# Feasibility Study on Anaerobic Digestion in West Cork

**Final Report**

| Client: | Consultancy Team | Date |
|---|---|---|
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## List of Acronyms

AD: Anaerobic Digestion
CBM: compressed biomethane
$CH_4$: methane (Biomethane)
CNG: compressed natural gas
DM: dry matter
ED: electoral district
EMP: Energy Master Plan
GWh: gigawatt-hour or a million kWh
GW: gigawatt capacity
kWh: kilowatt-hour or a thousand Wh of energy
kW: kilowatt capacity
kWe: kilowatt electrical capacity
IRR: Internal Rate of Return
LCOE: Levelised Cost of Energy
MWh: megawatt-hour or a thousand kWh
MWe: megawatt electrical capacity (1,000 kWe)
$Nm^3$: normalised cubic meter
NPV: Net Present Value
RE: Renewable energy
RES-e: electricity produced from renewable energy sources
RES-heat: Heat produced from renewable energy sources
$tCO_2$: tonne of $CO_2$
$t_{DM}$: tonne of dry matter
$t_{VS}$: tonne of volatile solid
tWM: tonne of wet matter
tFM: tonne of fresh matter
TWh: Terawatt-hour, or a billion kWh

## Executive Summary

Tackling climate change requires a radical transformation of Ireland's energy system towards decarbonisation by 2050. Agriculture has a key role to play and has the opportunity to tackle its climate impact by diversifying current farming systems towards renewable energy production. The Carbery Group aims to be at the forefront of this transformation together with farmers in West Cork and has commissioned XD Sustainable Energy Consulting Ltd. to undertake a feasibility study on anaerobic digestion[1] in the region. West Cork is a rural region in the southwest of Ireland, with a population of about 115,000, and a vibrant economy grounded in agriculture, food production and tourism. The overall objective of the study is to investigate the potential for biogas production to contribute to the region's energy needs in an affordable, secure and sustainable manner.

The first step of the study was to assess the potential feedstocks available in the study area for AD, including agricultural sources (grass silage and slurry) and municipal/industrial sources of organic waste (food & fish waste, municipal sewage sludge, industrial sewage sludge, slaughter and meat processing waste). Grass silage, with slurry and manures represent the vast majority of the feedstocks potentially available. While industrial/municipal organic waste represent a lower feedstock potential, their use in AD typically attracts gate fees and contributes to local, circular waste management in the study area. The assessment concludes that the practical potential of AD feedstocks is equivalent to 400 GWh/yr. This would be sufficient to meet the needs of 20 medium-sized AD plants (20 GWh/yr biogas production) installed in a farm setting, or 10 larger (40 GWh/yr), centralised plant more likely to be in an industrial setting. It also represents 10% of the estimated energy demand in West Cork.

A detailed spatial analysis of West Cork was undertaken to identify most suitable locations for AD development using a geographical information system and considering a range of criteria including feedstocks availability, energy demand, environmental protection, land cover, road infrastructure, special amenity areas, etc. The spatial analysis indicates that areas in the environs of main urban centres on the coast (Clonakilty, Skibbereen, Kinsale) and hinterland (Bandon), as well as a number of large food processing facilities, perform best in terms of suitability due to the conjunction of energy demand, feedstock availability and infrastructure. The siting of an AD plant is a very sensitive matter that will require detailed spatial and environmental planning, and careful stakeholder engagement and consultation with the community.

The study also includes a detailed review of key sustainability considerations for the development of AD in the study area, and the associated regulatory and compliance framework. In line with the proposed model for AD development at national level, it is intended that grass silage will be sourced primarily from beef farmers who will increase their yields by boosting their grassland fertility (initially with artificial fertilisers and lime, and then maintaining it with the application of AD digestate). The advantages of switching to Multi-Species Swards from ryegrass monocrops have also been discussed.

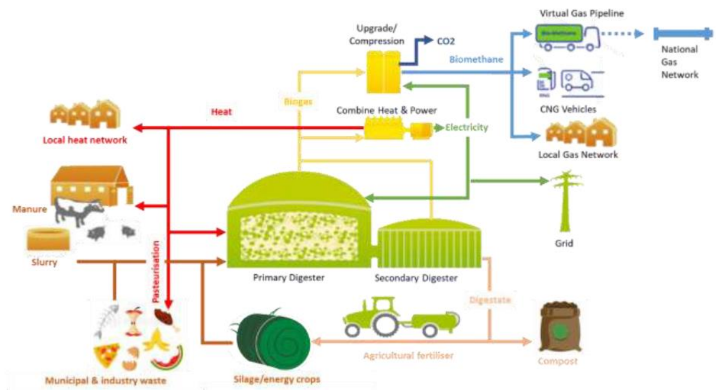
The environmental benefits of treating slurry with AD against spreading raw slurry have also been reviewed, including reducing odours, the pathogen load to the environment, and increasing the availability of nitrogen to plants. Capturing methane from slurry prevents it from being released to the atmosphere, thereby having the effect of being carbon negative and improving the overall GHG savings of the AD facility. Slurry therefore plays a key role in meeting the Revised Renewable Energy Directive's Sustainability Criteria (80% reduction in GHG emissions against fossil fuel comparators), and proposed AD project include 40% slurry in their feedstock mix. Since the slurry will have to be sourced from a number of farms in the study area, the Animal By-Products regulations will apply and require treatment with pasteurisation.

Applying the digestate as an organic fertiliser to the farmland producing the grass silage used for AD plant will help close the nutrient cycle in the project catchment area. It will also play an important role in improving the sustainability of the agricultural system underlying it. However, there are concerns relating to the potential increase in ammonia (NH3) and nitrogen oxide emissions (NO2), as well as the potential for excess phosphorus to leach into water bodies, when applying straight digestate compared to animal slurries. Managing the digestate is an important aspect of a sustainable AD project development and will require the application of appropriate application practices and a robust nutrient management plan

[1] Anaerobic Digestion (AD) is the process of breaking down organic materials to produce biogas (methane ($CH_4$) + carbon dioxide ($CO_2$)).

in conjunction with the farmers involved in the project. There is also a business case of adding a nutrient recovery system to the proposed AD projects to improve the quality of the organic fertilisers derived from the digestate, with significant added value for the environment and the project stakeholders. Finally, the potential integration of AD with grass-based biorefineries in the local agricultural sector was reviewed based on a study conducted for the Biorefinery Glas project. This indicates that the biogas produced from the digestion of a biorefinery's effluents would be sufficient to meet its energy requirements, it would not be in a position to make a net contribution to the wider energy requirements in the study area.

The next step was to analyse and compare a range of technological pathways for AD appropriate for West Cork. Biogas can be used as a renewable fuel for heat and power generation, or upgraded to compressed biomethane (CBM) to be injected into the natural gas grid, or used locally (e.g. at large industrial plants) or as a vehicle fuel.




When identifying different possible technological pathways for analysis, a number of key factors were considered: a) the implications of the animal by-product (ABP) regulations on the type of feedstock used[2], b) the energy end-use of the biogas produced, c) the potential to valorise the digestate and other products derive from the AD system (e.g. heat, food grade $CO_2$, etc.). The material and energy flows as well as the balance sheet of 11 different pathways were analysed for a standard year of operation in order to assess their viability.

The most profitable pathways involve the use of feedstocks available at no/low cost on site (slurry/manure from intensive agriculture, industrial organic waste, etc.), and/or feedstocks that are imported and attract a gate fee. Pathways that valorise by-products such as CO2, compost and excess heat, in addition to biomethane, also do significantly better. The addition of on-site CHP to cover the electricity usage of the biogas upgrading and CO2 liquefaction plants, as well as the heat demand of the digester, reduces operating costs and improve profitability.

An AD plant operating primarily on grass silage for biomethane production is less expensive to install and less complex to operate but have a poor profitability prospect without significant subsidies for the CBM produced and valorisation of by-products. Such farm-based plants are generally going to have to compress further the CBM produced and truck it to a grid injection point on the gas network or a local refuelling station to be used as a vehicle fuel. This last option requires the establishment of a local market for biomethane as a transport fuel.

Much smaller and simpler plants installed as part of a single farm with a significant herd and a milk or meat processing activity on-site where the biogas produced can be used locally, to fuel a gas-fired boiler or a CHP unit. Larger plants generate economies of scale but will need feedstocks from multiple sources and in turn will have to comply with ABP regulations in terms of feedstock treatment and administrative burden.

[2] In accordance with the EU animal by-products (ABP) legislation, feedstock materials of animal origin such as cattle slurry or food waste, are subject to stricter processing rules as opposed to AD plants utilizing solely grass silage.

The next steps in the study were to conduct further analyses of AD pathways selected by the client as most promising for development, in this case AD systems collocated with Carbery's wastewater treatment plant. The proposed AD systems include a) an AD plant to digest primarily the WWTP sludges and supply biogas to a CHP unit sized to meet the electricity requirements of the site, b) a much larger AD plant (40 GWh/yr) supplying biogas to a CHP meeting the site's electricity requirement, with the surplus biogas upgraded to CBM and exported to the nearby Carbery milk processing plant (this plant also includes CO2 liquefaction for commercialisation), c) a similar plant but without biogas upgrade. A more detailed technical assessment of the proposed systems was conducted on the basis of a preliminary design, as well as a more specific financial analysis to ascertain the viability of these potential projects. This techno-economic analysis indicates that these projects could provide a robust return on investment.

A co-operative society structure is recommended as the most appropriate business model for the development of AD in West Cork, promoting wide, democratic participation in ownership and control. It also more likely to engender local support and additional benefits for the community in terms of job creation, training and innovation, notably in terms of the green economy. Financing one or several AD projects will require combination of institutional financing instruments such as loans or debentures, as well as raising equity through community shares and subsidies. Partnership with a commercial developer is also an option in that it can bring valuable experience and financial capability, however this is likely to reduce potential dividends for the community.

## Chapter 1. Introducing the Feasibility Study

West Cork is a rural region in the southwest of Ireland, with a population of 111 thousand according to the Central Statistical Office (CSO)'s 2016 Census. The region's main urban centres are Bandon, Kinsale, Clonakilty, Bantry, Castletownbere, Skibbereen and Dunmanway. The region is renowned nationally and internationally for its scenery and its food. Agriculture and food production, together with tourism, are key pillars of the local economy.

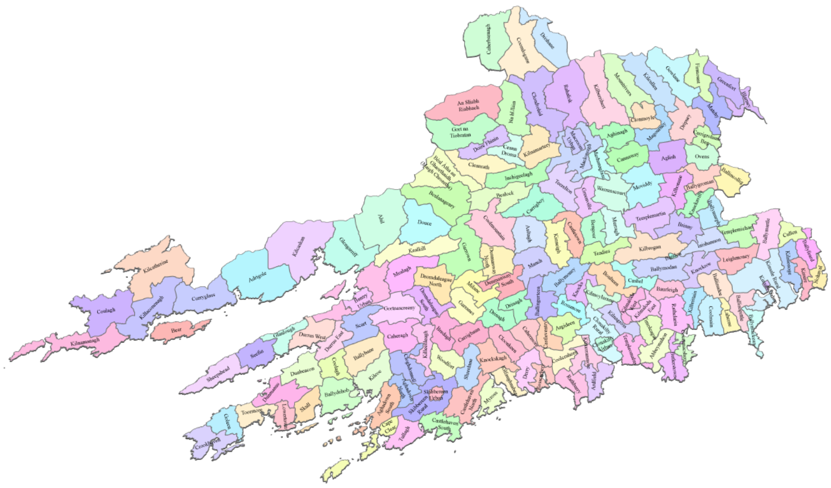


**Figure 1: Map of West Cork and its Electoral Districts.**

Climate change, with increased risks of flooding, droughts and storms, is a critical threat to the region's ecosystem and by extension its agriculture. Conversely, climate action represents real opportunities for the West Cork agri-food sector, including:

- Leveraging land as its primary asset to produce renewable energy.
- Adopting circular economy practices, using organic wastes as a valuable resource which can ultimately generate a high-quality fuel.
- Pioneering innovative, sustainable solutions to meet our national and global commitments to decarbonisation.

The Carbery Group aims to be at the forefront of this transformation together with farmers in West Cork and has commissioned XD Sustainable Energy Consulting Ltd. to undertake a feasibility study on anaerobic digestion[3] in the region. The overall objective of the study is to investigate the potential for biogas production to contribute to the region's energy needs in an affordable, secure and sustainable manner.

The specific objectives of the feasibility study are:

- To conduct a comprehensive assessment of the biomass resource available in the study area to determine their practical potential for biogas, their spatial distribution and cost.
- To initiate engagement with key stakeholders with a view to define a shared vision for anaerobic digestion and identify the core principles which should govern its development.
- To undertake a multi-criteria spatial analysis aiming to identify areas suitable for the development of anaerobic digestion plants.

[3] Anaerobic Digestion (AD) is the process of breaking down organic materials to produce biogas (methane ($CH_4$) + carbon dioxide ($CO_2$)).

- To investigate and compare suitable technical biogas pathways, from feedstock to energy end-use, considering their environmental, social and economic impacts.
- To conduct a preliminary design and a lifecycle cost analysis of selected anaerobic digestion systems based on the pathways deemed as being most feasible.
- To review business and financing models appropriate for community participation and provide the community with a roadmap for the deployment of anaerobic digestion in the region and guide the next steps for project development.

The study, funded by Gas Networks Ireland, is undertaken by XD Sustainable Energy Consulting Ltd., with a team of experts in biogas system design and engineering, advanced renewable energy systems and spatial planning.

# Chapter 2. Anaerobic Digestion Feedstocks Analysis

## A. Introduction

The objective of the feedstock analysis is to understand the potential of biogas production in the study area, based on a detailed assessment of the organic materials available, in terms of suitability for anaerobic digestion, quantities that can be practically mobilised and cost. The analysis relies on the Central Statistical Office (CSO)'s Population Census (2016) and Agriculture Census (2010), EPA licensing data for industrial sites and waste management facilities, as well as other published sources of data and information.

The following feedstocks have been analysed:

- Agricultural feedstocks: grass silage, cattle slurry, pig slurry and chicken manure.
- Municipal and industrial feedstocks: sewage sludge, food waste, fish processing waste.

## B. Agricultural Feedstocks

The following agricultural feedstocks have been considered in terms of potential for biogas:

a) **Grass silage:** forage biomass harvested and ensiled for use as winter fodder for cattle and sheep. Although silage is primarily produced as a feed, it is also an excellent feedstock for anaerobic digestion. Grass silage has a number of advantages: grass is widely available in the area, grass silage has a relatively high density and methane content, it can be transported over reasonable distances and can be stored seasonally. The disadvantages are that it is an expensive feedstock for AD, that is a key component of the existing agricultural system.
b) **Cattle slurry:** captured when the cattle are housed during the winter (typically 100 days) and generally stored under the cattle shed, or in adjacent above or below ground tanks in some cases. Cattle slurry is normally spread on land as an organic fertiliser. Its water content is high (above 90%).
c) **Poultry manure:** collected as litter or in pits, from poultry sheds housing broilers and layers.
d) Pig slurry: collected year-round on pig farms, stored in tanks or pits, and normally spread on land from February till October. Pig slurry has a high water content (typically over 95%).

Manure from sheep is not considered as practical feedstock for AD.

### 1. Grass Silage

#### a) Grass silage potential for AD in West Cork

The potential of grass silage as an AD feedstock was determined on the basis of the CSO Agricultural Census 2010 data, which provides detailed figures for crops and livestock down to the electoral division (ED) level. There are 191EDs considered part of the study area, West Cork. These electoral divisions can be seen in Figure 1 above.

A total of 329 thousand hectares were farmed in the study area, of which c.90% is grassland. Three classes of grassland are inventoried under the census: silage (82,000 ha), pasture (168,185 ha) and rough grazing (47,630 ha). The other factor affecting the potential of grass silage is grass yields. Dairy farms recording farm cover regularly on PastureBase Ireland

**Commented [EB1]:** Northern part of this area is not within the Carbery catchment. Suggest we revise this area to encompass whats under the 4 West Cork Coops.

**Commented [XD2R1]:** As discussed, the original scope was for West Cork as the study area. A specific analysis of the grass silage potential in the Carbery catchment area was conducted separately (with a slightly different approach) and the results are presented below and in the spatial analysis in chapter 3.

**Commented [EB3]:** Will be very difficult to capture this for AD in my opinion indicate average yields between 12-14 tDM/ha/year, and 10-12 tDM/ha/year for beef farmers, with West Cork showing some of the highest grass yields nationwide ( up to 17 tDM/ha/year).

Recognising that grass yields will vary in the region to reflect local conditions (soil, drainage, etc.) and grass management practices, three levels of average grass yields were assumed based on the stocking rates (heads of cattle per ha of grassland) in each electoral district:

- 12 tDM/ha/year where stocking rates are above 2.5 heads of cattle/ha, typically in EDs where dairy farming is the prominent farming enterprise.
- 8 tDM/ha/year where stocking rates are between 1.7 and 2.5 heads of cattle/ha, typically in EDs where beef farming is prominent.
- 5 tDM/ha/year where stocking rates are below 1.7, typically in EDs with low intensity farming and significant areas of rough grazing.

The potential availability of grass silage was calculated by multiplying the total area of grassland classified as 'silage' and 'pasture' in each ED, by the relevant yield figure above according the ED's stocking density. This results in a **theoretical grass availability of 2.3 million tonnes DM**, with a biomethane potential of 836 million Nm3 of biomethane (364 $Nm^3$ $CH_4/t_{DM}$) in the study area. This amount of biomethane has an energy content of 8.4 TWh/year, equivalent to the fuel used for heating close to 600 thousand homes.

In practice, all this grass is already accounted for feeding the cattle and sheep in the area, as fresh grass or silage. While silage is seen as a key feedstock for the deployment of AD in Ireland, it is relatively costly as a feedstock. Its availability will be strongly conditioned by its existing demand as a cattle feed in the winter, future changes in local agricultural systems linked to diversification in farming enterprises and/or improved grass land management, and very importantly the price farmers would receive for its supply to an AD project.

Following consultation with key stakeholders in the agricultural sector, it is assumed that most of the grass silage potentially available for anaerobic digestion would be derived from grassland where beef farming is prominent. The latest Farm Survey Results 2019 for the South-West region indicates that approximately 40% of dry cattle farms, 40% of sheep farms and 12% of dairy farms are vulnerable economically and could be incentivised to diversify towards the production of silage for biogas. Considering our analysis of stocking rates within the study area above, we assume there are circa 1836 farms in the study area that are primarily specialised in beef production, farming a total of 18,200 ha for silage and 36,000 ha as permanent pasture.

In line with the assumptions made in 'The Sustainability of Biomethane Production in Ireland' report (KPMG, Devenish, Gas Network Ireland, 2021), the technical potential of grass silage for AD in the study area has been derived by assuming that 20% of farmers primarily specialised in beef production increase their grass yields by 4 tDM/ha/year (in average from 8 to 12 tDM/ha/year) with improved grassland management and increased soil fertility (see Chapter 4.A.1). This could deliver an additional 43,400 tDM/year of silage technically available for AD. This represents a **technical potential of 15.8 million Nm3 CH4/year** with an energy content of 158 GWh/yr, equivalent to the heating fuel requirement of 11,200 homes.

#### b)**Specific assessment of the potential of grass silage in the Carbery Group catchment area**

Following a request by the members of the Carbery Group on the steering committee of this study, a more critical analysis of the potential availability of grass silage in the catchment area of the group, considering competing demand for the grass silage and likelihood of farmers to change their farming practices to supply AD plants with this feedstock. As discussed in the feedstock analysis in Chapter 2.B.1, it is anticipated that beef farmers are more likely to respond to an additional demand for silage created by the development of AD. In this context, further analysis of the CSO Agricultural Census data (2010 extrapolated to 2020) was conducted to attempt determining the spatial distribution of farm enterprises distribution in the Carbery catchment area, distinguishing electoral districts (EDs) where farming is primarily concentrated on beef farming or dairy farming. The key factor used in the statistical analysis to determine the primary specialisation of an ED was the ratio between the number of dairy cows and the number of other cows + bulls.

