation G-5**

$$\begin{aligned} \text{Centrate Ash} &= m_5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{A_5}}{100} \\ \text{Centrate Crude Protein} &= m_5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CP_5}}{100} \\ \text{Centrate Crude Fibre} &= m_5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CF_5}}{100} \\ \text{Centrate Fat} &= m_5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{F_5}}{100} \end{aligned}$$

**G.2. Mix 2: Combination of Thin Stillage and Centrate**

The total combined mass of thin stillage and centrate, dubbed as MVR feed ( $m_8$ ), was calculated as per [Equation G-6](#).

**Equation G-6**

$$m_5 + m_3 = m_8$$

The composition of the MVR feed ( $m_8$ ) was calculated as per [Equation G-7](#) to [Equation G-12](#).

**Equation G-7**

$$X_{DM_8} = \frac{\left( m_5 \cdot \frac{X_{DM_5}}{100} + m_3 \cdot \frac{X_{DM_3}}{100} \right)}{m_3 + m_5} * 100$$

**Equation G-8**

$$X_{MC_8} = \frac{\left(m5 \cdot \frac{X_{MC_5}}{100} + m3 \cdot \frac{X_{MC_3}}{100}\right)}{m3 + m5} * 100$$

**Equation G-9**

$$X_{A_8} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{A_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{A_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-10**

$$X_{CP_8} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CP_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{CP_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-11**

$$X_{CF_8} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CF_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{CF_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-12**

$$X_{F_8} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{F_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{F_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

The total mass of; dry matter, ash, protein, fibre, and fat in the MVR feed were calculated as per [Equation G-13](#).

**Equation G-13**

$$MVR \text{ Feed Ash} = m8 \cdot \frac{X_{DM_8}}{100} \cdot \frac{X_{A_8}}{100}$$

$$MVR \text{ Feed Crude Protein} = m8 \cdot \frac{X_{DM_8}}{100} \cdot \frac{X_{CP_8}}{100}$$

$$MVR \text{ Feed Crude Fibre} = m8 \cdot \frac{X_{DM_8}}{100} \cdot \frac{X_{CF_8}}{100}$$

$$MVR \text{ Feed Fat} = m8 \cdot \frac{X_{DM_8}}{100} \cdot \frac{X_{F_8}}{100}$$

**G.3. MVR Syrup Production**

The total mass of syrup produced in the MVR units was calculated using a dry matter balance on the MVR units under the assumption that all of the incoming dry matter contained in the MVR feed was contained in the produced syrup. The total mass of syrup (m13) produced was calculated according to [Equation G-14](#).

**Equation G-14**

$$m13 = \frac{\left(m8 \cdot \frac{X_{DM_8}}{100}\right)}{\frac{X_{DM_{13}}}{100}}$$

The dry matter content of the syrup was specified exogenously and was taken to be 32.316% wwt based on data from the distillery.

The total mass of dry matter, ash, crude protein, crude fibre, and fat in the syrup is the same as the total incoming mass of each constituent in the MVR feed. The composition of the dry matter contained in the syrup in terms of; ash, crude protein, crude fibre, and fat can be expressed using [Equation G-15](#) to [Equation G-18](#).

**Equation G-15**

$$X_{A_{13}} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{A_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{A_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-16**

$$X_{CP_{13}} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CP_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{CP_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-17**

$$X_{CF_{13}} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{CF_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{CF_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

**Equation G-18**

$$X_{F_{13}} = \frac{\left(m5 \cdot \frac{X_{DM_5}}{100} \cdot \frac{X_{F_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100} \cdot \frac{X_{F_3}}{100}\right)}{m5 \cdot \frac{X_{DM_5}}{100} + m3 \cdot \frac{X_{DM_3}}{100}} * 100$$

Syrup is to be prioritised for use in wet grain production, surplus syrup will then be used in DDG production if DDG production occurs. Finally, if the surplus syrup is available following DDG production it will be exported from the site as syrup.

**G.4. Mix 1: Combination of Draff and Cake Maize**

The total mass of draff ( $m1$ ) and cake maize ( $m4$ ) was calculated as per [Equation G-19](#).

**Equation G-19**

$$m4 + m1 = m6$$

The dry matter content, moisture content, ash, crude protein, crude fibre, and fat content of the mixture of draff and cake maize is calculated using [Equation G-20](#) to [Equation G-24](#).

**Equation G-20**

$$X_{DM_6} = \frac{\left(m4 \cdot \frac{X_{DM_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100}\right)}{m1 + m4} * 100$$

**Equation G-21**

$$X_{A_6} = \frac{\left(m4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{A_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100} \cdot \frac{X_{A_1}}{100}\right)}{m4 \cdot \frac{X_{DM_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100}} * 100$$

**Equation G-22**

$$X_{CP_6} = \frac{\left(m4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{CP_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100} \cdot \frac{X_{CP_1}}{100}\right)}{m4 \cdot \frac{X_{DM_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100}} * 100$$

**Equation G-23**

$$X_{CF_6} = \frac{\left(m4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{CF_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100} \cdot \frac{X_{CF_1}}{100}\right)}{m4 \cdot \frac{X_{DM_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100}} * 100$$

**Equation G-24**

$$X_{F_6} = \frac{\left(m4 \cdot \frac{X_{DM_4}}{100} \cdot \frac{X_{F_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100} \cdot \frac{X_{F_1}}{100}\right)}{m4 \cdot \frac{X_{DM_4}}{100} + m1 \cdot \frac{X_{DM_1}}{100}} * 100$$

The total mass of ash, crude protein, crude fibre, and fat contained in the mixture of draff and cake maize are calculated using [Equation G-25](#).

**Equation G-25**

$$m6 \cdot \frac{X_{DM_6}}{100} \cdot \frac{X_{A_6}}{100}$$

$$m6 \cdot \frac{X_{DM_6}}{100} \cdot \frac{X_{CP_6}}{100}$$

$$m6 \cdot \frac{X_{DM_6}}{100} \cdot \frac{X_{CF_6}}{100}$$

$$m6 \cdot \frac{X_{DM_6}}{100} \cdot \frac{X_{F_6}}{100}$$

**G.5. MVR Syrup to Wet Grain**

The mass of syrup ( $m9$ ) added to the mixture of draff and cake maize was based on the average daily mass of syrup added to the mix of draff and cake maize, divided by the mass of draff plus cake maize produced per day ( $R_{SyrupMoist\ Grain}$ ) as outlined in [Equation G-26](#).

**Equation G-26**

$$R_{SyrupMoist\ Grain} = \frac{m_{Syrup\ to\ wet\ grain} \text{ (kgwwt)}}{m_{6,daily} \text{ (kgwwt)}}$$

The average mass of syrup added per kg of draff plus cake maize for the period of analysis was found to be 0.04689 kgwwt Syrup/kgwwt Draff plus cake maize. The mass of syrup ( $m9$ ) to be added to the mixture of draff and cake maize for the production of moist grain was calculated according to [Equation G-27](#).

**Equation G-27**

$$m9 = m6 * R_{SyrupMoist Grain}$$

As stated earlier, the use of syrup is prioritised for the production of moist grain, if the total mass of syrup produced ( $m13$ ) is less than the mass of syrup required for the production of moist grain ( $m9$ ) then all of the syrup produced is used for the production of moist grain ( $m9 = m13$ ).

The mass of ash, protein, fibre, and fat contained in the syrup stream sent to the mixture of draff and cake maize are calculated according to [Equation G-28](#).

**Equation G-28**

$$m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{A9}}{100}$$

$$m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{CP9}}{100}$$

$$m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{CF9}}{100}$$

$$m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{F9}}{100}$$

**G.6. Mix 3: Moist Grain**

The total mass of moist grain is calculated as per [Equation G-29](#).

**Equation G-29**

$$m_{Moist Grain Total} = m6 + m9$$

The total mass of dry matter, as, crude protein, crude fibre, and fat contained in the moist grain is equal to the sum of each constituent contained in the incoming mixture of draff and cake maize, combined with the incoming mass of syrup. The dry matter content of the moist grains for stream ( $m7$  and  $m10$ ) is calculated as per [Equation G-30](#).

**Equation G-30**

$$X_{DM7} = \frac{\left(m6 \cdot \frac{X_{DM6}}{100} + m9 \cdot \frac{X_{DM9}}{100}\right)}{m6 + m9} * 100$$

Ash content, crude protein, crude fibre, and fat content of the dry matter fraction in the produced moist grains are calculated according to [Equation G-31](#) to [Equation G-34](#).

**Equation G-31**

$$X_{A7} = \frac{\left(m6 \cdot \frac{X_{DM6}}{100} \cdot \frac{X_{A6}}{100} + m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{A9}}{100}\right)}{m6 \cdot \frac{X_{DM6}}{100} + m9 \cdot \frac{X_{DM9}}{100}} * 100$$

**Equation G-32**

$$X_{CP7} = \frac{\left(m6 \cdot \frac{X_{DM6}}{100} \cdot \frac{X_{CP6}}{100} + m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{CP9}}{100}\right)}{m6 \cdot \frac{X_{DM6}}{100} + m9 \cdot \frac{X_{DM9}}{100}} * 100$$

**Equation G-33**

$$X_{CF7} = \frac{\left(m6 \cdot \frac{X_{DM6}}{100} \cdot \frac{X_{CF6}}{100} + m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{CF9}}{100}\right)}{m6 \cdot \frac{X_{DM6}}{100} + m9 \cdot \frac{X_{DM9}}{100}} * 100$$

**Equation G-34**

$$X_{F7} = \frac{\left(m6 \cdot \frac{X_{DM6}}{100} \cdot \frac{X_{F6}}{100} + m9 \cdot \frac{X_{DM9}}{100} \cdot \frac{X_{F9}}{100}\right)}{m6 \cdot \frac{X_{DM6}}{100} + m9 \cdot \frac{X_{DM9}}{100}} * 100$$

Current annual production of moist grains was found to be ca. 62,766 twwt/a. If the total mass of moist grain produced is found to be in excess of 64,617 twwt/a, any surplus moist grains will be further mixed with syrup and dried to produce DDG ( $m10$ ). In the event that the total combined mass of moist grain produced is lower than 64,617 twwt/a then the entire mass of the produced moist grains will be exported from the distillery as moist grains and no further production of DDG will occur.

