climate change

Scotland's centre of expertise connecting climate change research and policy

# Assessing the Scottish anaerobic digestion market based on agricultural waste

Lucy Montgomery, Gillian Finnerty, Théa Allary and Lucy Hopwood, NNFCC – The Bioeconomy Consultants
Audrey Litterick, Earthcare Technical

February 2023
DOI: http://dx.doi.org/10.7488/era/3859

# 1 Executive summary

## 1.1 Aims

Agriculture accounts for around 24% of Scotland's greenhouse gas emissions, of which methane accounts for around 44%. A significant proportion results from generation of manure and slurries in livestock production.

Anaerobic digestion (AD) is a biological process that generates a methane-rich biogas from resources such as manure and food waste. When carried out under controlled conditions, the biogas can be captured and converted to energy for heat and electricity.

The Scottish Government has recognised the potential for farmyard slurry to contribute to renewable and bioenergy ambitions. The 2021 Bioenergy Update recognised a need to examine the potential for a Scottish market for digestate - the nutrient-rich material produced by AD, which can be a good fertiliser. Having a market for digestate would remove constraints on greater production of biomethane.

This report examines the potential to reduce emissions by processing agricultural wastes through anaerobic digestion plants. The focus is on agricultural wastes that consist mainly of animal manures and slurries, which are highly underutilised resources.

## 1.2 Key findings

- There is a strong potential to expand the market for anaerobic digestion plants in Scotland using manures and slurries, with an initial focus on cattle, particularly dairy, followed by pig and poultry.
- Despite the significant volumes of manure available, stakeholders were unanimous in their belief that there were some challenges preventing wider adoption.
    - Language is important – 'waste' is interpreted differently across sectors, especially within legislation and licensing.

  - Manures and slurries are inherently associated with low-energy yield, as the bulk of the energy is extracted by the animal. Furthermore, transport of such materials is largely uneconomical, in particular for liquids (slurry) due to their high water content.
  - Farmers do not typically generate revenue from selling waste. The gas yield is also not sufficient to justify setting up their own plant facility as this would not generate enough biogas to allow upgrading to biomethane, and other uses of biogas (such as electricity generation) are unsubsidised.
- The most economically attractive use of biogas is for generation of biomethane for heating and transport. However, this is most suited to large-scale facilities, which would require prohibitively large amounts of manure.
- If avoided emissions from manure management are taken into account, combustion of biogas can generate electricity with a zero or negative carbon footprint. This means that, specifically for manures, electricity generation from biogas is an environmentally attractive use of biogas.
- Digestate – the residue from the process - can be used as a fertiliser and its nutrient content retained.
- Micro-scale solutions using solely manure and slurry are commercially available. These are suitable for a single farm or a cluster of farms and are mainly designed to generate electricity. New commercial concepts are also emerging for biomethane generation at farm-scale, with the use of mobile upgrading units. This technology is more costly, but allows biogas to be converted for use in heat and/or transport.

## 1.3 Conclusions

- AD is an important tool in the fight against climate change. However, manures and slurries do not yield high volumes of biogas and the latter typically has a low dry matter content. This means it is uneconomical to transport it to the large-scale AD plants that currently exist.
- On-farm plants are particularly suitable for farms generating liquid slurries throughout the year, such as dairy farms. Such plants can therefore operate all year round to produce biogas and/or electricity consistently.
- Manure and slurry-only farm-scale solutions are available, but there has been little uptake in recent years as policies have driven economies of scale. Although solutions exist, there is low visibility of farms running, in a profitable way, easy-to-operate micro-scale solutions that would be appropriate for individual farms.

## 1.4 Definitions

| | |
|---|---|
| AD | anaerobic digestion, a microbial process carried out in a sealed environment to convert biomass (including manure) into biogas |
| biogas | gas produced by AD consisting of 50-65% methane and 35-50% $CO_2$, with very small amounts of other gases such as water vapour, hydrogen sulphide, ammonia and siloxanes; in this report, all calculations assume a methane content of 55% |
| biogas upgrading | a process to remove most non-methane gas from biogas to generate biomethane at >95%; to reach UK grid gas calorific value, in most cases biomethane must be enriched with a small amount of propane |
| BRMT | Scottish Bioresource Mapping Tool |
| BtG | biomethane to grid, a type of AD plant that injects gas into the gas grid |
| manure carbon credit | mechanism of carbon accounting permitted in the recast EU Renewable Energy Directive (RED II) and related UK regulations; allowing −45 $gCO_2eq$ per MJ manure used to be applied in carbon accounting for biogas and biomethane, equating to around 54 $gCO_2eq$ per t fresh matter, depending on the energy content of the manure |
| CHP | combined heat and power, typically used to refer to a piece of equipment for generating electricity and heat from biogas (or other fuels) |
| $CO_2$ eq | carbon dioxide equivalents, a measure of global warming potential |
| DM | dry matter, used to describe the theoretical weight of feedstocks if water were removed; often more insightful than FM weight as varying water contents impact use of manures; see also FM and VS |
| FIT | Feed in Tariff, a previous 20-year fixed-tariff incentive from the UK government for renewable electricity that closed in 2019 |
| FM | fresh matter, used to describe the weight of feedstocks in contrast to DM or VS, which are used to describe the equivalent dry and volatile weights of manure |
| FYM | farmyard manure, animal faeces mixed with bedding, such as straw, routinely removed from livestock housing |
| GGSS | Green Gas Support Scheme, a current 15-year fixed-tariff incentive from the UK government for biomethane injection into the gas grid; currently accepting applications to November 2025 |
| GHG | greenhouse gas |
| kW | kilowatt, a measure of energy capacity |

| | |
|---|---|
| kWh | kilowatt hours, a measure of energy volume |
| $kW_e$ | kilowatts of electricity |
| litter | manure, particularly poultry manure, with residual bedding such as paper and shavings; see also manure, FYM and slurry |
| manure | in this report, manure is used as an umbrella term to cover all animal excreta; see also FYM, litter and slurry |
| $Nm^3$ | normal cubic meters, gas volume at 0 °C and atmospheric pressure; the units preferred by the biogas industry to describe biogas and biomethane volumes; 1 $Nm^3$ is equivalent to 1.05 scm |
| RHI | Renewable Heat Incentive, a previous 20-year fixed tariff incentive from UK government for renewable heat that closed in 2021 |
| scm | standard cubic meters, gas volume at 20 °C and atmospheric pressure; the units preferred by the UK gas grid to describe gas injection capacity; 1 scm is equivalent to 0.95 $Nm^3$ |
| slurry | liquid manure comprising faeces and urine (excl. bedding); see also manure and litter |
| SIU | Statutory Independent Undertaking; a disconnected gas grid supplied with liquified natural gas (LNG) or liquified petroleum gas (LPG) |
| tpa | tonnes per annum (metric tons per year) |
| VS | volatile solids, used to describe the theoretical weight of feedstocks if water and non-organic content ('ash') were removed; often more insightful that FM weight as varying water and ash contents impact use of manures; see also DM and FM |

# Contents

# 2 Introduction

## 2.1 Anaerobic digestion

Anaerobic digestion (AD) is a biological process that generates a methane-rich biogas from organic resources such as manure and food waste. When AD is carried out under controlled conditions, the biogas can be captured and converted to energy. Some biogas is used to generate heat and electricity, some is used to generate heat alone, and some biogas is 'upgraded' to biomethane, which is a renewable equivalent to natural gas and can be injected into the gas grid or used as transport fuel. In addition to biogas, AD generates a manure-like output called digestate. The AD process is shown in Figure 1.

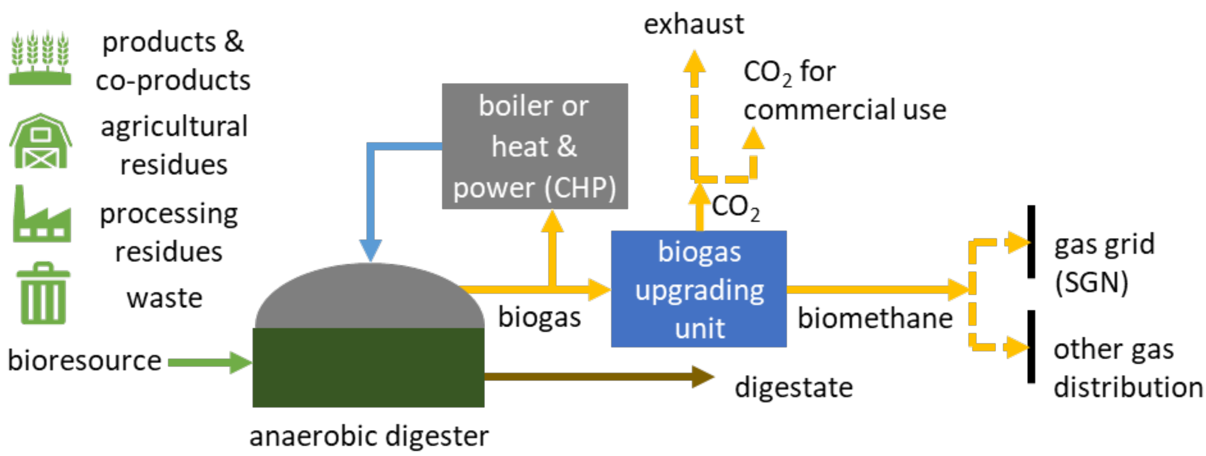


Figure 1: Overview of the production of biogas, showing a typical commercial AD plant. Bioresources flowing into the digester are shown with a green arrow, while digestate flowing out is shown with a brown arrow. Gases are shown in yellow. Heat returning to the digester is shown with a blue arrow.

A previous report (Fraser *et al.* 2022) suggested that while AD is already well established in Scotland, having a capacity of around 2 TWh per year, there is significant opportunity to at least double this output. This same work identified manure and distillery residues as being particularly available and suitable for AD.

## 2.2 Environmental imperative for AD of manure

Agriculture accounts for around 24% of Scotland's greenhouse gas (GHG) emissions, of which methane emissions account for around 44% (Freeman *et al.* 2020). Scottish GHG statistics show that agriculture was responsible for 4 million tonnes of $CO_2$eq in 2021. Roughly half a million tonnes of $CO_2$eq are generated from cattle manures alone (see appendix 10.2.1).

Methane is a potent greenhouse gas (GHG) and, to combat its emission, The Global Methane Pledge[1] was launched at COP26 in Glasgow, in 2021. This is a collective effort to reduce global methane emissions by at least 30 percent from 2020 levels by 2030. The UK joined the Pledge (BEIS 2022), and has committed to reducing methane emissions from agriculture, currently the UK's largest source of methane emissions.

Processing manures and slurries through AD avoids the emission of methane that would otherwise occur if manures were handled and applied to land conventionally. Whether all

[1] https://www.globalmethanepledge.org/

the methane emissions from manure can be captured depends on the AD technology used and the practices on farm, and requires further study.

The digestate output of AD retains the fertiliser value of the original manures and can replace synthetic fertilisers, whilst the biogas has value as energy. Biogas generated on farms can be used for electricity and heat, or – with emerging systems – can be upgraded and/or used as a vehicle fuel in farm vehicles. AD of agricultural wastes therefore offers a multitude of benefits, but to date deployment of agri-waste-fed facilities has been low.

## 2.3 This report

This report takes a closer look at the availability and distribution of bioresources for AD in Scotland, with a focus on agri-waste, and considers the best use of the resultant biogas. The report also looks at the use of the co-products, digestate and carbon dioxide ($CO_2$).

# 3 Agricultural waste availability and distribution

This report focuses on AD opportunities for rural areas, and on manures or slurries as a feedstock; it specifically excludes purpose-grown crops (such as maize or grass silage) or materials with alternative markets (such as distillery residues for animal feed).

It is important to note that the term 'waste' has a very specific definition in renewable energy regulations, which is not always the same as the definition in other areas of law (e.g. waste management). This has some implications for this report. This can be illustrated with the following example: a livestock farmer sets up an AD plant for their manure and supplements this with excess animal feed (to obtain good gas yields and improve process economics). This excess animal feed is usually *not waste*, according to the energy definition. Such an AD site can quickly fall foul of sustainability restrictions, such as the Green Gas Support Scheme (GGSS) requirement for a maximum of 50% of the gas being generated from non-waste. A full explanation of the regulatory context of 'waste' is given in appendix 10.1.

**To avoid confusion: in this report, agri-waste AD is used to mean AD plants that are located on or near farms and use predominantly manure or slurry.**

## 3.1 Agricultural AD and waste AD

The historic distinction between 'farm-fed' and 'waste-fed'[2] AD plants, or 'agricultural' and 'municipal/commercial'[3] AD plants, is made based on the source of predominant feedstocks, as well as licencing and permitting issues around waste handling (see appendix 10.1). In Scotland, owing to the high number of distilleries, a third category can be used: industry-fed AD plants.

As is shown in Figure 2, more AD plants in Scotland are farm fed than waste or industry fed, with 55 out of 84 plants being agricultural (according to the NNFCC AD database). However, the typically larger size of waste AD plants means that the fraction of biogas generated (for all applications: biomethane injection, electricity production and heat generation) from waste-fed or industry-fed plants is higher than the fraction of biogas generated from agricultural plants.

[2] https://www.biogas-info.co.uk/resources/biogas-map/
[3] https://adbioresources.org/resources/ad-plant-database/

It is important to note that operating agricultural AD plants only with manures – without purpose-grown crops or feed residues – places some constraints on what is possible owing to low gas yields.. Using crops (including grass) or feed residues in agricultural AD improves the process economics over manure-only systems, as crops typically give high gas yield compared with manure. An analysis of the advantages and drawbacks of using crops was outside of scope of this project.

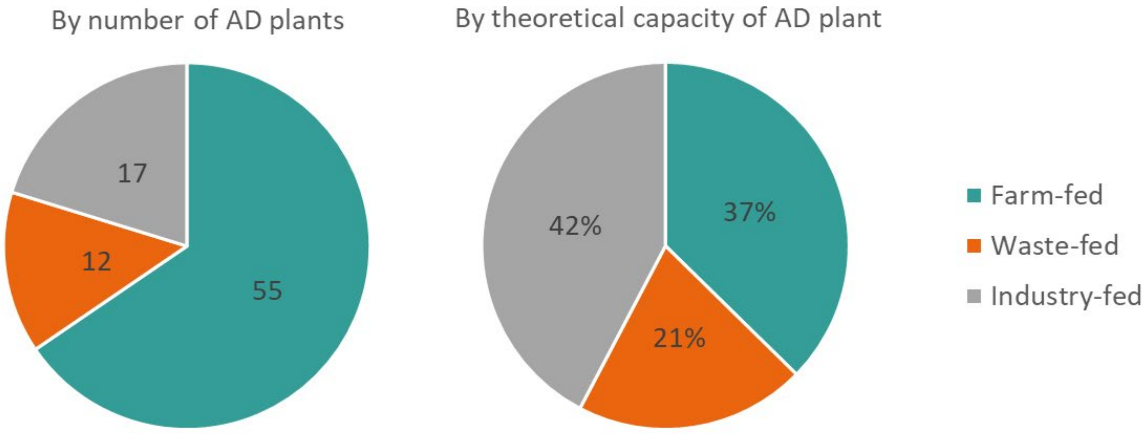


Figure 2: The AD landscape in Scotland, divided into farm-fed, waste-fed and industry-fed AD plant, as shown by number of plants and by their theoretical capacity.

## 3.2 Manure and slurry arisings in Scotland

Manure and slurry are terms used to describe animal excreta, where slurries are more liquid and can be pumped, while manure is solid and may contain bedding materials like straw. The term 'litter' is sometimes used for poultry manure, and can indicate the presence of other bedding materials such as paper and wood shavings. In this report, 'manure' is used as an umbrella term encompassing manure, slurry and litter.

Manures are generated from all livestock, with the most relevant in Scotland being cattle (1.72 million animals), sheep (6.83 million), pigs (341 thousand) and poultry (14 million) (RESAS 2021b). Not all manure can be collected, when animals are reared or grazed outdoors.

Further information on manure availability, its current fate and the emissions arising from it can be found in appendix 10.2. Further information on the geographical distribution of manures in Scotland can be found in appendix 10.3.

# 4 Commercial potential for AD plants in Scotland

## 4.1 Best use of biogas

Biogas is typically utilised in three ways: combustion in a boiler to provide useful heat, combustion in a CHP (combined heat and power) unit to provide electricity and heat, or it is upgraded to biomethane (a gas fuel virtually identical to natural gas).

Heat, electricity and purified gas can be used commercially for the same purposes as any other heat, electricity and gas, while purified gas (biomethane) is typically injected into the gas grid for use elsewhere.

The best use of biogas is highly dependent on local needs and on the scale of production. Environmentally, all uses of biogas from manures are favourable owing to the avoidance of on-farm methane emissions. Economically, AD plants that upgrade biogas to biomethane for grid injection (where it is subsequently used in gas-heated homes or as a transport fuel) are currently most feasible as there is financial support for this in the form of the GGSS and the Renewable Transport Fuel Obligation (RTFO). Direct use of biogas for electricity or heat is currently unsupported, and is therefore less economically favourable. Further detail on the economic and environmental best use of biogas can be found in appendix 10.4.

Although biomethane for grid injection is currently the most economically favourable route for biogas use, there are numerous practical considerations that limit this. In particular, it is [currently] only economically feasible to upgrade biogas to biomethane if at least 200 scm/h gas can be injected (medium-sized AD plant or larger), owing to economies of scale. As is highlighted in the next sections (4.2 and 4.3), this is not possible for manure-only AD systems. Possible directions of growth (including biogas use) for AD of manures are discussed in section 7.

## 4.2 Volume of biogas from manure

Various studies have looked into the biogas yield from different manures, and some indicative values are shown in Figure 3 and Appendix 11.4. Compared to other popular feedstocks, such as maize silage and food waste, the gas yield from manures and slurries is typically relatively low.

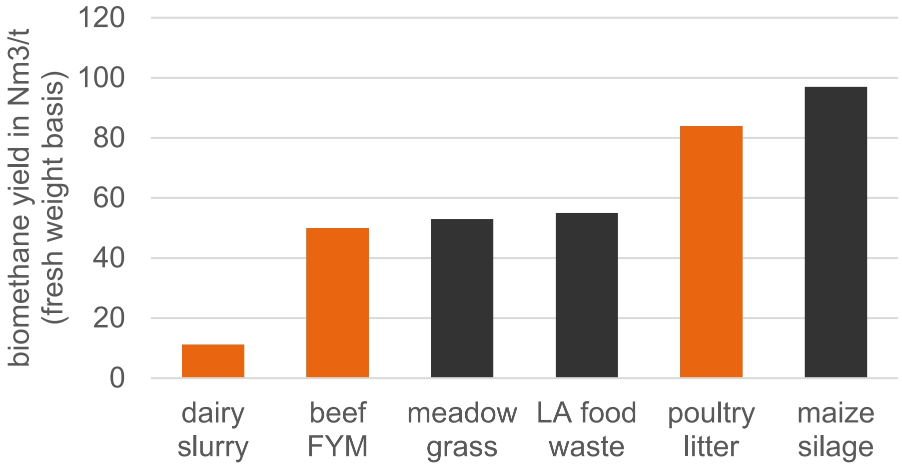


Figure 3: Typical biomethane yields from some manures compared to some other common feedstocks. See Appendix 11.4 for values and context.

As reported by Ford *et al*. (2017), AD of manure on its own has a proven poor business case at both farm and centralised facility scales. The gas yield of manure is not sufficiently high to justify third parties paying for manure, so farmers do not typically generate revenue from selling it to AD plants. The gas yield is also not sufficient to justify the inconvenience and expense to farmers of setting up their own AD plant, in particular because there is currently no subsidy or funding for farm-scale solutions. However, as the source of 24% of Scotland's emissions (Freeman *et al.* 2020), all emission-reducing solutions in agriculture should be considered.

## 4.3 Scale challenge for manure AD

Stakeholder engagement showed that there was a particular interest in AD of dairy slurry, as it is generated all year round and is associated with significant methane emissions. However, the size of dairy farms and the low volumes of biogas that can be generated from individual farms is associated with some challenges.

There are around 671 dairy holdings in Scotland with 100 dairy cows or more (RESAS 2022a), with most Scottish dairy holdings having between 100 and 300 cows, and only 10 having more than 1,000 cows. Table 4.1 shows the useful energy in the form of electricity or biomethane that can be generated from a medium-sized and large Scottish dairy farm.

Table 4.1: Indicative values for biogas yield (and useful energy yield) from dairy farms of various size. Calculations shown in Appendix 11.4.

| Size of dairy herd | Annual biogas yield ($Nm^3$) | Equivalent electrical capacity ($kW_e$) | Equivalent biomethane capacity (scm/h) | Equivalent size of AD plant |
|---|---|---|---|---|
| 150 cows | 75,000 | 19 | 5 | micro AD |
| 1,000 cows | 500,000 | 126 | 34 | (very) small AD |

Table 4.1 illustrates the limited potential of even the larger dairy farms. This scale issue constrains biogas valorisation options because upgrading to biomethane is currently only economically feasible at medium-scale AD plants or larger (see appendix section 11.6 and the associated table for more information on the sizing of AD plants used in this report). There are no micro- or small-sized biomethane AD plants operating in the UK.

Discussions with technology providers suggested that biogas upgrading is technically possible below 200 scm/h but that there is virtually no demand for this technology owing to costs. As can be seen from Table 4.1, it is not feasible for a biogas plant using only manure from a single farm to generate enough biogas to upgrade to biomethane.