The results of the spatial analysis, presented in Figure 4, Chapter 3.C.2.b), indicate that beef farms are primarily located on the Western side of Carbery's catchment area. If it is again assumed that the majority of the grass silage supply for AD will come from 20% of the pasture and silage land base within EDs specialised in beef farming, where grass yields are improved by an average of 4 tonnes by improving soil fertility, the resulting grass silage potential is 26,700 tDM/yr with a biomethane potential of 9.7 million Nm3/yr or 97 GWh/yr.

## 2. Slurry and manure

### a) Cattle slurry

The theoretical potential of cattle slurry for biogas was calculated based on the numbers of cattle per type taken from the census 2010 data, extrapolated to 2020 following changes in cattle numbers at Cork County level based on the CSO livestock surveys[4]. The results have been combined with indicators of slurry production (in tonnes of fresh weight) by cattle type during the housing period (16 weeks), taken from a study by Teagasc [13], see **Error! Reference source not found. Error! Reference source not found.**.

It is also assumed that 10% of the cattle is outwintered (some dry stock and dairy replacements). The DM content of slurry was taken to be 7% and its biomethane potential as 107 $Nm^3$ $CH_4/t_{DM}$. The practical biogas potential from slurry considers that slurry loses (10%) of gases during storage. The length of time of storage of waste in tanks negatively impacts gas yields, so cattle slurry's availability will vary seasonally.

Our modelling suggests there is close to 641 thousand head of cattle in the study area that produce 194 thousand tonnes in dry weight of slurry when housed. This slurry can be harvested for anaerobic digestion purposes and potentially produce 18,700 thousand Nm3 of biomethane per year, with 187 GWh/year in energy content, equivalent to the fuel use for heating of 13,245-homes.

**Table 1: Slurry Production by cattle type.**

| Cattle Type | Head of cattle 2010 (,000) | Head of cattle 2020 (,000) | Slurry that can be captured (tonnes/year/head) | Slurry Available for AD (,000 tonnes/year) |
|---|---|---|---|---|
| Dairy Cows | 164 | 226 | 5.84 | 1187 |
| Bulls | 4 | 4 | 5.84 | 23 |
| Other Cow | 60 | 47 | 5.20 | 219 |
| Other Cattle | 345 | 364 | 4.10 | 1,344 |
| Total | **574** | **641** | | **2,773** |

### b) Pig slurry

The agricultural census doesn't provide a head count of pigs reared in the study area. Two other sources were used to obtain an estimate of the biomethane potential arising from the pig slurry produced locally:

- The Annual Environmental Reports (AERs) for pig production facilities were sourced from the Environmental Protection Agency (EPA), using the most recent reports when available. A total of 7 pig production facilities were inventoried in that way, with a total count of 50,000 pigs. This inventory covers the largest pig farms in the study area.
- A previous study conducted by the author on the renewable energy potential for the Clonakilty district (Dubuisson, 2011) inventoried another 14 pig farms, with a total pig count of 35,000 unit.

Overall, it is estimated that there could be a total population 100,000 pigs in the study area, producing about an average of 100 litres of slurry per month per head. At a DM content of 3.7%, the total annual resource is estimated at 4,416 tonnes DM per year, with a biomethane potential of 0.9 million Nm3 of biomethane (9.1 GWh/yr), enough to heat 642 homes.

Please note that pig slurry has a very high water content and poor biomethane potential. Considering the volume it would occupy in a digester and the amount of heat required to maintain suitable digestion temperatures, the net energy

[4] See CSO database here: https://data.cso.ie/table/AAA10

contribution of pig slurry is very reduced. Where available locally, it can be considered as a co-substrate to digest other feedstocks such as grass silage and to compensate for the seasonality of cattle slurry.

c) **Chicken manure**

The agricultural census doesn't provide a head count of poultry reared in the study area. Two other sources were used to obtain an estimate of the biomethane potential arising from the poultry manure produced locally:

- The Annual Environmental Reports (AERs) for poultry facilities were sourced from the Environmental Protection Agency (EPA), using the most recent reports when available. Four poultry farms were inventoried in that way, with a total of 1.15 million broilers reared a year (assuming a 2-month lifecyle), producing a total of 2,100 tonnes of fresh manure (1.8 tonne per 1000 birds in average). This inventory covers the largest poultry farms in the study area.
- A previous study conducted by the author on the renewable energy potential for the Clonakilty district (Dubuisson, 2011) inventoried another 9 poultry farms, with a total 2 million birds reared per year, producing 3,691 tonnes of fresh manure.

Overall, it is estimated that there could be a total of 3.5 million birds reared per year in the study area, producing 6,300 tonnes of manure. At a DM content of 41.7%, the total annual resource is estimated at 2,630 tonnes DM per year, with a biomethane potential of 0.34 million Nm3 of biomethane (3.4 GWh/yr), enough to heat 241 homes.

Please note that chicken manure from broilers raised on a wood chips bedding is a problematic AD feedstock in that the high ammonia content of the manure isn't counterbalanced with the carbon content of the woodchips which cannot be easily digested. The more recent use of pelletised straw as bedding however has significant biogas potential as the straw in this case is relatively available carbon (it can be made even more by mechanical treatment), providing a balanced C:N ratio for digestion and potentially high gas yields per tonne of material. Litter from laying hens is very problematic due to the inclusion of substantial amounts of "grit" which settles and sets like cement in pipes and the base of digestion tanks, causing significant mechanical problems.

## C. Non-Agricultural Feedstocks

The collection and local treatment of municipal & industrial organic waste with anaerobic digestion has key benefits:

- It contributes to the circular management of organic waste, at a local level.
- It can generate revenue from the collection of gate fees for the waste management service.
- It reduces the amount of waste going to landfill and helps the region meets the legislative requirements in this regard.
- It avoids the environmental burden of traditional organic waste disposal approaches, in terms of GHG emissions, water and air emissions.

The following sections provide a preliminary inventory of municipal and industrial organic waste in the study area, based on published data.

### 1. Municipal Waste

a) **Sewage Sludge**

The practical potential for sewage has been calculated based on quantities of sewage sludge removed from wastewater treatment plants (WWTP) in the study area provided by the EPA. In total, treatment plants in the study area have the capacity to treat 99,500 population equivalents[5] (PE). Assuming these WWTPs operate at their nominal capacity year-round, it is

[5] This is a measurement of total organic biodegradable load, including industrial, institutional, commercial and domestic organic load, on a wastewater treatment plant, converted to the equivalent number of population equivalents (PE). One

estimate they would produce 12,100 tonnes of sludge, with a dry matter content of 18%. Using a biomethane potential factor of 120 $Nm^3CH4/t_{DM}$ for sewage sludge, the biomethane potential of the study area from this resource is estimated at 0.26 million $Nm^3CH4$/year, with an energy content of 2.6 GWh/yr, enough to heat 185 homes.

Please note that the practical use of WWTP sludge is extremely limited due to environmental regulations and Bord Bia's guidelines regarding use of digestates containing this waste on food-producing land - even after pasteurisation. This restricts recycling of digestate containing sewage sludge to few outlets such as forestry and energy crops.

b) **Food waste**

The treatment of food waste in anaerobic digestion is an efficient way to recover energy and nutrients from this resource and reduce CO2 emissions associated with its decomposition. There are two main sources of food waste in the study area: a) from households, b) from commercial/public streams. The total household food waste resource available was estimated using a figure of 85 kg of fresh food waste/person/yr factor (Cre, 2010) and a collection rate of 50% average between rural and urban areas (Southern Waste Region, 2017). This gives a total potential resource of 4700 tonnes of household food waste per year (1435 tDM/yr).

The average non-household source segregated organic waste collected in the South-West region during the 2011-2012 period was equivalent to 15 kg/inhabitant/yr, which gives a total potential in the study area of 1665 tonnes of fresh organic waste per year (510 tDM/yr).

Overall, the residential and non-residential food waste available in the area was estimated at 1945 tDM/yr, with a biomethane potential of 0.470 million Nm3 per year, with an energy content of 4.7 GWh/yr, enough to heat 333 homes.

## 2. Industrial waste

a) **Fish waste**

West Cork is a coastal region with a number of medium to large harbours where fish is landed. This includes Castletownbere (the second largest harbour in terms of fish landing in Ireland), Union Hall, Baltimore, Kinsale, and a number of smaller harbours. Fish waste is well suited for anaerobic digestion when co-digested with other feedstock such as food waste. It was assumed that all fish landings are processed locally and that the associated fish waste can be captured for treatment in anaerobic digesters in the study area.

According to the Sea Fisheries Protection Authority (SFPA, 2021), close to 40,000 tonnes of fish were landed in the inventoried West Cork harbours in 2019. Taking typical fish processing waste versus fish landing ratios by weight from previous studies (Nautilius Consultants Ireland, 2003) and the species distribution of fish landing in these harbours, it is estimated that a total of 12,600 tonnes of fish processing waste is available in the study area. A DM content of 32%, and a biomethane potential of 216 $Nm^3CH4/t_{DM}$ was used [22], to estimate a total biomethane potential of 0.87 million Nm3/yr in the study area, with an energy content of 8.7 GWh/yr, enough to heat 618 homes.

b) **Slaughterhouse waste**

Three slaughterhouses & meat processing plants in the study area were assessed, processing beef, pork and poultry respectively. Some slaughterhouse wastes can be used as feedstock for biodigestion, including paunch, guts, blood, etc. but should be used in modest proportions to the overall feedstock supply, due to strict regulations and the hazards of ammonia [23]. Overall, it was estimated that a total of 16,400 t of fresh waste were available across those three plants, based on EPA AER reports and previous studies (Dubuisson, 2011), with a biomethane potential of 0.80 million Nm3/yr. It is estimated that other meat processing facilities which have not been assessed specifically would have an additional biomethane potential of 0.53 million Nm3 CH4/yr. The overall biomethane potential is therefore estimated at 1.3 million Nm3/yr, with an energy content of 13.2 GWh/yr, enough to heat 950 homes.

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person is considered to generate 60g of BOD per day (BOD is the 5 day biochemical oxygen demand); and 1 PE is defined as being equivalent to 60g of BOD per day.

c) **Milk processing waste**

There are two large milk processing plants for which AERs to the EPA are available in the study area. These reports indicate that there are approximately 30,000 tonnes of fresh organic waste (whey and WWTP sludge). There is another dozen smaller milk processors producing milk, cheese and yogurts, which would share 20,000 tFM/yr of organic waste. The overall biomethane potential of these milk processing facilities adds to 0.67 million Nm3/yr, with an energy content of 6.7 GWh/yr, enough to heat 480 homes.

**Commented [EB4]:** In our case its closer to 17,500 MT

**Commented [XD5R4]:** OK. We have assumed in the pathway analysis:
Carbery Brown Sludge: 29 tFW/day
Carbery White Sludge: 19 tFW/day
Total of 17,520 tFW/yr. Please note we've taken 84%-87% methane concentration in biogas as per biogas potential test results provided.

## 3. Marine Algae

Marine algae, or seaweed, could potentially be a suitable feedstock for AD plants. Ireland also has significant seaweed resources on its coast, and the temperate oceanic climate is well suited to cultivating seaweed both naturally and through farms. The majority of seaweed harvesting in the country happens in counties Galway and Donegal, where it is used primarily for food. Seaweed is particularly suitable in combination with fish farming to recycle nutrients and increase plant growth. Some seaweed species also co-digest well with slurry, with a 2:1 ratio of seaweed to slurry being the optimum. Seaweed can be considered a third-generation biofuel source, with no land or freshwater requirements. Being third-generation, seaweed would fulfil the EU's criteria for advanced biofuels, which is required to supply 3.5% of our transport energy supply by 2030.

Despite the benefits and advantages of seaweed cultivation for AD, there are many challenges and disadvantages associated with it. It is difficult to estimate costs of wild seaweed harvesting for AD in Ireland - it is reported to cost around €50/tWM [26] and also €330/$t_{DM}$ [27]. Cultivation on fish farms would most likely be more economical, which would result in costs of around €20/tWM. However, these cost figures are optimistic and do not take initial investment costs into consideration. There is also no simple methodology to estimate the practical and economic potential for seaweed along the West Cork coastline. Wild seaweed quality varies according to season and local conditions and would require a careful harvesting plan. Salt levels in the seaweed would have to be monitored over time, as too much salt inhibits bacterial processes in AD plants. If wild seaweed were to be harvested, the impact on biodiversity would be a big issue and would have to be considered carefully. Due to the difficulties in assessing the practical potential of seaweed in West Cork, as well as the unlikelihood of it being financially viable, seaweed was not quantified as a feedstock for AD in this study. More can be read on marine algae for AD plants in **Appendix C – Potential for Algae**.

## D. Summary of AD feedstock analysis

Table 2 summarises the AD feedstock analysis in terms of quantities potentially available, the associated biomethane potential, energy content and equivalent home heating energy use.

**Table 2: Summary of biogas feedstock analysis.**

| | Feedstock Technical Potential (,000 tDM/year) | Biomethane potential (MioNm³ $CH_4$/year) | Energy potential (GWh/yr) | Equivalent home heating energy (# homes) |
|---|---|---|---|---|
| Silage | 43.4 | 15.8 | 157.9 | 11,192 |
| Cattle slurry | 194.1 | 18.7 | 186.9 | 13,245 |
| Pig slurry | 4.4 | 0.9 | 9.1 | 642 |
| Chicken manure | 2.6 | 0.3 | 3.4 | 241 |
| Sewage Sludge | 2.2 | 0.2 | 2.6 | 185 |
| Food Waste | 0.5 | 0.5 | 4.7 | 333 |
| Fish Waste | 4.0 | 0.9 | 8.7 | 618 |
| Slaughterhouse/meat processing waste | 10.1 | 1.3 | 13.2 | 939 |
| Milk processing waste | 10.1 | 0.7 | 6.7 | 476 |
| **Total** | **271** | **39.3** | **393.3** | **27,873** |

Overall, the above analysis has identified a range of AD feedstocks for which the estimated quantity available is 271 thousand tonnes in dry matter. The total biomethane potential has been estimated at 39 million Nm3, with an energy content close to 400 GWh/yr. This would be sufficient to meet the needs of 20 medium-sized AD plants (20 GWh/yr biogas production) installed in a farm setting, or 10 larger (40 GWh/yr), centralised plant more likely to be in an industrial setting. Generally, it is clear from the above analysis that agricultural feedstocks will play an important role in the production of biogas in the study area, with grass silage representing 40% of the total potential and slurry/manures another 51%.

While with a much smaller potential (1% of total potential), municipal and industrial feedstocks in the region would also play a part, as they typically attract a gate fee of between €20 and €50 per wet tonne. Further research into the potential of municipal and industrial waste from outside of the study area would be justified in terms of generating gate fee revenues for an AD plant based in West Cork.

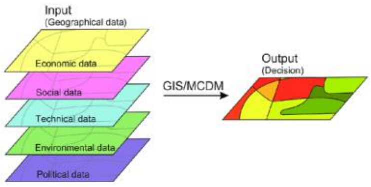
The seasonality of feedstocks must also be taken into consideration. Food waste and sewage sludge production in the study area would have a seasonality linked with the large influx of tourists as well as ramping up of some food processing during the summer months. Equally, the seasonality of slurry and silage harvesting, and storage will impact the potential material flows into AD plant(s) in the study area and this should be considered carefully in the planning of the feedstock supply logistics.

While there are no specific references on energy use in the study area, a simple calculation based on the national total energy use[6] per capita ratio of 35.3 Megawatt hour (MWh/yr) gives an estimated 3,900 GWh/yr energy use in West Cork across the whole economy (including for heat, electricity and transport). At a high level, this is promising in that the above analysis indicates that anaerobic digestion could potentially meet over 10% of the region's energy requirements, using local feedstocks to contribute to the local economy in a sustainable, circular manner. Chapter 3 will present the results of a spatial analysis of the potential for AD development in West Cork undertaken as part of the study to determine the distribution of AD feedstocks and suitable locations for AD plants. Sustainability issues pertaining to the integration of AD in the agricultural sector in terms of providing the feedstocks required will be reviewed in Chapter 4.

[6] This is the 'primary energy use' and it includes the fuels used in the production of electricity.

# Chapter 3. Spatial Multi-Criteria Analysis

## A. Introduction




The overall objective of this section of the study was to identify areas with a high degree of suitability for the location of potential AD projects, using a spatial multi-criteria analysis approach (MCA).

The key steps for the spatial MCA included:

- Identify key criteria to be considered and acquisition of relevant GIS datasets.
- Define scoring matrix for individual criteria in terms of suitability for AD development.
- Apply an overall suitability scoring system for all the parcels of land in the study area, compiling the individual criteria scoring.
- Produce a map with the overall scoring results with visual aids to help identify areas that are most suitable areas for AD development.

The spatial MCA will then enable conduct more detailed investigations on potential locations that have been shortlisted . The spatial MCA will also provide a basis to engage with the local community and key stakeholders at the early stages of potential project development.

## B. Criteria Considered

In a spatial MCA, *criteria* are defined as the set of guidelines or requirements used as basis for a decision. There are two types of criteria: *factors* and *constraints.* A *factor* is a criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration. *Constraints* serve to limit the alternatives under considerations. These are areas that are categorically unsuitable for development, and therefore are eliminated from the analysis. Various geographic layers containing information about the spatial distribution of factors and constraints relevant to siting an AD development have been sourced and form the key inputs into the analysis. These are summarised as follows:

**Table 3 Geographical layers included in the analysis.**

| Layer | Spatial Resolution | Source |
|---|---|---|
| **Total Heat Density (2015)** | 100m x 100m | Hotmaps Project (2016) |
| **Silage Potential** | ED Level | Agriculture Survey 2010 |
| **Slurry & Manure Potential** | ED Level | Agriculture Survey 2010 |
| **Municipal & Industrial Waste Potential** | Point data | Environmental Protection Agency licensed sites (2020) |
| **Land cover** | 100m x 100m | CORINE Land Cover 2018 |
| **Special areas of conservation (SACs) or special protected areas (SPAs)** | Vector Data | National Park and Wildlife Services (2019) |
| **Slope** | 90m x 90m | National Aeronautics & Space Administration (2012) |

## C. Factors

### 1. Heat Density

Heat density data was taken as a proxy to identify areas of high energy demand, where AD plants could contribute to the local energy supply. This is particularly relevant for district heating applications whereby the heat produced by an AD plant can be distributed to users in a concentrated area via a pipe network circulating hot water. An alternative would be to distribute the biomethane produced by an AD plant via an existing or newly installed gas distribution network.

Heat demand (or heat density) has been calculated for buildings in the EU28 + Switzerland, Norway and Iceland as part of the Hotmaps project[7] . The data were extracted and clipped to the bounds of the study area (Fig. 1). The total heat density ranges from 0 – 1350 MWh/(ha*year). As expected, areas of high heat demand are clustered around settlements. The heat density layer was normalised to range from 0-255 (0 = least suitable for AD development, 255 = most suitable for AD development). All mapped factors were normalised to this scale for the purpose of comparison.