The UFL of the produced moist grains can be calculated as per [Equation G-35](#).

**Equation G-35**

$$\text{Gross Energy moist grains (Stream } m7) GE_{m7} = 17.3 + 0.0617X_{CP7} + 0.2193X_{F7} + 0.0387X_{CF7} - 0.1867X_{ASH7}$$

$$\text{Organic Matter digestibility stream } m7 \text{ } Omd_7 = 95.81 + 1.911X_{CF_7} - 2.54$$

$$\text{Energy Digestibility of Stream } m7 \text{ } ED_7 = Omd_7 - 3.5 + 0.046X_{CP_7} + 0.155X_{F_7}$$

$$\text{Digestible Energy of Stream } m7 \text{ } DE_7 = GE_7 \cdot \frac{ED_7}{100}$$

$$\text{Metabolisable Energy of Stream } m7 \text{ } ME_7 = \left(\frac{DE_7}{100}\right) \left(86.38 - 0.099 \cdot \frac{X_{CF_7}}{1 - \frac{X_{ASH_7}}{100}} \cdot 100 - 0.196 \cdot \frac{X_{CP_7}}{1 - \frac{X_{ASH_7}}{100}}\right)$$

$$\text{Quotient Stream } m7 \text{ } q_7 = \frac{ME_7}{GE_7}$$

$$\text{Milk Efficiency Stream } m7 \text{ } kl_7 = 0.6 + 0.24(q_7 - 0.57)$$

$$\text{Maintenance Efficiency Stream } m7 \text{ } km_7 = 0.287q_7 + 0.554$$

$$\text{Fat Efficiency Stream } m7 \text{ } kf_7 = 0.78q_7 + 0.006$$

$$\text{Combined Efficiency } m7 \text{ } kmf_7 = km_7 \cdot \frac{kf_7(1.5)}{kf_7 + km_7 \cdot 0.5}$$

$$UFL_7 = ME_7 \cdot \frac{kl_7}{7.12}$$

#### G.7.Mix 4: DDG Production

If DDG is to be produced, additional syrup from the MVR stream ( $m_{11}$ ) will need to be mixed with the moist grains remaining after the export of moist grains ( $m_{10}$ ). The mass of dry matter contained in syrup added to the moist grains remaining for the production of DDG was calculated based on the annual mass of dry matter contained in DDG produced minus the mass of dry matter contained in the remaining moist grains. The resulting ratio of 0.6296 kgDM<sub>Syrup</sub>/kgDM<sub>MoistGrain</sub> ( $R_{SyrupDDG}$ ) is used to calculate the mass of syrup added to the remaining moist grains, using a dry matter content of syrup of 89.7% wwt based on data from the distillery. The mass of syrup added to the remaining moist grain ( $m_{11}$ ) for the production of DDG is calculated as per [Equation G-36](#).

#### Equation G-36

$$m_{11} = \frac{m_{10} \cdot \frac{X_{DM_{10}}}{100} \cdot R_{SyrupDDG}}{\frac{X_{DM_{13}}}{100}}$$

The total mass of DDG produced is based on the sum of the dry matter contained in the remaining moist grains, plus the dry matter contained in the syrup used for DDG production, divided by the dry matter content of the DDG as per [Equation G-37](#).

#### Equation G-37

$$m_{14} = \frac{m_{10} \cdot \frac{X_{DM_{10}}}{100} + m_{11} \cdot \frac{X_{DM_{11}}}{100}}{\frac{X_{DM_{14}}}{100}}$$

The ash content, crude protein, crude fibre, and fat content of the produced DDG are calculated as per [Equation G-38](#) to [Equation G-41](#).

#### Equation G-38

$$X_{A_{14}} = \frac{\left(m_{10} \cdot \frac{X_{DM_{10}}}{100} \cdot \frac{X_{A_{10}}}{100} + m_{11} \cdot \frac{X_{DM_{11}}}{100} \cdot \frac{X_{A_{11}}}{100}\right)}{m_{14} \cdot \frac{X_{DM_{14}}}{100}} \cdot 100$$

#### Equation G-39

$$X_{CP_{14}} = \frac{\left(m_{10} \cdot \frac{X_{DM_{10}}}{100} \cdot \frac{X_{CP_{10}}}{100} + m_{11} \cdot \frac{X_{DM_{11}}}{100} \cdot \frac{X_{CP_{11}}}{100}\right)}{m_{14} \cdot \frac{X_{DM_{14}}}{100}} \cdot 100$$

#### Equation G-40

$$X_{CF_{14}} = \frac{\left(m_{10} \cdot \frac{X_{DM_{10}}}{100} \cdot \frac{X_{CF_{10}}}{100} + m_{11} \cdot \frac{X_{DM_{11}}}{100} \cdot \frac{X_{CF_{11}}}{100}\right)}{m_{14} \cdot \frac{X_{DM_{14}}}{100}} \cdot 100$$

#### Equation G-41

$$X_{F_{14}} = \frac{\left(m_{10} \cdot \frac{X_{DM_{10}}}{100} \cdot \frac{X_{F_{10}}}{100} + m_{11} \cdot \frac{X_{DM_{11}}}{100} \cdot \frac{X_{F_{11}}}{100}\right)}{m_{14} \cdot \frac{X_{DM_{14}}}{100}} \cdot 100$$

The UFL and UFV content of the produced DDG can be calculated as per [Equation G-42](#).

**Equation G-42**

$$\begin{aligned}
 \text{Gross Energy DDG (Stream m14)} \quad GE_{m_7} &= 17.3 + 0.0617X_{CP_{14}} + 0.2193X_{F_{14}} + 0.0387X_{CF_{14}} - 0.1867X_{ASH_{14}} \\
 \text{Organic Matter digestibility stream m14} \quad OMD_{14} &= 95.81 + 1.911X_{CF_{14}} - 2.54 \\
 \text{Energy Digestibility of Stream m14} \quad ED_{14} &= OMD_{14} - 3.5 + 0.046X_{CP_{14}} + 0.155X_{F_{14}} \\
 \text{Digestible Energy of Stream m14} \quad DE_{14} &= GE_{14} \cdot \frac{ED_{14}}{100} \\
 \text{Metabolisable Energy of Stream m14} \quad ME_{14} &= \left( \frac{DE_{14}}{100} \right) \left( 86.38 - 0.099 * \frac{X_{CF_{14}}}{1 - \frac{X_{ASH_{14}}}{100}} * 100 - 0.196 * \frac{X_{CP_{14}}}{1 - \frac{X_{ASH_{14}}}{100}} \right) \\
 \text{Quotient Stream m14} \quad q_{14} &= \frac{ME_{14}}{GE_{14}} \\
 \text{Milk Efficiency Stream m14} \quad kl_{14} &= 0.6 + 0.24(q_{14} - 0.57) \\
 \text{Maintenance Efficiency Stream m14} \quad km_{14} &= 0.287q_{14} + 0.554 \\
 \text{Fat Efficiency Stream m14} \quad kf_{14} &= 0.78q_{14} + 0.006 \\
 \text{Combined Efficiency m14} \quad kmf_{14} &= km_{14} \cdot \frac{kf_{14}(1.5)}{kf_{14} + km_{14} * 0.5} \\
 UFL_{14} &= ME_{14} * \frac{kl_{14}}{7.12}
 \end{aligned}$$

**G.8. Syrup to Tankers**

In the event that there is residual syrup left after moist grain production and DDG production, the remaining syrup (m12) is exported from site in tankers. The mass of residual syrup produced is calculated as per [Equation G-43](#).

**Equation G-43**

$$m_{12} = m_{13} - m_9 - m_{11}$$

The UFL of exported syrup (m12) can be calculated using [Equation G-44](#).

**Equation G-44**

$$\begin{aligned}
 \text{Gross Energy moist grains (Stream m12)} \quad GE_{m_{12}} &= 17.3 + 0.0617X_{CP_{12}} + 0.2193X_{F_{12}} + 0.0387X_{CF_{12}} - 0.1867X_{ASH_{12}} \\
 \text{Organic Matter digestibility stream m12} \quad OMD_{12} &= 95.81 + 1.911X_{CF_{12}} - 2.54 \\
 \text{Energy Digestibility of Stream m12} \quad ED_{12} &= OMD_{12} - 3.5 + 0.046X_{CP_{12}} + 0.155X_{F_{12}} \\
 \text{Digestible Energy of Stream m12} \quad DE_{12} &= GE_{12} \cdot \frac{ED_{12}}{100} \\
 \text{Metabolisable Energy of Stream m12} \quad ME_{12} &= \left( \frac{DE_{12}}{100} \right) \left( 86.38 - 0.099 * \frac{X_{CF_{12}}}{1 - \frac{X_{ASH_{12}}}{100}} * 100 - 0.196 * \frac{X_{CP_{12}}}{1 - \frac{X_{ASH_{12}}}{100}} \right) \\
 \text{Quotient Stream m12} \quad q_{12} &= \frac{ME_{12}}{GE_{12}} \\
 \text{Milk Efficiency Stream m12} \quad kl_{12} &= 0.6 + 0.24(q_{12} - 0.57) \\
 \text{Maintenance Efficiency Stream m12} \quad km_{12} &= 0.287q_{12} + 0.554 \\
 \text{Fat Efficiency Stream m12} \quad kf_{12} &= 0.78q_{12} + 0.006 \\
 \text{Combined Efficiency m12} \quad kmf_{12} &= km_{12} \cdot \frac{kf_{12}(1.5)}{kf_{12} + km_{12} * 0.5} \\
 UFL_{12} &= ME_{12} * \frac{kl_{12}}{7.12}
 \end{aligned}$$