## 4.4 SWOT analysis for agri-waste AD

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td><ul><li>Solid and liquid manures are available in many Scottish regions and could be used in AD prior to land application.</li><li>Using manure for AD reduces on-farm methane emissions and when digestate is responsibly used, the use of farm-based AD can deliver improved nutrient, water and soil management.</li><li>Using manure for AD captures useful energy and fugitive methane that would otherwise be lost.</li><li>Manure is biologically a good feedstock for AD and with appropriate technology in place can be converted efficiently.</li></ul></td><td><ul><li>Low gas yield from manures compared with other feedstocks makes them less desirable and less economically attractive. This means that farmers typically do not generate revenue from selling manure to third party AD plants and are not very interested in installing their own AD.</li><li>Technology suited to manure-only digestion is not widely deployed in the UK, and small-scale solutions available to the market are not yet widely established.</li><li>Lack of awareness and promotion of small-scale solutions has led to a lack of interest in developing, commercialising and deploying such projects; policies have been focussed on larger-scale waste-fed solutions, delivering maximum renewable energy output whilst failing to grasp the wider benefits.</li></ul></td></tr>
<tr><th>Opportunities</th><th>Threats</th></tr>
<tr><td><ul><li>Technologies exist for on-site decarbonisation of heat and/or power supplies, or for use as a vehicle fuel.</li><li>AD of agri-waste on-site delivers direct decarbonisation of farming operations, with potential for integration into the existing business.</li><li>Capturing fugitive emissions from existing manure storage can offer additional revenue to farms, when investment in improved storage is required in the near future in any case, to meet new regulatory requirements.</li><li>Novel markets for biogas, such as supporting intermittent electricity supply or powering traditional and novel base load applications (e.g. data centres) are emerging, offering potentially higher value outlets for the gas, and higher returns to producers.</li><li>The wider benefits, beyond energy generation, need to be given a greater focus, to increase the overall value proposition for agri-waste based AD.</li></ul></td><td><ul><li>The recent and current policy focus on large-scale centralised plants, limits potential for using manure in rural areas.</li><li>The policy emphasis on energy outputs has driven interest in large-scale plants, with little or no consideration for other valuable benefits that can be delivered from smaller-scale on-site solutions (e.g. mitigation of methane emissions).</li><li>The investment focus is on larger-scale developments offering greatest returns, with little or no acknowledgement of the wider benefits from small-scale solutions.</li></ul></td></tr>
</table>

# 5 Potential for commercial use of digestate

Digestate is a nitrogen-rich organic fertiliser and includes liquid and solid materials arising from the AD of organic wastes, residues, products and co-products. Digestate may be classified as a waste, which can limit its use as a fertiliser. Whether it is a waste depends on feedstocks used for AD and their classification under waste regulations. The use of animal by-products for AD can further restrict the use of digestate. Rules around nitrate vulnerable zones (NVZ) and water pollution also limit the application of digestate.

Digestate can be a valuable fertiliser, providing all or some of the nutrients needed on farm. Its value can be calculated from the nutrient content and the fertiliser it replaces. However, digestate can also have some deleterious effects on the environment, particularly when not handled correctly. Microplastics in digestate from AD of packaged waste are also of concern.

Digestates typically contain higher levels of readily-available nitrogen compared to manures, so care must be taken when applying them to land as fertiliser. Best practice guidance exists to ensure digestate application minimises risk of environmental pollution, and quality assurance schemes may also carry additional guidance on the use of digestate. However, there is much anecdotal evidence that best practice is not always followed, in particular where digestate availability is high. More information can be found in appendix 10.7 to 10.10.

## 5.1 Market acceptability

Not all types of digestates can be used on all farmland. Some assurance schemes (in particular, Scottish Quality Crops (SQC)) and produce buyers (in particular, the maltsters) remain nervous of potential problems associated with some types of digestate (particularly those derived from food wastes, which can contain small amounts of plastic fragments). Relevant to this topic, the “Going with the Grain” project[4] is being led by the National Farmers’ Union of Scotland (NFUS) to examine and assess stakeholder views on the acceptability of using different types of bulky organic fertilisers (including digestates) on farmland. It also aims to evaluate the extent of carbon savings from using these materials. One outcome includes new guidance for SQC licensees on which types of digestate will be acceptable under SQC rules. New rules are likely to continue to restrict the types of digestate which can be applied under the SQC Assurance Scheme.

## 5.2 Realising the potential for digestate

Given the relatively low value of digestates and the high cost of haulage, storage and spreading, some of the larger AD plants regard digestate as a burden rather than a saleable asset. In order to better valorise the material and its inherent nutrients, a number of companies worldwide are working to develop methods to separate the valuable part of digestates (the nutrients) from the water. Technologies exist to dry digestate and/or strip the nutrients out to produce pelleted or granular fertilisers which are easier for users to handle, store and spread. However, these technologies are often energy intensive and many are not yet commercially available. For that reason, most farm-based AD plants are likely to continue to produce either whole digestate or

[4] https://www.nfus.org.uk/

mechanically separated liquid and fibre digestate for the next 5 years at least. Further information on digestate can be found in appendix 10.7 to 10.10.

## 5.3 SWOT analysis for digestate

| Strengths | Weaknesses |
| --- | --- |
| • Digestates are a useful source of fertiliser nutrients;<br>• Digestates contain a high proportion of readily available nitrogen (RAN) which can make them excellent fertilisers when used according to best practice.<br>• Fibre digestates are a useful source of organic matter, which can help build and maintain soil health.<br>• Digestates can help some farmers save money on imported fertilisers.<br>• There is plenty of good practice guidance explaining how farmers can get the best from digestates and minimise potential risks when using them. | • Digestates are bulky and expensive to transport.<br>• The high proportion of RAN present, particularly in whole and separated liquid digestates, means that significant nitrogen losses to the environment are possible unless digestates are stored, handled and used according to best practice guidance.<br>• Digestates should only be spread for around 6 months of the year, meaning costly storage is required to comply with such restrictions.<br>• Poor availability of precision spreaders can result in digestate being applied at inappropriate times of year.<br>• Agri-wastes are typically present in relatively small quantities on individual farms which are spread out across the landscape. The heavy, bulky nature of these feedstocks means that cost-effective transport to and from larger AD plants is not possible. |
| **Opportunities** | **Threats** |
| • Digestates offer the potential to reduce the carbon footprint of farming businesses, whether the farm operates its own AD plant or not.<br>• Digestates offer the potential to save money on imported fertiliser (the value of digestates is likely to increase in future as energy costs and the cost of phosphate (a finite resource) increase).<br>• Digestates offer the potential to generate income if sold off-farm.<br>• Valorisation opportunities including isolation and granulation/pelletising of fertiliser nutrients from digestate may result in financial opportunities for AD plants, but | • There is a lack of effective carbon footprinting software to accurately assess the benefits of using digestate on-farm.<br>• There remains inconsistent uptake and understanding of best practice guidance amongst farmers and contractors.<br>• Inefficient use of digestate will result in unacceptable emissions to air, water and soils.<br>• The lack of storage at AD plants and on farms is continuing to make it difficult for farmers and contractors wanting to apply digestate only at appropriate times of year, in appropriate weather and soil conditions.<br>• Some assurance schemes (in particular, SQC) and produce buyers (in particular, the maltsters) remain nervous of potential problems associated with some types of digestate (particularly those derived from |

| | |
|---|---|
| such technologies are not yet commercially available at scale. | food wastes). Current work is assessing stakeholder views and later this year they will produce new guidance for their licensees on which types of digestate will be acceptable under SQC rules. New rules are likely to continue to restrict the types of digestate which can be applied under these rules. |

# 6 Potential markets for $CO_2$ derived from agricultural wastes

## 6.1 Carbon dioxide from biogas

Anaerobic digestion generates biogas, which consists largely of methane and $CO_2$ (Calbry-Muzyka *et al.* 2022). If biogas is upgraded to biomethane, $CO_2$ removed from biogas during upgrading can be captured (depending on the upgrading technology in use). As this $CO_2$ is relatively pure, it can be compressed for further use. If biogas is not upgraded (i.e. used directly for electricity or heat), $CO_2$ capture is not currently feasible.

## 6.2 Current market for carbon dioxide

The Scottish market for $CO_2$ is around 48,000 tpa[5], with current uses including:

- food and beverage production
    - Sparkling beverages
    - Food freezing, storage and transport ($CO_2$ it its 'dry ice' form)
    - Modified atmosphere packaging
- humane livestock slaughter (where $CO_2$ is used for stunning)
- horticulture (where $CO_2$ is used in greenhouses to encourage plant growth)
- dry ice for entertainment,
- technical uses in electronics, metal fabrication, supercritical $CO_2$ extraction, $CO_2$ fire extinguishers and many more (Alberici *et al.* 2017).

Prices of $CO_2$ have been highly volatile in recent years and supply is dependent on a few producers, causing significant problems for the industries that rely on it (FDF 2022).

## 6.3 Potential markets for carbon dioxide

In addition to the existing markets mentioned in section 6.2, which are expected to continue to grow in line with national economic growth, there are many potential upcoming markets for $CO_2$ in the areas of fuels, chemicals, carbon offsetting and fertiliser production. Information on potential markets can be found in appendix 10.5.

[5] The UK $CO_2$ market was estimated to be in the range of 400,000–500,000 tpa in 2016 (Alberici *et al.* 2017), and more recently as 600,000 tpa (ADBA & REA 2022), but there are no figures specific to Scotland. The estimate given here is 8% of the total UK $CO_2$ demand. This is because the population and GDP of Scotland are around 8% of the UK total, and the turnover of the Scottish food and beverage sector is also around 8% of the total UK food and beverage sector turnover.

The advantage of making fuels and products from $CO_2$ is that it is a form of recycling (in contrast to using fossil resources to make fuels and products) and that there are no questions around land-use competition with food (in contrast to using biomass). For these sustainability reasons, the market for $CO_2$ is expected to grow.

## 6.4 Use of carbon dioxide from AD

Carbon dioxide capture is already carried out at several AD sites across the UK, including one in Dumfries and Galloway[6] that uses slurry from a large dairy farm and manure from a large beef farm (as well as energy crops and residues from the dairy). Equipment must capture the off-gas from the biogas upgrading unit and compress it, remove impurities and water vapour, liquify the $CO_2$ and remove any residual methane. Costs for this equipment are significant, in the order of 1–1.5 million GBP[7].

Only around 11 sites across the UK capture $CO_2$. If all current Scottish biomethane plants captured their $CO_2$, this would likely represent more than Scotland's current demand. However, not all systems are suitable to retrofitting $CO_2$ capture due to space or planning constraints, technical limits of the biogas upgrading equipment and cost, so full capture is very unlikely to occur. More information can be found in appendix 10.5.

## 6.5 Barriers to accessing potential carbon dioxide markets

The main barrier is that $CO_2$ is not easy to capture from AD plants that do not upgrade their biogas to biomethane, which currently excludes all micro and small AD plants. For plants where $CO_2$ capture is possible, costs can be prohibitively high. There are also hygienic reasons why $CO_2$ from AD cannot be used in all markets, in particular from AD plants using food waste (if the $CO_2$ is intended for the food and beverage market).

On the market side, technologies for $CO_2$ use are still being developed, and these are faced by the same barriers as all new technologies. It is unclear if there are specific barriers to $CO_2$ use over other types of new technology in the fuel, fermentation and fine chemicals space, and therefore unclear if specific support is needed.

As $CO_2$ already has a market and there are some existing supply chains, the sale of $CO_2$ from AD can fit in with conventional farm or AD business models. There are even a limited number of agricultural applications for $CO_2$ such as horticulture, although the potential is limited as gas production would be year-round, while horticulture is seasonal.

## 6.6 SWOT of carbon dioxide valorisation from AD

| Strengths | Weaknesses |
|---|---|
| • $CO_2$ can be collected from many large AD plants generating biomethane, both new and retrofit.<br>• $CO_2$ has many current market applications.<br>• There is considerable industry interest in diversifying production of commercial-grade $CO_2$. | • $CO_2$ cannot currently be captured from small AD plants or any biogas plants that do not upgrade their gas to biomethane.<br>• $CO_2$ venting from biomethane production is carbon neutral so there is a strong case for doing nothing. |

[6] https://www.carboncapture.scot/
[7] Personal communications.

| Opportunities | Threats |
|---|---|
| • Current trajectory of policy around renewable fuels likely to bring new markets for biogenic $CO_2$ in the next 5–10 years.<br>• Importance of BECCS for reaching net zero likely to bring new markets for biogenic $CO_2$ in the next 5–10 years. | • Lack of concrete commitments or incentives for BECCS. |

# 7 Potential for an expansion of AD using agricultural wastes in Scotland

The earlier analysis shows strong potential to access additional agricultural waste in Scotland, to increase AD deployment, and to deliver low-carbon energy whilst also reducing emissions from agriculture and delivering improved soil, water and nutrient management. Due to the distribution and scale of livestock farms in Scotland, small-scale, decentralised solutions are more favourable, avoiding the need to transport bulky, wet feedstocks between farms.

By valuing the wider benefits of manure-based AD, there is a strong investment case to align with incoming policies and regulations across the farming, waste and energy sectors. This section presents some of the solutions for treatment of agricultural waste at farm-scale, based on currently available technologies.

## 7.1 Potential AD solutions for manure

### 7.1.1 Micro AD, manure only

There are several manure-only solutions available at micro scale, with a current and early focus on dairy farms. Such approaches range from covers for existing slurry tanks and lagoons to small digesters (Figure 4). Micro-AD is suitable for the amount of biogas that can be generated by manure from up to around 730 dairy cows, i.e. appropriate to individual Scottish dairy farms (see appendix 11.6 for more detail on AD plant sizing in this report).

The cost for installing such a system would be around £75,000–£300,000, depending on scale and existing site infrastructure[8], with the lower costs representing small biogas-collecting covers for lagoons or existing tanks. However, it is likely that simple/cheaper biogas collection systems for existing storage tanks would collect less biogas (and have more fugitive methane emissions) than purpose-built biogas-collecting anaerobic digesters.

Biogas volumes of this scale are generally too small to allow biogas upgrading to biomethane on-site. Electricity can be generated, but there is no fixed-tariff subsidy for this scale and type of generation at present and farmers may have difficulties obtaining an electricity grid connection owing to grid constraints, or connection costs could be

[8] Stakeholder engagement

prohibitive. While improvements are needed in these areas this also opens up the requirement for alternative electricity and biogas markets.

Electricity generated on-site can be used to cover the farm demands or to supply external uses that require steady levels of power for 24 hours a day. Such external uses may be appropriate where feedstock supply and resultant gas production exceeds on-site demands, and strong markets are emerging for excess, decentralised production, such as power traditional or novel base load applications (e.g. data centres) for local users. Biogas at this scale could also be used for heat generation, either for process heat, hot water or space heating (for buildings or greenhouses).

The following sections explore the different approaches found in the evidence search.


Figure 4: Micro-scale AD solutions targeting dairy slurry. From top left to bottom right: Dairy Energy (a micro-scale digester), Bennamann (a covered slurry lagoon), Qube (a partially-coved lagoon) and Biofactory (a containerised digester).

### 7.1.2 Electricity and/or heat generation at micro scale

Electricity and/or heat can easily be generated at micro scale, from farms with a 100-head herd or more. Examples of micro-AD systems at dairy farms exist around the UK, but their roll-out stalled when government incentive (in the form of the Feed-in Tariff) for electricity ended. Current high energy prices and a growing awareness of methane emissions from manure management has re-awakened interest in these technologies. In the absence of export tariffs, alternative markets for electricity or biogas are required to make these profitable.

One suitable market for the electricity generated on-site is the farm's own demands, in particular if they have highly automated milking systems with round-the-clock electricity demands. Alternatively, markets are emerging for excess, decentralised production, such as powering traditional or emerging base load applications (e.g. critical infrastructure including data centres), which require a constant supply of electricity.

Biogas at this scale could also be used for heat generation, either for process heat, hot water or space heating (for buildings or greenhouses). This is only appropriate if suitable uses are available locally.

It is worth noting that although Germany no longer has a conventional fixed-rate electricity feed-in tariff for AD, they do still have one for manure-only AD. This special tariff for manure micro-AD 'Gülle-Kleinanlagen' is restricted to sites with a CHP installed capacity of 150 $kW_e$ or smaller (EEG 2023). This reflects a recognition of the wider benefits of manure-based AD.

### 7.1.3 Novel models for biogas upgrading at micro scale

Although biogas upgrading to biomethane is not typically feasible at micro or small scale, technologies are emerging that offer increased connectivity between sites that could, in effect, allow biomethane production at farm scale. Systems being proposed in the AD industry[9] are typically one of the two solutions below:

- A mobile biogas upgrader that travels around a group of farms every few weeks. Farms would need to be able to store several weeks worth of biogas on site, but this higher volume could allow mobile versions of conventional gas-upgrading equipment to be used. Upgraded biomethane could be delivered to a grid injection point elsewhere or used on farm if needed.
- A physical pipeline to deliver (non-upgraded) biogas to a central location for upgrading (and subsequent injection or local use).

Such solutions offer a means of valorising manure, whilst keeping capital costs low for farmers. Value of the biomethane (whether sold to third party or used on site) would be aligned with the market value of natural gas[10].

Biomethane at this scale could also be used as a vehicle fuel for domestic, commercial or agricultural vehicles. Compressed natural gas (CNG) tractors are commercially available and liquified natural gas (LNG) tractors are being developed, to offer a fully circular farming solution in the future, where the farm produces the fuel from their waste to run the vehicles needed to support their farming activities.

### 7.1.4 Small AD, manure and crops – electricity and heat or novel solutions

Manure can also be used in small on-farm AD plants with herds exceeding 500 heads of cattle (see appendix 11.6 for AD plant sizing used in this report). However, this approach is difficult to deliver in practice without additional feedstocks such as crops or crop residues.

Most farms that generate manure will also have access to additional feedstocks, such as outgrade crops and excess or spoiled animal feed. A small AD plant using a combination of feedstocks could deliver a greater energy output, but capital cost would also be greater as additional feedstock storage infrastructure would be required, technology would be more complex and regulatory compliance would also be less straightforward.

Small AD plants that use manure alongside crops or residues exist around the UK, but again, their roll-out stalled when the Feed-in Tariff for electricity ended. Subsidy-free electricity-generating small AD plants have been slow to emerge. For this approach to be successful without subsidy, a standard design would be beneficial, with standardised

[9] Stakeholder engagement

[10] Additional revenue, for example from RTFO or GGSS, would depend on compliance with these schemes. This would have to be confirmed on a case-by-case basis with the relevant authority (Department for Transport and Ofgem, respectively).

legal frameworks, contracts and permitting approaches developed to keep risk and costs low. Although being subsidy-free would liberate AD plants from the 50% non-waste requirements associated with subsidy (see appendix 10.1), market forces could also limit the use of non-waste.

One option that is supported in Germany is flexible electricity generation (i.e. with more generation on low-wind days or at peak-demand times) from biogas, which is supported by a special contract for difference (EEG 2023). Additional biogas storage capacity is needed for this to work, as well as an additional CHP. For example, only generating electricity half of the time would require double the amount of storage and CHP capacity.

The cost for installing such a system would be around £250,000–£2,500,000, depending on exact scale and existing site infrastructure[11].

### 7.1.5 Medium-sized, manure and crops – biomethane to grid

Medium sized AD would allow biogas upgrading to biomethane, unlocking more uses. However, owing to the low gas yields from manure, this would require very large volumes of manure (up to 20,000 cows), large tank capacity and a sizeable development footprint. This could be a good solution for areas with very high livestock density or for large beef, poultry or pig farms producing higher volumes of manure all year round. However, development and infrastructure costs would be high, and achieving the economies of scale required to make upgrading and grid injection viable would be difficult. Adding crops or residues to the feedstock mix would improve the gas output, but their amount that can be used is limited by the GGSS sustainability restrictions (see appendix 10.1.2).

Alternatively, manure can be sent to an off-farm AD facility and co-digested more centrally with other feedstocks. Any AD plant can take manure, including an AD plant primarily fed with food waste, as long as they have appropriate reception and storage equipment in place. However, transporting manure is costly given its bulky, wet nature, and therefore on-site treatment remains favourable.

To avoid manure transport and investment in costly upgrading and injection infrastructure, there could be an option to establish a virtual pipeline, whereby biogas (or biomethane) is collected from site and transported by pipeline or tanker to a central upgrading and injection facility. This approach is already being deployed in Scotland[12], to achieve the desired economies of scale. However, it is more expensive and more challenging in terms of logistics and management to operate multiple AD sites and arrange the transport of their biogas or biomethane, so these are challenging to run in terms of cost and management.

The cost for installing such a system would be in excess of £5,000,000, depending on exact scale and existing site infrastructure[19].

## 7.2 PESTLE analysis

It is evident from the analysis on availability, spatial distribution and specific opportunities, that manure can and should be more widely used in AD. However, low deployment of AD capacity for manure makes it evident a number of constraints remain. This PESTLE analysis summarises the external factors currently limiting growth and development, and highlights the main opportunities posed by such factors at present.