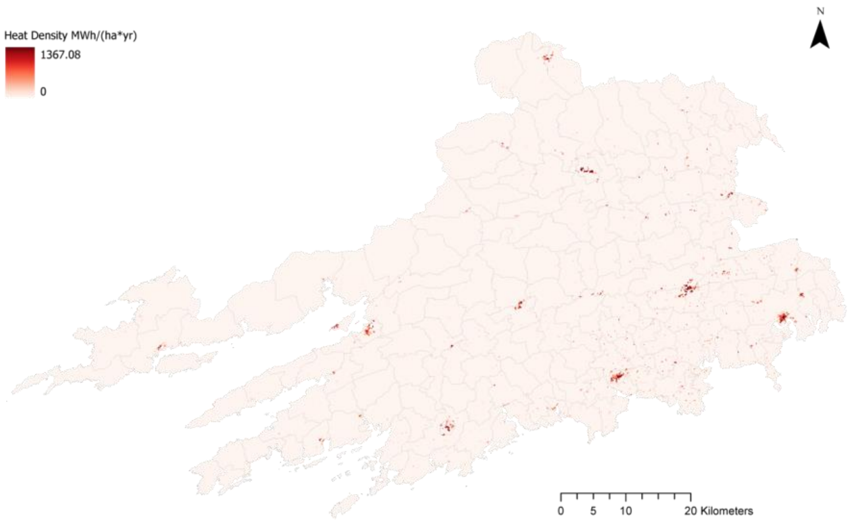



Figure 2: Heat demand in the study area. Source: Hotmaps.eu (2016)

## 2. Silage Potential

### a) The spatial distribution of grass silage in West Cork

The grass silage potential as an AD feedstock has been mapped at the ED level as part of the feedstock analysis section of the report and normalised to a scale of 0-255 for the purposes of the MCA. Silage production is concentrated in the Eastern and North-Eastern sides of the study area.

[7] EU H2020 Project: Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables). WP1 Report. 2016.

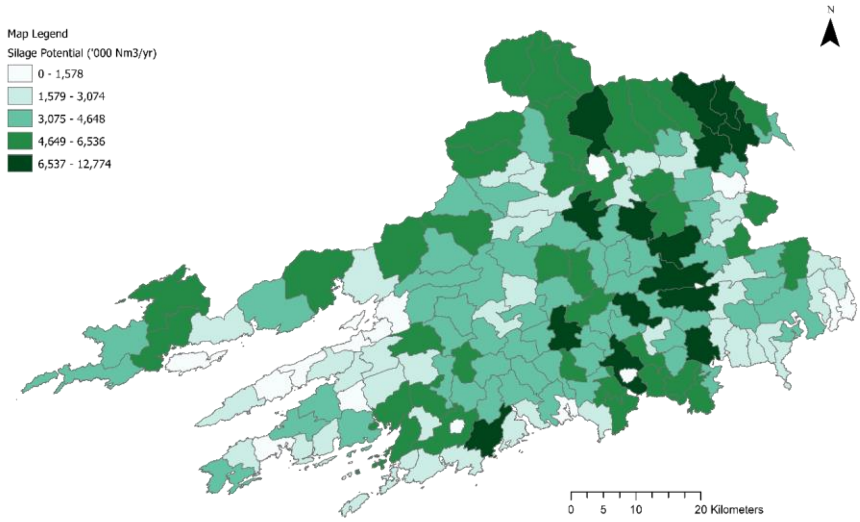



Figure 3 Silage potential per ED.

b)**A focused assessment of grass silage availability in the Carbery Catchment Area**

As discussed in Chapter 2.B.1.b), a separate spatial analysis of the potential of grass silage for AD in the Carbery Group's catchment area was conducted. This analysis attempts to distinguish EDs where farming is primarily concentrated on beef farming as it is anticipated that beef farmers are more likely to respond to an additional demand for silage created by the development of AD, than dairy farmers. The results of the statistical analysis on the ratio between the number of dairy cows and the number of other cows + bulls in a given ED were normalised to a scale of 0-255 for the purposes of the MCA and presented below in Figure 4.

This gives a contrasting picture to Figure 3 in terms of grass silage availability for AD, whereby the main potential source of silage supply to AD projects would be on the western side of the study area where the main specialisation is beef farming. This raises interesting questions with regard to the suitable location of AD plants and the logistics of delivering large quantities of grass silage to them. In the absence of high-resolution spatial data on grass silage production and farming enterprise specialisation, it is recommended that AD project developers survey farmers within a suitable radius to gain a reliable understanding of the potential supply of grass silage to the proposed plant, in terms of transport distance, quantities available and cost.

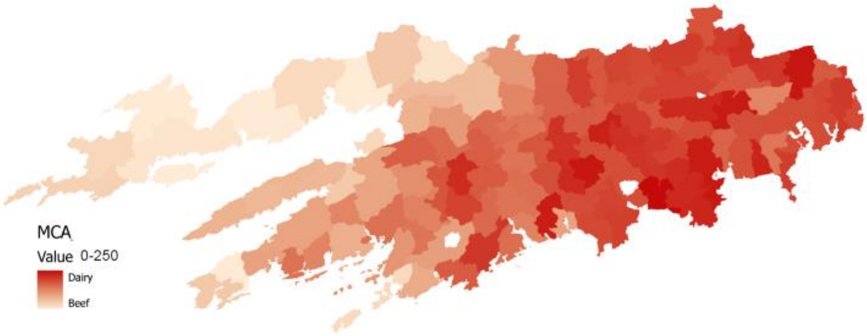



Figure 4: Distribution of farming enterprise specialisation in the Carbery catchment area.

## 3. Cattle Slurry Potential

The practical slurry potential has been mapped at the ED level as part the feedstock analysis. This factor represents the availability of slurry as a potential feedstock. The practical slurry potential layer was normalised to a scale of 0-255 for the purposes of the MCA. The ED boundary vector polygons were then converted to a raster grid with a resolution of 10m x 10m for the MCA analysis. High slurry potential is observed for Eastern and North-Eastern areas of the study region (cattle concentration naturally coincides with areas of high grass silage potential), with few EEs in Southern and Western areas of the study region also showing higher potentials for slurry. When assessing the potential for slurry and manure available for AD at a given location, this map should be looked at in conjunction with the slurry and manure potential arising from intensive agriculture sites assessed as part of the 'organic waste' map here after.

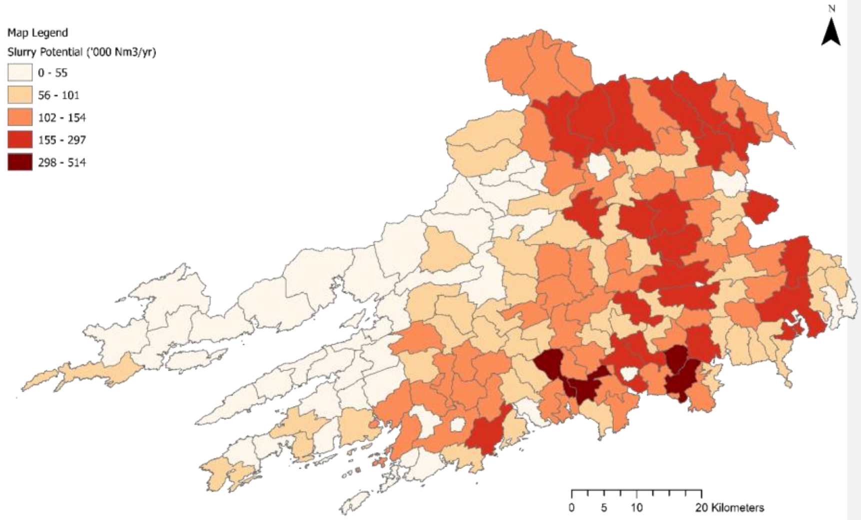



Figure 5 Practical slurry potential per ED.

## 4. Municipal/Industrial/Agricultural Organic Waste Potential

This factor represents the availability of organic waste suitable for AD arising from specific sites in three groups: municipal (wastewater treatment plants' sludge), industrial (slaughterhouses, milk and meat processing plants) and intensive agriculture (pig slurry and chicken manure). The biomethane potential of these sites were assessed as part of the feedstock analysis in chapter 2 and are represented as points in the MCA. Household and commercial/municipal food waste was assessed in the feedstock analysis in chapter 2 but not treated specifically in the spatial MCA. Its availability at a given location depends on the logistics of municipal solid waste collection in the study area, but the potential is likely to be concentrated around urban centres which can be clearly identified from land cover and the heat density maps.

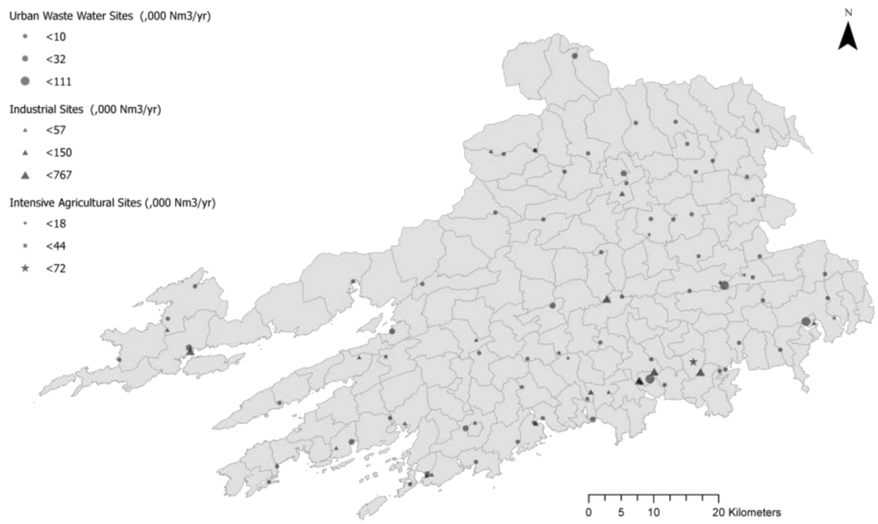



**Figure 6: Municipal/Organic waste sites**

## 5. Land cover

The land cover layer was sourced from the European CORINE Land Cover dataset for 2018. Nineteen land cover types were present within the study area. These were assigned scores (ranging from 0-255) based on their desirability as land cover types for AD development. Since these were categorical data, the scores assigned reflect the relative desirability of the different land cover types. The scores assigned to the land cover types were:

- Pastures = 255 (most desirable)
- Land principally occupied by agriculture with significant areas of natural vegetation, and natural grasslands = 255 – 25%(255) = 161
- Natural grasslands = 255 – 50%(255) = 128
- All other land cover types = not scored (neither desirable nor undesirable)

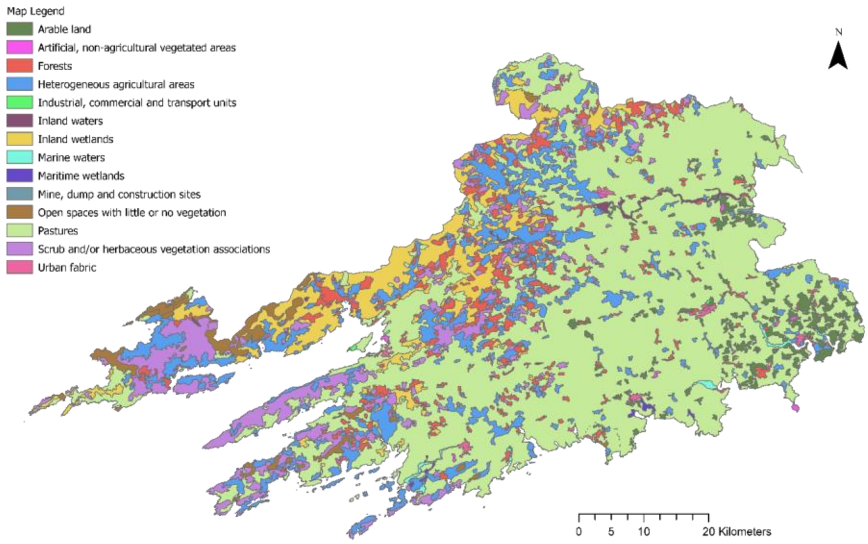



Figure 7: Land cover in West Cork. Data source: Copernicus Land Monitoring Service (2018)

## D. Protected Sites

Protected sites including special areas of conservation (SACs) and special protected areas (SPAs) were mapped from data obtained from the NPWS for 2019, see Figure 8. While development is not necessarily prohibited in these areas, it is more cumbersome. As such, the area *outside* of these areas may be considered more desirable for development. A data layer was produced representing the areas *outside* of designated sites. When performing MCA, only areas outside of the designated sites were analysed.

## E. Constraints

A constraints layer was produced to eliminate categorically unsuitable areas from the spatial MCA. Area inside the buffer of 250m around the settlements (derived from CORINE land cover) or with a slope of >15 degrees was used as constraint areas in combination with SAC and SPA designated sites. Additionally, all areas not meeting the criterion of suitable landcover was also used as constraint. The total geo-mapped area outside the constraint area was used for the MCA analysis, see Figure 9.

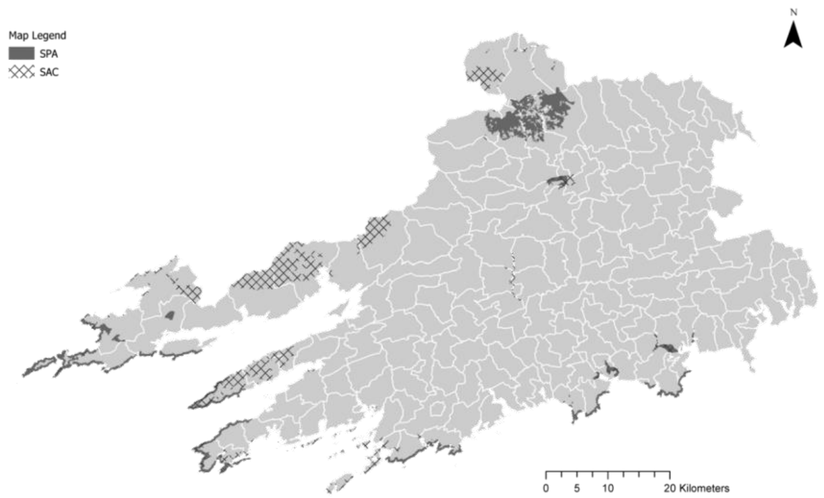



Figure 8: Protected sites. Data source: NPWS (2019)

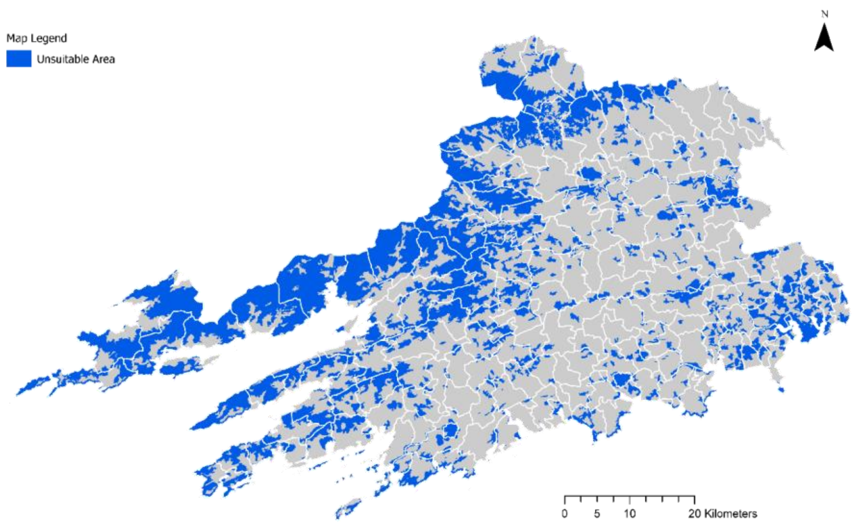



Figure 9: Constraint areas (areas excluded from spatial MCA).

## F. Performing the MCA

Using the raster calculator, the factor layers (Silage, Slurry and Landcover) were aggregated using a weighted linear combination, described mathematically as follows:

$S = \Sigma w_i x_i$x where:
$S$ = is the composite suitability score
$w_i$ = weights assigned to each factor
$x_i$ = factor scores (0-255)
$\Sigma$ = sum of weighted factors

The composite suitability score is unitless, with the highest values representing highest levels of desirability. The weights for different layers were decided based on the relative importance of the layers for planning of an AD site. We have chosen 0.4 for Silage Layer, 0.4 for Slurry layer, and 0.2 for Landcover layer as weights. The result of the exercise is shown in Fig. 27. Next, point data layer for EPA licensed sites and the heat density layers were superimposed on the suitability map to demarcate areas that are:

a) highly suitable with respect to Silage potential , Slurry potential and Landcover.
b) have high municipal/organic waste potential c) have high heat demand density.

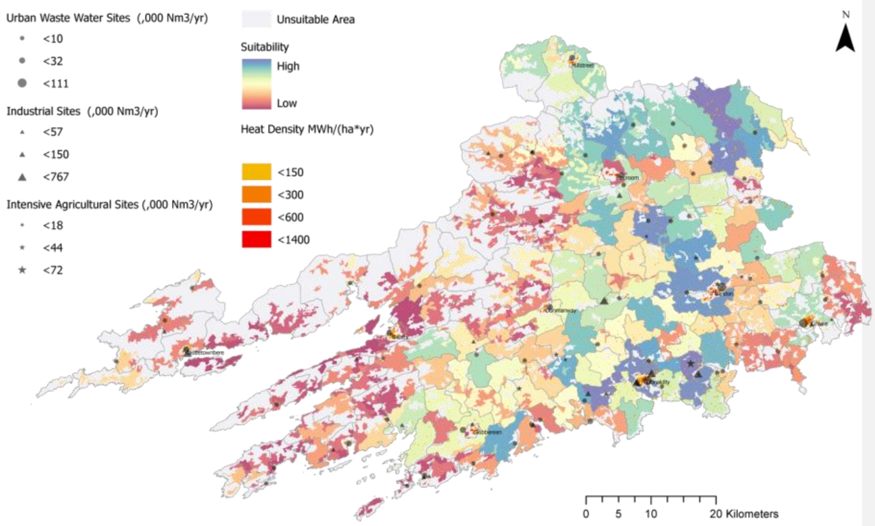



**Figure 10: Site suitability map for an AD development.**

## G. Interpretation of the MCA results

This spatial analysis indicates that the southern coastal areas of West Cork, in the Clonakilty district in particular, have a high degree of suitability due to a conjunction of highly productive grassland and organic waste from industrial, municipal and intensive agriculture sources (pig and poultry farms). Areas around Bandon and further North/Northwest also present a high degree of suitability, again with highly productive grassland and the availability of organic waste feedstocks from milk and meat processing. At the centre of the study area, the Carbery plant stands out in terms of availability of organic waste feedstocks (wastewater treatment sludge), energy demand and availability of grass silage and cattle slurry in the surrounding EDs. There are also potential opportunities around Macroom in terms of industrial organic wastes (milk processing) and agricultural feedstocks (silage and cattle slurry).

**Commented [EB6]:** Not in Carbery catchment
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The Western side of the study appear less suitable for AD development, with a lower concentration of feedstocks. However, as discussed in Chapter 2, this also where beef farming is concentrated, representing a strong potential for the production of grass silage and supply to AD plants as an opportunity to improve farm income. There could also be opportunities for smaller, farm-based AD plants sited in conjunction with local industrial activities, such as milk and meat processing plants. Another potential AD location of interest is Castletownbere with availability of a large quantity of fish waste from its harbour activities.

The siting of an AD plant is a very sensitive matter that will require detailed spatial and environmental planning, and careful stakeholder engagement and consultation with the community. The spatial analysis conducted above provides a basis of knowledge and data to support exploring the issues concerned and potential locations. The next steps in the feasibility study in terms of spatial analysis will be to assess potential locations identified from the MCA above, with a view to review at a higher resolution:

- The factors and constraints mapped during the MCA.
- The AD feedstocks available within an appropriate distance from the potential AD locations selected.
- Capacity to connect to nearby energy users, energy networks (electricity grid, gas grid, district heating, etc.), or potential refuelling points for vehicles.
- Access and the logistics of transporting the feedstocks to the proposed plants.
- Access and the logistics of transporting the biomethane produced by the plant to a distant user or injection point to the gras grid, as well as of distributing secondary products (digestate, compost, CO2, etc.).