## Appendix H: Feeds Recovery Plant Energy Consumption

Nomenclature	Description	Unit
$E_{GasDDG}$	Natural gas demand to dry distillers dried grains (DDG)	MWh <sub>th</sub> /a
$\eta_{Boiler}$	Boiler efficiency	%
$E_{ElectricityCentrifuge}$	Electrical energy consumption of centrifuge	MWh <sub>e</sub> /a
$S_{TK}$	Share of thick stillage used in anaerobic digestion	%
$m_2$	Mass of thick stillage	kgwwt/a
$E_{ElectricityDrier}$	Electrical energy consumption of dryer	MWh <sub>e</sub> /a
$m_{14}$	Mass of DDG produced	kgwwt/a
$m_{Thick,total}$	Total mass of thick stillage available	kgwwt/a
$E_{ElectricityPellet Mill}$	Electrical energy consumption of the pellet mill	MWh <sub>e</sub> /a
$E_{ElectricityMVR}$	Electrical energy consumption of the mechanical vapour recompression (MVR) system	MWh <sub>e</sub> /a

## H.1. Thermal Energy Consumption of Feed Recovery plant for DDG production

The production of DDG requires the use of steam in the feeds recovery plant. Hourly data on total steam consumption of the feed recovery plant was obtained from the SCADA system for the distillery, which measured the mass flow rate of steam in kg/hr used in each of the driers. The hourly steam pressure was also obtained. Hourly steam consumption was calculated in kg/hr using the trapezoidal rule. The specific enthalpy of evaporation of steam based on the pressure of steam used was used to calculate hourly thermal energy consumption. Hourly energy consumption in each drier was summed to give weekly total energy consumption for all the driers combined.

The specific energy consumption per week of DDG drying was calculated by dividing the weekly thermal energy consumption of the driers by the weekly mass of DDG produced. The specific energy consumption per tonne of DDG produced (on a weekly basis), and the total energy consumption per week are shown in Figures H-1 and H-2.

Regression analysis was performed using the Curve Fitting Toolbox in Matlab to fit a linear model to the specific weekly thermal energy consumption to dry the DDG. The resulting linear model is also shown in Equation G-1 with an intercept of -6.255 and a slope of 4083 (aR<sup>2</sup> of 0.3958).

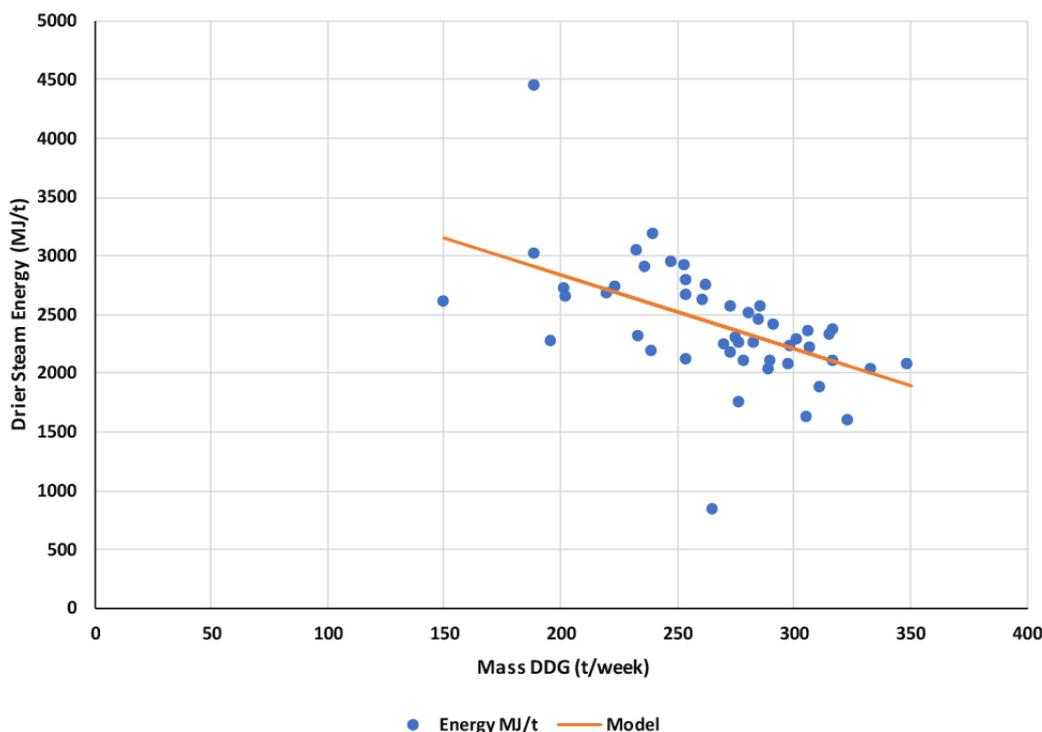


Figure H-1. Specific Thermal Energy Consumption of DDG.

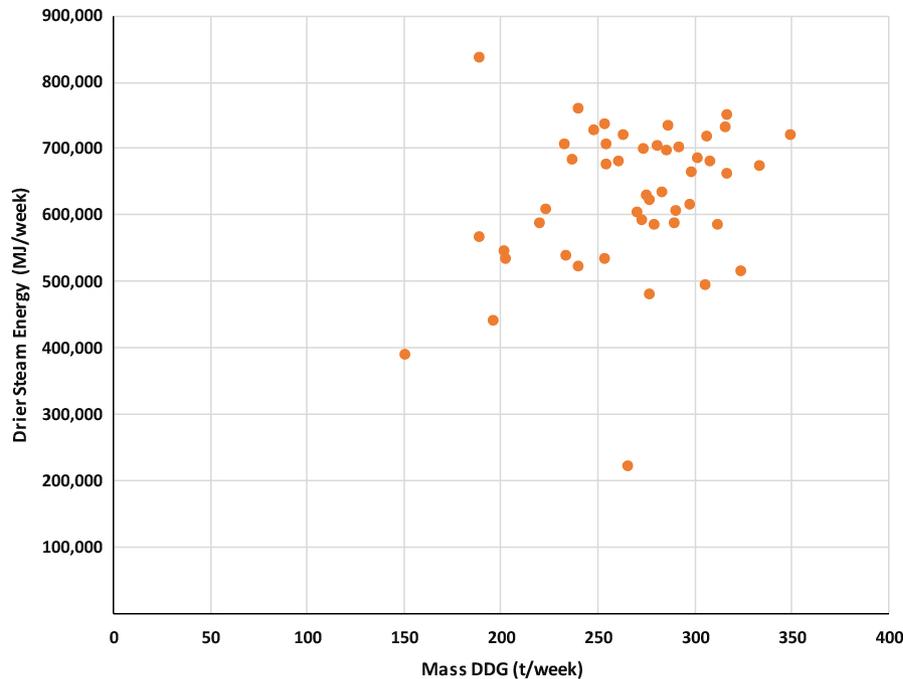


Figure H-2. Total Thermal Energy Consumption of DDG.

Specific thermal energy consumption per tonne of DDG produced reduces as DDG production increases, this could be a result of increased efficiency of the process as through put of DDG increases. The average thermal demand for the drying of DDG is 2,403 MJ/t<sub>DDG</sub>. The total consumption of thermal energy in the form of steam for drying of DDG was ca. 8,714 MWh.

Annual steam consumption of the dryers used for DDG production, if DDG production is to occur, is calculated as per Equation H-1 based on weekly values of DDG (assuming 50 weeks of operation). The consumption of natural gas required to produce this amount of steam is calculated by dividing the annual steam consumption of the driers by the efficiency of the steam boilers ( $\eta_{Boiler}=73.394\%$ ).

#### Equation H-1

$$E_{Gas_{DDG}} = \frac{\left( m_{14} * \frac{\left( \frac{m_{14}}{1000*50} * (-6.255) + 4083 \right) * \frac{m_{14}}{1000}}{3600} \right)}{\eta_{Boiler}} \left( \frac{MWh_{th}}{a} \right)$$

## H.2. Electrical Energy Consumption of Feeds Recovery Plant

### H.2.1. Centrifuge Electrical Energy Consumption

The total electrical energy consumption of the centrifuges used to process the thick stillage into cake maize and centrifuge liquor was calculated using average values of real power consumption (kW), between the period 28/02/2019 and 30/04/2019 as data prior to 28/02/2019 was not readily available.

Hourly energy consumption was calculated using the trapezoidal rule, hourly values of electrical energy consumption were summed over a day to give daily energy consumption.

The volume of thick stillage process was based on hourly flow rates (m<sup>3</sup>/hr) from flow meters. Hourly flow was found by numerical integration using the trapezoidal rule. Hourly flows were summed to determine total daily flows for the days corresponding to days when electrical energy consumption data was available for the centrifuges.

The specific electrical energy consumption per m<sup>3</sup> of thick stillage processed, and the total daily energy consumption for a given volume of thick stillage processed are shown in Figure H-3 for each of the centrifuges for which data was available. Regression analysis was conducted using the Matlab Curve Fitting Toolbox, an intercept value of -0.0003064 and a slope of 1.566 were calculated ( $aR^2 = 0.5122$ ). The linear model is also shown in Figure H-3 for the combined specific electricity consumption of centrifuge A and centrifuge D on a daily basis.

Specific electrical energy consumption of the centrifuges reduces as through put of thick stillage increased. The average electrical energy consumption per m<sup>3</sup> of thick stillage processed was 1.3 kWh/m<sup>3</sup>.