[11] Stakeholder engagement
[12] Stakeholder engagement

| Political | Economic |
|---|---|
| • AD of agri-waste can contribute to Net Zero in multiple ways, reducing carbon emissions through more effective agri-waste management and contributing low-carbon energy. Currently the wider benefits are not supported or incentivised, so are difficult to value when building an investment case.<br>• Policy focus remains on AD of wastes so feedstock restrictions or sustainability criteria discourage use of non-wastes, which are often a good supplementary feedstock for agri-waste based systems. | • AD can provide either additional revenue (from energy sales) or can save energy costs (if energy is used on-farm), providing stability during energy price volatility.<br>• Equipment cost is high and typically benefits from economies of scale, so small-scale systems find it difficult to justify investment.<br>• Additional revenue can be generating by distributing digestate as opposed to manure and slurry to the market, through more efficient nutrient management.<br>• Revenue can be secured from $CO_2$ sales, where supply volumes are sufficient and markets exist. |
| **Social** | **Technological** |
| • Few commercial agri-waste plants are in operation; farmers typically prefer to see working examples at similar scale before adopting new solutions. Uptake could be slow without further demonstration.<br>• Despite having Net Zero targets and being a major contributor of emissions, agriculture is seemingly one of the least active sectors in evaluating their impact and adopting measures to reduce emissions.<br>• Social acceptance of digestate from manure is good, but acceptance of $CO_2$ is low, owing to perceived hygiene fears. | • Manure does not generate large amounts of biogas and it is therefore difficult to operate a manure-only AD plant using conventional technology; new or novel lower-cost solutions are being developed for the market.<br>• Few technological solutions exist for upgrading biogas to biomethane at a scale appropriate to agri-waste fed systems; however, innovative mobile- or cluster-based solutions are being offered to overcome this. |
| **Legal** | **Environmental** |
| • Planning and permitting requirements can be onerous for small-scale projects; approaches should be standardised where possible, to keep costs low and to prevent delays in the pre- and post-development phase.<br>• Where third-parties are involved, as suppliers or offtakers, contracting costs can also be high; again, standardised supply and offtake agreement should be offered to ease the process and reduce costs. | • Using manure for AD reduces emissions from agriculture as it captures fugitive methane that would otherwise have been emitted from manure; however, such benefits are difficult to value and incentivise without good baseline data.<br>• Using digestate rather than untreated slurry and manure offers improved nutrient placement, although poor compliance with best practice may affect benefits.<br>• Biogas from AD can displace fossil fuel via a number of pathways; however, the best use of biogas is often highly site specific. |

# 8 Conclusions

## 8.1 The potential

There is a strong potential to expand the AD market in Scotland using agricultural waste. Enterprises that generate and store large amounts of liquid manures, such as dairy farms, were identified by stakeholders as a priority, as these are a large source of fugitive methane emissions that could be avoided with AD. However, all farms where manure is collected indoors such as pig and poultry enterprises are relevant.

Multifunctional enterprises or land use were not particularly studied in this report but if farms have uses for AD outputs such as heat (e.g. for food processing, greenhouses, homes or business premises), they may be particularly well suited for AD.

Earlier reports indicate current AD capacity of around 2 TWh per year in Scotland and show significant opportunity to at least double this output if manure and distillery residues are targeted.

Target areas would include anywhere with housed or partially housed livestock, with dairy farms being particularly relevant. Dairy farm density is concentrated in the south west, particularly Dumfries and Galloway and Ayrshire, although there are also a number of sizeable cattle farms in the central belt, Aberdeenshire, Moray and Orkney (see also Appendix 10.3, Figure 6).

Literature and stakeholders were in agreement that digestates are a useful source of nutrients when used according to best practice. However, significant nitrogen losses to the environment are possible unless the digestates are stored, handled and used according to best practice guidance. Technologies – such as pelleting or ammonia stripping – that allow digestate to be used further afield and in more applications were widely reported in academic literature, but no stakeholders were using such technologies.

## 8.2 Some challenges

There remain a number of challenges that need to be addressed to make AD of manure commercially attractive and to stimulate uptake in the agricultural sector. Suitable business models have been proposed by a number of businesses consulted as part of the project, but roll-out is limited so these remain an area of active debate.

A range of scale-appropriate technologies are available to valorise agricultural wastes in conventional or novel ways, considering the best use of biogas as dictated by the location, access to market and infrastructure requirements at individual site level.

Without wider recognition of the benefits, such as avoided emissions, the investment case for an AD plant treating manures to generate biogas for energy is poor. However diverse collaborative approaches whereby resources, equipment and infrastructure can be shared between operators can reduce both capital and operating costs.

Key gaps make it difficult to determine the level of support needed in order to deliver increased deployment of farm-scale AD treating agricultural wastes. Appropriate support or stimulus for this scale of AD is unclear, with other countries using a small-scale manure-specific energy tariff as support, but UK stakeholders suggesting installation grants to be more effective.

Stakeholders suggested that commercial demonstration sites are necessary, as UK farmers typically more willingly adopt after seeing similar investments deployed and in operation, beyond academic endeavours.

## 8.3 Next steps

To refine the potential and accelerate deployment, further consideration should be given to alternative technical solutions and business models better suited to pig and poultry farms, where waste arisings are significant, but less focus has been put to date.

The type, scale and nature of support or market stimulus required to incentivise and accelerate uptake could also be considered, where energy is not always the main driver, and other factors (such as emissions reductions) may influence investment decisions more strongly. Future solutions aligned with regulatory changes around nutrient, water and soil management would encourage wider consideration and justification for investment.

Furthermore, added value opportunities for the co-products, digestate and carbon dioxide ($CO_2$) at small-scale could also be considered, potentially seeking more scale-appropriate technical solutions, or developing a collaborative approach to share costs and reduce risk.

# 9 References

Alberici S, Noothout P, Ur Rehman Mir G, Stork M, Wiersma F, Mac Dowell N, Shah N, Fennell P (2017) Assessing the potential of $CO_2$ utilisation in the UK. A report for BEIS by Ecofys and Imperial College London, project number SISUK17099, available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf

Animal By-Products (Enforcement) (Scotland) Regulations 2013, SSI 2013/307, available at https://www.legislation.gov.uk/ssi/2013/307/contents/made

Animal By-Products (Miscellaneous Amendments) (Scotland) Regulations 2015, SSI 2015/393, available at https://www.legislation.gov.uk/ssi/2015/393/

APHA (2022) Livestock Demographic Data Group: Cattle population report. CP21/22, available at http://apha.defra.gov.uk/documents/surveillance/diseases/lddg-pop-report-cattle2022.pdf

Baltac S, Mitchell A, Calvo Conde EG, Platt R (2021) Understanding Opportunities for Developing a Scottish $CO_2$ Utilisation Economy. A report for CXC. http://dx.doi.org/10.7488/era/1683

BCS (2023) UK Biofertiliser Certification Scheme, available at https://www.biofertiliser.org.uk/

BEIS (2022a) Greenhouse gas reporting: conversion factors 2022, published 22 June 2022 and updated 20 September 2022. Accessed on 24th January 2023, available at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

BEIS (2022b) United Kingdom methane memorandum. Notice, published 15 November 2022, accessed 20th February 2023 and available at https://www.gov.uk/government/publications/united-kingdom-methane-memorandum/united-kingdom-methane-memorandum

BSI (2014) PAS110:2014 Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials, available at https://wrap.org.uk/resources/guide/bsi-pas-110-producing-quality-anaerobic-digestate

Calbry-Muzyka A, Madi H, Rüsch-Pfund F, Gandiglio M, Biollaz S (2022) Biogas composition from agricultural sources and organic fraction of municipal solid waste. Renewable Energy, 181, p1000-1007 https://doi.org/10.1016/j.renene.2021.09.100

CNG Fuels (2022) CNG Fuels opens its tenth biomethane refuelling station as demand for low-carbon fuel skyrockets by 100% across the UK. Press release from 5 September 2022, accessed on 27th January 2023, available at https://www.cngfuels.com/2022/09/05/tenth-biomethane-refuelling-station/

Defra (2018) Code of Good Agricultural Practice for Reducing Ammonia Emissions, PB14506, available at https://www.gov.uk/government/publications/code-of-good-agricultural-practice-for-reducing-ammonia-emissions

DfT (2022a) RTFO list of feedstocks including wastes and residues, updated 20 September 2022. Accessed on 30/01/2023, available at https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-feedstock-materials-used-for-creating-renewable-fuels/rtfo-list-of-feedstocks-including-wastes-and-residues

DfT (2022b) RTFO Guidance for Renewable Fuels of Non-Biological Origin. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1097045/rtfo-guidance-for-renewable-fuels-of-non-biological-origin.pdf

DfT (2023) Renewable Transport Fuel Obligation: Compliance Guidance 2023: 01/01/23 to 31/12/23. Accessed on 27th January 2023, available at https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-compliance-reporting-and-verification

Environmental Protection Act 1990, available at https://www.legislation.gov.uk/ukpga/1990/43

EEG 2023, Erneuerbare-Energien-Gesetz [German Renewable Energy Act], available at https://www.gesetze-im-internet.de/eeg_2014/

European Commission (2023) Commission Delegated Regulation (EU) of 10.2.2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. Available at https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

European Commission (2012) Regulation (EU) No 231/2012, laying down specifications for food additives listed in Annexes II and III to Regulation (EC) No 1333/2008 of the European Parliament and of the Council; Annex, 'E 290 CARBON DIOXIDE'. Available at https://www.legislation.gov.uk/eur/2012/231/annex/division/91

Farming and Scotland Water webpage (2022) New General Binding Rules on Silage & Slurry: What's changed? https://www.farmingandwaterscotland.org/know-the-rules/new-general-binding-rules-on-silage-and-slurry-whats-changed/

Farming and Water Scotland website, https://www.farmingandwaterscotland.org/

FAS (2021a) Management of inputs of heavy metals to agricultural soils and crops. Technical Note TN 753 (https://www.fas.scot/downloads/technical-note-tn753-management-heavy-metals-agricultural-soils/).

FAS (2021b) Phosphate and potash recommendations for crops grown in Highland and Islands FAS Technical Note TN715 https://www.fas.scot/publication/technical-note-tn715phosphate-and-potash-recommendations-for-crops-grown-in-highland-and-islands/

FAS (2020) Optimising the application of livestock farmyard manures and slurries TN736 https://www.fas.scot/publication/technical-note-tn736-optimising-the-application-of-livestock-farmyard-manures-and-slurries/

FAS (2019a) Agricultural use of biosolids, compost, anaerobic digestates and other industrial organic fertilisers TN699 https://www.fas.scot/downloads/tn699-agricultural-use-of-biosolids-composts-anaerobic-digestates-and-other-industrial-organic-fertilisers/

FAS (2019b) Phosphate and potash recommendations for crops grown in North East Scotland and Tayside FAS Technical Note TN717 https://www.fas.scot/publication/technical-note-tn717-phosphate-and-potash-recommendations-for-crops-grown-in-north-east-scotland-and-tayside/

FAS (2019c) Phosphate and potash recommendations for crops grown in Fife, Lothian and Scottish Borders FAS Technical Note TN718 https://www.fas.scot/publication/technical-note-tn718-phosphate-and-potash-recommendations-for-crops-grown-in-fife-lothian-and-scottish-borders/

FAS (2018) Phosphate and potash recommendations for crops grown in South West Scotland FAS Technical Note TN716 https://www.fas.scot/publication/technical-note-tn716-phosphate-and-potash-recommendations-for-crops-grown-in-south-west-scotland/

FAS (2017) Sulphur Recommendations for Crops Technical Note TN685 https://www.fas.scot/downloads/tn685-sulphur-recommendations/

FDF (2022) Falling flat: lessons from the 2018 UK CO2 shortage. Food & Drink Federation website, accessed on 03/03/2023, available at https://www.fdf.org.uk/fdf/resources/publications/reports/falling-flat-lessons-from-the-2018-uk-co2-shortage/

The Feed-in Tariffs Order 2012, SI 2012/2782, available at https://www.legislation.gov.uk/uksi/2012/2782/contents/made

Ford S, Williams M and Morris S (2017) Farmyard Manure and Slurry Management and Anaerobic Digestion in Scotland – Practical Application on Farm. Report for CXC, iQ 16-2017, available at https://www.climatexchange.org.uk/media/2977/farmyard-manure-and-slurry.pdf

Fraser A, Esposito G, Robinson B, Savage J, Chernick D, Hanson P, Hopwood H, Montgomery L (2022) Opportunities for Biomethane as a Transport Fuel in Scotland. A report for Scottish Enterprise and Transport Scotland by Zemo Partnership and NNFCC. Accessed on 19th December 2022, available at https://www.zemo.org.uk/assets/reports/Opportunities_for_Biomethane_as_a_Transport_Fuel_in_Scotland_June_2022.pdf

Freeman D, Wiltshire J & Jenkins B (2020) Establishing a manure/slurry exchange in Scotland – a feasibility study. A report for CXC by Ricardo Energy & Environment. Accessed on 19th December 2022, available at https://www.climatexchange.org.uk/research/projects/establishing-a-manureslurry-exchange-in-scotland/

The Green Gas Support Scheme Regulations 2021, SI 2021/1335, available at https://www.legislation.gov.uk/uksi/2021/1335/contents

IPCC, 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use, Chapter 10, Emissions from Livestock and Manure Management. Available at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf

Köster JR, Cárdenas LM, Bol R, Lewicka-Szczebak D, Senbayram M, Well R, Giesemann A, Dittert K (2015) Anaerobic digestates lower N2O emissions compared to cattle slurry by affecting rate and product stoichiometry of denitrification – An N2O isotopomer case study. Soil Biology and Biochemistry, 84, p65-74. https://doi.org/10.1016/j.soilbio.2015.01.021

Montgomery LFR & Bocmann G (2014) Pretreatment of feedstock for enhanced biogas production. Technical Brochure from IEA Bioenergy, ISBN 978-1-910154-05-2. Available at https://www.ieabioenergy.com/wp-content/uploads/2014/02/pretreatment_web.pdf

National Grid ESO (2022) Future Energy Scenarios 2022 Report. Available at https://www.nationalgrideso.com/document/263951/download

Nitrate Vulnerable Zones Regulations. Agriculture and the environment: Nitrate Vulnerable Zones. Scottish Government website https://www.gov.scot/policies/agriculture-and-the-environment/nvz/

NNFCC (2022) Anaerobic Digestion Database. A limited version is available at https://www.biogas-info.co.uk/resources/biogas-map/

Nutrient Management Guide (RB209) (webpage on AHDB website) https://ahdb.org.uk/nutrient-management-guide-rb209

Ofgem (2022a) NDRHI Guidance Volume 2: Ongoing obligations and payments. Version from 23 November 2022. Accessed on 27th January 2023, available at https://www.ofgem.gov.uk/publications/non-domestic-rhi-main-guidance

Ofgem (2022b) Green Gas Support Scheme Guidance v1.2 from 19 November 2022. Accessed on 27th January 2023, available at https://www.ofgem.gov.uk/publications/green-gas-support-scheme-guidance

Ofgem (2023) Gas Prices: Day Ahead Contracts – Monthly Average (GB). Accessed om 27th January 2023, available at https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators

The Renewable Heat Incentive (Amendment to the Energy Act 2008) Regulations 2011, SI 2011/2196, available at https://www.legislation.gov.uk/uksi/2011/2195/

The Renewable Transport Fuel Obligations Order 2007, SI 2007/3072, available at https://www.legislation.gov.uk/uksi/2007/3072/

RESAS (2016) Economic Report on Scottish Agriculture: 2016 Edition. Available at https://www.gov.scot/publications/economic-report-scottish-agriculture-2016/documents/

RESAS (2021a) Dairy Farmer-led Group: climate change evidence. ISBN 9781802017519, available at https://www.gov.scot/publications/resas-climate-change-evidence-dairy-farmer-led-group/

RESAS (2021b) June Agricultural Census 2021. Scottish Government. ISBN 9781802014792. Available at https://www.gov.scot/publications/results-scottish-agricultural-census-june-2021/

Ricardo Plc (2016) Scottish BioResource Mapping Tool. Extracts are available upon request from IBioIC, https://www.ibioic.com/scottish-bioresource-mapping-tool

Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. OJ L 140 5.6.2009, p. 16. Available at http://data.europa.eu/eli/dir/2009/28/2015-10-05

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). OJ L 328 21.12.2018, p. 82 http://data.europa.eu/eli/dir/2018/2001/2022-06-07

Salter F, Litterick A, Crooks B (2022) Digestate use on Scottish Farms, a report by SAC Consulting. Available at https://www.farmingandwaterscotland.org/wp-content/uploads/2022/05/202205_Digestate-Use-on-Scottish-Farms_Final.pdf

SEPA (2022) The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended): A Practical Guide. Version 9.1, March 2022, available at https://www.sepa.org.uk/media/34761/car_a_practical_guide.pdf

SEPA (2017) Regulation of Outputs from Anaerobic Digestion Processes. Position Statement WST-PS-016, version 5, available at http://www.sepa.org.uk/media/219842/wst-ps-016-regulation-of-outputs-from-anaerobic-digestion-processes.pdf

Scottish Executive (2005) Prevention of Environmental Pollution from Agricultural Activity (The PEPFAA Code), available at https://www.gov.scot/publications/prevention-environmental-pollution-agricultural-activity-guidance/

Scottish Government (2021) Heat in Buildings Strategy - achieving net zero emissions in Scotland's buildings. Publication – Strategy/Plan, 7 Oct 2021, ISBN: 9781802014464. https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/documents

Scottish Energy Statistics Hub (2022) Oil and gas consumption, Scotland 2020. https://scotland.shinyapps.io/Energy/?Section=OilGas&Chart=OilGasConsumption

Scottish Energy Statistics Hub (2023) Energy use in Scotland per day. https://scotland.shinyapps.io/Energy/?Section=OilGas&Chart=OilGasConsumption

Scottish Quality Crops website, https://www.sqcrops.co.uk/, Accessed 23.02.23

SRUC (2015) Managing soil phosphorus Technical Note TN668. Available at https://www.sruc.ac.uk/media/ootl1mnc/tn668.pdf

Taylor M, Rollet AJ, Tompkins D and Chambers BJ (2010) Digestate Quality and Fertiliser Value. Proceedings of the 15th European Biosolids Association Conference. Available at https://conferences.aquaenviro.co.uk/wp-content/uploads/sites/7/2018/08/65-Matthew-Taylor-1.pdf

The 4 Point Plan (web page on the Farming and Water Scotland website): https://www.farmingandwaterscotland.org/managing-water-on-your-farm/the-4-point-plan-4pp/

QMS (2022) Cattle & Sheep Standards https://www.qmscotland.co.uk/sites/default/files/qms_cattle_and_sheep_standards_2022_spreads_set-up.pdf

The Waste Management Licensing (Scotland) Regulations 2011, SSI 2011/228 https://www.legislation.gov.uk/ssi/2011/228/

The Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2021, SSI 2021/412, available at https://www.legislation.gov.uk/ssi/2021/412/

Waste Management Licensing (Scotland) Regulations 2011, available at https://www.legislation.gov.uk/sdsi/2011/9780111012147

Weinrich S, Schäfer F, Bochmann G, Liebetrau J (2018) Value of batch tests for biogas potential analysis; method comparison and challenges of substrate and efficiency evaluation of biogas plants. Murphy, J.D. (Ed.) IEA Bioenergy Task 37, 2018: 10 ISBN: 978-1-910154-49-6 (eBook electronic edition). Available at https://task37.ieabioenergy.com/technical-reports/

WRAP (2010) An investigation of clopyralid and aminopyralid in commercial composting systems. Final Report for Project OAV001-002.

Zero Waste Scotland (2020) Overview: Digestate Safety for Agriculture, available at https://www.zerowastescotland.org.uk/sites/default/files/ZWS1288%20Risk%20Assessment%20Docs%20Digestate%20v3%20Final_0.pdf

**If you require the report in an alternative format such as a Word document, please contact info@climatexchange.org.uk or 0131 651 4783.**



climateXchange

Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yards, Edinburgh EH1 1LZ

# 10 Appendix – additional context and analysis

## 10.1 Regulatory definitions of waste for AD

It should be noted that materials defined as 'waste' for energy and fuel purposes are not always the same as materials defined as 'waste' for permitting purposes.

Energy and fuel regulations aim to promote the use of waste over virgin materials. However, there is a significant risk of virgin feedstocks, such as animal feed, being intentionally spoiled in order to claim a premium for waste-derived energy or fuel. For this reason, regulators are strict about what feedstocks may be counted as waste. Where the risk of intentional spoilage is high, feedstocks are not permitted to be counted as waste. These materials would typically be classified as residues or even products.

In contrast, waste-management regulations aim to ensure that wastes are handled safely. Here, it is safer to declare more materials as waste; for example, declaring excess animal feed as waste would lead to it being transported separately from fresh feed and would avoid contamination of fresh feed (e.g. with mould).

This mis-match can cause confusion and frustration in the AD sector, for example when a material is delivered as a 'waste' by a waste handler, but not accepted as a waste for subsidy purposes.

### 10.1.1 AD site permitting with wastes

For permitting purposes, waste is defined by waste-management law[13]. Parties handling waste must be licensed to do so through the Scottish Environmental Protection Agency (SEPA). As a result of this legal distinction, AD plants were historically categorised as either waste-fed AD plants, which require waste-management licences, or farm-fed AD plants. However, as the AD sector evolves, it is now possible for farm-based AD plants to also be licensed as waste handlers.

Depending which feedstocks are used in these AD plants, various licenses or permits apply to agri-waste AD. These are summarised in Table 10.1 and described below. On top of the requirement for waste-management licencing, some AD plants are also licenced to handle animal by-products[14], which allows them to accept food waste.

[13] The Environmental Protection Act 1990 and the Waste Management Licensing (Scotland) Regulations 2011
[14] This is regulated under the Animal By-Products (Enforcement) (Scotland) Regulations 2013 and the Animal By-Products (Miscellaneous Amendments) (Scotland) Regulations 2015. An ABP category III registration is needed for AD plants accepting food waste or waste from a food factory (unless it is a vegetable-processing plant), which in Scotland goes through the UK Animal and Plant Health Agency (APHA). Such ABP category III approved AD plants must have additional equipment to pasteurise (or otherwise heat treat) their feedstocks or digestate. Although manure falls under ABP category III, manure is exempt from ABP registration.

Table 10.1: Types of AD plant and examples of feedstocks they can use, based on their licensing and equipment. Green-filled cells represent permitted feedstock and permit/licence combinations, while red-striped cells represent feedstocks that cannot be used with a given permitting/licencing arrangement. This work focusses on AD plants of type 1 & 2, but also covers type 3. The 4th type is out of scope for this report, and would commonly be described as a waste-processing merchant or commercial AD plant.

| | Type of AD plant based on permitting needed. | Crops | Manures | Distillery residues (not waste) | Crop / vegetable waste | Packaging-free food-factory waste | Packaged food waste |
|---|---|---|---|---|---|---|---|
| 1 | • No additional permitting | | | | | | |
| 2 | • SEPA approved as waste-handler | | | | | | |
| 3 | • SEPA approved as waste-handler<br>• ABP III approved, use pasteuriser | | | | | | |
| 4 | • SEPA approved as waste-handler<br>• ABP III approved, use pasteuriser<br>• Use de-packaging equipment | | | | | | |

Any AD plant with none, one, or both of the above-mentioned permits could be described as agri-waste AD, and are within scope of this report. Any plants that accept packaged food waste such as supermarket waste are out of scope for this report[15].