This will be done following the technical and financial assessment of different AD pathways (chapter 4), in conjunction with the preliminary design and detailed financial feasibility study of selected 'case study' projects (chapter 5).

High resolution copies of the maps presented above are available to facilitate this work.

# Chapter 4. Key Considerations About the Sustainability of Developing Anaerobic Digestion in West Cork

With a minimum of 1.6 TWh of biomethane likely to be developed by 2030, in line with the Government's National Energy and Climate Plan 2021-2030, Climate Action Plan and the Renewable Heat Obligation consultation, this could see the development of up to 80 medium-scale AD plants (with an average of 20 GWh/yr biomethane output).

In this chapter, we review key considerations for the sustainable development of AD in the study area, with a focus on the agri-based AD model utilising grass and slurry as primary feedstocks. Sustainability concerns relating to this model pertains to three key issues: feedstock procurement, nutrients management and greenhouse gas emissions. The associated regulatory and compliance framework associated with these issues will also be discussed. In addition, the integration of grass-based biorefineries with AD is considered in the context of farm diversification and a circular economy approach in the agricultural systems of West Cork.

## A. Sourcing AD feedstock sustainably

### 1. Grass silage

Grass silage is considered as the primary feedstock for AD development in the study area (and in Ireland) due to its wide availability and suitability for biogas production. As discussed in the feedstock assessment in Chapter 2.B.1, it is foreseen that grass silage would be primarily derived by increasing yields from existing grassland by an average of 4 tDM/ha/year. This is deemed achievable in a sustainable manner by implementing the correct management techniques. This assumes additional inputs of fertiliser and lime to **build soil fertility to optimum levels**, in a targeted manner (target index three). On average, increasing soil fertility levels requires between 35-50% more phosphorus and potassium fertiliser use (KPMG, Devenish, Gas Network Ireland, 2021). This general recommendation must be assessed in the context of relatively high soil fertility already achieved in the study area.

However once soils have reached optimum fertility, only maintenance fertiliser will be required at higher productivity rates. Digestate, the by-product of AD can be used as a biofertiliser to displace chemical fertiliser use and if it has sufficient nutrient quality and availability, it may be suitable as a maintenance fertiliser.

Ongoing work into **Multi-Species Swards (MSS)**[8] has showed promising results for feedstock production at reduced artificial fertilisers input, significantly improving the environmental impact of silage production and the sustainability of grass-based AD. In trials conducted by Devenish, nitrogen use was reduced by 58% and phosphorus use declined by 42% when optimal conditions were reached (after approximately 5 years), whilst improving yields by 2-3t DM/ha. Additional work from Dowth shows an increase in 300% of the earthworm population (an indicator species for soil health and biodiversity) under MSS compared to monoculture ryegrass, while MSS requires less pesticides and fertiliser than ryegrass.

[8] Multi-species swards refer to a mixture of three or more species whose growth characteristics complement each other resulting in improved productivity compared to the typical ryegrass monoculture. Perennial ryegrass and timothy provide strong early-season growth and quality while legumes like white and red clover feed the sward with nitrogen fixed from the atmosphere and boost protein. As well as providing excellent quality, mineral-rich forage in the summer months, deep-rooting herbs like ribwort plantain and chicory are extremely drought tolerant which is an increasing concern for many Irish farmers (source: https://www.dlfseeds.ie/multi-species-r-d)

## 2. Slurry

As discussed in Chapter 2, slurry is an important AD feedstock first because its readily available as a 'by-product' of beef or dairy farming in the study area. However, most of the slurry is only available during the cattle-housing period, and it has low dry matter content **and low energy density** (biogas potential per tonne of fresh weight). This has serious implications in terms of digester size (and the associated capital cost) as well transport requirements in terms of cost, traffic and fuel use.

On the plus side, the **treatment of slurry with AD** and application of the digestate as an organic fertiliser to land[9] has a number of positive environmental impacts, compared to spreading raw slurry (KPMG Sustainable Futures, 2021):

- It reduces the pathogen load to the environment compared with the spreading of raw slurry.
- The digestate contains significantly less volatile organic acids and therefore less odour emissions.
- The digestion process organic nitrogen (N) is released as ammonium (NH4+), with more N available to plants[10].
- The digestion of slurry reduces significantly GHG emissions compared to raw slurry storage in typically open tanks and application to land.

## 3. Sustainability Criteria of the Revised Renewable Energy Directive

For biomethane gas from AD plants to be classified as a zero-carbon renewable fuel, plants must be able to achieve strict sustainability criteria as outlined within the EU Renewable Energy Directive II ("RED II") and future RED III criteria. The RED II criteria stipulate that biomass fuels produced from agricultural biomass cannot be derived from raw material obtained from (1) land that was formerly peatland; (2) lands with a high biodiversity value; and (3) lands with a high carbon stock. In addition, RED II requires that all biomass fuels used for electricity, heating and cooling must achieve at least a 70% GHG emission saving, increasing to 80% for installations that start operating from 2026.

Capturing methane from slurry prevents it from being released to the atmosphere, thereby having the effect of being carbon negative and improving the overall GHG savings of the AD facility. Analysis has demonstrated that it will be possible for Irish AD plants using grass silage as its primary feedstock to produce biomethane which meets RED II sustainability criteria if slurry is included as a co-feedstock. The proportion of slurry required ranges from 40-55% to meet the 2026 (80% GHG emission savings) RED II Sustainability Criteria.

## 4. Animal By-Products Regulations

The EU Animal By-products regulation classifies livestock wastes such as cattle slurry and manure, as Class 2 Animal By-products (ABP). Use of these feedstocks in a biogas plant is subject to several constraints including thermal treatment, size reduction, validation, storage, plant layout, plant management, monitoring, recording and reporting; all of which have substantial capital and operating cost implications. The implications of complying with the ABP regulations require a step change in the complexity of the plant. There is only one exception: small volumes of slurry from a single farm (< 5,000 tFM/year) can be processed by an on-farm biogas plant without conforming to the ABP conditions above, provided that the digestate is recycled to land of the same farm

For the AD pathways considered in Chapter 5, agri-based AD plants will require very significant volumes of cattle slurry in addition to grass silage to meet the RED II Sustainability Criteria, which will have to be sourced from a number of farms. Compliance with the ABP regulations will be applied by default in the AD pathways considered.

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[9] Digestate is a nutrient-rich substance which consists of the organic products of digestion, left over indigestible material, live and dead micro-organisms. All the nitrogen, phosphorous and potassium present in the AD plant's feedstock will remain in the digestate. However, the nutrients are more available to plant growth than the original material.

[10] Ammonium is ionized and has the formula $NH_4^+$.

## B. Nutrients Management

### 1. AD digestate as an organic fertiliser

While digestate is a by-product of AD, it will play an important role in the industry. Digestate will supply sustainable quantities of the nutritional requirements of the plants forage feedstocks by being land spread at targeted stages in the crop's development cycle. As fossil-based fertilisers become more expensive, good management of the nutrient content of digestates will become important as a cost-saving measure for farms. Digestate is also packed with trace elements and potential animal and plant pathogens are significantly reduced, and in most cases are eradicated, due to the requirement to pasteurise the feedstock as required by the ABP regulations.

Spreading digestate falls under the Nitrates Action Programme and must adhere to strict conditions. The nutritional value of digestate varies depending on the AD plant's diet. Farm based digestate values, which is based on slurry and forage, has a higher dry matter but lower total and available N (3.6kg N/t and 2.8kg N/t respectively). Typical P values are higher at 1.7kg/t while K comes in much higher at 4.4kg/t. Food-based digestate (unseparated) could have a total N value of 4.8kg/t with around 3.8kg/t of this readily available; typical P values comes in at 1.1 kg/t while K comes in at 2.4kg/t with typical dry matter of 3.8% (KPMG, Devenish, Gas Network Ireland, 2021).

Managing the digestate is an important aspect of an AD project development and establishing a nutrient management plan in conjunction with farmers in the vicinity of the plant is an essential part of planning the project. Applying the digestate as an organic fertiliser to the grassland producing the grass silage used by the proposed AD plant will not only help close the nutrient cycle in the project catchment area, but also play an important role in improving the sustainability of the agricultural system underlying it.

The review conducted by KPMG, Devenish and Gas Network Ireland (2021) of best agronomic practices in Europe for nutrient management with AD highlights a number of key principles:

- Adherence to the Water Framework Directive as a minimum standard.
- The submission of a detailed nutrient management plan that addresses soil nutrient status, the nutrient value of the digestate and the nutrient requirements of the crop that is grown.
- Application techniques that minimise the risk of nutrient run-off and ammonia emissions are industry best practice and should be followed (see section 3 below).
- The provision of enough storage capacity at the AD facility and the facility's farms is of fundamental importance. All European countries have closed periods where no application is allowed.

### 2. Nutrients Recovery

Value of digestate depends on NPK content and nutrient availability, which can vary significantly with the feedstocks used, processing technology, application method and soil quality where is it applied. Nutrient recovery technologies aim to increase the availability of nutrients in the digestate and process it into a more concentrated form. The nutrients harvested from these processes can help improve the commercialisation of the digestate. As fossil-based fertilisers become more expensive, good management of the nutrient content of digestates will become important as a cost-saving measure for farms.

There are different nutrient recovery solutions commercially available in well-established markets such as France, Germany and the UK, and we refer to the work done in the framework of the Project Clover for recommended solutions and the associated business case (KPMG Sustainable Futures, 2021). In this feasibility study, the only digestate treatment considered is the separation of the solid fraction from the digestate and its composting to provide a horticulture grade compost to be commercialised as part of the proposed AD projects.

### 3. Impact of digestate on other farm emissions & eutrophication of waterways

While the AD digestate provides organic nitrogen more readily available to plants, there are concerns relating to the potential increase in ammonia ($NH_3$)[11] and nitrogen oxide emissions ($NO_2$) when applying straight digestate compared to animal slurries. This is because the AD process increases the pH of digestate (pH 7-7.5). However, mitigation strategies such as covered storage, trailing hoses/shoes, direct injection into soils and ammonia harvesting technologies will be standard on many plants.

Nitrous oxide ($N_2O$) is a naturally occurring GHG released from soils. Excess $N_2O$ is released when nitrogen fertilisers are added to soils. However, the use of digestate from AD has been shown to reduce $N_2O$ emissions. Research has demonstrated that the use of digestate can reduce $N_2O$ emissions to 0.25 g per kg N applied as slurry and digestate - compared with 1.49 g of $N_2O$ per kg Calcium Ammonium Nitrate ("CAN").

A major environmental concern with land application of digestate is the potential contamination of surface and ground waters with excess nitrogen and phosphorus. In terms of nutrient leaching, digestate is deemed to have at least a similar impact on water bodies as slurry. However, AD reduces the Biochemical Oxygen Demand (BOD) by circa 40% compared to slurries, and in turn the potential for water pollution. The nutrient leaching potential following the application of digestate depends on factors such as fertilisation strategies, soil texture, topography, precipitation and cropping systems.

Best management practices that mitigate nutrient leaching include nutrient management planning to predict the nutrient supply for the crop grown and the use of soil tests. Recommended digestate application techniques should follow Low Emission Slurry Spreading advice provided by Teagasc.

## C. AD and grass-based biorefineries in West Cork

In 2020, XD Sustainable Energy Consulting conducted a feasibility study on behalf of the Institute of Technology Tralee for the Biorefinery Glas project. The purpose of the study was to analyse the business case for the grass biorefinery system, assessing the potential for diversification from existing farming enterprises and recommend suitable business models for uptake and wider replication of the grass biorefinery.

The biorefinery system processes fresh grass as its primary feedstock to produce a number of products suitable for animal alimentation, as illustrated below. The following outputs are key products and by-products of the biorefinery plant:

- Protein concentrate: The protein concentrate is an excellent local, environmentally friendly replacement for imported soya meal to be used in the production of animal feed for cattle, pigs, poultry and pet food.
- Ensiled protein fibre: The press cake produced by the extrusion process is directly ensiled to preserve it. It serves as a roughage for cattle[12].
- Fructose Olio Saccharides (FOS): The FOS concentrate extracted from the juice by nanofiltration is a soluble dietary fibre with sugars that can improve the health of the intestine of both humans and animals., acting as a prebiotic.
- Phosphate and other minerals concentrate: This phosphate concentrate obtained by precipitation from the whey is a natural source of fertiliser equivalent to bone meal, albeit in liquid form.

[11] Ammonia is un-ionized and has the formula NH3. The major factor that determines the proportion of ammonia or ammonium in water is water pH.
[12] Feeding trials undertaken as part of the Biorefinery Glas project have shown that cows digest the ensiled fibre cake more efficiently than regular silage, with a positive effect on milk production and reduced ammonia and phosphate levels in the manure.

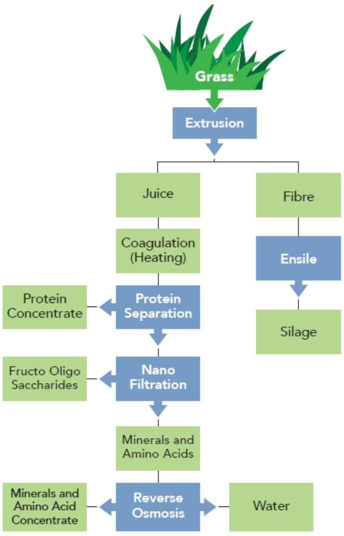


**Figure 11: Grass biorefining process. Source: biorefineryglas.eu**

**Figure 12: Mobile, containerised grass biorefinery plant. Source: biorefineryglas.eu**

Since the process is relatively energy intensive and the biorefinery whey is a good biogas potential, the feasibility study considered the integration of the biorefinery plant with an anaerobic digestion (AD) plant, equipped with a combined heat and power (CHP) unit to meet the heat and electricity requirements of the biorefinery system. Integrating AD with the biorefinery process has the additional benefit of increasing its circularity by treating its effluent to produce renewable energy, while reducing the requirement to divert an agricultural feedstock, grass silage, from food production.

To validate this, a mass and energy balance analysis of a biorefinery capable of processing 8 tonnes of fresh grass per hour, operating 16 hours per day, was conducted. An AD plant treats all of the biorefinery's effluent to produce biogas which is burned in a CHP unit. The further advanced is the biorefinery process, the lower will be the biomethane potential of the biorefinery effluent. If the biorefinery process doesn't include FOS extraction, the digestion of the effluent (the whey) produces enough biogas to meet the energy requirements of the biorefinery, leaving a surplus of approximately 100 kW of heat and 240 kW of electricity. If the biorefinery produces FOS in addition to the protein concentrate and the ensiled fibre, the digestion of the effluent (filtrate) will not produce sufficient biogas to meet the energy requirement of the biorefinery.

The financial analysis conducted as part of the above feasibility study concluded that the integration of AD with the biorefinery and the production of FOS are key to the profitability of a biorefinery project. In this context, the development grass biorefineries in West Cork will not make a net positive contribution to the supply of renewable energy in the region, unless very significant energy efficiencies can be achieved in the process (e.g. heat recovery). This is compounded by the fact that AD projects, as they are envisaged in this study, and biorefineries will largely be competing for the same feedstock, grass.

# Chapter 5. Technological Pathways Analysis

## A. Introduction

In this chapter, the methodology and results of the AD technological pathways analysis are reviewed. The objectives of the analysis were to:

- Map out AD technological pathways with a potential to become effective solutions for West Cork, identifying key elements of their value chain from feedstock harvesting to final energy distribution.
- Determine key inputs and outputs of selected technological pathways along their entire value chain, in terms of feedstocks quality and quantity, AD technologies' energy outputs as well as non-energy products (digestate, compost and CO2).
- Conduct a high-level techno-economic modelling of selected AD technological pathways to identify viable pathways and key factors impacting on their viability.
- Conduct a SWOT analysis and compare selected technological pathways, using modelling outputs.

## B. Technical assessment of AD pathways

There were two primary considerations used when shortlisting the AD pathways to be analysed: a) the nature of the feedstocks used and b) how the biogas is used to produce useful energy.

### 1. Pathway Selection - Feedstocks

There are a number of key considerations when selecting an AD technical pathway in terms of feedstock: availability within a reasonable transport distance, biomethane potential, pre-treatment, plant design and operation, supply costs, environmental impacts and regulatory requirements. Concerning the latter, the EU Animal By-products (ABP) legislation[13] classifies livestock wastes such as cattle slurry and manure (of which there are substantial amounts at a low cost in the study area) are classified as Class 2 Animal By-products (ABP). Use of these feedstocks in a biogas plant is subject to several constraints including thermal treatment, size reduction, validation, storage, plant layout, plant management, monitoring, recording and reporting; all of which have substantial capital and operating cost implications. The implications of complying with the ABP regulations require a step change in the size and complexity of the plant.

There is only one exception: small volumes of slurry from a single farm (< 5,000 tWM/year) can be processed by an on-farm biogas plant without conforming to the ABP conditions above, provided that the digestate is recycled to land of the same farm.

The feedstock pathways presented in this report reflect the implications of the ABP regulations. Four principal pathways were considered in this analysis:

- The first is a small farm-based AD plant, using on-farm agricultural feedstocks and milk processing by-products (sludge or whey).
- The second represents a medium-sized farm-based AD plant (20 GWh/yr energy output), using grass silage and slurry.
- The third represents a medium-size AD plant (20 GWh biomethane output) co-located with a food processing operation, primarily accepting on-site feedstocks and grass silage.
- The fourth represents a large AD plant (40 GWh biomethane output) co-located with a food processing operation, accepting a range of organic wastes from industrial, municipal and agricultural sources, as well as grass silage.

[13] The European Union (Animal By-products) Regulation 2014 (S.I. No 187 of 2014) and in accordance with Regulation (EC) No.1069 of 2009 and Regulation (EU) No. 142 of 2011.

## 2. Pathway Selection - Processes

Figure 13 provides a general view of the various process pathways that may be implemented for AD, considering two main variations around the core anaerobic digestion process itself:

- **Heat only:** the biogas produced is used by the digester is cleaned and burnt into a gas boiler, to heat the digester(s) and substitute existing fuel use on the site (e.g. for heating the farmhouse and for food processing heat requirements) or nearby.
- **Combined Heat and Power:** the biogas produced by the digester is cleaned and injected in a gas engine driving an electricity generator, with heat recovery from the exhaust gas and engine cooling. This is referred to as a combined heat and power (CHP) plant. The electricity generated can be used on site if there is a sufficient demand (e.g. large processing plant) or exported to the electricity distribution grid. The heat recovered from the CHP unit can be used at the AD plant itself to heat the digesters, pasteurise the feedstocks if necessary and/or can be exported to heat nearby buildings or industrial processes via a local heat network.
- **Compressed biomethane (CBM):** the biogas is cleaned, its $CO_2$ content is removed (between 40-50% of the biogas content by volume) along with other contaminants and compressed to a high pressure. The compressed biomethane can be injected into the natural gas grid or used locally to fuel vehicles whose engines have been specially manufactured to use Compressed Natural Gas (CNG) engine, or in vehicles that are converted to dual fuel use. Alternatively, the biomethane can collected in a tanker and shipped to an injection at an appropriate distance (up to 50 km). The upgrading/compression plant produces heat which contributes to the AD plant thermal requirements.