Annual electrical energy consumption by the centrifuges processing thick stillage is calculated according to Equation H-2 based on daily volumes of thick stillage to be processed (assuming 351 days of operation).

#### Equation H-2

$$E_{Electricity_{Centrifuge}} = S_{TK} \cdot m_2 * \frac{\left( \frac{S_{TK} \cdot m_{Thick_{total}}}{365-14} * (-0.0003064) + 1.566 \right)}{1000} \left( \frac{MWh_e}{a} \right)$$

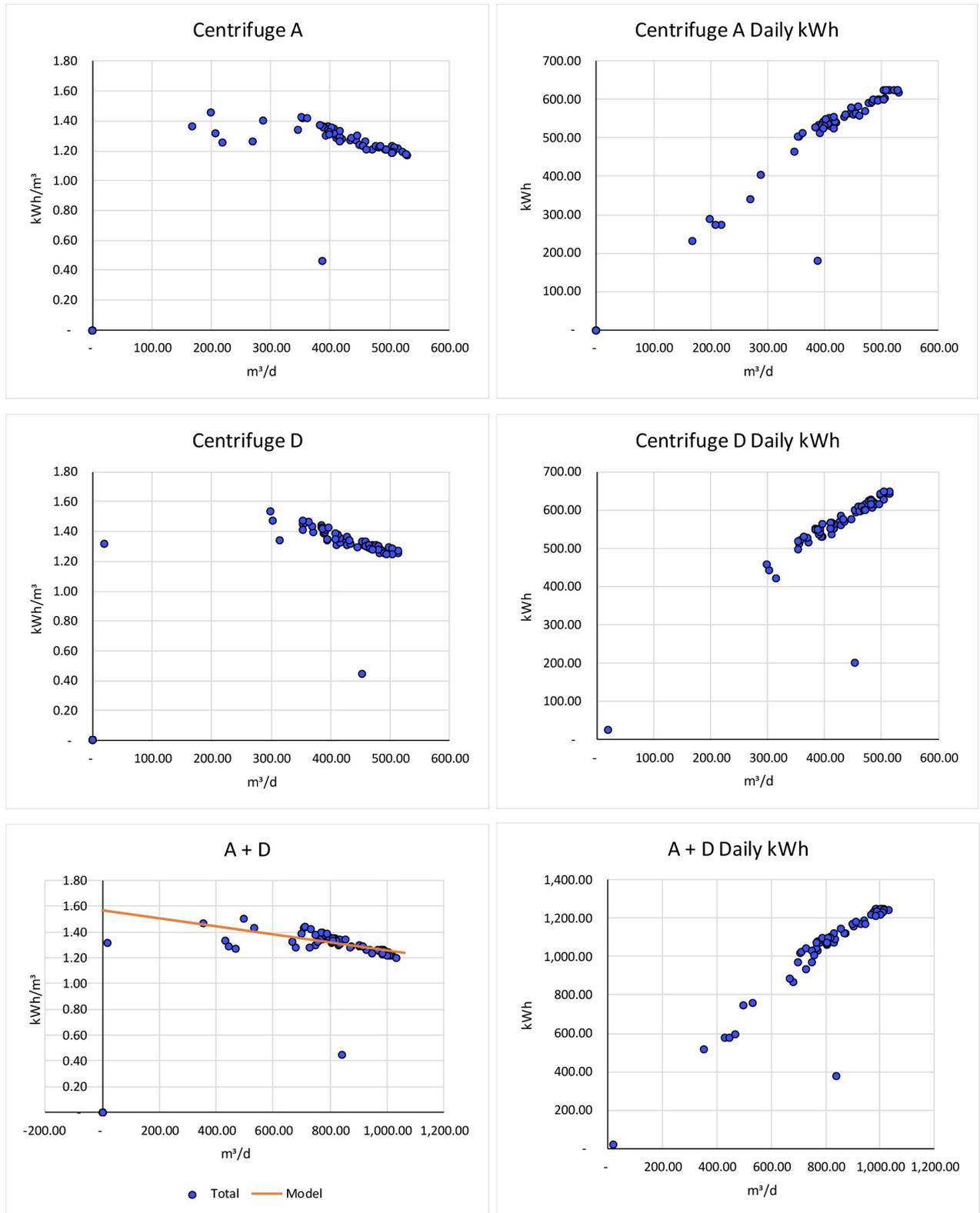


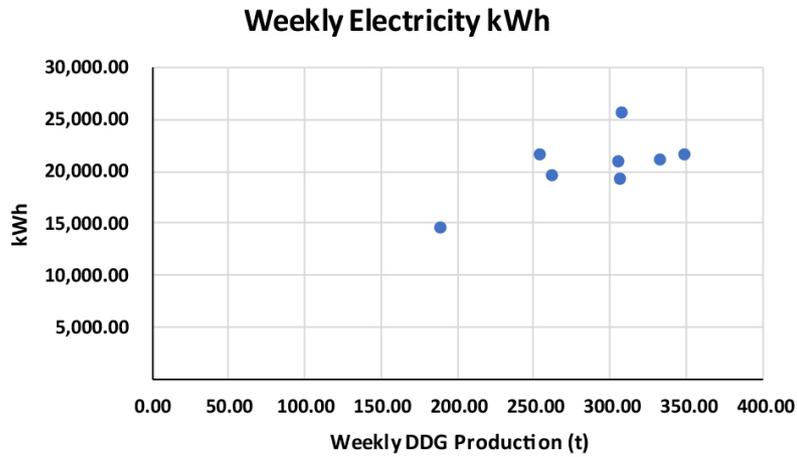
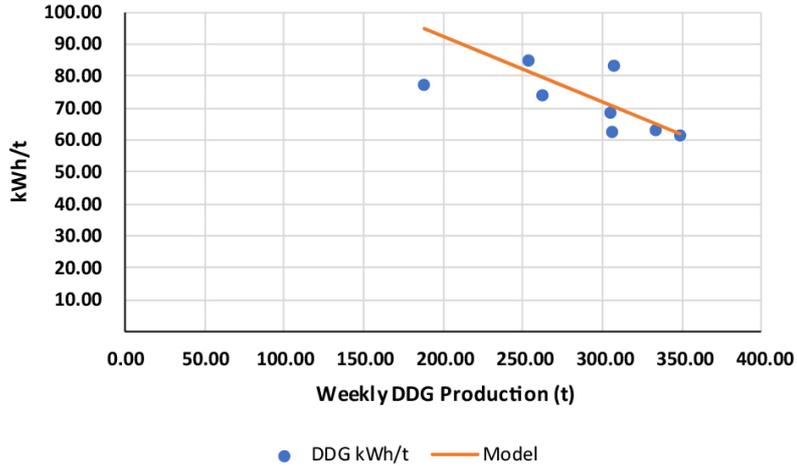
Figure H-3. Electrical Energy Consumption of Centrifuges.

**H.H.2. DDG Drier Electrical Energy Consumption**

The total electrical energy consumption of the driers used to dry the moist grain to form DDG was calculated using average values of real power consumption (kW) between the period 28/02/2019 and 30/04/2019 as data prior to 28/02/2019 was not readily available.

Hourly energy consumption was calculated using the trapezoidal rule for each drier, hourly values of electrical energy consumption were summed over a week to give weekly energy consumption as data on the mass of DDG produced was only available on a weekly basis.

The specific electrical energy consumption of the driers per t of DDG produced, and the total daily energy consumption of the driers for a given tonnage of DDG produced are shown in **Figure H-4**. A linear model was fitted using Matlab (intercept value = -0.206, slope = 133.6, aR<sup>2</sup>=0.433) and is also shown in **Figure H-4**.



**Figure H-4.** Drier Electrical Energy Consumption.

Specific electrical energy consumption reduced as DDG production increased, the average electrical energy consumption of the driers per tonne of DDG produced was 72.21 kWh/t.

Annual electrical energy consumption of the driers producing DDG is calculated from **Equation H-3** based on weekly production figures of DDG (assuming 50 weeks of operation per year);

**Equation H-3**

$$E_{ElectricityDrier} = m_{14} * \frac{\left(\frac{m_{14}}{1000*50} * (-0.206) - 133.6\right)}{1000} \left(\frac{MWh_{Gas}}{a}\right)$$

**H.2.3. Pellet Mill Electrical Energy Consumption**

The electrical energy consumption was calculated for the pellet mills in the same manner as the electrical energy consumption of the driers. Data was sourced for the same time period, real power consumption was obtained. A linear model relating specific electrical energy consumption to weekly DDG processed was fitted with Matlab (intercept = -0.7275, slope = 35.94, aR<sup>2</sup>=0.7569), the results are shown in **Figure H-5**.