### 10.1.2 Waste as defined by energy legislation

Biomethane or electricity generated from biogas can be described as derived from waste, residues, or [co-]products, and this distinction is defined in law. Various policy instruments incentivise the use of waste for biomethane production and/or cap the use of products. For energy-generation purposes, 'waste' is defined by several pieces of UK legislation shaped by the EU Renewable Energy Directive (2008/98/EC) Annex IX. For biomethane for transport, this is the Renewable Transport Fuel Obligations Order 2007 and its subsequent amendments, and a current list of feedstocks defined as 'waste' is available from the Department for Transport website (DfT 2022). Similar lists apply for electricity (The Feed-in Tariffs Order 2012 and subsequent amendments) and heat (The Renewable Heat Incentive Regulations 2011 and The Green Gas Support Scheme Regulations 2021, as well as their subsequent amendments). The distinction is important for national statistics, subsidy schemes and international trade.

The Green Gas Support, as well as the previous Renewable Heat Incentive and Feed-In Tariff, place a limit on the number of products that can be used for AD. Only 50% of biogas can be generated from products; biogas generated outside of this limit does not count towards renewable energy statistics and is not subsidised by Ofgem. Owing to the low biomethane potential of manures, it takes around 7 tonnes of cattle slurry to generate the same amount of biomethane as 1 tonne of maize (see appendix section 11.4). The Renewable Transport Fuel Obligation has a different mechanism: biomethane

[15] Plants accepting this material typically have de-packaging equipment.

as a transport fuel is awarded double Renewable Transport Fuel Certificates if it is derived from a specific subset of wastes, defined by the Department for Transport. Although this does not limit the amount of non-waste that can be used, it makes it less profitable. Renewable Gas Guarantees of Origin, which are traded domestically and overseas to evidence biomethane purchase through pipelines, are also typically described as waste or non-waste, with 'waste' RGGOs having higher market value.

## 10.2 Agri waste availability – further detail

Several studies have quantified manure arisings in Scotland (Ricardo 2016, Ford *et al.* 2017, Freeman *et al.* 2020). Although these reports use the reference year of 2015, arisings are likely to be similar as dairy cow numbers have been stable over the last 10 years and beef cattle numbers have only declined slightly since 2015 (RESAS 2021b).

The Scottish Bioresource Mapping Tool (Ricardo, 2016) estimates 14.4 million tonnes per annum (tpa) of manure and slurry arisings (reference year 2015), with around 90% coming from the beef and dairy sectors (see 11.3 for calculation details). This is in accordance with findings from Freeman *et al.* (2020), which also explains that as most pig and poultry farms are located on arable farms, resultant wastes are most likely directly spread on local fields. Ford *et al.* (2017) estimates are a little higher with manure and slurry arisings from cattle as around 17 million tpa. Although methodology details are missing in these literature resources, manure arisings are typically calculated by taking agricultural statistics of livestock numbers and applying a factor for excreta volumes and taking into account farming practice (in particular, seasonality of animal housing).

To check the validity of the literature data as part of this report, Scottish livestock data were taken, a manure factor from literature was applied and assumptions about animal housing were made. Even before animal housing was considered, manure arisings differed from calculated values, being lower for cattle and higher for poultry (Appendix11.3). It was therefore concluded that available manure tonnages are likely to be lower than previously reported in literature. Nonetheless, in the absence of other data, manure tonnages from the Bioresources Mapping Tool (BRMT) were used, in particular as a regional breakdown is provided. An overview of manure arising, based on the BRMT, is shown in 10.3.

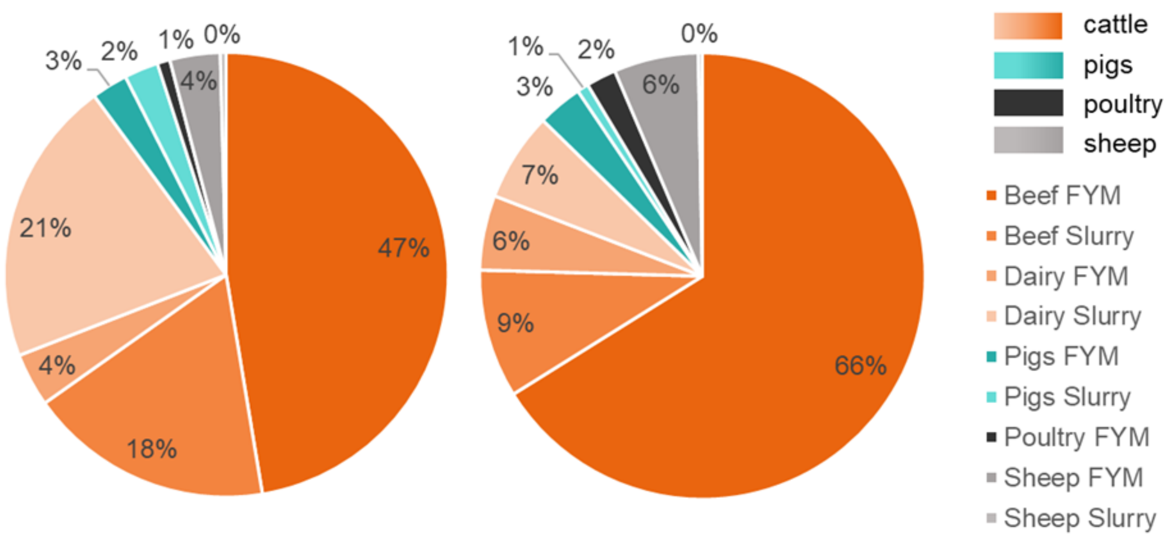


Figure 5: Manure arising in Scotland according to the Bioresource Mapping Tool. Left-hand chart shows manure arising by weight and right-hand chart shows manure arising by methane yield. This shows that farmyard manure (FYM) yields more methane than slurry, owing to the high water content of slurry.

As reported elsewhere (Freeman *et al.* 2020), only around 5% of manure is exported from farms, either for AD or for manure exchanges, so it is expected that much of the manure would be available for processing through AD if processing capacity increased. The remaining 95% is used on farm where it is spread to land.

Dairy farms are of particular interest because, while all livestock generate manure, it is only possible to collect manure and slurry from animal housing (rather than from grazing land), and dairy cows attend the milking parlour every day, all year round. In contrast, many small- to medium size beef herds are typically only housed indoors for part of the year, depending on weather, region, breed and local practice making supply seasonal, whilst larger-scale herds may be housed year-round, making this another suitable target for supply.

### 10.2.1 Emissions from manures

For international statistics, emissions from livestock manure management are typically calculated from livestock populations rather than manure volumes (IPCC 2006). Looking at cattle only, Scotland has 488,751 dairy cows and 1,217,044 other cattle, and their manure management leads to around 11,241,273 and 8,519,308 kg of methane, respectively, which is associated with a total of almost 500 million kg $CO_2$eq.

Looking at it another way, the EU 2018 recast Renewable Energy Directive (RED II) recognises the positive effect of AD on preventing emissions from manure, giving a value of 54 kg $CO_2$ equivalents for every tonne of manure processed through AD. Applying this same value to cattle manure arising suggests just under 700 million kg $CO_2$eq are generated from Scottish manure every year.

### 10.2.2 Current fate of manures

The Bioresource Mapping Tool categorises all manures in Scotland as being spread to land, although the NNFCC AD database (2022) suggests that up to 257,530 tpa of manure and slurries are currently used in Scottish AD plants. This represents just 1.8% of manure arisings across Scotland.

Land spreading of manure is not considered a competing use for manure in this report because digestate – the residual material that exits the anaerobic digester – retains its nitrogen, phosphorus and potassium fertiliser value and can still be used in the same way as manure for land-spreading. In theory, all manures currently put to land can be processed through AD first. However, the installation and operation of an AD plant on farm involves cost, effort and know-how, while the export of manure to a 3rd party AD plant (and receiving digestate in exchange) involves effort and potentially unknown risks for the farmer. In many cases it will be more convenient to use manures directly on farm, rather than to go through AD.

#### 10.2.3 Other feedstocks arising in Scotland

Other agricultural wastes that could be feedstocks for AD can be difficult to quantify as they are not generated consistently, and a wider range of feedstocks are available off farm. Examples of on-farm waste include expired animal feed or animal feed that has been trampled on by livestock – these can be used to supplement manures but are likely to make up less than an additional 5% gas yield (compared to gas from the manure generated)[16]. It would not be good practice to allow more feed to genuinely go to waste, as feed is costly. A farmer may have more feed than they need. However, excess feed is not considered as a 'waste' by Ofgem, it is considered either a product (to prevent from intentional 'wasting' of good feed) or, in some circumstances, a residue of livestock-feed handling. This means it would be outside of scope of agri-waste AD. Cereal straw could also be generated on a livestock farm, but it is poorly suited to AD without pre-treatment. Pre-treatment of straw has been demonstrated at full scale in Germany[17], but this is at very large scale (an AD plant with an installed capacity of 6,000 kWh), suggesting the economic feasibility at most scales is not favourable.

Wastes from other farms could include vegetables that were cultivated but were unsuitable for the intended market, or where no market was found at harvest time. These are not typically available for use in AD as they are incorporated into soil without harvesting or harvested and composted on farm.

Waste feedstocks arising off-farm could include vegetable-processing waste and food-factory waste. Data is not available on their generation. However, businesses are required to dispose of their waste appropriately, so these may already be contracted to existing AD or composting sites. The same is true of local authority food waste.

Distillery residues are not wastes under the definition of 'waste' for energy production. Given that they are generally not classed as wastes, they are outside of scope of this report.

## 10.3 Spatial variation of the organic agricultural waste

To understand current demand for manure from AD, the NNFCC AD database (2022) was used to estimate manure use by local authority area. This was subtracted from the values for manure arisings (see 11.3 for calculation details). Figure 6 shows cattle density and the location of manure-using AD plants. As expected, manure-using AD plants are present in the areas with high cattle populations.

[16] Stakeholder engagement
[17] https://zorg-biogas.com/industry-solutions/grain-farming

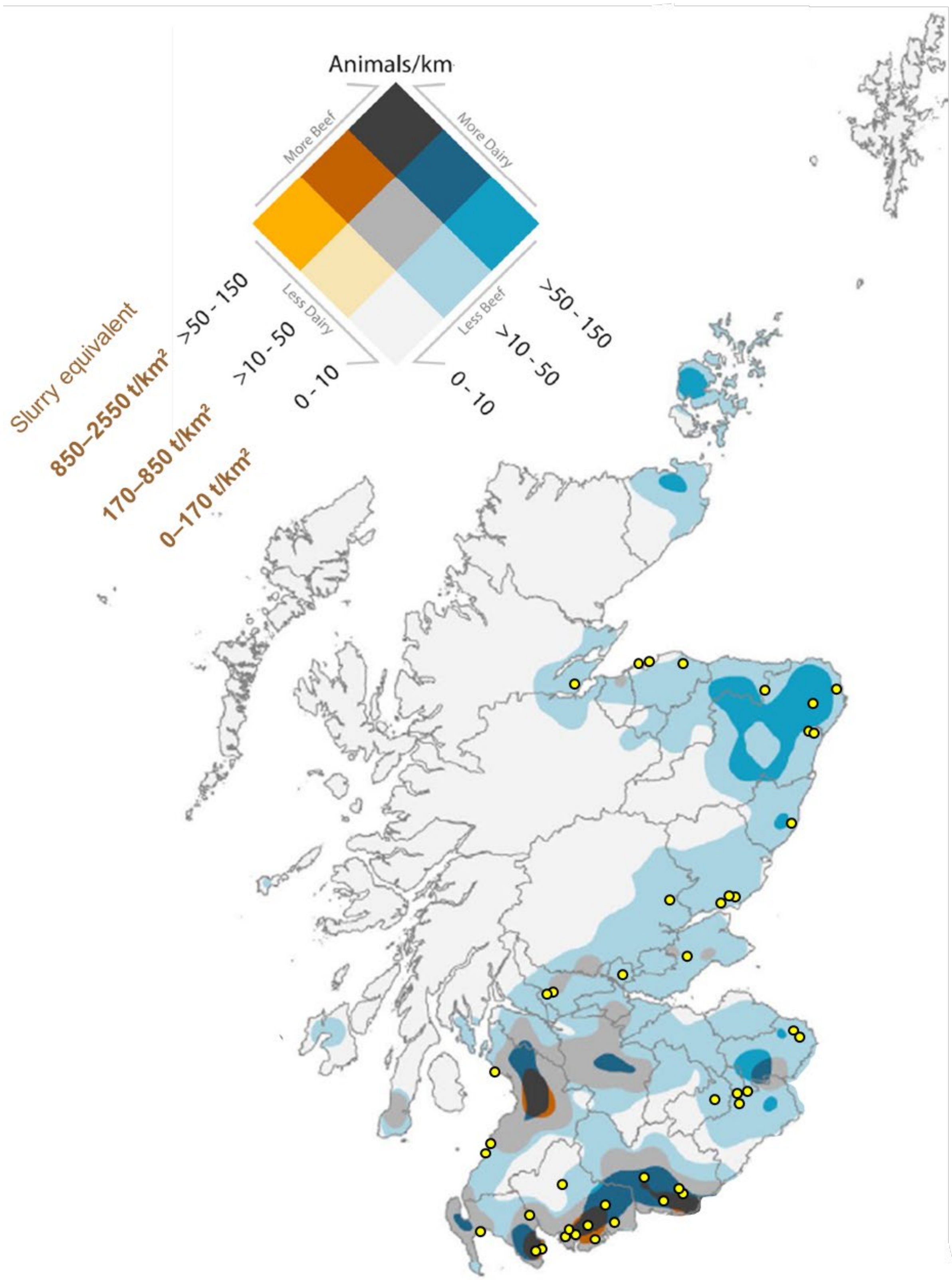


Figure 6: Cattle density in animal per square kilometre and resultant slurry generation. Darker shades represent highest density at up to 150 animals/km² (or slurry at 2,550 t/km²) and blue indicates predominance of dairy cattle while orange indicates predominance of beef cattle. Adapted from APHA 2022. Calculations for manure tonnage shown in Appendix 11.3. Yellow dots represent existing AD plants that use at least some manure.

Only 12 out of 32 local authority areas currently have AD plants that are known to use manure as a feedstock (as part of a feedstock mix). In terms of absolute tonnage, the highest manure demand for AD is in Dumfries and Galloway at 121,600 t, representing 5.6% of manure arising in that area (compared with total manure availability written in the BRMT for Dumfries and Galloway). This means that at least 94% of manure is available in all local authority areas. The low amount of manure used for AD can be attributed to decisions on both the supply and the demand side. On the supply side, farmers are able to apply manures to land directly and there is no incentive to send their manures for AD; this would involve additional effort (and, depending on the arrangement with the AD plant, cost of transport). On the demand side, AD plants typically do not actively seek out manures as gas yields from manures are low and do not justify its transport. It is possible that AD plants accredited to GGSS may seek out manure as this will be associated with a negative carbon emission in GGSS (in contrast to RHI). However, no GGSS-accredited AD plants were commissioned in Scotland and the time of writing (September 2023) and only a handful are expected in Scotland before the scheme closes.

We will summarise the general points for the four agricultural regions for Scotland. Generally, there is a limited opportunity in city authorities, and challenges for those areas with low population density.

### 10.3.1 North West

Orkney Islands stands out as the local authority with the highest manure density and no existing AD capacity (551 t/km²). Although the Highlands do not have high available-manure density overall (39 t/km²), this is a statistical artefact attributable to the high area covered, and it is clear from Figure 6 that there are areas around Thurso and Inverness with relevant cattle numbers. Shetland Islands do not have particularly high manure potential, nor do the Eilean Siar.

There is no connection to the national gas grids on any Scottish islands or in most of the Highlands, so biomethane for grid injection is not possible in these areas, although there are Statutory Independent Undertakings (SIUs, disconnected gas grids supplied with liquified natural gas) in Thurso & Wick that could potentially be compatible with biomethane. Nonetheless, biogas can be used to generate electricity or heat in these areas.

### 10.3.2 South West

There is significant potential in the south west. Dumfries and Galloway have clear hotspots illustrated in Figure 6 and although there are a number of AD plants already, they only use 5.6% of manure arising, leaving an average manure density of 309 t/km².

Although there is little manure arising in Glasgow, surrounding areas have considerable manure densities, but no manure-utilising AD plants. Full data can be found in the supplementary information in Table 11.6.

Clackmannanshire and Stirling have moderate manure availability at 230 t/km² and 178 t/km², respectively, taking into account the existing demand from AD. Again, manure density in Stirling will be higher in the southern parts.

Argyll and Bute have low overall manure density (73 t/km²), but Figure 6 suggests potential in parts of Islay and in the southern part of the Kintyre peninsula, near Campbeltown. Campbeltown has a disconnected gas grid (SIU) that could potentially be compatible with biomethane.

### 10.3.3 North East

Aberdeenshire and even Aberdeen have significant available manure densities (443 t/km² and 351 t/km², respectively), with hotspots visible in Figure 6 in the north eastern part. Moray has a reasonable manure density at 282 t/km².

### 10.3.4 South East

Although Edinburgh and Midlothian do not have significant manure volumes, West Lothian has higher manure density (378 t/km²) and East Lothian has some manure availability (263 t/km²). The Borders also have a high overall density (297 t/km²), with clear hotspots visible in Figure 6 in the flatter landscapes.

Dundee does not have any manure availability, but Fife has a reasonable manure density at (302 t/km²), although with no hot spots visible in Figure 6. The overall manure density in Angus and Perth and Kinross is moderate (162 and 96 t/km², respectively), but volumes are likely to be higher in the southern parts of these areas, as is visible in Figure 6.

## 10.4 Best use of biogas

There are three main conversion technologies for the biogas generated from AD:

1) Combustion in a boiler to generate heat
2) Combustion in a combined heat and power unit (CHP) to generate heat and electricity, and
3) Biogas upgrading to biomethane, a fuel equivalent to natural gas.

There are many end uses for the outputs of these technologies, and some overlap. For example domestic heat can be provided by biogas boiler, CHP or by biomethane. The main uses for biogas are:

a) Biomethane for heating, commonly distributed via the gas grid. Heat can also be provided by biogas directly, without the need for upgrading, but this cannot be distributed in the gas grid.
b) Biomethane for transport, fuelling domestic, commercial or agricultural vehicles.
c) Biogas for electricity, for on-site use of supply into the local transmission system.

However, some are more feasible or favourable than others for logistical, technical or economic reasons. Ultimately, the best use of biogas is dictated by the location, access to markets and infrastructure requirements at individual site-level.

There are also other, emerging uses of biomethane, such as to make hydrogen, or as a feedstock for the chemicals industry which may be considered, particularly for larger-scale developments.

### 10.4.1 Environmental best use of biogas

Although biogas from AD generates renewable energy, its greenhouse gas (GHG) emissions are not always low, especially if measures are not taken to prevent fugitive methane emissions on site. Using manure for AD, rather than waste or even crops, is associated with a carbon credit[18] owing to the avoided emissions from spreading manure directly to land without any treatment. Table gives an overview of the emissions associated with AD when the biogas is used to produce biomethane for heating or transport, and when biogas is used for electricity.

[18] According to the methodology given in the recast EU Renewable Energy Directive (2018), RED II, which is also the methodology used by UK government for energy emissions accounting.

Some emissions in Table 10.2 are negative. This is because all emissions analysis in this report take into account the positive effect of capturing the methane that would otherwise have been emitted if manures were not digested. The added impact of using manure versus other organic wastes (that are not associated with methane emissions) is visible by comparing the 'waste' values in Table 10.2 with the 'manure' values.

Saved emissions from manure management are counted in the biogas generated, rather than on the farm operations, because emissions from renewable energy must be reported by energy generator. This is a well-developed and highly regulated field, with uniform and transparent carbon accounting methodologies embedded in law. In contrast, farmers are not required to report on their emissions. Further work would be needed to determine the exact carbon savings possible on farm using AD; these would depend on the extent of methane captured.

Table 10.2: Overview of greenhouse gas emissions associated with the preferred biogas conversion pathways (EU Directive 2018/2001). Where an AD plant uses multiple feedstocks, it is common practice (EU Directive 2018/2001) to divide the biogas generated into parts, proportional to the gas yield of each feedstock used, and allocating emissions to each. A biomethane AD plant that uses only 5% manure can claim that this 5% of biomethane is associated with 22 $gCO_2eq/MJ$ or less for reporting or certification purposes.

| | | Reasonable worst case emissions ($gCO_2eq/MJ$) | Reasonable best case emissions ($gCO_2eq/MJ$) |
|---|---|---|---|
| Biomethane for heating | waste | 71 | 10 |
| | manure | 22 | -103 |
| Biomethane for transport | waste | 75.6 | 13.3 |
| | manure | 26.6 | -99.7 |
| Biogas for electricity | waste | 57 | 9 |
| | manure | 10 | -88 |

Emissions from digestate spreading (versus manure spreading) were not investigated in this study. This is because methane emissions in manure management are primarily associated with storage of slurries and manures (without methane capture), rather than their spreading. However, spreading of fertiliser is associated with the emission of nitrous oxide, a potent greenhouse gas. While nitrous oxide emissions are dependent on many factors including soil type and climate, organic fertilisers (such as manure and digestate) are associated with higher nitrous oxide emissions than chemical fertiliser. It is unclear if using digestate in place of manure affects nitrous oxide emissions, as some studies show an increase and others a decrease in emissions (Köster *et al.* 2015).