Secondary process variations include:

- **Digestate & compost:** the AD digestate is a nutrient-rich substance produced by anaerobic digestion that can be used as a fertiliser to replace synthetic fertilisers. It consists of left-over indigestible material and dead micro-organisms - the volume of digestate will be around 90-95% of what was fed into the digester. The solid fraction of the digestate (15-20%), separated by a screw press and composted to provide a very valuable soil fertiliser and enhancer for use in gardening and horticulture.
- **Carbon dioxide**, a by-product of the biogas upgrade to biomethane, can be compressed, stored at high pressure in steel containers and sold in horticulture or industry. Certain biogas upgrade technologies can produce high concentration $CO_2$, with virtually no contaminants, which can be used in the food & drinks industry and attract a high price.

As we will see in the cost/benefit analysis of the different pathways, valorising these by-products should play an important role in the financial viability of the proposed AD projects.

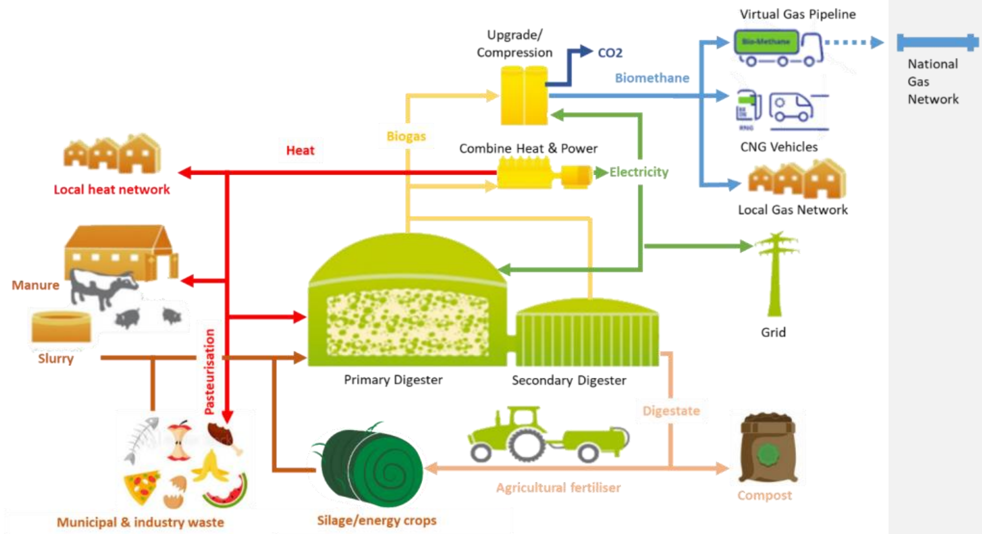


Figure 13: Overview of the AD pathways analysed. Source: XDC

## 3. Summary of pathways analysed

The following table summarises the pathway options investigated:

Table 4: Summary of pathways analysed.

| Pathway Name | Feedstocks | | | Processes & energy systems | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Agricultural feedstocks | Food Processing Waste | Other Organic Waste | Pasteurisation | CHP | Heat only | CBM transported to Grid | CBM injected to Grid | CO2 |
| 1) Small - Single Farm - CHP | V | V | | | V | | | | |
| 2) Small - Single Farm - Heat Only | V | V | | | | V | | | |
| 3) Medium – Multiple Farms – CBM | V | | | V | | | V | | |
| 4) Medium – Multiple Farms – CBM + CO2 | V | | | V | | | V | | V |
| 5) Medium – Multiple Farms – CBM + CO2 + CHP | V | | | V | V | | V | | V |
| 6) Medium – Co-located – CBM | V | V | | | | | | V | |
| 7) Medium – Co-located – CBM + CO2 | V | V | | | | | | V | V |
| 8) Medium – Co-located – CBM + CO2 + CHP | V | V | | | V | | | V | V |
| 9) Large – Co-located – CBM | V | V | V | V | | | | V | |
| 10) Large – Co-located – CBM + CO2 | V | V | V | V | V | | | V | V |
| 11) Large – Co-located – CBM + CO2 + CHP | V | V | V | V | | | | V | V |

## 4. Key technical parameters used

The following assumptions were taken in relation to the feedstocks' biomethane potential, delivered cost or gate fees:

**Table 5: Feedstocks' biomethane potential and costs.**

| | DS<br>(%FM) | VS<br>(%FM) | VS/DS<br>(%) | Methane Yield<br>(LCH4/kgDS) | Methane Yield<br>(LCH4/kgVS) | CH4/biogas<br>(%) | Biogas yield<br>(Lbiogas/kgVS) | Biogas yield<br>m3/tFM | Costs (+) Gate Fees (-)<br>€/tFM |
|---|---|---|---|---|---|---|---|---|---|
| Grass Silage | 23 | 20.9 | 0.85 | 340 | 400 | 60% | 667 | 130 | 30 |
| Cow Slurry | 8 | 6.0 | 0.75 | 107 | 143 | 60% | 238 | 14 | 5 |
| Farmyard Manure | 20 | | 0.85 | 232 | 273 | 60% | 455 | 77 | 5 |
| Food Waste | 30.6 | 27.1 | 0.88 | 242 | 274 | 60% | 457 | 124 | -30 |
| WWTP sludge (dewatered) | 17 | | 0.65 | | 200 | 60% | 333 | 37 | -10 |
| Milk processing brown sludge | 14.5 | 10.3 | 0.71 | 202 | 284 | 84% | 338 | 35 | - |
| Fish Waste | 32.2 | 17.8 | 0.55 | 216 | 390 | 60% | 650 | 116 | -20 |
| Offal | 32.2 | 17.8 | 0.55 | 216 | 390 | 60% | 650 | 116 | -20 |
| Pig slurry | 3.70 | 2.6 | 0.70 | 205 | 292 | 60% | 487 | 13 | 5 |
| Chicken manure | 42 | 22.0 | 0.52 | 130 | 248 | 60% | 413 | 91 | 5 |
| Milk processing white sludge | 21.2 | 11.0 | 0.52 | 410 | 788 | 87% | 894 | 99 | - |

Other technical assumptions made with regard to different elements of the AD pathways systems are outlined hereafter. These are based on typical industry standards and technical specifications received from technology suppliers:

- Electricity usage:
  - Digester: 0.438 kWh per $m^3$ of digester volume
  - Biogas upgrading: 0.3 kWh/$Nm^3$ biogas
  - Biomethane compression: 0.3 kWh/$Nm^3$ biogas
  - $CO_2$ liquefaction: 1.4 kWh/$Nm^3$ $CO_2$
- Heating requirement:
  - Biodigester: 15% of gross energy output (biogas)
  - Pasteurisation: 10% of gross energy output (biogas)
- Heat output:
  - CHP: 39% of gross energy input (biogas)
  - Biogas upgrading: 0.25 kWh/$Nm^3$ biogas
  - Biomethane compression for storage: 0.25 kWh/$Nm^3$ biogas
  - $CO_2$ liquefaction: 1.4 kWh/$Nm^3$ $CO_2$
- Average operating times:
  - Biodigester: 8300 hours
  - CHP unit: 8000 hours
  - Biogas upgrade and CBM compression plant: 8000 hours

## C. Financial assessment of the different pathways analysed

### 1. Methodology and assumptions

A preliminary financial analysis was conducted for each pathway to assess the financial operating balance (effectively a profit and loss account) on a typical year of operation of the associated AD systems. This analysis considers the following variables:

- **The capital expenditure** required to build and commission the AD system: Turnkey (supply/install/commission) budget costs were sourced for the ***biogas plant***[14], the biogas ***upgrade/compression*** and $CO_2$ ***liquefaction*** plants[15]. Cost estimates for the supply and install of ***CHP plants*** were taken from previous projects.
- The annual operating cost including:

[14] Preliminary quotations by Tank Storage Systems of Ireland, and Host-Bioenergy, UK
[15] Preliminary quotations by Bright Biomethane

- Cost of acquiring ***feedstocks*** including production (in particular silage) and transport costs, considering gate fees for municipal & industrial organic waste, taken from the feedstock analysis undertaken in WP2.
- ***Energy*** costs (electricity, biomass fuels, etc.) taken from SEAI's Commercial Fuel Costs publication or actual energy costs for a given user when available.
- Cost of disposing of ***the digestate*** at the end of the process, based on transport and application to land costs of €2/tonne.
- ***Repairs and maintenance*** costs, based on information provided by suppliers and general biogas plant operating costs relative to plant capital costs
- Plant operators, management, administrative ***staff costs based on typical biogas plant operational requirements, plus*** overheads (30% of staff cost) and ***insurance*** (based on 1% of total capital cost).
- Cost **of biomethane delivery and injection** into natural gas grid (GNI, 2019):
    - Biomethane haulage: €0.055/MWh,km (round trip of 70 km).
    - Biomethane injection: assumed to be borne by gas network operator.
- The cost of ***financing*** the capital expenditure above, based on debt-to-equity ratio of 80:20, interest rate of 4.5%, loan repayment period of 10 years.
- Depreciation based on ***straight-line depreciation*** over 15 years for machinery (CHP, pumps, compressors, upgrading plants, etc.) and 20 years for buildings, digesters and other non-mechanical plant.

- The potential revenues derived from:
    - Production of energy including:
        - ***Electricity*** produced by biogas CHP to replace on-site electricity use (€0.11/kWh) or exported to the grid (existing feed-in tariff of €0.15/kWh)
        - ***Surplus heat*** available for export (sum of outputs from CHP, biogas upgrading, compression and $CO_2$ liquefaction, minus digesters and pasteurisation heating requirements). Heat has been valued at €0.05/kWh to allow for additional cost of heat distribution (assume €0.03) and remain competitive with pre-existing heating costs (oil and LPG). A renewable heat subsidy in line with the SSRH was assumed[16].
        - ***Compressed biomethane*** used on site (priced at €0.0215/kWh) or exported to the gas grid (priced at wholesale cost of €0.02 per kWh), and a subsidy of €0.025/kWh[17].
    - The sale of food grade $CO_2$ as a by-product of the biogas upgrade process, taken as €0.3/$m^3$ or €0.2/kg.
    - The sale of the ***compost*** produced at €25 per tonne (sale in bulk).

The following key performance indicators (KPIs) were derived from the cost/benefit analysis of the pathways analysed above:

- **Profit & Loss (P/L) account** for an average year of operation, **before tax**, including total revenues, operational expenditure, depreciation and interest payments (for mid-repayment period year).
- **Return on Capital (ROC, %)** as a measure of the profitability and value-creating potential of companies relative to the amount of capital invested by shareholders and other debtholders. The ROC is calculated by dividing the sum of [initial capital expenditure and interest payment] by the P/L value.

- **Net Present Value (NPV):** Difference between the present value of cash inflows and the present value of cash outflows over a period of time. It applies the discount rate to account for the time value of money.
- **Internal Rate of Return (IRR):** A discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. It measures the rate return on the investment made.

## 2. Results of the financial analysis of the AD pathways analysed

The results of the techno-economic analysis of the pathways assessed, is summarised in Table 6, next page.

[16] If heat exported is above 2400 MWh/yr, there is no subsidy from the SSRH. This applies to medium and large AD projects, such as those envisaged to service the Carbery Group.
[17] There is no clarity currently on the potential subsidies becoming available for biogas or biomethane. For the time being, a subsidy equivalent to the value of $CO_2$ avoided priced at €130/$tCO_2$.

There are several pathways showing profitability and positive return on investment, with the following as likely reasons for this:

- The pathways relating the AD plants collocated with an industrial site (6-11) and co-digesting agricultural feedstocks with industrial/municipal organic wastes, significantly reduce their feedstock costs by attracting gate fees for the treatment of organic wastes or by using their own organic wastes at no cost.
- The extraction and liquefaction of $CO_2$ for sale in the food industry increases significantly revenues and profitability. The sale of compost and heat also make a useful contribution in that regard.
- Doubling the size of the AD plant from pathways 6-8 to 9-11 also increase profits and return on investment due to economies of scale.
- Energy costs of operating the plant (electricity and heat) are a significant part of the operational costs (30 to 50%). Electricity use by the biogas upgrading and compressing system as well as the $CO_2$ recovery plant represents 15% of the gross energy output of the AD plant, and the addition of a CHP system also improves profitability by reducing energy costs on site (pathways 5/8/11). However, it is worth noting that the operation of a CHP unit requires additional biogas production and increased feedstocks cost, primarily taken as grass silage.
- Heat recovery from the CO2 production process contributes to meeting the heating requirement of the digester. If there is a CHP unit on site, there is excess heat which can be exported to a nearby heat user (e.g. industrial plant or district heating system) and generate an additional revenue (5-10% of total revenues in pathways 8 and 11).

The factors contributing to the poor financial performance of pathways 3 to 5 are:

- The AD plants use grass silage as their primary feedstock which is expensive, or slurry which has a low biomethane potential and costly to transport.
- The plants do not process organic waste which would attract gate fees, but they still need pasteurisation since they are sourcing slurry from and return digestate to multiple farms.
- They do not have direct access to a gas grid injection point or a nearby large biomethane user, and therefore most born the costs of compressing and storing the biomethane, and its transport it to its point of use.

While small on-farm AD projects do not appear profitable, the associated AD plant is simple and relatively low-cost in construction, particularly in pathway 2 where the biogas is used in a boiler to provide home and process heating. These projects also benefit from the use of organic waste feedstocks available on the farm at no cost. With a decent subsidy or if energy prices go up significantly, these potential projects might become attractive for farm-based artisan food processors in West Cork.

### Table 6: Financial Analysis of Selected AD Pathways

| Pathways Analysed | units | (1) Small - Single Farm - CHP | (2) Small - Single Farm - Heat Only | (3) Medium – Multiple Farms – CBM | (4) Medium – Multiple Farms – CBM + CO2 | (5) Medium – Multiple Farms – CBM + CO2 + CHP | (6) Medium – Co-located – CBM | (7) Medium – Co-located – CBM + CO2 | (8) Medium – Co-located – CBM + CO2 + CHP | (9) Large – Co-located – CBM | (10) Large – Co-located – CBM + CO2 | (11) Large – Co-located – CBM + CO2 + CHP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ECONOMIC MODEL** | | | | | | | | | | | | |
| **CAPEX** | | | | | | | | | | | | |
| Planning and initial | € | 30,000 | 30,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 |
| Project management | € | 30,000 | 30,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 |
| Digester turn-key | € | 300,000 | 300,000 | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 | 2,100,000 | 2,100,000 | 2,800,000 |
| Electrical and controls | € | 70,000 | 70,000 | 200,000 | 200,000 | 200,000 | 200,000 | 200,000 | 200,000 | 300,000 | 300,000 | 400,000 |
| Feed system | € | 35,000 | 35,000 | 330,000 | 330,000 | 330,000 | 330,000 | 330,000 | 330,000 | 500,000 | 500,000 | 660,000 |
| Digestate system (press+store) | € | 25,000 | 25,000 | 70,000 | 70,000 | 70,000 | 70,000 | 70,000 | 70,000 | 90,000 | 90,000 | 90,000 |
| Digestate liquid storage | € | 60,000 | 60,000 | 280,000 | 280,000 | 280,000 | 280,000 | 280,000 | 280,000 | 420,000 | 420,000 | 560,000 |
| Civils | € | 75,000 | 75,000 | 280,000 | 280,000 | 280,000 | 280,000 | 280,000 | 280,000 | 420,000 | 420,000 | 560,000 |
| Grid connection | € | - | - | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 |
| ABP reception + pretreatment | € | - | - | 250,000 | 250,000 | 250,000 | - | - | - | 250,000 | 250,000 | 250,000 |
| CHP plant and gas conditioning | € | 32,098 | - | - | - | 345,714 | - | - | 356,418 | - | - | 708,957 |
| Biogas-to-CBM upgrading plant | € | - | - | 685,000 | 685,000 | 685,000 | 685,000 | 685,000 | 685,000 | 1,225,000 | 1,225,000 | 1,225,000 |
| Biogas-to-CBM compression plant | € | - | - | 100,000 | 100,000 | 100,000 | - | - | - | - | - | - |
| CBM storage | € | - | - | 80,000 | 80,000 | 80,000 | - | - | - | - | - | - |
| CO2 recovery and storage | € | - | - | - | 670,000 | 670,000 | - | 670,000 | 670,000 | - | 670,000 | 670,000 |
| District energy network | € | - | - | - | - | - | - | - | - | - | - | - |
| Back-up boiler | € | - | - | 146,122 | - | - | 116,712 | - | - | 674,618 | 303,240 | - |
| Biogas boiler | € | - | 43,640 | - | - | - | - | - | - | - | - | - |
| Gas Grid Connection | € | - | - | - | - | - | - | - | - | - | - | - |
| Other Civils | € | - | - | - | - | - | - | - | - | - | - | - |
| **Total Build Cost** | € | **657,098** | **668,640** | **4,061,122** | **4,585,000** | **4,930,714** | **3,601,712** | **4,155,000** | **4,511,418** | **6,219,618** | **6,518,240** | **8,163,957** |
| Site acquisition | € | - | - | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 |
| Capital Grants/Subsidies | | - | - | - | - | - | - | - | - | - | - | - |
| **Net Capital Expenditure** | € | **657,098** | **668,640** | **4,211,122** | **4,735,000** | **5,080,714** | **3,751,712** | **4,305,000** | **4,661,418** | **6,369,618** | **6,668,240** | **8,313,957** |
| **Cost of Finance** | | | | | | | | | | | | |
| Debt to Equity Ratio | % | 80% | 80% | 80% | 80% | 80% | 80% | 80% | 80% | 80% | 80% | 80% |
| Amount Borrowed | € | € 525,679 | € 534,912 | € 3,368,898 | € 3,788,000 | € 4,064,571 | € 3,001,370 | € 3,444,000 | € 3,729,134 | € 5,095,694 | € 5,334,592 | € 6,651,165 |
| Interest Rate | % | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% | 4.5% |
| Loan Repayment Period | years | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **Annual Loan Repayment** | **€/year** | **66,435** | **67,602** | **425,757** | **478,723** | **513,676** | **379,310** | **435,249** | **471,284** | **643,988** | **674,179** | **840,566** |
| **Revenues** | | | | | | | | | | | | |
| Sale of Electricity | €/y | 29,901 | - | - | - | 51,093 | - | - | 70,903 | - | - | 94,581 |
| Sale of Heat | €/y | 11,364 | 47,681 | - | 32,103 | 76,029 | - | 11,785 | 150,400 | - | - | 51,895 |
| Heat Subsidies | €/y | 6,705 | 28,132 | - | 18,941 | 44,857 | - | 6,953 | 88,736 | - | - | 30,618 |
| Sale of CBM/biogas | €/y | - | - | 558,260 | 558,260 | 536,574 | 559,374 | 559,374 | 531,876 | 1,125,670 | 1,125,670 | 1,101,112 |
| CBM Subsidies | €/y | - | - | 500,067 | 500,067 | 480,641 | 501,065 | 501,065 | 476,433 | 1,008,330 | 1,008,330 | 986,332 |
| Sale of CO2 | €/y | - | - | - | 385,231 | 306,347 | - | 250,292 | 274,875 | - | 641,069 | 666,507 |
| Sale of Compost | €/y | - | - | 178,763 | 178,763 | 229,950 | 141,255 | 141,255 | 187,245 | 325,215 | 325,215 | 422,885 |
| **Total Revenues** | *€/y* | **47,970** | **75,812** | **1,237,089** | **1,673,363** | **1,725,491** | **1,201,694** | **1,470,725** | **1,780,467** | **2,459,215** | **3,100,284** | **3,353,929** |
| **Operational Expenditure** | | | | | | | | | | | | |
| Feedstocks (net cost) | €/y | - | - | 791,750 | 791,750 | 868,700 | 416,100 | 416,100 | 722,700 | 166,075 | 166,075 | 817,209 |
| Digestate Disposal | €/y | - | - | 65,149 | 65,149 | 83,804 | 51,480 | 51,480 | 68,240 | 118,523 | 118,523 | 154,118 |
| CBM Haulage & Injection | €/y | - | - | 75,947 | 75,947 | 72,997 | - | - | - | - | - | - |
| Labour, Insurance, Overheads | €/y | 14,696 | 14,811 | 62,718 | 67,957 | 77,745 | 53,486 | 59,019 | 68,270 | 102,415 | 105,401 | 133,937 |
| Maintenance and Repairs | " | 11,913 | 9,473 | 66,472 | 63,550 | 99,237 | 62,884 | 60,550 | 97,342 | 110,042 | 102,615 | 188,933 |
| **Total OPEX** | **€/y** | **26,609** | **27,840** | **1,414,557** | **1,393,420** | **1,202,482** | **897,006** | **878,163** | **956,552** | **1,295,731** | **1,212,195** | **1,294,197** |
| ***Depreciation*** | ***"*** | ***28,390*** | ***29,159*** | ***190,241*** | ***225,167*** | ***248,214*** | ***176,281*** | ***213,167*** | ***236,928*** | ***310,475*** | ***330,383*** | ***416,764*** |
| **Annual profit and loss** | | | | | | | | | | | | |
| Total Revenue | €/y | 47,970 | 75,812 | 1,237,089 | 1,673,363 | 1,725,491 | 1,201,694 | 1,470,725 | 1,780,467 | 2,459,215 | 3,100,284 | 3,353,929 |
| Total OPEX | " | 26,609 | 27,840 | 1,414,557 | 1,393,420 | 1,202,482 | 897,006 | 878,163 | 956,552 | 1,295,731 | 1,212,195 | 1,294,197 |
| Depreciation | " | 28,390 | 29,159 | 190,241 | 225,167 | 248,214 | 176,281 | 213,167 | 236,928 | 310,475 | 330,383 | 416,764 |
| Loan Interest | " | 11,828 | 12,036 | 75,800 | 85,230 | 91,453 | 67,531 | 77,490 | 83,906 | 114,653 | 120,028 | 149,651 |
| **Profit/Loss** | **"** | **(18,857)** | **6,777** | **(443,509)** | **(30,454)** | **183,342** | **60,876** | **301,906** | **503,082** | **738,357** | **1,437,678** | **1,493,318** |
| Return on Capital | **%** | **-1.1%** | **2.8%** | **-9.1%** | **1.2%** | **5.6%** | **3.6%** | **9.1%** | **13.0%** | **13.7%** | **23.9%** | **20.1%** |
| **Discounted Cash Flow Analysis** | | | | | | | | | | | | |
| **IRR** | **%** | **0%** | **4%** | | | **5%** | **2%** | **13%** | **18%** | **19%** | **30%** | **26%** |
| **NPV** | **€/2021** | **(419,876)** | **(157,387)** | **(6,763,479)** | **(2,613,637)** | **(691,801)** | **(1,034,297)** | **1,239,469** | **3,014,511** | **4,595,611** | **12,056,394** | **11,953,803** |