Please cite this article as: O'Shea R., Lin R., Wall D.M., Browne J.M., Murphy J.D. Distillery decarbonisation and anaerobic digestion: balancing benefits and drawbacks using a compromise programming approach. Biofuel Research Journal 31 (2021) 1417-1432. DOI: [10.18331/BRJ2021.8.3.2](https://doi.org/10.18331/BRJ2021.8.3.2)

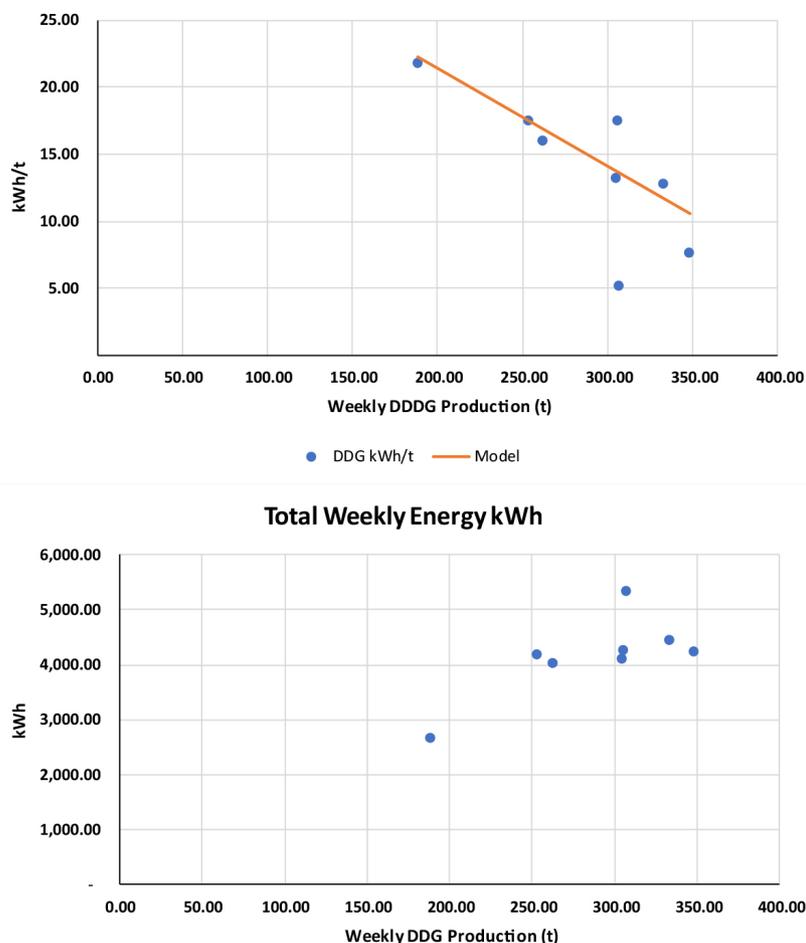


Figure H-5. Pellet Mill Electrical Energy Consumption.

Once again, the specific electrical energy consumption of the pellet mills reduced as DDG production increased, the average electrical energy demand for pellet production was 14.5 kWh/t. Limited data is available for electrical energy consumption of the driers, as such these results are to be treated with caution.

Annual electrical energy consumption of the pellet mills is calculated as per Equation H-4 based on weekly DDG production figures (assuming 50 weeks of operation per year).

#### Equation H-4

$$E_{\text{ElectricityPellet Mill}} = m_{14} * \frac{\left(\frac{m_{14}}{50} * (-0.7275) + 35.4\right)}{1000} \left(\frac{MWh_e}{a}\right)$$

#### H.2.4. Electrical Energy Consumption: MVR Units

Electrical energy consumption was calculated for the 2 MVR units operating at the distillery for the production of syrup from thin stillage and centrifuge liquor. Data on real power consumption for MVR1 was obtained for the period 01/05/2018 to 01/05/2019. Data on real power consumption for MVR2 was obtained for the period 01/05/2019. Hourly energy consumption was calculated using the trapezoidal rule for each of the MVR units, hourly values were summed within each day to obtain the daily electrical energy consumption of each MVR unit.

Syrup production volumes from MVR1 and MVR2 were calculated using data flowmeters. Flow data for each of the flowmeters was used to obtain hourly syrup flow from each MVR unit using the trapezoidal rule. Hourly flows within a day were summed to obtain daily syrup flow from each MVR.

The total electrical energy consumption of MVR1 and MVR2 was 5,132 MWh<sub>e</sub> and 1,263 MWh<sub>e</sub> respectively. The electrical energy consumption of MVR1 is higher owing to the fact that it was in operation for a longer period of time than MVR2 which was newly installed in 2018.

The specific daily electrical energy consumption of each MVR unit per m<sup>3</sup> of syrup produced is shown in Figure H-6. MVR displays a clear reduction in specific energy consumption with an increase in volumetric syrup production, the same trend is not visible for MVR2. This could be due to the fact that MVR2 is a new unit and operated under a start-up condition for longer than MVR1. The average specific electrical energy consumption of MVR1 was found to be 140 kWh/m<sup>3</sup>, MVR2 had an average electricity consumption of 91 kWh/m<sup>3</sup>, while both systems combined has an average electrical energy consumption of 127 kWh/m<sup>3</sup> of syrup produced. A first order exponential model was fitted to the combined specific energy consumption of the MVR units with respect to the daily mass of syrup produced using Matlab (scale = 327.6, exponent = -0.006033, aR<sup>2</sup>=7192), results are shown in Figure H-6.

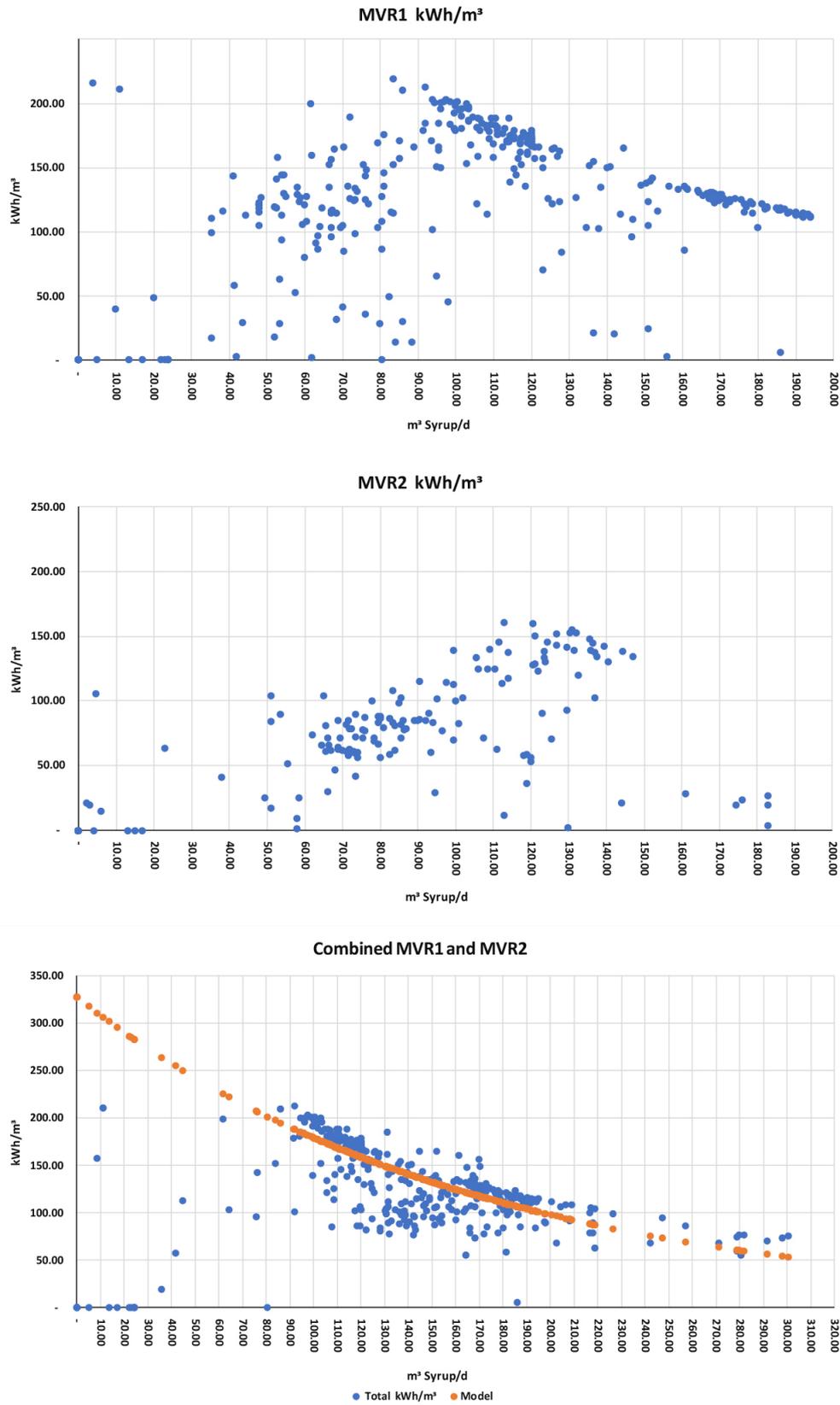


Figure H-6. MVR Specific Electrical Energy Consumption.

Additional data was sourced for MVR1 and MVR2 based on the volume of thin stillage and centrate that was processed by each MVR. Flow data for each of the flowmeters was used to obtain hourly thin stillage and centrate flow to each MVR unit using the trapezoidal rule. Hourly flows within a day were summed to obtain daily thin stillage and centrate flow to each MVR.

The specific electricity consumption per m<sup>3</sup> of thin stillage and centrate processed by each MVR unit was calculated based on the daily volume processed by each MVR unit. Linear models were fit to the resulting data using the Matlab curve fitting toolbox, results for MVR1 (Intercept: 6.67, slope: 0.008581, aR<sup>2</sup>: 0.7809) and MVR2 (Intercept: 1.72, slope: 0.008061, aR<sup>2</sup>: 0.7658) are shown in Figure H-7.