As natural gas in the UK grid has a carbon intensity of 56.2 $gCO_2eq/MJ$, biomethane from manure can provide significant emissions saving even in the reasonable worst case scenario (where sites operate inefficiently and measures have not been taken to avoid methane leakage). As diesel (e.g. for heavy goods vehicles) has a carbon intensity of 71.2 $gCO_2eq/MJ$, here biomethane from manure can also provide significant emissions saving even in the reasonable worst case scenario. However, it should be noted that, as stated above, upgrading biogas to biomethane at typical farm-scale is not currently technically or economically feasible, and therefore such savings are hard to achieve.

At first glance, electricity generation from manure does not look competitive because Scotland's electricity grid uses a lot of wind energy and has a relatively low carbon intensity of 13 $gCO_2eq/MJ$. The reasonable worst case scenario for manure-derived biogas electricity is only a little below this at 10 $gCO_2eq/MJ$.

Nonetheless, manure-derived biogas for electricity should be considered a good solution for the following reasons:

- biogas for electricity is, at a technical level, one of the easiest ways to valorise biogas at small scale, i.e. farm scale,

- avoiding methane emitted from poorly-stored manure is important, regardless of how the electricity generated compares to other type of renewable electricity, and

- the electricity grid is less favourable on lower-wind days; National Grid grid-intensity estimates for Scotland show that, in 2022, on 25% of days the carbon intensity of electricity is over 31 $gCO_2eq/MJ$. Scotland has pledged to keep grid carbon intensity below 13.9 $gCO_2eq/MJ$ (50 $gCO_2eq/kWh$).

### 10.4.2 Economic best use of biogas

An overview of the revenue opportunity for the top three uses of biogas is shown in Table 10.3. Further analysis can be found in Appendix 0.

For biomethane, revenue comes from direct sales, which is influenced by the market price of natural gas, and from support mechanisms.

For biomethane for heat, support is in the form of direct payments per kWh of biomethane injected for 15 years from commissioning, under the Green Gas Support Scheme (GGSS) (Ofgem, 2022b). Currently only new AD plants producing biomethane for grid injection are eligible for support from the GGSS, with feedstock restrictions stipulating at least 50% of the biomethane output must be waste-derived.

For biomethane for transport, support comes under the Renewable Transport Fuel Obligation (RTFO) (DfT, 2023). This is a certificate-based mechanism rather than a fixed-rate payment, and values are subject to market fluctuations and contractual arrangements with biomethane sellers, dependent on general market dynamics. The RTFO awards 1.9 certificates per kg of biomethane and double this (3.8 certificates per kg) when the biomethane is waste-derived. RTFCs are awarded to the fuel supplier, at the duty point. In an on-farm situation, if biomethane was used to fuel agricultural vehicles, RTFCs would be awarded to the vehicle operator, which could also be the biomethane producer. In more conventional cases, on larger projects, RTFCs are awarded to suppliers of fuel at public or privately run filling stations, and a proportion of the revenue is passed back down the value chain to the biomethane producer.

Table 10.3: Overview of revenue potential for the preferred biogas conversion pathways. Electrical efficiency of CHPs is only around 35%. Revenue from support mechanisms is taken from January 2023. See Appendix 0 for assumptions and calculations.

| | | Estimated revenue from sales ($p/kWh_{biomethane}$ or $p/kWh_{electricity}$) | Estimated revenue from support mechanism ($p/kWh_{biomethane}$ or $p/kWh_{electricity}$) | Total revenue as $£/Nm^3_{biogas}$ |
|---|---|---|---|---|
| Biomethane for heating | waste | 3.41 | 5.51 | 0.463 |
| | manure | 3.41 | 5.51 | 0.463 |
| Biomethane for transport | waste | 3.41 | 6 | 0.489 |
| | manure | 3.41 | 6 | 0.489 |
| Biogas for electricity | waste | 10 | 0 | 0.182 |
| | manure | 10 | 0 | 0.182 |

For biogas for electricity, revenue comes from direct sales as there is currently no support mechanism for new AD plants generating electricity. Novel markets for biogas electricity were proposed by some stakeholders, such as intermittent electricity supply (for low-wind-power periods) or powering data centres (where 100% renewable energy is desired but intermittent supply is not suitable. Such novel markets could offer higher value for electricity generation, although further research is needed to determine how much.

### 10.4.3 Biomethane for heating (in place of natural gas)

Biogas can be upgraded to biomethane by removing the $CO_2$ fraction of the biogas. Biomethane can be supplied to the gas grid, typically by direct injection. Once on the gas grid, the biomethane can be used for any purpose that natural gas is used for. In 2019, around 48.5 TWh of natural gas was used in Scotland (Scottish Energy Statistics Hub, 2022), the vast majority (96%) for heating, including domestic and non-domestic heat.

### 10.4.4 Economic opportunity

Gas prices have been volatile in recent years, particularly owing to the 2022 Russian invasion of Ukraine. Prior to 2022, natural gas prices floated around 0.5 GBP/therm, but prices have been fluctuating around 2 GBP/therm since then (Ofgem, 2023). Assuming that AD plants could sell their biomethane for 1 GBP/therm, this would be equivalent to 0.0341 GBP/kWh.

On top of this, there is currently an incentive in the Green Gas Support Scheme (GGSS). Although the tariff is subject to degression, the current tariff is 0.0551 GBP/kWh for up to 60 million kWh per year.

### 10.4.5 Environmental opportunity

Gas from the GB gas grid currently has a carbon intensity of 56.2 gCO2eq/MJ (202.3 gCO2eq/kWh) (BEIS, 2022). Biomethane supported by a government subsidy such as RHI or GGSS must comply with sustainability guidance, which includes a maximum carbon intensity. Biomethane injected under the RHI has a carbon intensity of less than 34.8 gCO2eq/MJ (Ofgem, 2022a), and biomethane generated under the GGSS has a carbon intensity of less than 24 gCO2eq/MJ (Ofgem, 2022b). These figures are from cradle to gate, where gate is the point of biomethane injection into the grid. However, as biomethane is used the same way as natural gas, values for natural gas use or biomethane use will be similar.

The GGSS is based on the EU RED II, which also contains default and typical values for biomethane from manure. Depending on the set-up of the AD plant and its operating efficiency, biomethane from manure has a carbon intensity of 22 gCO2eq/MJ (default figures for a more polluting set-up) and as low as −103 gCO2eq/MJ (typical figures for the least-polluting set up). This is illustrated in Figure 7.

Table 10.4 : Carbon footprint of natural gas and various types of biomethane.

| | $gCO_2eq/kWh$ | $gCO_2eq/MJ$ |
|---|---|---|
| Natural gas | 202.3 | 56.2 |
| Highest biomethane (RHI) | 125.3 | 34.8 |
| Highest biomethane (GGSS) | 86.4 | 24 |
| Highest biomethane from manure | 79.2 | 22 |
| Lowest biomethane from manure | -370.8 | -103 |

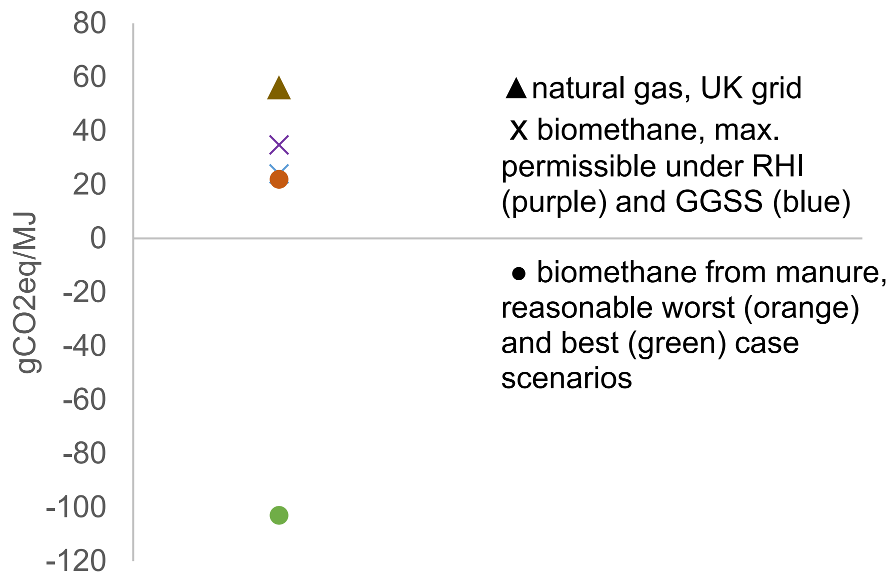


Figure 7 : Carbon footprint of natural gas (brown triangle) compared to biomethane under different scenarios: maximum permitted biomethane carbon footprint under RHI (purple X) and GGSS (blue X) as well carbon footprint of biomethane from manure in reasonable worst- (orange circle) and best-case (green circle) scenarios.

This suggests that using biomethane for domestic heat is associated with a carbon savings of at least 21.4 $gCO_2eq/MJ$ (plants operating under RHI), at least 32.2 $gCO_2eq/MJ$ (plants operating under GGSS) and between 34.2 $gCO_2eq/MJ$ and 159.2 $gCO_2eq/MJ$ for AD plants using only manures.

### 10.4.6 Demand and timeline

Biomethane is a direct replacement for natural gas, so to look at demand and timeline, planned phase out of natural gas was considered. As the main natural gas demand in Scotland is for heating, the timeline of gas demand reduction will depend on the success of heat decarbonisation measures, in particular the roll-out of heat pumps. The Heat in Buildings Strategy (Scottish Government, 2021) aims to replace natural gas heating with a low-carbon alternative in half of Scottish homes, roughly halving Scottish gas consumption, by 2030. To comply with the aim of net zero by 2045, there is no place for natural gas heating in Scotland by 2045. These highly ambitious aims see natural gas demand in Scotland for heating going from its 2021 level of 47.4 TWh/year to around 23 TWh/year in 2030 and around 0 TWh/year in 2045.

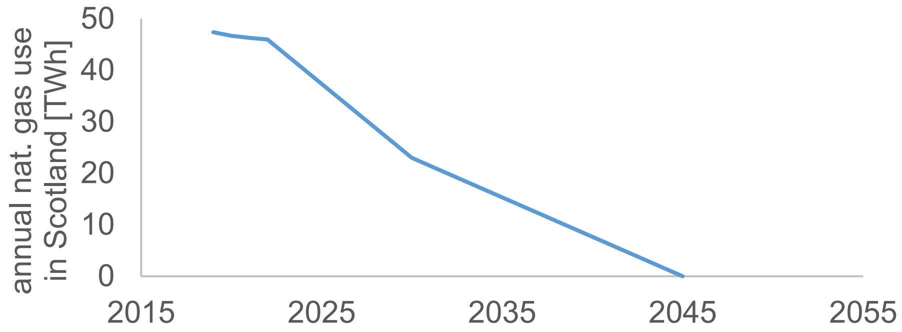


Figure 8: Natural gas use in Scotland and its planned decline based on ambitious targets in the Heat in Buildings Strategy 2021. As biomethane is injected into the gas grid to be used in place of natural gas, a phase-out of natural gas may also be a phase out of biomethane.

### 10.4.7 Biomethane for transport

Once on the gas grid, biomethane can be used for any purpose that natural gas is used for. Transport is a growing use for biomethane, particularly for heavy goods vehicles (HGVs). Compressed biomethane is typically referred to as bio-CNG. Liquified biomethane (typically referred to as bio-LNG) is also possible, although this is not yet widely used. Although official data for biomethane for transport is not available, industry reports that demand doubled from 2021 to 2022 (CNG Fuels, 2022).

### 10.4.8 Economic opportunity

As with biomethane for heating, AD plants could sell their biomethane for 0.0341 GBP/kWh, assuming a wholesale price of 100 GBP/therm.

On top of this, there is currently an incentive in the Renewable Transport Fuel Obligation (RTFO). In contrast to GGSS, this is not a fixed-rate tariff. Instead, it is a market mechanism that places an obligation on transport fuel suppliers to provide a percentage of renewable fuel, via Renewable Transport Fuel Certificates (RTFCs), or face a penalty fee. The fee, sometimes referred to as the ‘buy-out price’, sets the maximum price of a RTFC. Under current rules, one kilogram of biomethane generates 1.9 RTFCs (DfT, 2023), unless the biomethane is made from one of the wastes that DfT designate for double counting (DfT 2022), in which case it generates 3.8 RTFCs.

The buy-out price is currently 0.5 £/RTFC, and the market value fluctuates below that around 0.37 £/RTFC. The RTFC is generated by the biomethane seller, but typically a percentage is returned to the biomethane producer. A biomethane generator can typically gain 0.03 or 0.06 GBP/kWh, where the higher price represents biomethane from certain wastes (including manure).

#### 10.4.9 Environmental opportunity

A previous report (Fraser *et al*. 2022) investigated the environmental opportunity of biomethane for transport by comparing it to other low-emissions solutions in the heavy goods vehicle (HGV) sector. Biomethane from crops outperformed diesel, its use in HGVs being associated with around half of the GHG emissions of diesel, but better GHG savings could be provided by battery electric vehicles (BEV). Biomethane from waste was more competitive with BEV, although if low-carbon electricity is used, BEV still outperformed biomethane.

Biomethane from manure was not considered for HGVs, only for tractors. Again, using biomethane from crops, emissions could be halved compared with a diesel tractor. Using manure enabled a carbon credit to be applied, leading to negative emissions associated with the use of biomethane from manure in transport. It is worth noting however that 'long duration, high load activities' for haulage and/or machinery applications that electrification solutions are not always considered suitable. This is in part, due to the refuelling requirements that would be necessary. However, it is not clear if the use of biomethane as a transport fuel for these vehicles or machines would face similar refuelling challenges, as gases are not handled the same way as liquid fuels. This may require analysis on an individual basis for each machinery application.

#### 10.4.10 Demand & timeline

Fraser *et al.* (2022) identified electrification as the main decarbonisation route in transport, with demand for biomethane as a transport fuel in Scotland peaking between 2030 and 2037 (depending on modelled scenario) at around 1.5 TWh/year. Current biomethane production in Scotland is around 0.8 TWh/year.

#### 10.4.11 Biogas with CHP for electricity

Biogas can be combusted in a CHP to generate electricity and heat (in roughly equal proportions). Some electricity will be needed to run the AD plant, but the rest can be used in any way that is needed, including by exporting it into the electricity grid.

#### 10.4.12 Economic opportunity

Like gas prices, electricity prices have been extremely volatile. Prior to 2022, prices fluctuated around 50 GBP/MWh (0.05/kWh), but since then they have fluctuated widely around 200 GBP/MWh (Ofgem, 2023).

Previously, AD sites running a CHP were supported under the Feed in Tariff scheme (FIT), which paid a fixed tariff for every kWh of electricity generated (Feed-in Tariffs Order 2012). However, this scheme is now closed and there is currently no incentive for electricity generation from biogas.

#### 10.4.13 Environmental opportunity

The carbon intensity of electricity from biogas made from crops is typically higher than the carbon intensity of other forms of renewable electricity (such as wind or solar). Furthermore, previous regulations (such as FIT and RHI, which are both aligned with the first EU Renewable Energy Directive 2009/28/EC) did not take into account the carbon benefit of using manure as an AD feedstock, and gave the carbon intensity of electricity from biogas as typically around 50–70 $gCO_2eq/MJ$. However, the recast Renewable Energy Directive is associated with a methodology change for calculating GHGs, and electricity from manure-derived biogas is now associated with a carbon intensity of 11 $gCO_2eq/MJ$ or even a negative emission as low as −267 $gCO_2eq/MJ$.

Scottish electricity is, on average, already low carbon compared with other parts of the UK. Although the carbon intensity of the electricity grid in Scotland varies from day to day and year to year, the annual average has been below 13.9 $gCO_2eq/MJ$ (50 $gCO_2eq/kWh$) for several years.

Nonetheless, carbon intensity is higher on low-wind days. National Grid estimates show that the median carbon intensity of the Scottish electricity grid was 43 $gCO_2eq/kWh$ in 2022, meaning that half of time points when carbon intensity was measured were over this. The data also show that on 25% of days, the carbon intensity of electricity in Scotland is over 113 $gCO_2eq/kWh$ (i.e. this is the 75$^{th}$ centile).

### 10.4.14 Demand & timeline

Exact electricity demand scenarios are not available for Scotland but in National Grid's Future Energy Scenarios (National Grid ESO 2022), electricity demand is expected to increase by around 20-50% by 2035 (compared with 2021 values), depending on the scenario.

In 2021/22, Scotland's peak electricity daily demand was 99 GWh and the minimum demand was around half at 52 GWh (Scottish Energy Statistics Hub, 2023), suggesting that electricity demand could be as high as 148 GWh/day by 2035. Electricity generation from biogas, particularly as part of a capacity mechanism to balance out intermittent renewable generation, could play a role in Scotland's future electricity mix.

### 10.4.15 Biogas or biomethane for industrial heat

Heat can be generated from biogas by either combusting the biogas directly (using a CHP or a biogas boiler) or by upgrading the biogas to biomethane and combusting it in a gas boiler.

Heat generation, particularly with a boiler, is especially relevant to industries such as distilleries, which require high-temperature heat that is traditionally supplied by natural gas, oil, coal or biomass, and where low-temperature low-carbon heat solutions like heat pumps are not suitable. Example of distilleries producing biogas to generate heat in distillery boilers include Glenmorangie in Tain[19].

### 10.4.16 Economic opportunity

There is little competition for biogas/biomethane for renewable high-temperature industrial heat. Other sources of renewable (high-temperature) industrial heat include conventional biomass burning or, potentially, renewable hydrogen (which is not currently widely available). If industry currently uses natural gas for heat, a switch to biogas or biomethane will not require major investment for heating equipment.

Since the closure of the RHI, there is no government incentive to using biogas or biomethane for renewable heat. However, biomethane market prices are currently comparable to natural gas.

### 10.4.17 Environmental opportunity

Other than biomethane, there is little competition for biogas for renewable high-temperature industrial heat. Other sources of renewable (high-temperature) industrial heat include conventional biomass burning or, potentially, renewable hydrogen (which is not currently widely available). The exact environmental benefit will depend on the heating system being replaced, but this is likely to be fossil-based.

Insufficient evidence is available on demand & timeline for industrial heat.

[19] https://www.vibes.org.uk/case-studies/2017/the-glenmorangie-company-ltd/

### 10.4.18 Biogas with CHP or boiler for district heating

District heat can be provided from AD using a biogas boiler, a biomethane boiler or using the heat from a CHP. Since the closure of the RHI, there is no incentive for new AD plants to generate usable heat.

District heating can be used in new housing estates or office blocks. Although no examples of biogas district heating exist in Scotland or the UK, there are a number of district heating sites in Scotland that operate on natural gas[20]. Biogas or biomethane provides an opportunity to bring renewable heat into these existing district heating networks, which cannot easily be done otherwise owing to lack of large-scale renewable heat technologies. Insufficient evidence is available on demand & timeline for district heating.

### 10.4.19 Biomethane for hydrogen production

Hydrogen is described in different colours, depending on its source[21]. Hydrogen is currently made from natural gas, and this is called fossil hydrogen. Fossil hydrogen with CCS is called 'blue' hydrogen, while hydrogen from water electrolysis with renewable energy is called green hydrogen. However, methane reforming to hydrogen is also possible from biomethane using the same process and existing equipment, and this also generates green hydrogen (although this process has not been considered in the UK Hydrogen Strategy). As the technology to reform methane already exists, there is industry interest in using biomethane to make green hydrogen. This process could be economically feasible if there were incentives for clean hydrogen production, or if additional revenue could be generated from bio-$CO_2$ released from methane reforming.

While the question here is biomethane to hydrogen, it should be noted that there is also considerable academic interest in converting $H_2$ into methane[22]. Both are technically possible and interest in hydrogen vs methane is dependent on if or when the UK national grid converts to hydrogen.

### 10.4.20 Non-energy uses for methane

Methanol, an important feedstock for the chemicals industry, is currently made from natural gas, but it is also possible from biomethane using the same process and existing equipment. It is one of several routes to greener methanol, with other routes including combining hydrogen gas with captured $CO_2$ (either fossil-derived or bio-based $CO_2$).

Biomethane can also be used to make food or feed (in the form of microbial single-cell protein), with some companies currently producing animal feed from methane[23].

## 10.5 Potential markets for $CO_2$

In addition to the existing markets mentioned in section 6.2, which are expected to continue to grow in line with national economic growth, there are many potential upcoming markets for $CO_2$.

[20] https://www.heatnetworksupport.scot/map/#
[21] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf
[22] Further information on biomethane production from hydrogen (including augmentation of methane content in biogas) can be found elsewhere, https://doi.org/10.1016/j.rser.2021.111536 and https://doi.org/10.1016/j.biortech.2014.08.023
[23] https://calysta.com/

The potential market for $CO_2$ is only starting to be explored. In contrast to using fossil or bio resources, advantages of making fuels and products from $CO_2$ include that it is a form of recycling and that there are no questions around land use.

Several potential markets for $CO_2$ are described below, with comments on the advantage of biogenic $CO_2$ (which includes $CO_2$ from biogas upgrading) in these markets, if relevant.

### 10.5.1 Fuel

Policy in the UK and EU supports renewable fuels of non-biological origin (RFNBOs), which are liquid or gaseous transport fuels in which none of the energy content is derived from biological origin. Energy must have come from electricity or heat from renewable sources. Typically, RFNBOs are made of water and/or $CO_2$; an example is methanol made from hydrogen (from water electrolysis) and $CO_2$ (DfT 2022b). The RFNBOs are treated equally to RTFOs (mentioned in section 10.4.2) and fall under the same support mechanism. This is a market for $CO_2$ with government support.

Despite the name, 'non-biological origin', biogenic $CO_2$ can and should be used for these fuels; the 'non-biological origin' element refers specifically to the energy content of the fuel, which comes from electricity (or heat). In contrast, RFNBOs are likely to become an important market for $CO_2$ of biological origin. Currently, while RFNBO technology is being developed, any source of $CO_2$ is accepted for RFNBOs. However, EU policy (European Commission, 2023) is clear that there will be no place for fossil-derived $CO_2$ use in fuels in a net-zero world. This means that in the longer term, policy is expected to be updated to only permit $CO_2$ of biological origin or $CO_2$ from direct air capture to make RFNBOs. The same policy direction is expected in the UK.