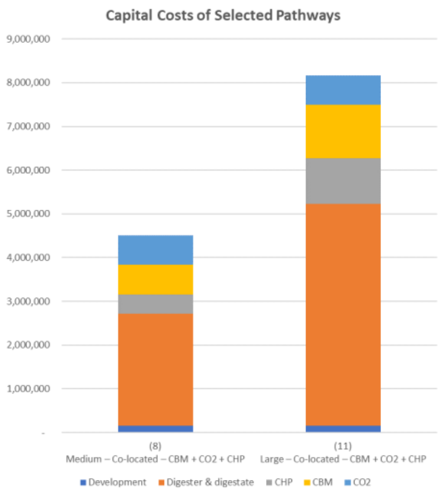


Figure 14: Distribution of capital costs in selected pathways.

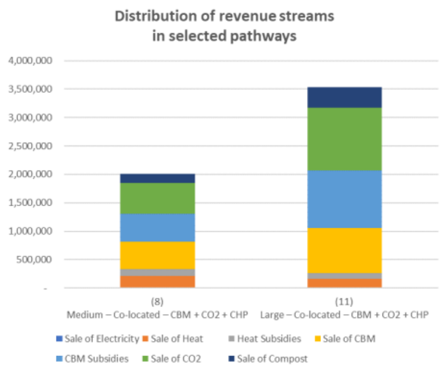


Figure 15: Distribution of sources of revenue in selected pathways.

Capital costs for the construction and engineering of the AD plant and associated systems vary from close to €700 thousand for the small AD plant to above €8 million for the largest, most complex plant. As per Figure 14 showing the distribution of the capital expenditure for pathways 8 and 11, the digester and associated systems represent the largest part of the investment (>60%), but the addition of the biogas upgrading plant and the CO2 recovery plant nearly add 15% to the investment each.

Figure 15 shows that the main sources of revenue in pathways 8 and 11 relate to the valorisation of CBM. In pathway 11, it is assumed that most of the biomethane produced is injected into the grid where it is assumed to get the whole sale gas price. In pathway 8, it is assumed to be used by the industrial plant collocated with the AD plant and substituting natural gas, fetching a higher price than when injected into the grid.

However, the assumed CBM subsidies make a very significant contribution to the revenue streams in both cases, at least equivalent to the value of the renewable fuel itself. As mentioned above, in the absence of clear outlook on the availability and value of a national subsidy for biogas/biomethane, we have assumed a subsidy equivalent to the reduction in carbon taxes at a unit cost of €130/t$CO_2$ (as anticipated in 2030). Looking at it the other way round, this can be seen as the cost of decarbonising by substituting natural gas with biomethane, whether it is borne by the energy user buying the biomethane at a premium, or by the taxpayer through a national subsidy scheme.

Selected pathways will be reviewed further and be subject to a more detailed technical and financial assessment in chapter 6. In Chapter 5, the business and financing models appropriate for community participation in the development of anaerobic digestion will be reviewed.

**Commented [EB9]:** Agree with the concept, why this figure? Current ETS is at €60/t are you taking longer term price into the formula?

**Commented [XD10R9]:** Yes, thinking towards 2030. Effectively, want to factor in cost of decarbonisation.

# Chapter 6. Design of AD system & Life Cycle Cost-Benefit Analysis

This chapter builds on the AD pathways review and cost/benefit analysis undertaken in Chapter 5 and explores in more detail the design of two specific AD systems co-located with the Carbery's Wastewater Treatment Plant (WWTP):

1) An AD plant digesting primarily the sludges from the WWTP, supplying biogas to a combined heat and power plant (CHP) sized to meet the electricity requirement of the WWTP site (average of 500 kWe or 4380 GWh/yr of electricity use), in addition to the AD plant's electricity & heat requirement . The biogas produced by the AD plant is cleaned before being fed into the CHP plant. Grass silage provides the balance of feedstock necessary to meet the biogas requirement of the plant.
2) An AD plant digesting the sludges from the WWTP, grass silage, slurry and food waste, sized to produce approximately 40 GWh/yr of biogas. The AD plant supplies biogas to a CHP unit as well as to a biogas upgrade plant to produce compressed biomethane (CBM) which is then exported to the Carbery milk processing plant via a gas pipeline. The biogas upgrade plant is combined with a $CO_2$ liquefication unit which produces a high-quality food grade $CO_2$ for commercialisation. The CHP unit is sized to meet the electricity requirement of the WWTP plant, the AD plant, the biogas upgrade and $CO_2$ liquefaction plant. The treatment of slurry and food waste requires pasteurisation of these feedstocks.

A preliminary design of the proposed AD systems above has been completed, on the basis of which cost estimates were produced and detailed discounted cash flow analysis completed.

## A. Preliminary design of the proposed AD system

This section provides a process flow diagram, a layout drawing and a description of the plant for the proposed systems.

### 1. AD + CHP plant

Since this plant uses the WWTP sludges and grass silage, this plant's process doesn't include pasteurisation. Here is a functional description of the plant:

a) **Feedstock reception:** Grass silage (delivered by contractors or directly by farmers) is brought into the plant and weighed at the weighbridge. The existing storage facilities at the WWTP will be adapted to store enough grass silage for day-to-day operation all year (average of 10 tFM/day; 3,400 tonnes per year[18]).
b) **Digester feeding:** A front-end loader operated by the plant manager, feeds silage into a large 20-tonne feed-hopper which is equipped with weigh-cells; allowing a controlled amount of silage and sludges to be fed into the digester every day. The WWTP sludge (48 tFM/day) is fed to the digester feed hopper together with the silage.
c) **Digester:** The digester is a large, insulated tank (circa 2500 m3) in which the feedstocks are mixed continuously and heated to an operating temperature of 40 °C. The digester roof is a double-membrane system in which the inner membrane rises and falls to allow for gas storage. The biogas produced (c.6300 m3/day) is cleaned before being supplied to the CHP unit.
d) **CHP unit:** The gas-powered generator and heat recovery unit is operating year-round at an average electrical output of around 550 kWe, to meet the electricity requirement of the WWTP (taken as an average of 500 kWe) and the AD plant. It also provides the digester heating requirement (c.1180 MWh/year), which leaves approx. 3,400 MWh/yr in excess heat to be dissipated[19].
e) **Digestate and products**: The liquid digested waste (digestate) produced by the digester is passed through a screw-press to separate the fibrous solids from the liquid portion. The high-fibre digestate solids are stored and stabilised in covered bays with a view to producing a valuable peat-like compost (c.3700 tFM/yr) which can be sold as a by-product for horticulture. The liquid digestate (17,500 tFM/yr) is stored in a large storage tank[20] (90 days winter

[18] Assuming a silage trailer capacity of 20 tonnes, this requires 170 deliveries per year.
[19] This is a substantial amount of heat with a value estimated at €170,000 (at €50/MWh). Finding a local use either on site (digestate drying/composting, horticultural production, etc.) or locally via a district heating system would further enhance the sustainability of the project.
[20] It is proposed to reuse the existing sludge storage tank to store the digestate. The only capex requirement associated with digestate storage is the covering of the tank with a gas-tight membrane and facilities to recover the secondary biogas produced in the tank.

storage) for recycling back to agricultural land as a valuable fertiliser, reducing the need for artificial fertilisers and contributing to cheaper, more sustainable grass production for participating farmers.

The following process flow diagram illustrates the different stages described above:

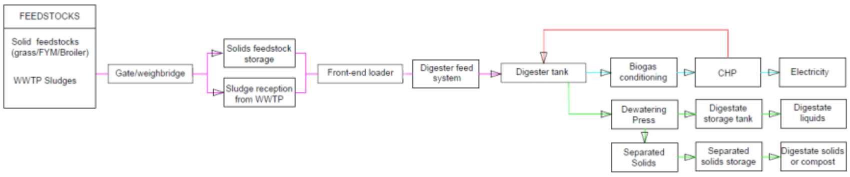


Figure 16: Process flow diagram of AD + CHP system.

The **plant layout** of this first AD system is presented in Figure 18, together with 3D visual impressions of the proposed plant.

## 2. AD + CHP plant + CBM export

This AD system is an upscaled version of the previous one, which can be built as an extension of the first AD system described above. Here is a functional description of this larger, more complex system:

a) **Feedstock reception:** The feedstock reception area builds on the existing storage facilities to store a larger amount of grass silage for year-round supply to the digester i.e. 82 tFM/day or 30,000 tonnes per year). In addition, an enclosed building accommodates the food waste reception and processing system.
b) **Digester feeding:** A front-end loader operated by the plant manager, feeds silage into a large 20-tonne feed-hopper which is equipped with weigh-cells; allowing a controlled amount of silage to be fed into the digester every day. WWTP sludge is fed to the digester as per above.
c) **Pasteurisation:** the feedstocks subject to ABP regulations are pasteurised before being fed into the digester to eliminate potential pathogens.
d) **Digester:** Four 3,500 digesters with a similar design to the above, produce a total of 17,000 Nm3/day of biogas.
e) **CHP unit:** The CHP unit has an average electrical output of 900 kWe, to meet the electricity requirement of the WWTP, the AD plant, the biogas upgrade system and CO2 liquefaction plant. The CHP unit, together with the biogas upgrade system and the $CO_2$ liquification plant produce a large amount of heat (c.10,300 MWh/yr), which is used to pasteurise the ABP feedstocks and heat the digester (c. 8,000 MWh/yr), leaving approx. 2,300 MWh/yr in excess heat to be dissipated or valorised locally.
f) **Upgrading biogas to biomethane:** Biogas is produced continuously and comprises mainly methane (65% average content) with most of the balance being carbon dioxide and some water. It also has trace compounds of which the most important is the corrosive gas hydrogen sulphide. Biogas is processed semi-continuously by an upgrading facility that produces biomethane. This has several stages as follows:
    1. Clean the biogas removing mainly hydrogen sulphide and moisture
    2. Separation of carbon dioxide and methane. The biogas is pressurised and passed through a series of membranes which separate these gases with a high degree of efficiency.
    3. Heat recovery. Heat produced by compression of biogas (to pass through the gas separation membranes) is recovered for use in the digestion and pasteurisation process.
g) **$CO_2$ liquefaction:** High purity carbon dioxide is produced by the upgrading facility (3,100 Nm3/day or 236 kg/hr). Instead of releasing this $CO_2$ to the atmosphere, it is compressed and stored for sale as a by-product. The compression of carbon dioxide also produces heat which can be recovered for use by the digester.
h) **Digestate and products**: A total of c.13,000 tFM/yr of high-quality compost is produced and a total of 62,000 tFM/yr of liquid digestate is produced, stored onsite temporarily and then spread on agricultural land.
i) **Gas pipeline:** An underground gas pipeline transports compressed biomethane from the AD facility to the Carbery processing plant. A total of 20,300 MWh/yr of biomethane is exported.

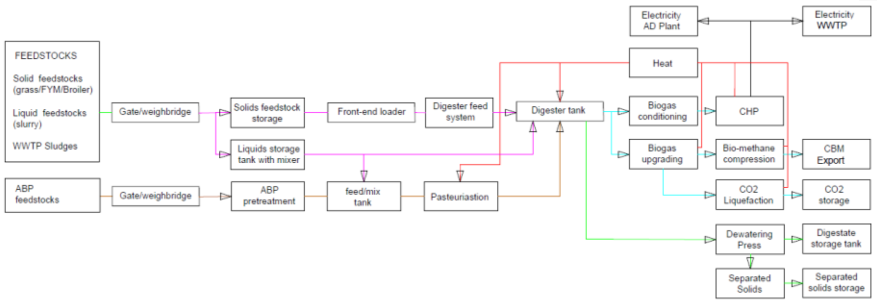


Figure 17: Process flow diagram of AD + CHP + CBM + CO2 pathway.

The **plant layout** of this second AD system is presented in Figure 19.

## 3. Alternative Scenario: AD + CHP plant + biogas export

An alternative scenario to the above plant design was explored whereby, instead of upgrading the biogas to CBM, the biogas is cleaned, pressurised and transported via a gas pipeline to the Carbery processing plant where it is burned in the existing boilers and/or CHP plants (equivalent thermal energy supplied of 23,700 MWh/yr).

The advantages of such system design are:

- The overall system is simplified (less plant) and more robust (less wear and tear).
- This results in less CAPEX and OPEX.
- The onsite electricity requirement is greatly reduced (-55%) and more renewable gas can be exported to the milk processing facility (+17% in thermal energy terms).

The disadvantages of this alternative system design are:

- There is no $CO_2$ extraction involved, foregoing an important revenue stream for the project.
- Biogas, while it has been scrubbed of H2S, has a lower calorific value than biomethane and its combustion might require adaptations to existing plants at the food processing facility.
- There is a shortfall in heat production (no heat from the biogas upgrading & CO2 liquefaction, and gas compression), which needs to be supplied by a boiler using biomass or biogas.

(Add process flow diagram)

**The financial analysis of the two primary systems' design and the alternative scenario above, is presented hereafter.**