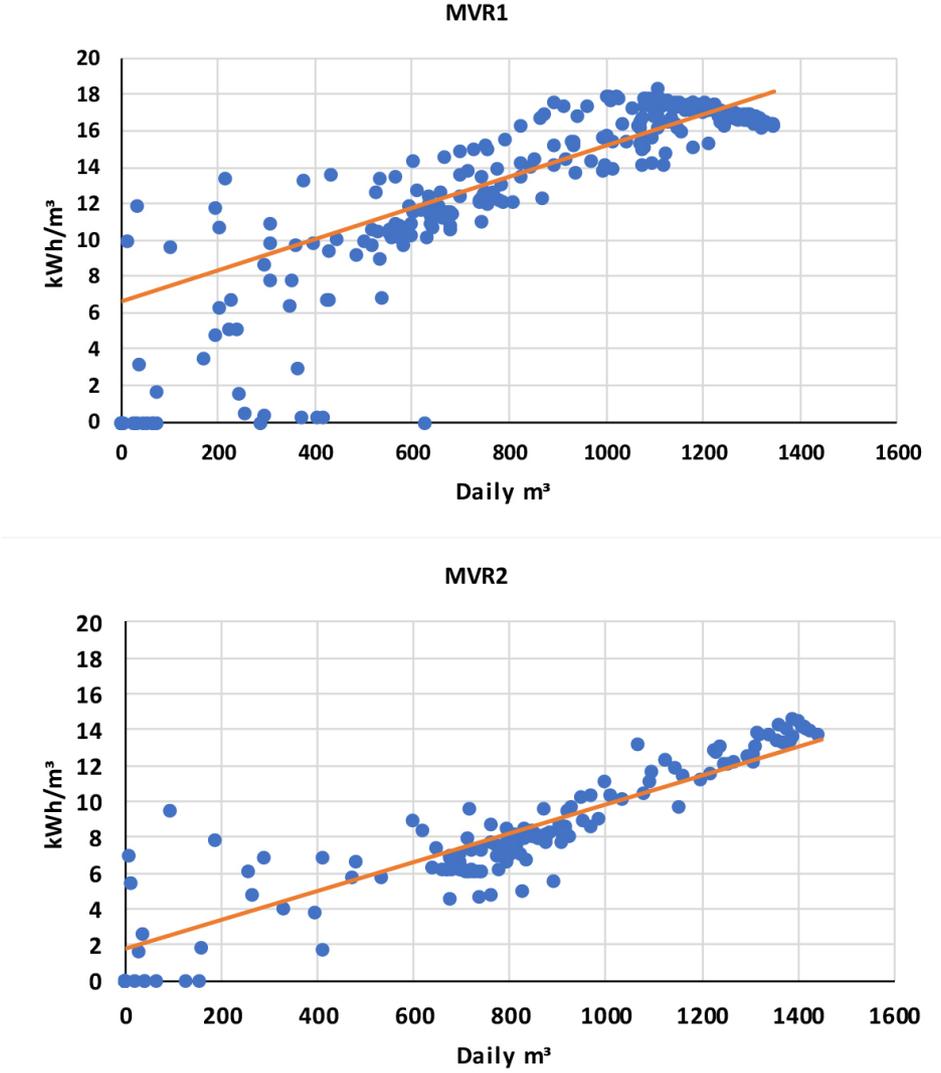


Figure H-7. Specific Energy Consumption of MVR1 and MVR2.

The annual average specific electricity consumption of MVR1 was 16.369 kWh/m<sup>3</sup> of input thin stillage and centrate, the annual average specific electricity consumption of MVR2 was 9.9 kWh/m<sup>3</sup> of input thin stillage and centrate. The total volume of thin stillage and centrate processed by MVR1 was 313,490 m<sup>3</sup>, the total annual volume processed by MVR2 was 127,429 m<sup>3</sup>. Therefore, 71% of thin stillage and centrate was processed by MVR1, while 29% of thin stillage and centrate was processed by MVR2.

Annual electricity consumption of the MVR units was calculated based on the daily volume of thin stillage and centrate processed by each MVR unit. It was assumed that 79% of thin stillage and centrate was processed by MVR1 and 29% was processed by MVR2 (as outlined in Appendix G). The total electricity consumption of both MVR units was calculated as per Figure H-5.

Equation H-5

$$E_{Electricity_{MVR}} = \frac{\left(m_B * \frac{0.71}{365-14} * 0.008581 + 6.67\right)}{1000} + \frac{\left(m_B * \frac{0.29}{365-14} * 0.008061 + 1.72\right)}{1000} \left(\frac{MWh_e}{a}\right)$$

**Appendix I: Feeds Recovery Plant Energy Savings**

Nomenclature	Description	Unit
$m_{DDG_{Baseline}}$	Mass of distillers dried grains (DDG) produced in baseline scenario	kg
$SE_{DDGDrier_{Thermal}}$	Specific thermal energy demand to dry DDG	MWh/t
$E_{Natural Gas_{Feeds}}$	Avoided natural gas demand to produce steam used in feeds recovery plant	MWh/a
$\eta_{boiler}$	Boiler efficiency	%
$E_{Gas_{DDG}}$	Natural gas demand to produce DDG in scenario assessed	MWh/a
$m_{CO_2_{Feeds}}$	Mass of CO <sub>2</sub> eq associated with animal feed production	kgCO <sub>2</sub> eq
$SE_{CO_2}$	Specific CO <sub>2</sub> eq emission of natural gas	kCO <sub>2</sub> eq/MWh
$m_{TK_{Baseline}}$	Mass of thick stillage available in baseline scenario	kgwwt
$SE_{Centrifuge}$	Specific energy consumption of the centrifuge	kWh/m <sup>3</sup>
$SE_{Drier}$	Specific energy consumption of the dryer	kWh/t
$SE_{Pellet}$	Specific energy consumption of the pellet forming machine	kWh/t
$SE_{MVR1}$	Specific energy consumption of the mechanical vapour recompression (MVR) unit 1	kWh/m <sup>3</sup>
$SE_{MVR2}$	Specific energy consumption of the mechanical vapour recompression (MVR) unit 2	kWh/m <sup>3</sup>

**I.1. Thermal Energy Savings**

The thermal energy reduction when the AD plant is operational is calculated based on the current thermal energy consumption of the feeds recovery plant processing the current mass of DDG produced ( $m_{DDG_{Baseline}}$ ), the specific thermal energy consumption of the driers ( $SE_{DDGDrier_{Thermal}}$ ), minus the reduced thermal energy consumption of the feeds recovery plant when the AD plant is operational. The avoided natural gas consumption when the feeds recovery plant no longer operates ( $E_{Natural Gas_{Feeds}}$ ) is calculated using [Equation I-1](#).

**Equation I-1**

$$E_{Natural Gas_{Feeds}} = \frac{m_{DDG_{Baseline}} * SE_{DDGDrier_{Thermal}}}{\eta_{boiler}} - E_{Gas_{DDG}}$$

The reduction in GHG emissions associated with avoided natural gas consumption in the feeds recovery plant is calculated using the specific CO<sub>2</sub>eq emission factor for natural gas ([Eq. I-2](#)).

**Equation I-2**

$$m_{CO_2_{Feeds}} = E_{Natural Gas_{Feeds}} * SE_{CO_2}$$

**I.2. Electrical Energy Savings**

The reduction in electrical energy consumption of the feeds recovery plant is the difference between baseline electrical electricity consumption and the electricity consumption of the feeds recovery plant when a given share of by-products are used in a potential AD plant. Baseline electricity consumption of the centrifugal processing of thick stillage is calculated based on the current throughput of thick stillage ( $m_{TK_{Baseline}}$ ) and the specific electricity consumption of the centrifuge ( $SE_{Centrifuge}$ ). Base line electricity consumption of the DDG driers is calculated based on the current mass of DDG processed and the specific electricity consumption of the drier ( $SE_{Drier}$ ). Baseline electrical energy consumption of the pellet mill is calculated based on the current mass of DDG processed and the specific electricity consumption of the pellet mill ( $SE_{Pellet}$ ). Baseline electricity consumption of the MVR units is calculated using the current volume of thin stillage and centrate processed, the share of thin stillage and centrate sent to each MVR unit, and the specific energy consumption of each MVR unit ( $SE_{MVR1}$ ,  $SE_{MVR2}$ ).

## Appendix J: Animal Feed Replacement Calculation

Nomenclature	Description	Unit
$\Delta Protein_{Moist\ Grain}$	Difference in protein production between scenario and baseline contained in moist grains	kg
$m_{Moist\ Grain_{BASE}}$	Mass of moist grains in baseline	kg
$X_{DM_{Moist\ Grain}}$	Dry matter content of moist grains	%
$X_{CP_{Moist\ Grain}}$	Crude protein content of moist grains	%DM
$m_7$	Mass of moist grain exported from the distillery	kgwwt
$X_{DM_7}$	Dry matter content of exported moist grains	kgwwt
$X_{CP_7}$	Crude protein content of exported moist grains	%DM
$\Delta UFL_{Moist\ Grain}$	Difference in UFL production between scenario and baseline contained in moist grains	UFL
$UFL_{Moist\ Grain}$	UFL in moist grain	UFL
$UFL_7$	UFL in exported moist grain	UFL
$\Delta Protein_{DDG}$	Difference in protein production between scenario and baseline contained in dried distillers grains (DDG)	kg
$m_{DDG_{BASE}}$	Mass of DDG in baseline	kgwwt
$X_{DM_{DDG}}$	Dry matter content of DDG	%
$X_{CP_{DDG}}$	Crude protein content of DDG	%DM
$m_{14}$	Mass of DDG produced	kgwwt
$X_{DM_{14}}$	Dry matter content of DDG produced	%
$X_{CP_{14}}$	Crude protein content of DDG produced	%DM
$\Delta UFL_{DDG}$	Difference in UFL production between scenario and baseline contained in DDG	UFL
$UFL_{DDG}$	UFL in DDG in baseline	UFL
$UFL_{14}$	UFL in DDG in scenario	UFL
$\Delta Protein_{Syrup}$	Difference in protein production between scenario and baseline contained in syrup	kg
$m_{Syrup_{BASE}}$	Mass of syrup in baseline	kgwwt
$X_{DM_{Syrup}}$	Dry matter of syrup	%
$X_{CP_{Syrup}}$	Crude protein content of syrup	%DM
$m_{12}$	Mass of syrup exported from site in scenario	kgwwt
$X_{DM_{12}}$	Dry matter content of syrup in scenario	%
$X_{CP_{12}}$	Crude protein content of syrup in scenario	%DM
$\Delta UFL_{Syrup}$	Difference in UFL production between scenario and baseline contained in syrup	UFL
$UFL_{Syrup}$	UFL in syrup in baseline	UFL
$UFL_{12}$	UFL I syrup in scenario	UFL
$m_{AF}$	Mass of imported animal feed "AF"	kgwwt
$CP_{AF}$	Crude protein content of imported animal feed "AF"	kg/kgwwt
$UFL_{AF}$	UFL content of imported animal feed "AF"	UFL/kgwwt

The shortfall in energy and protein in the case of Moist Grains can be calculated using [Equation J-1](#).