There are no known barriers to the use of $CO_2$ from biogas upgrading in these markets. Only the economies of scale, as $CO_2$ from each biogas upgrading unit is relatively small scale, so large-scale $CO_2$ producers are likely to have a competitive advantage in the market.

Although there are currently no UK producers of RFNBOs using $CO_2$, this is a market with a high degree of investor confidence as it is backed by a government support mechanism. There are several RFNBO technologies at pilot scale and some volumes are expected to enter the market within the next 5 years[24]. Volumes and timelines for RFNBOs are still unclear.

### 10.5.2 Storage

Carbon capture and storage (CCS) is another market where biogenic $CO_2$ is likely to be valued over fossil $CO_2$. When biogenic $CO_2$ from energy production (including biomethane production) is used to generate biogenic $CO_2$, this is termed bioenergy with CCS (BECCS). Bioenergy with CCS (BECCS) is a carbon-negative process and seen as an essential part of the world's journey to net zero. As part of the 6$^{th}$ Assessment Report (AR6), IPCC Working Group III modelled scenarios to keep global temperature increases below 1.5 °C and 2 °C (IPCC 2022), and BECCS plays a key role in 4 out of 5 scenarios[25] (where the 5$^{th}$ scenario is radical reduction in consumption and considered unlikely to be achieved).

Carbon dioxide from biogas upgrading is suitable for this process, although, again, economies of scale may favour larger $CO_2$ production facilities. In addition, $CO_2$ would need to be transported to CCSS sites, which would be with conventional transport routes

[24] Stakeholder engagement
[25] https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf

(e.g. road, rail, ship, etc) as a $CO_2$ pipeline connecting AD plants is not likely. One UK AD company[26] is already exploring this route, having signed up to exporting $CO_2$ from its planned UK biomethane sites to Norway for injection into their Northern Lights CCS project. Some CCS projects are being explored for Scotland, notably the Scottish Cluster[27] and Acorn Project, so $CO_2$ from Scottish AD plants could be used there as BECCS.

The funding mechanisms for BECCS are outside of scope of this report, but they could be private (funded for carbon offsetting purposes in the private sector) or public (through future mechanisms).

#### 10.5.3 Chemicals

A previous report (Baltac *et al.* 2021) identified several uses of $CO_2$ as a feedstock in the [bio-]chemical industries as particularly relevant for Scotland. This included the use of $CO_2$ via fermentation, to make proteins and/or omega 3 for aquaculture feed, the use of $CO_2$ in specific types of algal cultivation to make a range of products, and the use of $CO_2$ in chemical conversion to methanol (which can be used as a fuel or as a chemical feedstock).

In most of these scenarios, there are a wide range of products that can be made, including higher-value products. The use of biogenic $CO_2$ allows a cradle-to-gate product carbon footprint to be carbon negative (ISO 14067:2018), which may be particularly valuable in consumer-facing products (such as personal-care ingredients) where making “carbon neutral” claims are valuable. Assuming food or chemical grade $CO_2$ would be sufficient, there are no known barriers to the use of $CO_2$ from biogas for chemicals production, other than the food-market barriers for waste-derived biogas mentioned in section 10.6.

The chemicals markets identified in Baltac *et al.* (2021) are particularly relevant to Scotland owing to their focus on fermentation as a technology and aquaculture as a market, areas where Scotland already has expertise.

#### 10.5.4 Fertiliser

Another potential market for $CO_2$ is in fertiliser production. This is currently being explored by a UK company who react $CO_2$ with ammonia and fibre (which are both availably from digestate) to generate a stable solid fertiliser[28]. In addition to capturing carbon, this system is beneficial in areas where digestate or slurry offtake is limited by the available landbank. A dry, chemical fertiliser product is easier to transport and market than digestate. Although any source of $CO_2$ can be used, $CO_2$ from biogas upgrading is a target for this technology owing to the co-location of the two other materials needed.

## 10.6 The use of $CO_2$ from biogas

Carbon dioxide can be captured from AD plants upgrading their biogas to biomethane, but not from AD plants using their biogas directly for heat or electricity. Equipment must capture the off-gas from the biogas upgrading unit and compress it, remove impurities and water vapour, liquify the $CO_2$ and remove any residual methane. Costs for this equipment are significant, in the order of 1–1.5 million GBP[29].

---

[26] https://www.futurebiogas.com/beccs/
[27] https://www.thescottishcluster.co.uk/
[28] https://www.ccmtechnologies.co.uk/technology
[29] Personal communications.

Only around 11 sites across the UK already capture $CO_2$. Some sell directly to companies that sell a range of gases[30], while others sell to specialist $CO_2$ companies, focussed on dry ice[31] or food and beverage[32] markets.

If all current Scottish biomethane plants captured their $CO_2$, this would represent approximately 120,000 t of $CO_2$ per year (see Appendix 11.5), presumably more than Scotland's current demand. However, not all systems are suitable to retrofitting $CO_2$ capture due to space or planning constraints, technical limits of the biogas upgrading equipment and cost, so full capture is very unlikely to occur.

Currently, the majority of $CO_2$ on the market is sourced from fossil resources, and shortages and price spikes (attributed to the $CO_2$ supply chain being dependent on only a few large producers) have had serious impacts on the industry in recent years (FDF 2022). While the UK government stepped in to help bridge supply gaps in Autumn 2021[33] and February 2022[34], government has made clear that this is not a long-term solution; there have been considerable efforts between various government bodies (BEIS, DEFRA and the EA), the biomethane industry and the food and beverage industry to reduce barriers to $CO_2$ capture from biogas upgrading and to provide a more resilient $CO_2$ market[35].

Carbon dioxide for food use is considered a food additive and the minimum specifications are defined in the retained EU Commission Regulation (EU) 231/2012 under additive number E290. However, the EU specification was not developed with waste-derived-biogas upgrading in mind, and there is industry reticence on potential risks, most clearly stated in the European Industrial Gases Association (EIGA) quality standard for $CO_2$ as: "Carbon dioxide feedgas from a biogas plant that uses waste, or a mixture of waste and energy crops, requires greater care than for energy crops in evaluation as a potential source of carbon dioxide for use in food and beverages."[36]

Although agricultural wastes, including manure, could be considered risky, there is precedence in the UK of these types of $CO_2$ being used in the food and beverage sector[37]. It is particular, $CO_2$ separated out of biogas derived from post-consumer food waste – where consumers can accidentally contaminate their waste with anything – that is perceived as risky.

Other main markets mentioned in section 6.2 require only technical grade $CO_2$ and there are no known barriers to the use of biogas-derived $CO_2$ in these markets.

The current interest in fitting new biomethane plants with carbon capture equipment reflects the increasing $CO_2$ price in recent years – although it is not clear whether this high price will be sustained – along with the assumption that demand for biogenic $CO_2$ will increase in the future.

---

[30] Such as Pro Gases UK https://progasesuk.com/the-carbon-dioxide-industry-and-its-future-with-biogas/
[31] http://dryicescotland.co.uk/
[32] https://www.biocarbonics.com/
[33] https://www.gov.uk/government/news/agreement-reached-to-ensure-supplies-of-co2-to-businesses
[34] https://www.gov.uk/government/news/new-agreement-to-ensure-supplies-of-co2
[35] https://www.r-e-a.net/wp-content/uploads/2022/02/CCU-Technologies-Speaking-Note-from-Defra-meeting-on-22-January-2022.pdf
[36] https://www.eiga.eu/uploads/documents/DOC070.pdf
[37] Personal communications.

## 10.7 Digestate

Digestates can be defined and described in five main ways and these are important in determining how and in which markets the digestates can be used. They can be defined and described in terms of:

- Their physical properties (primarily dry matter content and particle size)
- Whether they are derived from wastes or not and whether the resultant digestate is classed as a waste or not
- The feedstock types from which they are derived
- Their nutrient content
- Whether they contain animal by-products (ABPs) or not

### 10.7.1 Physical properties

Digestate is primarily available to users as whole, liquid digestate, but it is increasingly common practice to separate whole digestate into liquid and fibre fractions, with the liquids typically having 3–7% dry matter and the fibre typically 20–27% dry matter. Producers typically separate digestate into these fractions to make it easier to store and use. The fibre fraction is often easier and cheaper to store on hard-standing and contains useful quantities of organic matter as well as plant nutrients. However, separated liquid digestates contain fewer solid particles and can therefore be easier to spread. The reduced total volume of digestate produced in a liquid form can also reduce the requirement for expensive bunded storage tanks. The percentage of dry matter in the three main forms of digestate is shown in Table 10.51.

Table 10.5: Percentage of dry matter in the three main digestate types

| Digestate type | Dry matter content (%) |
|---|---|
| Whole liquid | 4 – 7 |
| Separated liquid | < 6.0 |
| Separated fibre | > 20 |

Due to the low dry matter, digestates are both heavy and bulky. For that reason, the cost of transporting them can in some cases be considerable, particularly where there is competition for landbank locally. Specialists marketing digestates in Scotland for large waste AD operators typically aim to apply digestates to land within 40 miles of the plant.

As a result of its bulky nature, AD plant operators are keen to further process digestates in ways that will result in reducing the water content, concentrating or extracting the nutrients and potentially increasing the financial value of the products. This is known as digestate valorisation (Section 5.2).

Digestate contains nutrients in varying proportions, depending on the feedstocks from which it is made and the nature of any separation process used post-digestion (see also Appendix 0). Nutrient contents are widely documented, but advisors working with digestate typically report significant variability from reference values, as composition is highly feedstock and process specific. For that reason, all producers are advised to test their digestates regularly in order to understand its nutrient content and resultant value.

### 10.7.2 Digestate value

The fertiliser value of digestate is dictated by the price of synthetic fertilisers, which have increased considerably during the past year, due to large increases in energy prices and supply difficulties. The price of nitrogen (N, based on UK-produced ammonium nitrate), phosphate (P, based on triple superphosphate) and potash (K, based on muriate of potash) in synthetic form is currently around £1.83, £1.39 and £0.99/kg, respectively[38]. These prices have fallen slightly in recent months, but according to the agricultural trade press, are likely to remain high[9].

Based on current fertiliser prices, the apparent value of typical whole, separated fibre and separated liquid digestates based on their major nutrient content would be as shown in Table 10.62. However, whilst it is usually considered that all of the P and K present in digestates would remain in the soil after application so can be valued in terms of its benefit to plants, the same is not true for N, which is very readily lost from digestates following application.

Table 10.6: The theoretical financial value (£) of the total amount of nutrients present in farm-based whole, separated liquid and separated fibre digestates (Digestate nutrient contents obtained from SAC Consulting, 2022; Fertiliser prices from AHDB fertiliser prices web page, March 2023).

| | Total N | Total $P_2O_5$ | Total $K_2O$ | Total value/ (tonne or $m^3$) |
|---|---|---|---|---|
| Whole digestate | | | | |
| Nutrient content (kg/$m^3$) | 3.6 | 1.7 | 4.4 | |
| Financial value (£/$m^3$) | 6.59 | 2.36 | 4.36 | £13.31 |
| Separated liquor | | | | |
| Nutrient content (kg/$m^3$) | 1.9 | 0.6 | 2.5 | |
| Financial value (£/$m^3$) | 3.48 | 0.83 | 2.48 | £6.79 |
| Separated fibre | | | | |
| Nutrient content (kg/t) | 5.6 | 4.7 | 6.0 | |
| Financial value (£/t) | 10.25 | 6.53 | 5.94 | £22.72 |

[1]Fertiliser prices (March 2023): N = £1.83/kg; P = £1.39/kg; K = £0.99/kg

It is not possible to show a gross margin for digestates in general or digestates from particular AD plants. This is because digestate production costs vary between AD plants and are not publicly available. The AD plant managers interviewed as stakeholders during this project said that digestate production was only financially feasible as a result of revenues gained from subsidy and/or sales of gas/electricity. No AD plants would be profitable on the basis of revenues gained from digestate sales. It is possible to fine-tune and maximise the financial performance of digestate use through an in-depth knowledge of agronomy and best practice. Some of the AD plant managers interviewed during this

[38] AHDB, March 2023 https://ahdb.org.uk/GB-fertiliser-prices

project conduct detailed nutrient budgets in order to establish when within their rotations (i.e. on which crops) and where on their farms they can most profitably use digestate.

The nitrogen (N) in digestate is typically in a more readily-available form (mainly ammonium) than in slurries and manures. Whole and separated digestates typically contain around 80 to 90% readily available N (or RAN) and fibre digestates around 25 to 30% RAN, whilst undigested slurries and manures typically contain around 45% and 10–20% RAN respectively. Nitrogen is therefore less readily lost from cattle slurries than from whole digestate and less readily lost from solid manures than from fibre digestates. However, the high RAN content of digestates makes them good fertilisers when used according to best practice guidance, making N more readily available to actively growing crops.

Nitrogen use efficiency (NUE) can be defined as the percentage of the N present in any applied fertiliser (including manures and digestates) which is taken up by the crop. The NUE of fertilisers and manures is never 100%, because there will always be losses following application. However, Scottish farming and environmental regulations combined with good practice guidance aim to ensure that losses are minimised so that farmers can get the maximum amount of financial benefit from applied materials.

The NUE of bulky organic materials including digestates is usually somewhat less than that from synthetic fertilisers. The NUE from digestate applications (and other bulky organic fertilisers) varies depending on the time of year at which they are applied (in relation to crop demand for N), the weather and soil conditions during application, soil depth, soil texture, the type of equipment being used to apply it and whether the digestate is incorporated straight after application. The impact of application time alone on the percentage of the N which is taken up by the crop (crop available N) and therefore the value of whole digestate is shown in Table 10.7.

There is good, clear, recent Scottish guidance for farmers on how to comply with the relevant legislation and how to implement best practice with a view to maximising the financial value of digestates and minimise losses to the environment. However, consultation with specialist advisers in Scotland indicate best practice has not yet been widely adopted, and there is a need for knowledge exchange to further improve NUE.

Given that typical whole digestates are currently worth around £10/m3 (based on 50% NUE) and fibre digestates around £11.80/m3 (based on a “best case” 20% NUE for fibre digestates, SAC Consulting, 2022), digestate is not always valued at these levels commercially. The following bullets summarise the factors to consider before deciding whether to use digestate and to inform its value to the recipient; an expanded list is available in Appendix 010.8.

- Haulage and storage costs
- Seasonality of demand and land access limitations
- Spreading costs and availability of suitable equipment
- Contractual term and commercial arrangements

### 10.7.3 Feedstock type and waste status

There is good, clear, recent Scottish guidance for farmers on how to comply with the relevant legislation and how to implement best practice with a view to maximising the financial value of digestates and minimise losses to the environment. However, consultation with specialist advisers in Scotland indicate best practice has not yet been widely adopted, and there is a need for knowledge exchange to further improve NUE.

Given that typical whole digestates are currently worth around £10/$m^3$ (based on 50% NUE) and fibre digestates around £11.80/$m^3$ (based on a “best case” 20% NUE for fibre digestates, SAC Consulting, 2022), digestate is not always valued at these levels commercially. The following bullets summarise the factors to consider before deciding whether to use digestate and to inform its value to the recipient; an expanded list is available in Appendix 0.

- Haulage and storage costs
- Seasonality of demand and land access limitations
- Spreading costs and availability of suitable equipment
- Contractual term and commercial arrangements
- Feedstock type and waste status

Table 10.7: The financial value (£) of typical whole digestate (3.6 kg N/m$^3$ and more than 50% readily available N (RAN)) applied at different times of year and to different soil and crop types[1].

| Scenario | % crop-available N | Value of N in digestate (at £6.59/m$^3$) | Total value of digestate (£/m$^3$) |
|---|---|---|---|
| Digestate applied Aug. to Oct. to cereal crops grown on sands, sandy loams and shallow soils. | 10 | 0.66 | £7.38 |
| Digestate applied Aug. to Oct. to grass crops grown on sands, sandy loams and shallow soils. | 15 | 0.99 | £7.71 |
| Digestate applied Aug. to Oct. to cereal crops grown on all soils other than the above | 15 | 0.99 | £7.71 |
| Digestate applied Aug. to Oct. to grass crops grown on all soils other than the above | 30 | 1.96 | £8.68 |
| Digestate applied Feb. to Apr. and in Summer to all crops on all soils | 50 | 3.30 | £10.02 |

[1] N = £1.83/kg; P = £1.39/kg; K = £0.99/kg. The value of the P and K within the digestate remains the same in all scenarios at £2.36 and £4.36/m$^3$ respectively. Fertiliser prices were from AHDB fertiliser prices web page, March 2023. NUE values were derived from SAC Consulting, 2022.

The digestates which are worth most to the farmer are local materials that come with little or no haulage cost, so farms with their own AD plant have a clear advantage. Spreading digestate at the wrong time or in poor weather conditions can hamper its value and impact, and even when used according to best practice, by the time the farmer has paid for haulage, storage (if required) and precision application, the savings compared with using synthetic fertilisers can be marginal. However, there is clear anecdotal evidence that many of the farmers currently using digestate believe it is an excellent form of fertiliser and feel there are advantages over synthetic fertilisers. Following consultation with Scottish farmers and consultants, the following advantages have been reported (the first two are scientifically proven, the others are not):

- Useful amounts of magnesium and sulphur present in digestate, adds value;
- Useful amounts of trace elements present in the digestate, adds value;
- Faster crop response with digestate than with synthetic fertiliser;

- Improved soil health and soil structure (particularly with fibre digestates);
- Improved soil P status (only one farmer reported this);
- Improved soil organic matter content following repeated fibre digestate applications (contrary to popular opinion, whole digestates supply very little organic matter to soils, even when applied repeatedly at typical rates).

## 10.8 Digestate types and regulations for their use

### 10.8.1 Digestates – waste or not?

The question of whether digestate is classed as waste or not is complex. Given that waste legislation is a devolved matter, the situation is different in different UK countries. In Scotland, digestate will not be regulated as waste if it:

- Is based only on non-food waste feedstocks such manures, slurries and purpose-grown crops and is used only on the farm on which the feedstock is produced. Digestates are also unlikely to be classed as wastes if they are produced by a co-operative of farmers and used only on farms belonging to members of that co-operative.
- Is certified as compliant with the requirements of the UK Biofertiliser Certification Scheme (BCS) in accordance with PAS 110 (2014) Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials (BSI, 2014).
- Complies with the requirements of the relevant SEPA position statement (SEPA, 2017): "Regulation of outputs from anaerobic digestion processes". This means that the digestate must be applied in accordance with:
    - all regulatory controls (the Controlled Activities Regulations and NVZ regulations [where applicable]) Section;
    - agricultural best practice as defined in the PEPFAA Code (Scottish Executive, 2005) and the Four Point Plan.

Any digestate that does not comply with these controls will be classed as waste and can only be applied to agricultural land in Scotland under a Waste Management License Exemption (Paragraph 7) (The Waste Management Licensing (Scotland) Regulations 2011).

### 10.8.2 Feedstock types (how the intended markets define what they permit)

The organic materials that are used in AD processes are called feedstocks. AD plant managers must understand the best type and mix of feedstocks to use in order to ensure a safe, functional, profitable and legally compliant system which is likely to produce digestates suitable for local markets. The feedstock types in digestate will determine:

- The rules and regulations that the AD plant manager must comply with;
- The type(s) of good practice advice that should be complied with;
- The fertiliser nutrient content of the finished digestate(s);
- Potential risks to the business and the environment in which the digestate(s) will be used.

AD plants can broadly be separated into those which accept waste feedstocks and those which do not, and this will determine the factors which must be considered when determining digestate markets. Specialist help and/or advice from the regulator is often required to determine whether feedstocks must be classed as wastes. The most frequently used feedstocks are:

- **Purpose-grown crops** - In Scotland, these are primarily grass silage, energy beet and wholecrop cereals (e.g. hybrid rye);
- **Agricultural manures and slurries** - These are often used as part of the feedstock in AD processes. Due to their typically low gas yield, they are usually mixed with other materials such as purpose-grown energy crops.
- **Agricultural crop residues** - These are produced as an integral part of the commercial production of agricultural crops. They include damaged or misshapen fruit or vegetables, trimmings and other plant parts, which are not the intended end product (e.g. straw, leaves or tops). They can be collected from the field or from a packing unit, prior to leaving the farm-gate. Some are classed as wastes, therefore, the resultant digestate may be classed as a waste under certain conditions (Section 10.8.3). SEPA guidance assists AD plant operators to decide whether feedstock materials are wastes or not (SEPA, 2014).
- **Domestic and commercial food wastes** – This includes material collected from domestic households, retail premises, restaurants, cafes, hotels, schools and other residential premises. To be acceptable for PAS110-accredited wet AD, food waste must be source separated, which means it has never have been mixed with other non-biodegradable wastes. Some of this waste must be de-packaged before it becomes suitable for AD.
- **Food and drinks processing wastes** – This includes material such as brewers grain and chaff from distilleries and breweries, butchery wastes, abattoir wastes and waste from vegetable packing and processing factories.
- **Sewage sludge** – While this is commonly treated through AD prior to land spreading, the resulting material is still considered to be sewage sludge and its use in agriculture must comply with The Sludge (Use in Agriculture) (Amendment) Regulations 1990, No.1263. Any material that contains sewage sludge cannot be considered as digestate and is not covered in this project.

### 10.8.3 Regulations on digestate storage and use

Several pieces of legislation affect those using digestates on agricultural land and it is the land manager's responsibility to ensure compliance with the legislation relevant to their situation. The relevant legislation is outlined below.

*Waste Management Licensing (Scotland) Regulations 2011 (WMLR)*

The storage and application of waste digestates to land is regulated by the Scottish Environment Protection Agency (SEPA). To apply waste digestates to agricultural land, the farmer must register a Paragraph 7 Waste Management Licence Exemption (Land treatment for benefit to agriculture or ecological improvement). All applications to SEPA must include a "Certificate of Agricultural Benefit" (prepared by a suitably qualified individual), which demonstrates that the material will result in agricultural benefit or ecological improvement when used as described. Both soil and digestate analysis are required. The addition of total nitrogen (N) attributable to the use of the waste (and any other organic materials) on land in any 12-month period must not exceed 250 kg/ha.