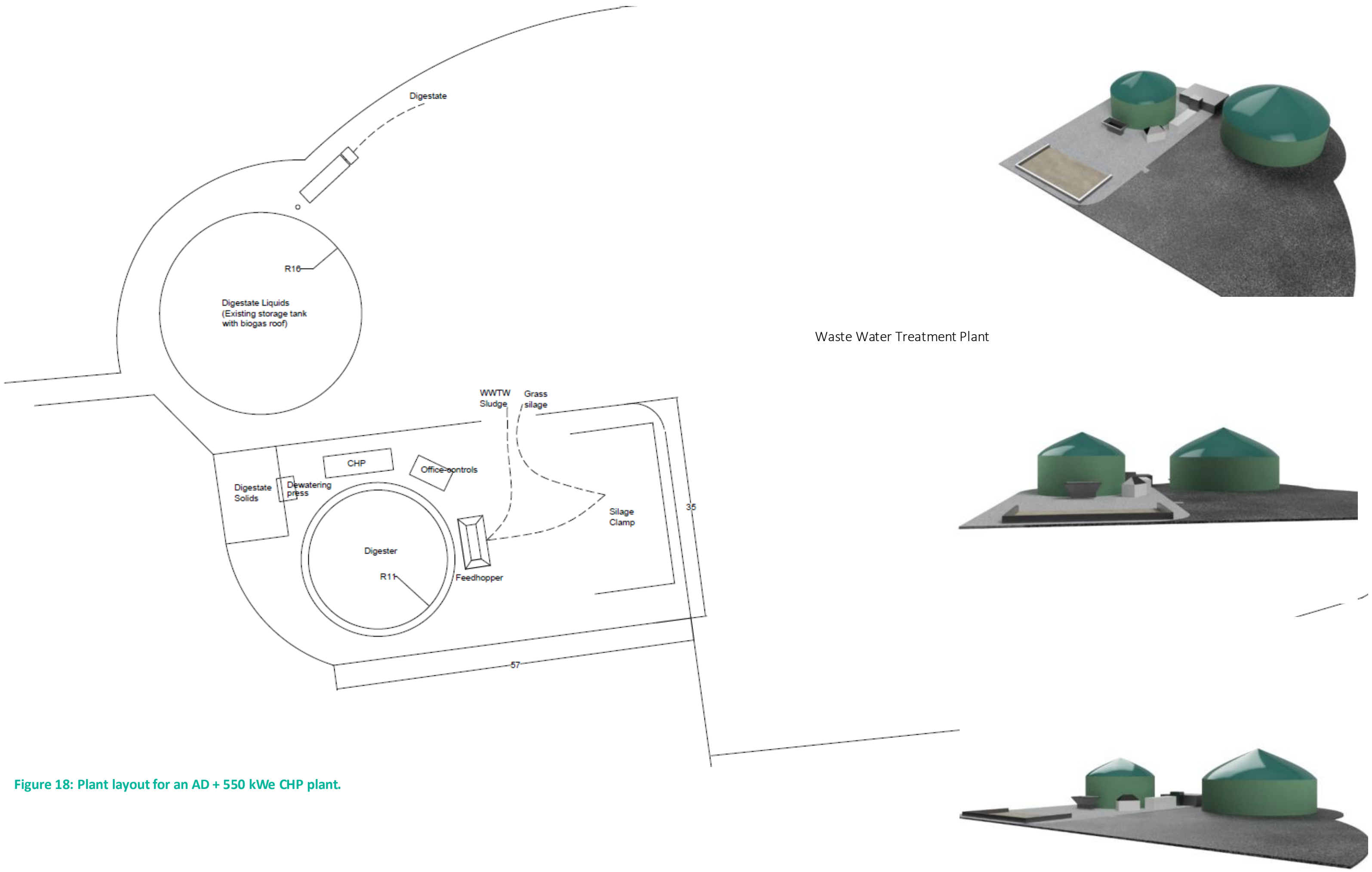


**Figure 18: Plant layout for an AD + 550 kWe CHP plant.**

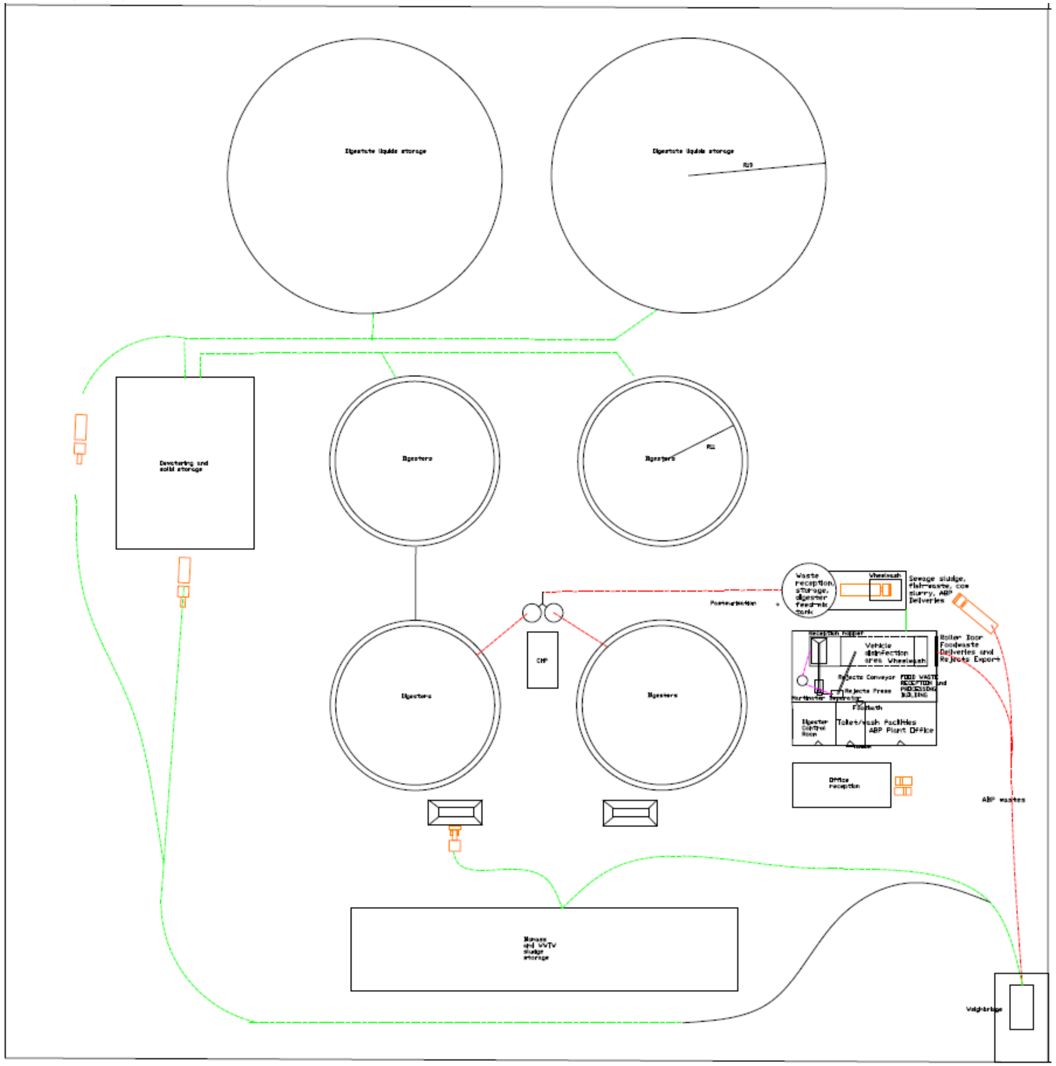


Figure 19: Plant layout for 40 GWh/yr AD plant with ABP treatment, CHP and CBM for export.

## B. Life Cycle Cost Analysis

The life cycle cost analysis uses the data and assumptions applied in the AD pathways cost/benefit analysis to determine the cash flow of each project over a 20-year lifetime. The annual cash flows are discounted with a rate of 8%, assumed to be the weighted average cost of capital cost for such a project (Ricardo Energy & Environment, 2017). A general annual inflation rate of 2% has been applied to both operational costs and revenues.

The following key performance indicators of financial performance are used for the lifecycle cost analysis:

- **Net Present Value (NPV):** Difference between the present value of cash inflows and the present value of cash outflows over a period of time. It applies the discount rate to account for the time value of money.
- **Internal Rate of Return (IRR):** A discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. It measures the rate return on the investment made.

The NPV and IRR are calculated for the project cash flows before tax. The full value of the initial capital investment has been applied as a negative cash flow on year 0 (no loan repayment and finance costs) so that the IRR values obtained indicate the potential return on investment from the perspective of the equity investor or institutional lender. The results of the discounted cash flow analysis for the AD systems proposed above are presented hereafter. The discounted cash flow analysis takes into account the replacement cost of some of the machinery on year 15 and end-of-life value for the plant and associated infrastructure (including land).

The analysis, summarised in Table 7,shows that for all three AD systems envisaged, the project generates a healthy return on investment with IRRs before tax of 17%, 12% and 16% respectively. The NPVs of the project is €0.97 million, €1.62 million and €3.41 million respectively. These results indicate that:

a) the first AD system designed to meet the site's energy requirements of the site is the most profitable. This can be explained by the fact that the system is simpler and uses primarily free feedstocks available on site.
b) the second AD system designed to meet the site's energy requirements is less profitable due to its increased complexity, higher CAPEX and OPEX. The substantial increase in feedstock costs due to the use of grass silage as the primary feedstock is only partially compensated by gate fee paying feedstocks.
c) the alternative AD system exporting biogas instead of CBM is more profitable due to the reduced CAPEX (no biogas upgrading and $CO_2$ liquefication plant) and OPEX (less O&M and energy costs), despite the absence of revenue from the sale of $CO_2$.

**Commented [EB11]:** Any sense of what the increased traffic to the WWTP would be like if we went with the grass option?

**Commented [XD12R11]:** Yes, we can check that. 10 tFW/day grass silage for scenario 1, 82 t/FW/day in scenario 2. How much silage on a silage bale trailer?

**Commented [XD13R11]:** See estimate for first pathway (3400 tFM/yr silage) , using 20 t silage trailer, that's 170 deliveries per year. 8 times that for pathway 2!!

**Table 7: Discounted Cash Flow Analysis of the three AD systems pre-designed**

| Pathways Analysed | units | Carbery WWTP AD-CHP system | Carbery WWTP AD-CHP+ CBM export | Carbery WWTP AD-CHP+ biogas export |
|---|---|---|---|---|
| **ECONOMIC MODEL** | | | | |
| **CAPEX** | | | | |
| Planning and initial | € | 65,000 | 80,000 | 80,000 |
| Project management | € | 65,000 | 80,000 | 80,000 |
| Digester turn-key | € | 500,000 | 2,800,000 | 2,800,000 |
| Electrical and controls | € | 150,000 | 250,000 | 250,000 |
| Feed system | € | 150,000 | 310,000 | 310,000 |
| Digestate system (press+store) | € | 115,000 | 115,000 | 115,000 |
| Digestate liquid storage | € | 60,000 | 425,000 | 425,000 |
| Civils | € | 150,000 | 350,000 | 350,000 |
| Grid connection | € | - | - | - |
| ABP reception + pretreatment | € | - | 250,000 | 250,000 |
| CHP plant and gas conditioning | € | 470,184 | 781,278 | 579,968 |
| Biogas-to-CBM upgrading plant | € | - | 1,012,173 | - |
| Biogas-to-CBM compression plant | € | - | - | - |
| CBM storage | € | - | - | - |
| CO2 recovery and storage | € | - | 731,244 | - |
| District energy network | € | - | 80,000 | - |
| Back-up boiler | € | - | - | 298,096 |
| Biogas boiler | € | - | - | - |
| Gas Grid Connection | € | - | - | - |
| Other Civils | € | - | - | - |
| **Total Build Cost** | € | **1,725,184** | **7,264,695** | **5,538,065** |
| Site acquisition | € | - | - | - |
| Capital Grants/Subsidies | | - | - | - |
| **Net Capital Expenditure** | € | **1,725,184** | **7,264,695** | **5,538,065** |
| | | | | |
| **Cost of Finance** | | | | |
| Debt to Equity Ratio | % | 80% | 80% | 80% |
| Amount Borrowed | € | € 1,380,147 | € 5,811,756 | € 4,430,452 |
| Interest Rate | % | 4.5% | 4.5% | 4.5% |
| Loan Repayment Period | years | 10 | 10 | 10 |
| **Annual Loan Repayment** | **€/year** | **174,421** | **734,483** | **559,915** |
| | | | | |
| **Revenues** | | | | |
| Sale of Electricity | €/y | 438,000 | 438,000 | 438,000 |
| Sale of Heat | €/y | - | - | - |
| Heat Subsidies | €/y | - | - | - |
| Sale of CBM/biogas | €/y | - | 574,320 | 723,556 |
| CBM Subsidies | €/y | - | 514,453 | 648,133 |
| Sale of CO2 | €/y | - | 327,060 | - |
| Sale of Compost | €/y | 94,484 | 326,858 | 326,858 |
| **Total Revenues** | €/y | **532,484** | **2,180,690** | **2,136,547** |

| Pathways Analysed | units | Carbery WWTP AD-CHP system | Carbery WWTP AD-CHP+ CBM export | Carbery WWTP AD-CHP+ biogas export |
|---|---|---|---|---|
| **ECONOMIC MODEL** | | | | |
| **Operational Expenditure** | | | | |
| ***Feedstock Costs/Income*** | | | | |
| Grass Silage | €/y | 104,296 | 897,900 | 897,900 |
| Cow Slurry | €/y | - | 82,125 | 82,125 |
| Farm Yard Manure | €/y | - | - | - |
| Food Waste (brown bin) | €/y | - | (101,835) | (101,835) |
| WWTW sludge (dewatered) | €/y | - | - | - |
| Carbery Brown Sludge | €/y | - | - | - |
| Fish Waste | €/y | - | (109,500) | (109,500) |
| Offal | €/y | - | - | - |
| Pig slurry | €/y | - | - | - |
| Chicken manure | €/y | - | - | - |
| Carbery White Sludge | €/y | - | - | - |
| ***Feedstocks (net cost)*** | **€/y** | ***104,296*** | ***768,690*** | ***768,690*** |
| ***Digestate Costs/Income*** | | | | |
| ***Digestate Disposal*** | **€/y** | ***34,434*** | ***119,121*** | ***119,121*** |
| ***Cost of CBM Haulage & Injection*** | | | | |
| CBM Haulage | €/y | - | - | - |
| CBM Grid Injection | €/y | - | - | - |
| ***CBM Haulage & Injection*** | **€/y** | - | - | - |
| ***Energy Costs*** | | | | |
| Electricity Imports | €/y | - | - | - |
| Heating Fuel | €/y | - | - | 93,155 |
| ***Energy costs*** | **€/y** | - | - | ***93,155*** |
| ***Labour, Insurance, Overheads*** | | | | |
| Staffing Ratio | | 0.5 | 1.0 | 2.0 |
| Plant operator | €/y | 11,250 | 22,500 | 45,000 |
| Management | €/y | 3,125 | 6,250 | 12,500 |
| Admin | €/y | 1,250 | 2,500 | 5,000 |
| | €/y | | | |
| Overheads | €/y | 4,688 | 9,375 | 18,750 |
| Insurance | €/y | 17,252 | 72,647 | 55,381 |
| ***Labour, Insurance, Overheads*** | **€/y** | ***37,564*** | ***113,272*** | ***136,631*** |
| ***Maintenance and Repairs*** | | | | |
| Digester O&M | €/y | 18,300 | 69,500 | 69,500 |
| Boiler O&M | " | - | - | 5,962 |
| CHP O&M | " | 48,535 | 80,648 | 59,868 |
| CBM O&M | " | - | 30,365 | - |
| ***Maintenance and Repairs*** | " | ***66,835*** | ***180,513*** | ***135,330*** |
| **Total OPEX** | **€/y** | **243,130** | **1,181,597** | **1,252,927** |
| ***Depreciation*** | | | | |
| Buildings | €/y | 33,750 | 167,000 | 167,000 |
| Machinery | " | 51,346 | 210,980 | 95,871 |
| ***Depreciation*** | " | ***85,096*** | ***377,980*** | ***262,871*** |

| Pathways Analysed | units | Carbery WWTP AD-CHP system | Carbery WWTP AD-CHP+ CBM export | Carbery WWTP AD-CHP+ biogas export |
|---|---|---|---|---|
| **ECONOMIC MODEL** | | | | |
| **Annual profit and loss** | | | | |
| Total Revenue | €/y | 532,484 | 2,180,690 | 2,136,547 |
| Total OPEX | " | 243,130 | 1,181,597 | 1,252,927 |
| Depreciation | " | 85,096 | 377,980 | 262,871 |
| Loan Interest | " | 31,053 | 130,765 | 99,685 |
| **Profit/Loss** | **"** | **173,206** | **490,349** | **521,064** |
| Return on Capital | **%** | **11.8%** | **8.5%** | **11.2%** |
| | | | | |
| **Discounted Cash Flow Analysis** | | | | |
| Year 0 | | - 1,725,184 | - 7,264,695 | - 5,538,065 |
| Year 1 | | 295,142 | 1,019,075 | 901,292 |
| Year 2 | | 301,045 | 1,039,457 | 919,318 |
| Year 3 | | 307,066 | 1,060,246 | 937,705 |
| Year 4 | | 313,207 | 1,081,451 | 956,459 |
| Year 5 | | 319,471 | 1,103,080 | 975,588 |
| Year 6 | | 325,861 | 1,125,141 | 995,100 |
| Year 7 | | 332,378 | 1,147,644 | 1,015,002 |
| Year 8 | | 339,025 | 1,170,597 | 1,035,302 |
| Year 9 | | 345,806 | 1,194,009 | 1,056,008 |
| Year 10 | | 352,722 | 1,217,889 | 1,077,128 |
| Year 11 | | 359,776 | 1,242,247 | 1,098,670 |
| Year 12 | | 366,972 | 1,267,092 | 1,120,644 |
| Year 13 | | 374,311 | 1,292,434 | 1,143,057 |
| Year 14 | | 381,798 | 1,318,282 | 1,165,918 |
| Year 15 | | 28,105 | - 250,091 | 542,391 |
| Year 16 | | 28,667 | - 255,092 | 553,239 |
| Year 17 | | 29,240 | - 260,194 | 564,304 |
| Year 18 | | 29,825 | - 265,398 | 575,590 |
| Year 19 | | 30,421 | - 270,706 | 587,101 |
| Year 20 | | 103,113 | 56,804 | 836,978 |
| **IRR** | **%** | **17%** | **12%** | **16%** |
| **NPV** | **€/2021** | **968,362** | **1,619,732** | **3,407,376** |

## C. Sensitivity Analysis

By way of **sensitivity analysis**, key variables in the discounted cash flow analysis have been altered by -40% and +40% around their baseline values as used in the central analysis presented above, to measure their impact on the NPV of the three AD projects analysed above. The results are listed in the tables below.

Table 8: Sensitivity analysis results – minus 40% and plus 40% change in key variables.

| Pathways Analysed | | Carbery WWTP AD-CHP system | Carbery WWTP AD- CHP+ CBM export | Carbery WWTP AD- CHP+ biogas export |
|---|---|---|---|---|
| ***Change in key variables*** | | Change in NPV (€) | | |
| Value of biogas/CBM produced | *-40%* | 968,362 | (843,521) | 304,049 |
| Value of electricity substituted | *-40%* | (910,216) | (258,846) | 1,528,798 |
| Value of CO2 | *-40%* | 968,362 | 216,976 | 3,407,376 |
| Cost of silage | *-40%* | 1,415,685 | 5,823,050 | 7,610,695 |
| Capital cost | *-40%* | 1,616,724 | 4,991,158 | 5,590,680 |
| Value of biogas/CBM produced | *+40%* | 968,362 | 4,082,985 | 6,510,703 |
| Value of electricity substituted | *+40%* | 2,846,940 | 3,498,310 | 5,285,954 |
| Value of CO2 | *+40%* | 968,362 | 3,022,488 | 3,407,376 |
| Cost of silage | *+40%* | 521,038 | (2,583,586) | (795,942) |
| Capital cost | *+40%* | 319,999 | (1,751,695) | 1,224,073 |

The following observations can be made from the sensitivity analysis results above:

- The AD system with CHP only is most sensitive to the value of the electricity substituted: a 40% reduction results in a negative NPV (194% drop in NPV).
- The AD system exporting CBM is most sensitive to the cost of silage: a 40% increase (€42/tonne) results in a negative NPV with a 260% drop. This system is also very sensitive to capital cost due as it is significantly more capital intensive than the other two systems.
- The AD system exporting biogas is most sensitive to the cost of silage (123% drop in NPV), but by a lower degree than with CBM export.

It is worth noting that the recent developments in electricity and natural gas prices, with relative increases close to 100%, would dramatically improve the viability of the project should they be applied in the cash flow analysis above. Industrial CO2 prices have also increased considerably since the initial analysis conducted in Chapter 5. The following table reflects these recent changes observed in these key factors. While they have a dramatic impact on the profitability of these projects (NPV is seven times higher for the system producing CBM + CO2), it is very unclear if these price increases are here to stay, and these results should be taken with caution.

| Pathways Analysed | | Carbery WWTP AD-CHP system | Carbery WWTP AD- CHP+ CBM export | Carbery WWTP AD- CHP+ biogas export |
|---|---|---|---|---|
| ***Change in key variables*** | | Compounded change in NPV (€) | | |
| Value of biogas/CBM produced | *+60%* | 5,195,162 | 13,048,302 | 12,289,167 |
| Value of electricity substituted | *+90%* | | | |
| Value of CO2 | *+100%* | | | |

Overall, the simpler systems requiring less capital investment and operating costs are more resilient. The larger systems relying primarily on grass silage (58% of the energy content of the biogas produced) are quite vulnerable to its cost. This can be mitigated by engaging with farmers in medium to long-term supply contracts and incentivising them with a stake in the profitability of the proposed AD projects.

In this regard, Chapter 7 explores business & financing models appropriate for community-owned anaerobic digestion project development.

## D. Recommendations for the deployment of AD systems at Carbery's

Considering the cost/benefit analysis conducted above, our recommendation is to plan for a gradual development of the AD system collocated with Carbery's WWTP based on the following steps:

- Install first the AD with CHP system to meet the AD and WWTP plants' electricity requirement. This plant will act as a pilot project, demonstrated AD with limited technical complexity yet good profitability.
- In time, scale up the plant to increase its biogas production by four, covering the site's electricity requirements and exporting the balance of biogas to the Carbery's milk processing plant via a gas pipeline. While processing slurry and food waste at the plant bring in gate fees, and increases its sustainability and circular economy impact, a decision can be made to use non ABP feedstocks only (grass silage & WWTP sludges).
- The next step up would be to upgrade the biogas to CBM before it is exported, supplying a more refined and versatile fuel (e.g. for use as a transport fuel), and producing industrial grade $CO_2$.

Such a modular approach to AD development at Carbery's would allow a gradual learning curve, reducing technical and financial risks while offering opportunities to innovate and increase the impact of the project within the group and the wider stakeholder community.

# Chapter 7. Business & Financing Models Appropriate for Community-Owned Anaerobic Digestion Project Development.

The objective of this chapter of the study is to review business and financing models appropriate for community participation in the development of anaerobic digestion in West Cork, in consultation with key stakeholders. Models of community ownership promote wide participation in ownership and management, engender local support, are inclusive and deliver tangible and intangible local benefits, particularly for individuals that do not have sufficient funds to invest.