## Equation J-1

$$\Delta Protein_{Moist\ Grain} = m_{Moist\ Grain_{BASE}} \cdot \frac{X_{DM_{Moist\ Grain}}}{100} \cdot \frac{X_{CP_{Moist\ Grain}}}{100} - m_7 \cdot \frac{X_{DM_7}}{100} \cdot \frac{X_{CP_7}}{100}$$

$$\Delta UFL_{Moist\ Grain} = m_{Moist\ Grain_{BASE}} \cdot UFL_{Moist\ Grain} - m_7 \cdot UFL_7$$

In the case of DDG, the loss of energy and protein can be expressed as per [Equation J-2](#).

## Equation J-2

$$\Delta Protein_{DDG} = m_{DDG_{BASE}} \cdot \frac{X_{DM_{DDG}}}{100} \cdot \frac{X_{CP_{DDG}}}{100} - m_{14} \cdot \frac{X_{DM_{14}}}{100} \cdot \frac{X_{CP_{14}}}{100}$$

$$\Delta UFL_{DDG} = m_{DDG_{BASE}} \cdot UFL_{DDG} - m_{14} \cdot UFL_{14}$$

For syrup, the shortfall in protein and energy can be calculated using Equation J-3.

**Equation J-3**

$$\Delta Protein_{Syrup} = m_{SyrupBASE} \cdot \frac{X_{DM_{Syrup}}}{100} \cdot \frac{X_{CP_{Syrup}}}{100} - m_{12} \cdot \frac{X_{DM_{12}}}{100} \cdot \frac{X_{CP_{12}}}{100}$$

$$\Delta UFL_{Syrup} = m_{SyrupBASE} \cdot UFL_{Syrup} - m_{12} \cdot UFL_{12}$$

The mass of imported animal feed ( $m_{AF}$ ) required to replace the total reduction in energy and protein output from the feeds recovery plant when a portion of distillery by-products are used in an AD plant can be calculated using Equation J-4. The goal of the optimisation model was to minimise the required mass of imported animal feeds.

**Equation J-4**

$$\min \sum_{AF=1}^{n_{AF}} m_{AF}$$

$$s. t. \begin{cases} \sum_{AF=1}^{n_{AF}} m_{AF} \cdot CP_{AF} = \Delta Protein_{Moist\ Grain} + \Delta Protein_{DDG} \Delta Protein_{Syrup} \\ \sum_{AF=1}^{n_{AF}} m_{AF} \cdot UFL_{AF} = \Delta UFL_{Moist\ Grain} + \Delta UFL_{DDG} + \Delta UFL_{Syrup} \end{cases}$$

**Appendix K: GHG emissions associated with the production of imported replacement animal feed**

Nomenclature	Description	Unit
$SE_{CO_2AF_j, Country i}$	Specific CO <sub>2</sub> eq emissions from the production of animal feed (AF) type “j” in country “i”	kgCO <sub>2</sub> /kgwwt
$AF_j$	Animal feed type “j”	Na
$Country i$	Country “i”	Na
$m_{Production CO_2AF_j}$	Mass of CO <sub>2</sub> eq emissions from the production of animal feed (AF) type “j” in country “i”	kgCO <sub>2</sub> eq
$n_{Country}$	Number of countries	Na
$n_{AF}$	Number of animal feed types	Na

The three largest feed types by mass in each year (in no order) from 2011 to 2018 are;

- Brewing or distilling dregs and waste.
- Oilcake and other solid residues from the extraction of soya-bean oil.
- Maize stalks, maize leaves, fruit peel and other vegetable materials, waste, residues and by-products for animal feeding.

From 2013 to 2018 the fourth largest source of feed by mass was: Residues from the manufacture of starch from maize, of a kind used in animal feeding (excl. dog or cat food put up for retail sale).

The single largest type of animal feed imported varies between years; in 2010, 2011, 2014 and 2015 the largest source of feed was oilcake and other solid residues from the extraction of soya-bean oil. In 2012 and 2013 maize stalks, maize leaves, fruit peel and other vegetable materials, waste, residues and by-products for animal feeding, was the main feed imported. In 2016, 2017, 2018 brewing or distilling dregs and waste was the single largest feed type imported by mass.

The use of these feed types cannot be determined from the data sourced from the CSO.

From initial inspection it would appear that the majority of feed imported is suitable for cattle, whether the feed is used in beef production or in the dairy sector is not yet known.

The two main countries from which feed is imported into Ireland are the USA and Argentina, the USA was the main source of imported in feed in all years from 2010 to 2018, with the exception of 2012 in which Argentina was the largest source of imported feed. In total. Between 40% and 50% of all animal feed imported into Ireland was sourced from the USA and Argentina. The USA provided between 17-29% of animal feed imports to Ireland while Argentina provided between 15-24% of animal feed imports to Ireland.

The regions from which the third and fourth most feed was imported from between 2013 and 2018 were Northern Ireland and Great Britain.

The GHG emissions ( $SE_{CO_2AF_j, Country i}$ ) associated with the production of each imported animal feed ( $AF_j$ ) in a given country ( $Country i$ ) was sourced from literature (Blonk and Paassen, 2018). The GHG emission values associated with the production of imported feeds used in this work are shown in [Table K-1](#).

**Table K-1.** GHG emissions associated with imported feed production.

Imported Feed	Country	kgCO <sub>2</sub> eq/kg Product - Excluding Land Use Change
Brewing or distilling dregs and waste	RER	1.010023831
Brewing or distilling dregs and waste	USA	0.949292199
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	AR	0.285383355
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	GLO	0.286887048
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	UK	0.325435996
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	AR	0.567626764
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	GLO	0.570617492
Oilcake and other solid residues resulting from the extraction of soya-bean oil – Soyabean hulls	UK	0.647291226
Residues from the manufacture of starch from maize of a kind used in animal feeding	GLO	1.660244515

AR: Argentina, RER: Europe, USA: United States of America, GLO: Global, UK: United Kingdom of Great Britain and Northern Ireland

**Table K-2.** Share of imported feed from each country.

Brewing or distilling dregs and waste		Oilcake and other solid residues resulting from the extraction of soya-bean oil		Residues from the manufacture of starch from maize of a kind 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		
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				

The total GHG emissions associated with the production of imported animal feeds ( $m_{production\ CO_2AF_j}$ ) are calculated based on the mass of animal feed imported from each country, and the specific GHG emissions associated with the production of animal feed in each country (Eq. K-1).

**Equation K-1**

$$m_{Production\ CO_2AF_j} = \sum_{j=1}^{n_{AF}} \left( m_{AF_j} * \sum_{i=1}^{n_{Country}} \left( AF_{j,Country\ i} * SE_{CO_2AF_j,Country\ i} \right) \right)$$

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**Appendix L: Transportation of Imported Animal Feed**

Nomenclature	Description	Unit
$SE_{CO_2road}$	Specific CO <sub>2</sub> eq emissions from road transportation	kgCO <sub>2</sub> eq/t.km
$SE_{CO_2ship}$	Specific CO <sub>2</sub> eq emissions from ship transportation	kgCO <sub>2</sub> eq/t.km
$SE_{CO_2barge}$	Specific CO <sub>2</sub> eq emissions from barge transportation	kgCO <sub>2</sub> eq/t.km
$SE_{CO_2rail}$	Specific CO <sub>2</sub> eq emissions from rail transportation	kgCO <sub>2</sub> eq/t.km
$m_{Transport CO_2AF_j}$	Total mass of CO <sub>2</sub> eq emissions associated with transportation of animal feed type “j”	kgCO <sub>2</sub> eq

Distances for each mode of transportation for imported feed products are based on prior work by the authors and are outlined in [Table L-1](#).

**Table L-1.** Transportation distances for imported feed.

Origin	Destination	Road (km)	Rail (km)	Barge (km)	Maritime Ship (km)	Reference
IE	IE	58	1	-	0	Prior Work
AR	IE	-	-	-	16147	Prior Work
CA	IE	-	-	-	4578	Prior Work
NL	IE	-	-	-	1163	Prior Work
SE	IE	-	-	-	2719	Prior Work
UK	IE	-	-	-	441	Prior Work
US	IE	-	-	-	5700	Prior Work
VN	IE	-	-	-	17455	Prior Work
PY	IE	-	-	-	16147	Prior Work
AR	AR	410	80	-	10	Prior Work
BR	BR	867	477	-	101	Prior Work
US	US	182	619	1019	-	Prior Work
NL	NL	56	2	19	-	Prior Work
SE	SE	92	39	-	-	Prior Work
UK	UK	84	11	-	-	Prior Work
CA	CA	1096	0	-	-	Prior Work
VN	VN	-	-	-	-	Prior Work
PY	PY	-	-	1637	-	Prior Work

For the purposes of this project, the CO<sub>2</sub>eq emissions associated with the road transportation of freight ( $SE_{CO_2road}$ ) will be 0.1878 kgCO<sub>2</sub>eq/t.km (prior work). Emissions associated with return journeys shall be equal to 20% of the total emissions associated with the transportation of freight by road (prior work). The CO<sub>2</sub>eq emissions associated with sea transportation of goods ( $SE_{CO_2ship}$ ) used in this work will be 0.00544 kgCO<sub>2</sub>eq/t.km (prior work). The CO<sub>2</sub>eq emissions associated with the transportation of goods by inland vessels ( $SE_{CO_2barge}$ ) are 0.0188 kgCO<sub>2</sub>eq/t.km (prior work). Rail transportation ( $SE_{CO_2rail}$ ) was assumed to result in the emission of 0.0304 kgCO<sub>2</sub>eq/t.km in The Netherlands (prior work). The GHG emissions associated with the transportation ( $m_{Transport CO_2AF_j}$ ) 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 ([Eq. L-1](#)).