*Nitrate vulnerable Zones (NVZ) Regulations*

In NVZs, of which there are five in the arable areas of Scotland, the total quantity of N applied in organic materials must be included in crop nutrient requirement calculations. In NVZs, there are mandatory closed spreading periods for high readily available N (RAN) organic materials (i.e. those which contain more than 30% of their total N content as RAN). Most liquid digestates contain a high percentage of their total N as RAN, with farm-based whole and separated liquor digestates typically containing between 65% and

90% respectively of their total N as RAN. Some fibre digestates are also classed as high RAN and are therefore also subject to closed spreading periods.

*The Water Environment (Controlled Activities)(Scotland) Regulations (as amended)*

Controls exist under General Binding Rule 18 (GBR 18: The storage and application of fertiliser) within the Controlled Activities Regulations (CAR Regulations) that regulate the storage and land spreading of organic and manufactured fertilisers including digestates (SEPA, 2022).

GBR 18 stipulates that organic fertilisers must not be applied to land that:

- Is within 10 m of any river, burn, ditch, wetland, loch, transitional water or coastal water;
- Is within 50 m of any spring that supplies water for human consumption or any well or borehole that is not capped to prevent water ingress;
- Has an average soil depth of < 40 m and overlies gravel or fissured rock, except where the application is for forestry operations;
- Is frozen (except where the fertiliser is farmyard manure), waterlogged, or covered with snow; or
- Is sloping, unless it is ensured that any run-off of fertiliser is intercepted (by means of a sufficient buffer zone or otherwise) to prevent it from entering any river, burn, ditch, wetland, loch, transitional water or coastal water towards which the land slopes.

The rules also state that fertiliser of any type (including digestate) should not be applied in excess of crop requirements and that equipment used for spreading must be maintained in a good state of repair. If fibre digestate is stored in a heap in field, it must be applied to land within 6 months of the commencement of the storage. Other requirements within GBR 18 are covered in the practical guide to the CAR Regulations (SEPA, 2022).

Recent amendments to the CAR Regulations directly impact the digestate market and all those working within this sector need to ensure that they read and understand the changes that have been made (Farming and Scotland Water webpage (2022). In Scotland, all non-waste, whole and separated liquor digestates must be stored in a liquid digestate storage system, slurry storage system or slurry bag. The base and walls must be impermeable, protected against corrosion, capable of withstanding loads, not situated within 10 m of any surface water, operationally maintained and must have drainage pipes with two lockable values. Liquid digestate storage systems and slurry bags, which were constructed, or which were granted planning permission before 1 January 2022 have until 1 January 2024 to comply. All liquid digestates must be applied using precision equipment (as opposed to splash plate slurry spreaders) from 1st January 2023.

*The Animal By-Products Regulations*

Digestates, which have been derived (or partly derived) from animal by-products (ABPs), which includes most food waste feedstocks, must have been processed in an Animal-By-Product-approved facility and must only be applied to agricultural land in accordance with the Animal By-Products Regulations. These EU regulations are implemented in Scotland by the Animal By-Products (Enforcement) (Scotland) Regulations 2013 and the Animal By-Products (Miscellaneous Amendments) (Scotland) Regulations 2015. There are grazing bans of defined length when digestates based partly or wholly on ABPs are applied to pasture or to land used to grow forage crops:

- The land cannot be used for grazing within 8 weeks of the application date for pigs; and
- 3 weeks for other farmed animals.

Farmers who use ABPs must keep records of the date, quantity and description of the materials applied, and the date on which pigs and other farmed animals first have access to the land after application.

#### 10.8.4 Best practice guidance relating to digestate storage, handling and use

Agricultural best practice guidance applies to all digestate types used in all farm situations and most farm assurance schemes require compliance with it (see below). Digestates can present a considerable environmental risk if not stored, handled and applied carefully. Best practice rules and guidance for farmers on the storage, handling and application of organic fertilisers is provided in the PEPFAA Code. A "Risk Assessment for Digestate Use Map" must be prepared for the farm and must be made available to spreading contractors. This must identify areas of high risk where field heaps must not be located and where digestate must not be spread. Information on how to create these maps, other relevant good practice guidance and regulations are available in the PEPFAA code and from the Farming and Water Scotland website (Scottish Executive, 2005; https://www.farmingandwaterscotland.org/).

#### 10.8.5 Farm Assurance Schemes and produce buyer's rules

Some of the UK and Scottish farm assurance schemes have developed their own rules governing where and when organic materials including digestates can be used on their scheme members' land. For example:

- Quality Meat Scotland requires that digestates made partly or wholly from wastes are either PAS110-certified or (for some types) have an authorisation from SEPA. In addition, physical contaminants should not exceed 8% of those permitted under PAS110, as per SEPA's additional requirements in Scotland (QMS, 2022).
- Scottish Quality Crops (SQC) also allow PAS110-certified digestates, as well as use of digestate made on farms under their own SQC Approved Digestate Scheme. They do not permit the use of waste digestates, mainly due to the presence of small fragments of plastic present in de-packaged food wastes. Although the SEPA limits for plastic in digestate (which are relevant in Scotland) are considerably stricter than those in England and Wales, food waste digestates still typically contain small amounts of plastic. Further information and guidance can be found on the SQC website.

All land managers wishing to use digestate of any type must ensure, in advance of spreading, that their plans are compliant with their farm assurance scheme rules.

Some buyers have rules (which may be unwritten), which prohibit the use of certain types of digestate on crops that they buy, or even within the rotation. All land managers wishing to use digestate must ensure, in advance of spreading, that their product buyers are happy with their planned use of the relevant type(s) of digestate.

## 10.9 Impacts of digestate use

#### 10.9.1 Potential beneficial impacts of digestates on crops, soils and the wider environment

Digestates are primarily fertilisers, which can supply a considerable proportion (in a limited number of situations, all) required crop nutrients (SAC Consulting, 2022). They contain useful concentrations of major plant nutrients (i.e. nitrogen (N), phosphate (P), potash (K) and sulphur (S) which are essential for plant growth and therefore sustainable crop production (Taylor *et al.*, 2010). They can thus replace some or all of the farm's requirements for bagged fertiliser, in some cases saving money and improving the sustainability and carbon footprint of the farm. Digestates can also be useful soil conditioners (soil organic matter builders), depending on their dry matter content and the rates at which they are applied. Whole and liquid digestates are often wrongly classed as soil conditioners in the farming press and by those marketing and selling both AD plants and digestates. In fact, only fibre (solid) digestates which (due to their relatively low nutrient concentration relative to crop demand) can be applied at sufficiently high rates to allow appreciable amounts of carbon (in the digestate) to be applied to the soil can realistically be called soil conditioners.

### 10.9.2 Potential deleterious impacts of digestates on crops, soils and the wider environment

The storage, handling and spreading of digestates can present considerable short and long-term environmental risks if agricultural best practice is not followed.

The short-term risks are primarily caused by direct exposure of, humans, livestock, soils, air and water to digestates. Digestate should never be allowed to come into direct contact with humans or livestock, because it will always pose a potential risk to them, just as farmyard manures and slurries would. Digestate is a biologically active material, which contains high concentrations of plant-available nutrients, especially nitrogen (N), which is typically mainly present in the form of ammonium. There is very little documented evidence that digestates are being applied in inappropriate weather and soil conditions and at inappropriate times of year, when there is no crop demand. However, there is a great deal of anecdotal evidence that this is happening, both in Scotland and England, particularly when AD plants have insufficient storage capacity for digestate. Both SEPA and the Environment Agency are aware of problems resulting from digestates being stored, handled and spread in inappropriate ways. For this reason, they have implemented new rules, published new guidance and have provided a limited amount of funding to help digestate producers and users improve digestate storage capacity and spreading machinery. Examples of recent changes to rules and guidance include the Code of Good Practice for Reducing Ammonia Emissions (Defra, 2018) and the revisions to the CAR Regulations in Scotland which aim to reduce the risks associated with storage, handling and spreading of digestate.

The long-term risks are associated with the potential build-up of plastics and potentially toxic elements in soils and the release of pesticides and pharmaceuticals (including veterinary medicines) into our agri-food system. There is an additional long-term risk associated with the excess N and phosphorus which can be released into the environment.

Microplastics remain an ongoing concern for society in general and the amounts found in digestates will depend on the feedstock type. Following problems in the past, visible plastics (>2 mm) are less of a concern where digestates are made from feedstocks which have little or no plastics in them (such as those made from farm-produced energy crops, manures and distillery wastes). They are also less of a concern in the quality digestate (PAS110-accredited digestate) market in Scotland due to improvements in source separation and on-site quality control measures, which remove plastics from feedstocks and from the digestate.

There are limits on the concentration of PTEs in PAS110-accredited digestates and PAS110 accredited producers must test their products regularly to ensure compliance. Given that the feedstocks for most AD processes are naturally low in PTEs and organic pollutants, few digestate producers have trouble in producing digestate, which also contains low concentrations of these pollutants.

Whilst non-accredited digestate producers might not conduct regular testing for PTEs, such testing is strongly recommended, along with the testing of nutrient concentrations required under the Controlled Activities Regulations (GBRs) (section 5.3).

The limits on PTE concentrations in PAS110-accredited digestate and the likely low concentrations of PTEs and pollutants in all digestates helps to ensure that long term risks, such as the potential build-up of PTEs, phosphate and other pollutants in soil remain low. In general the amounts of PTEs applied to land in digestate applications will be similar to those when animal manures and slurries are applied to land.

However, some Scottish digestate feedstocks contain elevated levels of one or more PTEs (e.g. distillery wastes are typically high in copper). These wastes are currently mainly spread to land under Paragraph 7 waste management licence exemptions. If such wastes are to be used as feedstocks for PAS110 AD systems, they will undergo the same feedstock risk assessment process as other food and food processing wastes do, to ensure that the resulting digestate remains safe, PAS110-compliant and exempt from waste legislation.

Soil testing and reporting on background PTE concentrations in fields regularly used for spreading organic products and wastes (such as digestates and distillery wastes) is becoming increasingly important for compliance. Testing of receiving soils for PTE concentrations should always be considered if there are any long-term concerns with PTE build-up. Additional information on management of PTEs/heavy metals in agriculture is available in Technical Note TN753: Management of inputs of heavy metals to agricultural soils and crops (FAS, 2021) and Zero Waste Scotland's Overview: Digestate Safety for Agriculture (Zero Waste Scotland, 2020).

The risks associated with build-up of pesticides and pharmaceuticals in soils following application of digestate is thought to be low, given that the feedstocks for most AD processes naturally contain very low concentrations of these types of substances (SAC Consulting, 2022). The main notable exception can be the persistent herbicides clopyralid and aminopyralid, which are commonly used to control broadleaved weeds in grassland. These herbicides can persist in grass and animal manures used as feedstocks for AD and can also be present in the digestate product being spread to land. There have been reports of small concentrations of such herbicides present in composts made from recycled organic wastes reducing germination and growth of horticultural crops (WRAP, 2010).

### 10.9.3 Nutrient content (and the limitations which that can put on digestate spreading)

The nutrient content and physical properties of digestates depend on both the feedstock from which they were made and the nature of the AD and post-AD processes. The nutrient content of the digestate is directly correlated with the nutrient content of the feedstocks, since (unlike some other waste treatment processes such as composting) nutrients are not typically lost during the AD process. When digestates are separated, most of the N and potassium (K) typically end up in the liquid and most of the phosphorus (P) ends up in the fibre. However, the extent to which that happens depends on the nature of the separation process.

A high percentage of the N present in whole and separated liquid digestates is typically present as ammonium-N. That and the small amount of nitrate-N present in digestates is termed readily-available-N (RAN). The percentage of the total N present as RAN in whole and separated liquid digestates is typically between around 65 and 90%, although values outside that range do occur. The typically high RAN content in whole and separated liquor digestates makes them excellent N fertilisers, however, there is also a high potential for N losses when they are applied inappropriately, and this means that they must be stored, handled and spread with great care. Fibre digestates tend to have lower RAN contents (around 10 to 24%). However, RAN contents of > 30% (which render them subject to NVZ closed periods) are possible.

Typical dry matter, RAN and nutrient contents of food-based and farm-based digestates are shown in Table 11.10. However, digestate properties can vary widely from the values shown and for this reason, digestate users are always advised to test digestates (or obtain test data from the producer) prior to use. The accuracy and value of such tests depends on obtaining a sample, which is genuinely representative of the whole. This means that digestate within a tank or lagoon should be thoroughly mixed prior to testing and removal for spreading.

Table 10.8: Typical dry matter (DM) and nutrient contents of digestates (data obtained from SAC Consulting, 2022).

| | | | kg/t (solids) or kg/m$^3$ (liquids) Total | | | | |
|---|---|---|---|---|---|---|---|
| Digestate type | DM[1] (%) | RAN[2] (%) | N | $P_2O_5$ | $K_2O$ | $SO_3$ | MgO |
| Food-based, whole | 4.1 | 79 | 4.8 | 1.1 | 2.4 | 0.7 | 0.2 |
| Food-based, separated liquor | 3.8 | 89 | 4.5 | 1.0 | 2.8 | 1.0 | 0.2 |
| Food-based, separated fibre | 27 | 25 | 8.9 | 10.0 | 3.0 | 4.1 | 2.2 |
| Farm-based, whole | 5.5 | 78 | 3.6 | 1.7 | 4.4 | 0.8 | 0.6 |
| Farm-based, separated liquor | 3.0 | 89 | 1.9 | 0.6 | 2.5 | 0.1 | 0.4 |
| Farm-based, separated fibre | 24 | 25 | 5.6 | 4.7 | 6.0 | 2.1 | 1.8 |

[1]DM = dry matter; [2]RAN = readily-available nitrogen

Further information can be found on the BCS website and FAS Technical Note 736 (FAS, 2020). Total N and RAN content in whole and separated liquid digestates are particularly critical, given the importance of applying appropriate amounts of N to crops. These can vary throughout the year, as the balance of feedstocks changes and can also be affected by evaporation or rainfall ingress during outdoor storage of digestate in uncovered lagoons.

### 10.9.4 Calculating fertiliser replacement value

Whether using published values for the nutrient content of organic fertilisers or test results from the material a farmer is planning to use, the availability of the nutrients for crop uptake must be assessed before the fertiliser replacement value of an application can be calculated. This is a relatively complex matter, which is best done by agronomists who specialise in the application of organic materials to land, or by land managers who have taken time to get to grips with technical guidance on safe, cost-effective use of digestates in their work. A simplified summary of how to calculate the fertiliser replacement value of digestates is presented here. The most recent detailed Scottish guidance is set out in SAC Consulting 2022.

*Nitrogen*

The amount of N available to the crop following digestate application will depend on how much of the N applied is lost through nitrate leaching and ammonia emissions. Nitrogen losses from digestate can be significant and great care is needed to minimise them. The amount of N leached as nitrate following land application is mainly related to the:

- Application rate;
- Percentage of RAN present in the digestate;
- The amount of rainfall after application;
- Soil texture.

Since ammonium-N is rapidly converted in the soil to nitrate-N, applying digestate (or most other forms of N fertilisers) during the autumn or early winter period should be avoided, as over-winter rainfall is likely to be sufficient to wash a large proportion of this nitrate out of the soil before the crop can use it. Delaying digestate applications until late winter or spring will reduce nitrate leaching and increase the efficient use of applied N. This is particularly important for whole and liquid digestates, which typically have a high RAN content.

Research studies have shown that ammonia emissions digestates can be reduced by using precision application equipment such as band spreaders or shallow injectors. Such equipment allows digestate to be spread evenly, increasing the nutrient use efficiency.

The percentage of total N taken up by the crop following application of whole and separated liquid digestate is shown in Table 11.11. On studying this table, it will immediately become clear that even those applying these types of digestates responsibly with best practice will only succeed in getting a maximum of 50% of the N present into the crop. Many land managers still fail to understand that, but current high fertiliser prices are encouraging more of them to read widely around the subject and try to ensure the best possible N use efficiency when applying digestates.

Table 10.9: Percentage of total N taken up by crop following application of whole and separated liquid digestate (use the value in brackets for grassland, winter oilseed rape and brassicas). Table is based on that in SAC Consulting (2022).

| | August to October | | February to April | Summer |
|---|---|---|---|---|
| % RAN | Sands, sandy loams, shallow soils | All other soils | All soils | All soils, all crops |
| < 50% | 10(15) | 15(30) | 40[1] | 40[1] |
| > 50% | 10(15) | 15(35) | 50[2] | 50[2] |

[1]Default value in NVZs of 40% applies regardless of the timing of the application.

[2]Default value in NVZs of 50% applies regardless of the timing of the application.

As fibre digestates usually contain low RAN content (< 30%), they are not usually subject to the closed spreading periods in the NVZ Action programme rules. Although the amount of N taken up by crops following application of fibre digestates is relatively low, N contained in organic forms is broken down slowly to become potentially available for crop uptake over a period of months to years (Table 11.12). The risk of causing water pollution by spreading stackable solid materials is lower than for liquids, however, surface run-off can still occur if heavy rain falls shortly after an application.

Table 10.10: Percentage of total N taken up by crop following application of fibre digestates. Table is based on that in SAC Consulting (2022).

| August to October | | November to January | | February to April | Summer |
|---|---|---|---|---|---|
| Sands, sandy loams, shallow soils | All other soils | Sands, sandy loams, shallow soils | All other soils | All soils | Grassland |
| 10 | 10 | 15 | 15 | 20 (25[1]) | 20 |

[1]Incorporation by ploughing within 24 hours after application.

Surface application rates for fibre digestate should never exceed 50 t/ha, and liquids should never exceed 50 $m^3$/ha (Scottish Executive, 2005). However, many farmers prefer to limit applications of whole and liquid digestate to no more than 30 t/ha (or even 20 t/ha) in a single application, recognising the risks associated with applying high RAN to both crop health and to the environment.

Repeat applications should not be made for a period of at least 3 weeks (or 2 weeks where a 20 t/ha application has been made) (SAC Consulting, 2022). This is necessary to allow the crop to utilise the available nutrients and reduces risk of scorch. More frequent applications may smother herbage and increase the chances of leaching and run-off.

All applications should take account of the soil conditions and the amount of rain forecast. Fibre digestates are usually applied through side or rear discharge spreaders. The more advanced models can achieve a very even spread of material within each pass. Spreading machinery should be calibrated to accurately quantify application rates. Only by knowing the weight of material in the spreader, the nutrient content (in kg/t of fibre digestate), and the number of spreader loads applied per hectare will it be possible to gain an accurate understanding of the amount of nutrients applied.

Where fibre digestate is surface-applied, nitrogen losses (ammonia) can be minimised by ploughing the material in as quickly as possible after spreading, ideally within 6ix hours. Applications should be managed to avoid compaction or damage to soil structure, incorporation should be restricted to the top 30 cm of soil, and they should not take place when soil conditions are poor.

*Phosphate and potash*

For digestates, it is estimated that around 50% of P will be available to the crop following application. However, the amount of P that is taken up by that crop might differ, depending on the:

- Placement of P in relation to the establishing crop roots
- P sorption capacity of the soil
- Root depth
- Yield potential
- Soil temperature
- Crop type

These issues also apply to crop uptake of P from water-soluble P fertilisers. The P sorption capacity (PSC) of a soil refers to its capacity to bind with applied P, thus making that P temporarily unavailable for plant uptake. The PSC varies depending on soil chemistry, soil texture, pH and soil organic matter content (see SRUC Technical Note

668 [SRUC, 2015] and FAS Technical Notes 715 to 718 (FAS, 2018, 2019b, 2019c and 2021b). The applied P that is not taken up by the first crop will be released slowly over the crop rotation and will become available over a period of years.

Where crop responses to P are expected (e.g. where soils have very low or low P status); or where responsive crops (e.g. potatoes or vegetables) are grown on moderate P status soils, 50% of the total P content of the organic fertiliser should be used when calculating the P contribution. Where soil P status is at the target level (M-, M+ or H, depending on the crops grown in the rotation) or above (e.g. H or VH), 100% of the total P content of the digestate should be used in planning the balance that should be applied as manufactured P. Where crops are sown in cold soil conditions and slow crop establishment is expected, farmers are advised to ensure that some soluble P fertiliser is applied at sowing.

Where soil P status is above target, land managers must take care to ensure that total P inputs do not exceed the amounts removed in crops during the rotation by checking that the concentration of extractable P in soil test results is not increasing over time. This will avoid the soil P status becoming high and will reduce the risk of P pollution to surface water.

Around 90% of potassium (K) is in a soluble form in digestates, therefore, readily available for crop uptake. K, unlike P, moves freely in soil solution. It is recommended to subtract 90% of the total K in digestates from bagged fertiliser requirement where soil K status is below target and particularly important in K-responsive crops such as carrots, parsnips and beet. Where soil K status is at the target level (M- or M+), depending on the crops grown in the rotation) or above (e.g. H or VH), 100% of the total K content of the digestate should be used in planning the balance that should be applied as manufactured K.

*Sulphur and magnesium*

Recent research published in AHDB (2017) “Nutrient Management Guide (RB209)” has quantified sulphur (S) supply from biosolids applications and it is appropriate to use the same advice for digestate applications.

- For autumn applications, the % of total S applied, which is available for the following crop may be 10-20%.
- For spring applications, S availability is expected to be higher; and
- As a rule around 20% of the S in digestate will be available to the crop in the year of application.

An understanding of the expected S uptake in different crops and yields is helpful, and data can be found in FAS Technical Note 685 (FAS, 2017).

Magnesium (Mg) behaves in soil more like K than P. However, Mg moves less freely in soil solution than K does, with movement being reduced in low soil temperatures. Fibre digestates can supply useful quantities of Mg (around 20 to 40 kg/ha in typical applications).