## A. Ownership & Organisational Model

There are two possible structures to raise equity in the framework of a community-owned project: a limited company or a co-operative, also known as an Industrial and Provident Society (I&Ps). These two organisational structures are governed by separate legislation but subject to broadly similar requirements.

Both types of organisations provide 'limited liability', which means that members/ shareholders cannot be sued for more money than they have invested in the organisation. This protection is important for any group but particularly for community ventures. The organisation becomes a 'legal person' that has its own identity and can enter into contracts of various sorts including owning property, buying and selling. If things go horribly wrong, the organisation 'dies and members lose the money they have invested but there is no recourse to individuals' personal wealth.

The main differences that impinge on this project are the governance, the number of members and requirements regarding share offers. Some other differences regarding shares may also be relevant in terms of ensuring a truly community enterprise.

### 1. Governance & Membership

Both companies and I&P societies are managed on a day-to-day basis by a board of directors, elected by general meetings of the shareholders. Both need to have a governing document that is registered with the Company Registration Office. Both need to report annually to the CRO. Both can raise share capital, and both can make payments to shareholders.

Companies are controlled by their members (or shareholders) and controlled on the basis of share ownership; those who hold more shares wield more votes and exercise greater control over the company. The maximum number of members that a company can have is 100. This could be a major limiting factor as community projects aim to have hundreds of members.

Co-operatives are controlled by their members, who are also the shareholders. Each member has one vote, regardless of how many shares they hold. This prevents a small number of members from seizing control. There is no limit to the number of members that a Co-op can have.

### 2. Share Raising

Companies raise capital by selling shares, which they can do on an informal basis with small numbers of engaged people but if they issue a public share offer, they will need to comply with detailed legislation that will require lawyers and accountants at significant expense. European Securities and Markets Authority (ESMA) list all European share prospectuses.

Co-ops can issue a share offer without great expense and raise the required capital. Interest can be paid on this to incentivise investment although the rate paid should only be sufficient to obtain and retain the investment. The finances should be sufficient to pay an average (IRR) of about 6% and be sufficiently attractive to raise the equity necessary.

### 3. Registering an I&Ps

Co-ops or I&Ps are governed by Rules and the Irish Co-operative Organisation Society (ICOS) has Model Rules that can be used as a basis for many new societies. They have helped a dozen energy co-ops to register, using bespoke Rules. This is the advised route and ICOS would be supporting the group to develop the necessary Rules. There are plenty of useful documents on the ICOS website, including a guide to starting a new co-op.

I&Ps are registered with the Registry of Friendly Societies, which is held by Companies Registration Office (CRO). They charge €100 to register a new society.

The following table provides a summary and comparison of the key characteristics of Co-operative and Company legal structures.

Table 9: key characteristics of Co-operative and Company legal structures

| | I&Ps/Co-operative | Company |
|---|---|---|
| number of members | 7 to unlimited | 1 to 100 |
| governing document | Rules | Memorandum and Articles of Association |
| registration | Registrar of Friendly Societies (RFS) | Companies Registration Office |
| can raise shares | ✓ | ✓ |
| requirements | share offers >€30k must have the intention registered with RFS | share prospectus >€1M must comply with the new Prospectus Regulation |
| returns | interest and dividends | dividends |
| taxable | interest no; dividends yes | yes |
| pros | Model Rules available good support from co-operative organisations inexpensive registration process lightweight reporting requirements interest to members is an allowable expense secure community ownership possible with 'asset lock' can raise equity and loans simply from its members simple share offer document that ordinary people can understand | well recognised organisational form Mem' & Art's can be written to permit anything [legal] can invest in other enterprises can be junior partner in a joint venture can invest for profit |
| cons | community shares not well understood by many interest payments limited must be in control of its own trade—cannot be a junior partner in a joint venture | shareholder membership is limited to 100 for private limited companies onerous reporting requirements share prospectus expensive to develop |

## 4. Co-operative principles

An Industrial and Provident Society embraces the co-operative principles set out by the International Co-operative Alliance. The seven core principles of co-ops are:

- voluntary and open membership.
- democratic member control—one member, one vote.
- member economic participation.
- autonomy and independence—never owned as a subsidiary.
- education, training and information.
- co-operation among co-operatives.
- concern for community.

It is clear that these principles fit easily with the values of community-based organisations and provide a good structure for carrying out a business enterprise for the benefit of the community.

## B. Financing A Community Owned Anaerobic Digestion Project

There are various types of agreement that can be used to secure the required capital for an anaerobic digestion project. Broadly, these can be classified as debt and equity. Debt involves money from a creditor or 'lender', who will expect to be repaid with interest and this can be in the form of a loan, bond or debenture. Equity means ownership and it is typically expressed as shares, with each person owning one or several shares of the total project being an 'investor'.

Debt carries higher risk for the lender, who in turn demands greater returns. Generally speaking, interest payments on debt is an allowable expense for tax purposes but dividends to shareholders is paid from the after-tax profits. The exception is community shares where interest on shares is an allowable expense for tax purposes.

The amount borrowed or invested is termed 'capital' or 'principal'; the extra payments made to the lender or investor are 'interest', 'returns', 'coupon rate' or 'dividend' (although this is technically distinct). Some terms are used interchangeably but the following are descriptions of the main distinctives as generally understood.

### 1. The specificities of financing a community renewable energy project

Research into the experience of community owned renewable energy projects in securing finance has indicated a number of commonalities (Ricardo Energy & Environment, IEA-RETD Operating Agent, 2016). Debt financing is often expensive for communities due to the risks perceived by commercial investors such as banks and pension funds. Co-operatives might have a reputation to offer lower investment returns, and the corresponding cultural acceptance of community RES projects with lenders and investors, creates barriers to securing financing. Debt is also often more expensive for smaller community RES projects because lenders are not offered a portfolio of many projects to spread their risk. In a larger, more diversified investment portfolio, the risk of default on the entire principal is much lower.

Development costs include feasibility analysis, project management, securing financing, planning, and advisory fees. There are issues with availability and cost of debt financing for communities, especially for the planning and development stage of projects. Cash poor, and general risk averse communities, will have much less cash available. In addition, small RES projects are unable to leverage economies of scale for construction and developmental costs. Shared ownership models that required complex agreements or community-owned projects that did not have previous experience had a greater need for advisory support by the community.

However, there are plenty of positives:

- Community projects inevitably use volunteer time from the member base at different stages of the project. If volunteer labour is used during the construction phase it can help reduce installation costs.
- Communities also usually have personal relationships with various local businesses and stakeholders, which can enable them to get good deals, for example on equipment rentals or leases on land.
- Community RES projects can sometimes be seen as a demonstration project and can attract discounts on equipment, donations of materials, and funding.
- Various grants and additional funding are available for the development of community projects, especially for feasibility assessments as a critical component of on-going community energy planning projects.
- On the other hand, community consultation costs may be small or negligible for community-owned or shared community projects depending on the level of engagement of the community. However, the process may often be protracted.
- Complete community ownership of the project can then be seen as an even greater participation with the benefits and challenges of such projects and if there is capacity and commitment within the community to embrace this, they will be the richer for it.

### 2. Financing instrument options

Developing a community-owned project typically involves a combination of equity, generally 20 to 30% of the investment, and the balance is financed by debt. We review hereafter the common financing instruments available for renewable energy projects such as anaerobic digestion plants:

a) **Loans**

Loans are the most familiar type of borrowing arrangement. The lender offers money, and the borrower commits to repaying the capital and interest. In this case, the loan is likely to be taken with a bank or other financial institution and be secured in that it is backed by some form of collateral. Loans are generally not tradable.

b) **Bonds**

Bonds are certificates of debt that are issued specifically to raise funds. They should be secured against the assets of the company. Some people refer to unsecured bonds, but these are better described as debentures. There will be a clear repayment schedule for the interest and capital is generally repaid 'on maturity', i.e., at the end of the loan term. Bonds will have the same terms and conditions for all bondholders of that particular bond. They can generally be traded.

c) **Debentures**

Debenture is a general term for bespoke debt instruments used to raise capital for an enterprise. They are generally unsecured (against assets of the company) but may include some type of security arrangement in case problems arise. As with all debt mechanisms, they do not give any ownership of the company. There will be a detailed offer document that explains the terms and conditions of the agreement. Debentures may be allowed to be traded. The rate of interest can sometimes be referred to as the coupon rate and may be fixed at the outset or variable according to the performance of the enterprise.

d) **Shares**

Companies can raise capital by offering a stake in the enterprise. Investors become linked to the fortunes and misfortunes of the company. If the company does well, they will be paid a dividend and the value of the shares may increase above the price paid for them. This 'capital gain' is only realised when the shares are sold. Conversely, if the company does poorly, there may be no return on the investment and the value of the shares may reduce, even to zero. If the company is liquidated, the shareholders get a slice of the residual value once all other liabilities have been fulfilled. Shares can be bought and sold and may appear on public trading platforms like Euronext Dublin.

e) **Community Shares**

When an I&Ps issues shares, different rules apply. The shares still give a part-ownership of the enterprise, but the value of the shares can never increase above the face value, referred to as 'par value'. The shares cannot be freely traded, and all transfers of ownership must be managed by the society's board. They can also transfer the shares back to the society whereupon they are cancelled. These mechanisms prevent the financial speculation that can happen with company shares. Both interest (in proportion to investment) and dividends (in proportion to interactions with the society) can be paid. Interest is an allowable expenditure for tax purposes, but dividends are generally paid from taxed profits.

Community shares are often referred to as 'patient capital' as the investors are not out to make 'a quick buck' but are keen to support a community enterprise and are willing to let their money be used for this over an extended period of time.

## 3. Community buy-in to commercial projects

There may be some cases where a commercial developer will offer communities a stake in a renewable energy development and communities should look carefully at all such offers. The main advantage of such a scheme is that an experienced developer has carried out the hard work of investigating the potential and developing the business case; they have taken the risk and secured the various permissions necessary. In addition, partnering with commercial developers makes access to affordable debt easier, but often decreases the share owned by the community, and hence the benefits. Partnering also imposes new challenges in terms of framing the partnership and engaging on an equitable footing with better-resourced and more-experienced commercial developers and financiers.

It is difficult to find good models for such part-ownership and the terms and conditions of the offer will need to be assessed on their own merit. Wholly owned community projects are of more benefit to communities but require much more work.

When a community has ownership in a renewable energy project, there is an income stream that can pay interest to the local investors and, depending on the energy distribution arrangements (e.g. heat distribution, transport fuel, etc.), there may be benefits in terms of reduced energy costs in the community. It has been well demonstrated that when people have a stake in a development, they are much less focussed on any downsides and much more conscious of the benefits that arise. There is also better engagement with the underlying issues that the development addresses, be it climate change, fuel poverty or community enterprise when individuals in the local community are members of the organisation and own part of the development.

All investment carries risk and with community schemes, the risk is mainly carried by the members. If something goes wrong or if the generator does not perform as expected, the investor members may not receive the returns that they expect and may need to dip further into their pockets to rectify problems that become evident. It is at least theoretically possible that the investors could lose all of their investment.

When things go according to plan and when a well-researched scheme is implemented, local people benefit financially from their local energy resources and that in turn translates into more money in the local economy for purchases and other investments. Depending how the co-op is set up, there could be explicit funding for local community projects as part of the designed outcomes. Communities have gone on to build various community facilities where there is such an established income stream.

Where a commercial developer offers a share of the project to a community group, they will have factored that into their business model and unless the pay-outs are linked to performance, the income that comes to the community may be minimal because the developer will need to give some type of commitment to pay a certain amount and that will therefore be at the lower end of the range of what they can afford so that years of poor performance do not bankrupt the project. It is therefore expedient to negotiate a true equity stake where the community share in the fortunes (and misfortunes) of the project.

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## Appendices

# A. Appendix C – Potential for Algae

Written by David Wall

Seaweed biomass can potentially provide an attractive feedstock for anaerobic digestion (AD) in particular circumstances. Ireland has a significant potential with its considerable coastline (7500km) and temperate oceanic climate to accumulate a sizeable seaweed resource both naturally and through farm cultivation. Irish brown seaweeds include for *Ascophyllum nodosum*, *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Saccorhiza polyschides*. Of these, *Laminaria digitata* and *Saccharina latissima* have been identified as having most potential due to their rich organic composition (Tabassum et al., 2017). The estimated production of Irish seaweeds is 29,500 tonnes wet weight per annum, occurring naturally (Tabassum et al., 2018). This harvest is dominated by *Ascophyllum nodosum* which mainly accumulates in the north west of Ireland in Donegal and Galway (Murphy et al., 2013). At present, the natural seaweed resource in Ireland is used primarily for food and not biofuels (Tabassum et al., 2016a).

Seaweed (macro-algae) can be considered a third-generation biofuel source as it does not have any land or freshwater requirements as compared to traditional energy crops. It is also proposed as a feedstock that can achieve higher growth rates and higher rates of carbon fixation than land-based energy crops (Tabassum et al., 2017). Additionally, due to the absence of lignin (complex polymers) and hemicellulose, seaweed can be a more suitable biomass for digestion that allows for easier fermentation and  minimal pre-treatment (Tabassum et al., 2018; Xia et al., 2015). However, the morphology of brown seaweed can vary substantially depending on the growth conditions at a given location; this includes for temperature, nutrients, sunlight and water flow. The body of the plant can be divided into different sections, namely the holdfast, stipe and frond, and the composition of each component can vary in terms of organic content. The frond has been identified as the most significant fraction in terms of contributing to biogas production (Tabassum et al., 2018). Despite the potential of natural seaweed stock for energy production, certain biodiversity issues must obviously be considered. Thus, a more favourable pathway proposed is the farm cultivation of seaweed, a concept known as integrated multi-trophic aquaculture (IMTA). Such a method combines seaweed cultivation with fish (salmon/mussel) farms. The benefit of this approach is that the nutrient waste from the fish can be sequestered by the seaweed and thereby cause increased plant growth as compared to pristine waters. The prospect of such a strategy will depend on the location of fish farm sites, however this is deemed the most economical method for seaweed farming (Tabassum et al., 2016a). Yields of 40-150 tonnes wet weight per hectare per annum have been indicated for seaweed farm cultivation.

The seasonal variation of seaweed is one of the main characteristics to be considered if it is to be used as a biomass resource for AD. The biochemical composition of seaweed will vary throughout the year as the seaweeds becomes 'ripe'. This will have inherent impact on the biogas production. For brown seaweed, the build-up of carbohydrates has typically been reported in the summer and autumn; in the winter, carbohydrates are used as an energy source in cellular activities (Tabassum et al., 2016b). Additionally, the ash content of seaweeds will vary throughout the year, for AD the feedstock should have as minimal ash as possible. Another concern is the build-up of polyphenols, inhibitory compounds for AD, which is dependent on the geographic location, harvest time light intensity and nutrient availability amongst other factors. Significant seasonal variation has been reported for brown seaweeds. Literature studies have previously shown that high polyphenol content in summer months adversely affected biogas production for *Ascophyllum nodosum*; two potential harvest dates were thus suggested, March and October. In October the SMY reported was 215 L $CH_4$ kg $VS^{-1}$ (47 $m^3$ $CH_4$ $t^{-1}$) equivalent to a gross energy yield of 116 GJ $ha^{-1}$ $year^{-1}$ (Tabassum et al., 2016b). For *Laminaria digitata*, significant seasonal variation in biochemical composition is evident. August was indicated as the optimal harvest time for this seaweed species with the SMY reported at 327 L $CH_4$ kg $VS^{-1}$ (53 $m^3$ $CH_4$ $t^{-1}$) equivalent to a gross energy yield of 200 GJ $ha^{-1}$ $year^{-1}$. The SMY was 40% higher than that for a December harvest indicating the impact of seasonal variation.

From a biogas production perspective, the potential for seaweed in Ireland is dependent on the availability of other feedstocks (in the vicinity) that can be used in co-digestion, for example, farm slurries and the organic fraction of municipal solid waste (OFMSW). This is deemed a more integrated approach. Indicative laboratory trials, co-digesting cultivated *Saccharina latissima* with dairy slurry at a ratio of 2:1 (on a volatile solids basis), have been shown to generate a specific methane yield (SMY) of 252 L $CH_4$ $kg^{-1}$ VS at an organic loading rate (OLR) of 4 kg VS $m^{-3}$ $d^{-1}$ (Tabassum et al., 2016a). For natural stock *Laminaria digitata* co-digested with dairy slurry at a ratio of 2:1 (on a volatile solids basis), the SMY reported was 232 L $CH_4$ $kg^{-1}$ VS at an OLR of 5 kg VS $m^{-3}$ $d^{-1}$ (Tabassum et al., 2016a). These can be considered quite high OLRs.

Seaweeds typically have much higher chloride content as compared with land-based biomass sources, due to their origin in the marine environment. A particular concern for the use of seaweed for AD is the accumulating salt concentrations, which can be deemed the inorganic, ash component of the plant. Ensuring that the inoculum (microorganisms) in the digester are acclimatised to tolerate higher salt concentrations is of importance to maximising the biogas production (Tabassum et al., 2016a). In the laboratory trials reported for cultivated *Saccharina latissima* and natural stock *Laminaria digitate*, chloride concentrations increased to high levels in digestion but were not found to be detrimental to operation. However, accumulation of salts was evident and accelerated at higher loading rates, thus, longer term operation of such digesters would require carefully monitoring (Tabassum et al., 2016a).

Beyond brown seaweed*, Ulva Lactuca* is a species of green seaweed, commonly referred to as sea lettuce, that appears along the Irish coastline in shallow estuaries and on beaches. Green seaweed accumulates due to over excessive agricultural practices and more specifically, eutrophication, whereby water sources become contaminated and overly enriched with nutrients. Such circumstances are referred to as "green tides" or "algal blooms" and are a common occurrence in Ireland and worldwide in countries such as France, Denmark and Japan. Algal blooms can result in the closure of beaches and dangerous conditions due to the build-up of toxic gases such as hydrogen sulphide ($H_2S$) as the high sulphur containing seaweed rots. One example of this problem is in Timoleague in West Cork, where every year 10,000 tonnes of sea lettuce washes up on the strand as a result of eutrophication of the bay. The problematic sea lettuce is removed manually at a cost. However, *Ulva Lactuca* may present a potential resource if it can be utilised for AD. *Ulva Lactuca* could be combined with slurry and excess grass available from local farmers or food waste from local supermarkets to increase the biogas produced. Optimum conditions reported for *Ulva Lactuca* in digestion were reported at a mix of 25% fresh *Ulva lactuca* and 75% dairy slurry (on a volatile solids basis) which generated a SMY of 170 L $CH_4$ kg$^{-1}$ VS at an OLR of 2.5 kg VS m$^{-3}$ d$^{-1}$ (Allen et al., 2014). Despite being a more difficult substrate to work with due to high sulphur levels and a low C:N ratio, utilising AD to treat *Ulva Lactuca* would not only provide a source of indigenous energy in Ireland but also a means of reducing the detrimental effects caused to the amenity of the Irish coastline.

The importance of seaweed in the future is its merit as a third generation (advanced) biofuel in transport. The latest recast of the EU Renewable Energy Directive (REDII) requires that 3.5% of transport energy must come from advanced biofuel sources by 2030. The target may be achievable by applying innovative technologies using seaweed as an alternative substrate for gaseous fuel production. The transport biofuel must also achieve 65% greenhouse gas emissions savings as compared to fossil fuels. Emissions savings from seaweed biomethane systems are varied depending on how they system is configured (22-70% savings have been suggested) (Czyrnek-Delêtre et al., 2017).