**Equation L-1**

$$m_{Transport CO_2AF_j} = \sum_{j=1}^{n_{AF}} \left( m_{AF_j} * AF_{jCountry} * \left( d_{roadAF_j} * SE_{CO_2road} + d_{railAF_j} * SE_{CO_2rail} + d_{bargeAF_j} * SE_{CO_2barge} + d_{shipAF_j} * SE_{CO_2ship} \right) \right)$$

**Appendix M: Compromise Programming**

Nomenclature	Description	Unit
$x_j$	Input criteria values	Na
$f(x_j)$	Total multi-criteria decision analysis (MCDA) problem	Na
$f_i(x_j)$	Individual functions of each input criteria	Na
$f_i$	Function “i”	Na
$f_i^{IDEAL}$	Ideal solution for function “i”	Na
$f^{IDEAL}$	Ideal solution to total MCDA problem	Na
$f^{OPT}$	Optimal solution to total MCDA problem	Na
$f^{NADIR}$	Nadir solution to total MCDA problem	Na
$f_i^{NADIR}$	Nadir solution for function “i”	Na
$d_i(x_j)$	Degree of closeness of solution for function “i” to the ideal solution	Na
$p$	Power	Na
$w$	Criterion weight (implies relative importance of criterion)	Na
$f(x^{UTOPIA})$	Utopia solution to total MCDA problem	Na
$f(x_j)$	Non-utopian solution	Na
$r$	Regret, distance between non-utopian and utopian solutions to the MCDA problem	Na
$f(x^{REF})$	Reference point solution to total MCDA problem	Na

The method of compromise programming was initially proposed by Zeleny in the 1970’s (Zeleny, 1974; Zeleny, 1976), the purpose of compromise programming is to allow a decision maker to come to an informed decision based on a large number of potential solutions, comparing each solution based on often conflicting criteria. This method is seen as a solution to the problem faced by decision makers in relation to the comparison of multiple alternatives with multiple criteria. The method is based on the identification of an “ideal” solution that is generally infeasible, the identification of a “nadir” solution (again infeasible), and the use of these to aid in the selection of an “optimal” solution which is furthest from the nadir and closest to the ideal.

Compromise programming is used to compare different solutions, each of which have multiple criteria, based on differing input values ( $x_j$ ). The total MCDA problem ( $f(x_j)$ ) is comprised of individual functions for each criterion ( $f_i(x_j)$ ). The initial step of the compromise programming approach is to identify the ideal solution for each individual criteria ( $f_i$ ) expressed as  $f_i^{IDEAL}$ , which combined provide the ideal solution to the total MCDA problem  $f^{IDEAL}$ . This ideal solution is not possible, it is infeasible owing to the conflicting nature of each of the individual criteria functions. Therefore, the goal of the decision maker is to identify the feasible solution that is as close to the infeasible ideal solution as possible, this is referred to as the optimal solution  $f^{OPT}$ . Additionally, the decision maker wants to identify an optimal solution that is as far away as possible from the nadir solution of the MCDA problem. The nadir solution of the total MCDA problem,  $f^{NADIR}$ , can be identified by finding the most non ideal solutions for each of the individual functions forming the total MCDA problem  $f_i^{NADIR}$ .

The degree of closeness ( $d_i(x_j)$ ) of an individual function,  $f_i(x_j)$ , to the ideal solution if said function,  $f_i^{IDEAL}$ , can be expressed knowing the ideal and nadir solutions to  $f_i$  as per Equation M-1.

**Equation M-1**

$$d_i(x_j) = \frac{|f_i^{IDEAL} - f_i(x_j)|}{|f_i^{IDEAL} - f_i^{NADIR}|}$$

Division by the difference between the ideal and nadir solutions allows for normalisation of the distance from a given solution for a given criteria function to the ideal of said criteria function on a scale of 0 to 1. It is evident that the ideal solution would result in a degree of closeness of 0. The use of geometric distance for the expression of the degree of closeness for MCDA problems was proposed by Zeleny (1974) and is based on  $L_p$ -metrics as per Equation M-2.

**Equation M-2**

$$L_p(x_j) = \left[ \sum_{i=1}^n \left( \frac{f_i^{IDEAL} - f_i(x_j)}{f_i^{IDEAL} - f_i^{NADIR}} \right)^p \right]^{1/p}$$

$1 \leq p \leq \infty$

Owing to the fact that not all criteria are of equal importance, a general form of Equation M-2 can be generated accounting for the relative degrees of importance ( $w_i$ ) of each individual criteria  $f_i$  as per Equation M-3.

**Equation M-3**

$$L_p(x_j) = \left[ \sum_{i=1}^n w_i^p \left( \frac{f_i^{IDEAL} - f_i(x_j)}{f_i^{IDEAL} - f_i^{NADIR}} \right)^p \right]^{1/p}$$

$1 \leq p \leq \infty$

$\sum_{i=1}^n w_i = 1$

The impact of the “p” metric according to Zeleny (1974) is that as “p” increases from 1 to infinity, greater weight is given to larger deviations from the ideal solution. At the point when “p” equals infinity the problem reduces to a minimisation of the maximum deviation in  $d_i$ .

Please cite this article as: O’Shea R., Lin R., Wall D.M., Browne J.M., Murphy J.D. Distillery decarbonisation and anaerobic digestion: balancing benefits and drawbacks using a compromise programming approach. Biofuel Research Journal 31 (2021) 1417-1432. DOI: [10.18331/BRJ2021.8.3.2](https://doi.org/10.18331/BRJ2021.8.3.2)

The concept of compromise programming is also described by Yu (1985) in which the “ideal” point is also referred to as the “utopia” point ( $f(\underline{x}^{UTOPIA})$ ) owing to its unattainable nature. Owing to the fact that this “utopia” point is unattainable, some compromise between the individual criteria functions is required. Yu (1985) proposes that the “regret” resulting from the use of a non-utopian solution ( $f(\underline{x}_j)$ ) can be approximated as the distance between  $f(\underline{x}^{UTOPIA})$  and  $f(\underline{x}_j)$ ;

**Equation M-4**

$$r(f(\underline{x}_j)) = \|f(\underline{x}_j) - f(\underline{x}^{UTOPIA})\|$$

Where  $r(f(\underline{x}_j))$  is typically a  $L_p$  norm, the general expression of which is;

**Equation M-5**

$$r(f(\underline{x}_j); p) = \left[ \sum_{i=1}^n (f(\underline{x}_j) - f(\underline{x}^{UTOPIA}))^p \right]^{\frac{1}{p}}$$

The aim of compromise programming is to minimise the regret function in order to come to an agreeable compromise solution (Yu, 1985). The regret function is similar to the degree of closeness outlined previously by Zeleny (1974 and 1976). Alteration of the value of “p” used will result in different solutions. The regret function given in Equation M-4 assumes that the deviation of each criterion from its optimal value are all equally important. If the criteria are not equally important then a set of weights, ( $w_i$ ) can be applied to the criteria;

**Equation M-6**

$$r(f(\underline{x}_j); p, w) = \left[ \sum_{i=1}^n w_i^p (f(\underline{x}_j) - f(\underline{x}^{UTOPIA}))^p \right]^{\frac{1}{p}}$$

$$r(f(\underline{x}_j); p, w) = \left[ \sum_{i=1}^n (w_i f(\underline{x}_j) - w_i f(\underline{x}^{UTOPIA}))^p \right]^{\frac{1}{p}}$$

The weighted expression of regret proposed by Yu (1985) is scale dependant, as are the weights proposed to be used by Yu (1985), this differs from the non-scale dependant method proposed by Zeleny (1976) in which the regret of each individual criteria is normalised on a scale of 0 to 1 through the use of the Nadir outlined in Equation M-1.

A discussion on the use of compromise programming, also known as “the method of global criterion” is provided by Miettinen (1998) in which the method is describe as the minimisation of distance between a reference point and a feasible point. The discussion by Meittinen (1998) also makes use of an “ideal” or “utopia” point, termed the “reference point ( $f(\underline{x}^{REF})$ )” and a similar expression to the closeness or regret function used by Zeleny (1976) and Yu (1985) respectively. Normalisation of the distance between the solution in question and the reference solution is also prosed by Meittinen (1998) in the same manner as that used by Zeleny (1976) in Equation M-1. Utilisation of differing criteria weights in conjunction with “the method of global criterion” is dubbed the “method of weighted metrics” by Meittinen (1998), the formulation of the “method of weight metrics” is the same as that outlined in Equation M-6.

A further review of compromise programming was counted by Marler and Arora (2004) in which they describe compromise programming as the minimisation of distance between a potential optimal point and a utopia point using a Euclidian norm, ensuring that the objective functions are normalised, effectively the same method as Equation M-3 with  $p=2$  as outlined by Zeleny (1974 and 1976). Normalisation is recommended in order to ensure commensurable units are used in weighted a priori calculation of multi-objective optimal points, a discussion of appropriate normalisation methods is provided in additional work by Marler and Arora (2005). The recommended normalisation procedure is that of the “Upper-Lower-bound approach”, which is the same as the normalisation method used to calculate the distance value in Equation M-1 (Zelany, 1974; Zenely, 1976).

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