### 10.9.5 Financial value of digestates

Fertiliser prices have increased significantly in the past 18 months and for this reason, the financial value of bulky organic materials, including digestates have increased too. AD plant managers selling digestates are seeing increased interest in their products, farmers are enquiring about purchasing digestates for the first time and those already using them are particularly keen to gain maximum value from the fertiliser nutrients within them. The current UK convention is to put a financial value on all of the P and K present in bulky organic manures, and to value only the percentage of N, which is going to become available to crops, which is to a large extent dependent on when the digestate is applied. Financial values are not typically put on the S, Mg or trace element content of digestates, or the organic matter content of fibre digestates, although most cropping systems will benefit from the presence of these things in organic materials, to some extent.

Table 11.13 shows the financial values of three different examples of digestate. A value is put on all the P and K present, and three scenarios are given for the value of N within the digestates, depending on different percentages of crop-available N. For fibre digestates, crop available N also depends on whether grass or another crop is being grown and on whether the material is ploughed down within 24 hours.

The financial value of whole and separated liquid digestates varies greatly depending on the application time and method, with potential losses being higher the higher % RAN the digestate contains. Crop-available N can be as little as 10% or as high as 50%. The example for separated liquor digestate with < 50% RAN in Table 11.13 is valued at between £3.63 and £5.11/ $m^3$. If that digestate was applied at 20 t/ha over a 10 ha field, then the value of digestate applications for that field, with 10 or 50% crop-available N, would be £726 or £1,022 respectively. The financial impact of poor digestate application practices is greater where digestates contain > 50% RAN, because the N is more easily lost.

The financial value of separated fibre digestates does not vary greatly depending on the way they are applied (mainly because crop available N from fibre digestates is generally relatively low and because a higher percentage of their value comes from P and K, which are less easily lost from soils than N is).

Fertiliser prices will continue to fluctuate, but they are likely to increase further in future years as energy prices rise and the availability of mined rock phosphate decreases. The value of recycled fertilisers such as digestate is therefore also likely to increase in future.

Table 10.11 Financial value of three example digestates, based on fertiliser prices of £1.87 /kg (N), £1.17 /kg ($P_2O_5$) and 90 p/kg ($K_2O$)[1]. Valuations are based on scenarios where Crop N availability from digestate in the year of application is 10, 20, 30 or 50%, but in practice, crop N availability might be anywhere between 10 and 50%[2] (FAS, 2019). All of the phosphate and potash present are valued. Table based on that in SAC Consulting (2022).

| Digestate example | N 10% | N 20% | N 30% | N 50% | $P_2O_5$ 100% | $K_2O$ 100% | Total value of digestate (£)[3] |
|---|---|---|---|---|---|---|---|
| *Whole digestate (< 50% RAN)* | | | | | | | |
| Total nutrient content ($kg/m^3$) | 4.8 | 4.8 | 4.8 | 4.8 | 1.5 | 3.4 | |
| Crop-available nutrient ($kg/m^3$) | 0.5 | N/A[3] | 1.4 | 2.4 | 1.5 | 3.4 | |
| Financial value of nutrients (£) | 0.94 | N/A | 2.62 | 4.49 | 1.76 | 3.06 | £5.76-£9.31 |
| *Separated liquor (< 50% RAN)* | | | | | | | |
| Total nutrient content ($kg/m^3$) | 3.2 | 3.2 | 3.2 | 3.2 | 0.8 | 2.7 | |
| Crop-available nutrient ($kg/m^3$) | 0.3 | N/A[3] | 0.96 | 1.6 | 0.8 | 2.7 | |
| Financial value of nutrients (£) | 0.56 | N/A | 1.80 | 2.99 | 0.94 | 2.43 | £3.93-£6.36 |
| *Separated fibre* | | | | | | | |
| Total nutrient content (kg/t) | 8.0 | 8.0 | 8.0 | 8.0 | 6.0 | 4.5 | |
| Crop-available nutrient (kg/t) | 0.8 | 1.6 | N/A[4] | N/A[4] | 6.0 | 4.5 | |
| Financial value of nutrients (£) | 1.50 | 2.99 | N/A | N/A | 7.02 | 4.05 | £12.57-£14.06 |

[1]Fertiliser prices were obtained from the AHDB website (https://ahdb.org.uk/GB-fertiliser-prices) and were last updated in February 2022.

[2]Financial value of digestate varies, mainly depending on fertiliser prices and on crop nitrogen availability. Crop nitrogen availability depends primarily on the time of year at which digestates are applied, but also to some extent on soil texture, soil depth, crop type, rainfall and method of application. See FAS Technical Note TN699, Planet Scotland (URL or reference) or Manner NPK (URL or reference) for details of how to estimate crop-available N.

[3]No published scenarios exist where 20% of the nitrogen in whole or separated digestate is crop-available.

[4]Research has shown that a maximum of 20% of the nitrogen in fibre digestates is likely to become crop available when surface applied and not ploughed in within 24 hours.

### 10.9.6 Landbank for digestates in Scotland

The most recent assessment of the landbank for organic and inorganic wastes and products across Scotland (including animal manures and digestates as well as sewage sludge, distillery effluents and other materials) was commissioned by SEPA and completed in August 2020 (SAC Consulting, 2020). It was authored jointly by Bill Crooks and Audrey Litterick, one of the authors of this report. Although it considers thirteen broad categories of wastes and products (rather than just digestates), the entire report is directly relevant to this project, since all of these materials are effectively "competing" for the same Scottish landbank. There are no more recent useful Scottish landbank studies than this one.

The report aimed to determine whether there was sufficient landbank at the time of writing (2019/2020) and in future for the safe, sustainable and beneficial use of all materials (including organic and inorganic bulky wastes and products) produced in Scotland. In the context of that main question (and in this report), the terms "landbank", "safe", "sustainable" and "beneficial" are defined as follows:

- *Landbank* means land which is available for the spreading of some or all types of materials in agriculture, forestry, amenity and brownfield land restoration.
- *Safe* in this context, means without causing harm to crops, wild plants, humans, animals or the environment now and in the future.
- *Sustainable use* in this context means that materials are used in such a way that they can be used indefinitely in the prescribed manner without causing harm of any sort. In some cases (particularly for finite resources, such as the annual tonnage of compost from a single organics recycling site) it can also mean that the material is used in such a way that supplies of it are not depleted unnecessarily by applying more than the minimum required to provide benefit at each location. Conservation of finite resources is particularly important in some stockless arable areas where alternatives to synthetic fertilisers in the form of bulky organic manures are in short supply.
- *Beneficial use* in this context means that materials used in such a way will result in positive impacts on soils, crops, the wider environment, humans and other animals.

The SAC Consulting report contained five main sections as follows:

***Section 1*** An assessment of the extent to which application of materials to land is restricted in four key sectors (agriculture, forestry, amenity and brownfield land) by physical, legislative, soil, land management, seasonal, climatic and economic barriers. The assessment of the (twenty) factors affecting/restricting the application of materials to land in agriculture (which were determined as a result of work conducted under the SAC Consulting project) is directly relevant to this project.

***Section 2*** A description of the tonnages of different types of organic and inorganic materials produced in Scotland and, where possible, descriptions of the places where some of these materials are produced. Future tonnage estimates are discussed with named references where possible.

***Section 3*** Describes the GIS datasets developed under the project. These datasets are the first stage in developing the means to assess landbank for spreading of materials at a range of scales. This part of the report is relevant, but is incomplete at present. Further work (as defined in the project) would be required to develop it to a stage where it could be useful to AD plant developers and policy makers.

***Section 4*** presents key points and conclusions from first three chapters in the report and considers the value and limitations of the work done. It then addresses fundamental questions from the project as a whole.

***Section 5*** provides recommendations on changes required to policies, guidance and practices to ensure the use of materials on land is sustainable over the next 20 years

The report drew conclusions which are key to those being considered in this project. The most relevant of these in relation to availability of landbank in Scotland are summarised here.

It was not possible to determine whether there was sufficient landbank in future for the safe, sustainable and beneficial use of all of the materials [defined in the project] produced in Scotland in 2020 (or in future) in simple terms due to a lack of easily searchable, publicly-available or other information defining the:

1. tonnages and chemical/physical properties (e.g. agricultural benefit parameters) of named materials produced at defined locations; and the
2. precise areas and location of land in Scotland affected by some or all of the factors affecting spreading.

If all of the materials considered in the project could be spread on all parts of Scotland, then there would likely be sufficient landbank to which to apply all of them to land somewhere. However, the high cost of transport for bulky materials (which limits the cost-effective transport distance), along with the fact that much of the landbank in Scotland is affected by one or more other controls on spreading means that the availability of landbank for the materials in question differs depending on geographical area as well as on the number and location of premises producing them.

### 10.9.7 Factors affecting spreading

- Of the twenty main factors affecting (or potentially affecting) the application of materials to land (used for agriculture, forestry, amenity and brownfield), land capability, which is linked to topography, climate, altitude, slope and to some extent soil properties, is probably the most important. 51% (4,000,000 ha) of Scotland's land area is in land capability for Agriculture (LCA) class 6.1 or above, which effectively means that the land will have little or no requirement for applied materials.

- The main regulatory controls on spreading of digestates are:
    - Controlled Activities (General Binding Rules), which apply to all land in Scotland.
    - NVZ Regulations (which mainly limit N loading rates from organic materials and application time for high RAN materials in NVZs).
    - Rules under exemptions from the Waste Management Licencing Regulations (2011), which affect the use of waste digestates in agriculture (through paragraph 7 exemptions).
    - UK Organic Farming Regulations (for agricultural land that is certified organic).
    - Various pieces of legislation relating to designated sites, which cover a large part of Scotland's land area.

- The ways in which most of the other factors studied impact on spreading depend to some extent on the above legislation (and associated good practice guidance), which generally aim to reduce risk. These factors include, for example, seasonal and climatic factors, slope and topography and phosphate loading rates.
- In broad terms, the SAC Consulting report concluded that, together, each of twenty factors and controls studied maximised the benefits of land applications and minimised the risks.
- Scotland has a continuing overall net crop demand for N, P and K, even after livestock manures and slurries have been accounted for (SAC Consulting, 2020). For P, however, the spatial distribution of this net demand is largely restricted to the eastern half of the country. There are also pressure points in and around intensive agricultural areas and areas where large amounts of organic materials, such as digestate are produced, but the geospatial evidence indicates that land spreading of current and projected organic materials arising from non-farm sources can be done sustainably assuming there are no socio economic controls.
- In Scotland, the highest net crop demand for nutrients (N and P) occurs in geographically distinct areas associated with high yielding arable production in the east of the country. The specific geospatial points at which some organic fertilisers, such as digestate and composts are arising do not always correspond, geospatially, with this demand.
- Historic and economic factors have meant that many fixed point sources of organic fertilisers in Scotland, such as distilleries, digestates and livestock manures from intensive production (poultry and dairy) are located in areas where local crop nutrient demand is limited or fixed. Their land application can be associated with high haulage costs if they are to be land spread without posing long term environmental concerns.
- Any future industry data on volumes and nutrient values of waste arising and intended for land spreading must be attributed to fixed locations and be sufficient detailed to predict with reasonable accuracy the amounts of N, P and K that are being made available for land spreading on an annual basis.

#### 10.9.8 Landbank determination

- There are significant gaps in current Scottish GIS datasets on landbank (SAC Consulting, 2020).
- In order to determine whether there is sufficient landbank in Scotland to beneficially take the likely volumes of materials in future with little or no risk, it will be necessary to quantify the available landbank (taking into account the twenty controls and barriers defined in the project) at a relatively small scale across Scotland, since bulky materials tend not to travel far because of the high cost of haulage. The main current exception is that food-based digestates are often transported for long distances across Scotland from West to East in order to find appropriate markets. The resulting high haulage costs of this unsustainable transport are only feasible for these AD Plants due to government subsidies which help sustain them (J. Grant, pers. comm.). Particular attention is likely to

be paid to digestate transport distances in future, as most businesses seek to attain net zero.

- Transport distances of no further than an approximate radius of 30 to 50 km from the site of production are common, due to the high and increasing cost of haulage.
- To provide a more accurate assessment of the "true" land base available for spreading, a set of model parameters that define the types of acceptable landbank will be required. This will allow for the exclusion of land based on all twenty defined barriers and controls (including legislative controls). Datasets detailing current soil test data for key nutrients (P and K status) would be required to fully define the spreadable land base. There may also be a few cases where concentrations of particular PTEs (e.g. Cu in areas where large historic applications of pig slurry or distillery waste have taken place, or Ni in areas where soil parent material is derived from some types of basaltic rocks) are sufficiently high to preclude spreading of some types of organic material. Such instances are likely to be rare but could be of some significance locally.

### 10.9.9 Policy recommendations to generate accurate and useful landbank information

- All future formal processes that detail the generation of, and eventual land spreading of, organic fertilisers should be required to have a spatial (GIS) component. This would include all waste management licence exemptions and applications for planning permission (including for AD plants, composting facilities, sewage treatment works and intensive animal production facilities).
- GIS has now developed to the point that its use is often the most cost-effective means of creating information that is already required for such applications (for example Risk Assessment for Manures and Slurries [or RAMS] maps). Costs associated with the creation of GIS data are now wholly predictable and can therefore be included within those associated with the sustainable end use for organic materials. Deliberate changes and incentives within the waste market which have been supported by or implemented by Scottish Government, SEPA and Zero Waste Scotland have resulted in land spreading becoming a cost-effective and reliable outlet for organic material. It is now time for some of the profits made by those producing organic products and wastes to be invested in providing meaningful and accurate data to ensure they are being used sustainably, with benefit and in such a way that harm to the environment and human health is minimised.

### 10.9.10 Potential markets for digestate and the barriers to increased use in these markets

The potential markets for digestate are:

- Livestock agriculture
- Mixed (livestock and arable agriculture)
- Arable agriculture

- Field-scale horticulture (which usually also includes arable cropping)
- Protected horticulture (crops grown in glasshouses and polytunnels)
- Ornamental field scale horticulture
- Ornamental horticulture (container nurseries)
- Young plant production (ornamental and edible crops)
- Forestry
- Land restoration

These markets are discussed in more detail in the following sections. In each case, key (named) stakeholders were consulted in order to form conclusions as to the opportunities, challenges and barriers to increased use of digestate.

*Livestock agriculture* - Many livestock farmers are happy to take digestate (whether they run their own AD Plant or take digestate from a local source) providing the price is acceptable to them and providing their assurance scheme and produce buyer are happy with them using the type of digestate concerned. Livestock agriculture is a major Scottish market for digestate.

*Mixed (livestock and arable agriculture) and stockless arable* farms - As above, but crop growers assured through SQC tend to be more nervous about using digestates than those producing only livestock on grass. Certain types of digestates are banned under the SQC rules and some produce buyers (especially the maltsters) will not buy crops from fields that have ever been treated with some types of digestates. It is possible that this situation will change to allow more types of digestates to be applied in future.

*Field-scale horticulture (which usually also includes arable cropping)* – High value crop growers tend to be wary of using some types of digestate and currently most do not use digestate at all. This market may open up in future as pressure to work towards net zero increases. However, it is likely that food assurance schemes and produce buyers are likely to favour digestates based mainly on farm-produced energy crops and certain types of drinks processing wastes (e.g. draff and pot ale) only.

*Protected horticulture (crops grown in glasshouses and polytunnels)* – Digestates are not currently applied in this sector and this market is not likely to develop in future. The relatively small percentage that fertiliser represents in terms of the high costs associated with production means that producers are rarely prepared to take the risk and make the effort of using digestates.

*Ornamental field scale horticulture*- Very little fertiliser is required in this sector, which is very small in Scotland anyway. This sector is not likely to represent a significant market for digestate in future.

*Ornamental horticulture (container plant production) and young plant production (edible crops)*

Whilst the use of digestate as a component of growing media for container production in both the amateur and professional sectors has been discussed and reported, digestate could only be used in a small way in this manner due to its chemical and physical properties. This sector is not likely to represent a significant market for digestate in future.

*Forestry* – Whilst digestate could potentially be used with benefit in forestry, it is unlikely ever to be used in forestry in a big way, because the forestry sector would be unprepared to pay for the true cost of digestate (including the price for the product, the haulage and spreading). Precision spreading would also not be possible in forestry settings unless purpose-designed machinery was built.

*Land restoration* – Digestate is already used to a small extent in land restoration, but the economics of land restoration are such that those engaged in it will never pay for it. Land restoration companies typically only accept waste digestate (along with a gate fee) which has no alternative market. This sector will never represent a significant market for digestate in future.

#### 10.9.11 Options for additional processing of digestate (valorisation) e.g. to increase value or reduce the need for landbank)

Given the relatively low value of digestates and the high cost of haulage, storage and spreading it is not surprising that some of the food-waste AD plants regard digestate as a burden rather than a saleable asset. The cost of hauling, storing and spreading digestate can easily be higher than the value of the fertiliser nutrients within it. For that reason, several companies worldwide are working to develop methods to separate the valuable part of digestates (the nutrients) from the water. Technologies exist to dry digestate and/or strip the nutrients out to produce pelleted or granular fertilisers. However, these technologies are energy intensive, exist at relatively small scales at present and not yet commercially available. For that reason, AD plants are likely to continue to produce either whole digestate or separated liquid/fibre digestate for the next 5 years at least.

#### 10.9.12 The carbon footprint of digestates

The growth of the AD sector has been a positive step toward finding a beneficial, sustainable and safe way of recycling food and other organic wastes into valuable resources. Techniques to determine the carbon footprint of the AD sector, including digestate use are, as yet, relatively undeveloped. It is likely that digestion of food wastes is better for the environment than the material going to landfill, given that the methane produced is captured and used rather than released into the air above landfill sites. It may be the case that digestate production and/or use could reduce a farm's carbon footprint. However, every farm and every AD plant will be different and there is a lack of reliable data and tools to help farmers and AD plant managers make the necessary calculations accurately. According to several professional "land-finders", some AD plants are currently having to transport their digestates for many miles across Scotland by tanker in order to find farmers willing to spread them (J Grant, personal communication). There are two key areas to consider in relation to the carbon footprint of using digestates on land:

1. The main reason for applying whole and liquid digestates is for the fertiliser nutrients that they contain. Whole and liquid digestates contain very little organic matter, and much of that which is present is quickly broken down, with the carbon being released as carbon dioxide ($CO_2$) gas. Only fibre digestate applications are likely to contribute meaningful amounts of organic matter to soils. Only those digestates which are applied responsibly, to address crop nutrient requirement at times of crop demand will result in the maximum possible financial value and carbon footprint.
2. The carbon footprint associated with the transport and spreading of the digestate cannot be ignored. Whole digestates are bulky, their transport and spreading is energy intensive, and this must be considered as part of a carbon footprinting process.

The role of AD and digestates in helping address climate change requires further quantification.

## 10.10 Key considerations for digestate use

Below is an expanded list of the key factors a farmer should explore prior to considering the use and value of digestate.

- *Haulage cost* – The farmer must pay for the digestate to be delivered to the farm either at a time when it can justifiably be applied to crops, or to a covered or uncovered store suitably located (see below). The cost of haulage is typically higher than for synthetic fertilisers due to the low dry matter, high labour demand and high fuel costs for distribution. It is rarely economic to transport farm-produced whole or liquid digestate more than a few miles to market.
- *Availability at times to maximise the value* - digestates are rarely delivered to farm in tankers ready to spread at exactly the right time of year to match crop demand, in good weather and soil conditions, particularly when the farm does not own the AD plant and is reliant on outside contractors to spread the digestate. Contractors typically have a great deal of spreading to do when weather, soil and crop conditions are right and inevitably, some digestate ends up being spread at inappropriate times and in inappropriate conditions. Some farmers have had such a poor service with contractors that they simply do not want to risk signing up to take digestate in future. Others invest in storage and take steps to improve access to precision spreaders (see below).
- *Storage cost* – Most AD plants have some storage, but rarely for more than 6 months of their annual production. Farmers may choose to invest in storage on their own farm if making digestate or regularly taking digestate from a local plant, but this increases the cost of using digestate rather than synthetic fertiliser, which can be easily stored under cover in relatively small spaces. Because NUE from digestates (and therefore the financial value of digestates) is maximised when they are spread between February to around the middle or end of Summer (the exact date will differ depending on farm location) , digestates should be stored for the remainder of the year and NOT spread to land. AD plants (and potentially satellite farms) situated in mixed and livestock areas should have access to at least 6 months storage, whereas those in arable areas should ideally have access to at least 9 months storage. Specialist UK agronomists and advisors agree that the need for storage to improve NUE in digestates is still poorly understood in both the farming community and amongst AD plant developers. Storage is expensive, but it is the only way to minimise N losses to the environment, maximise NUE and therefore the financial value of digestates.
- *Spreading cost and availability of precision spreader* – digestates are more costly to spread than synthetic fertiliser because modern precision spreaders are more expensive and they typically use more diesel and travel more slowly than synthetic fertiliser spreaders. Precision spreaders result in fewer N losses to the environment and must now be used by law to spread digestates in Scotland, but there is still a shortage of these in some areas, which can put some farmers off taking digestate. This situation is likely to improve.
- *Fixed contracts/co-operative* – Some farmers sign up to supply feedstocks (usually energy crops) to a local AD plant and receive an agreed amount or proportion of the output back in return. Digestates produced under such agreements are usually cheaper than those offered on the open market and can therefore be more attractive to farmers.

- *Feedstock type and waste status.* Farmers are advised to check with their assurance scheme(s) and produce buyers before using digestates. Some assurance schemes and buyers prohibit digestates made partly or wholly from food wastes and/or or animal by-products, and several prohibit waste digestates (i.e. those not accredited to either the PAS 110 standard or to the Scottish Quality Crops digestate standard). The reduced markets for some types of digestate can result in lower prices for digestates sold.

# 11 Appendix – methodology and raw data

## 11.1 Overall approach

As a first step, internal project stakeholders were consulted to identify particularly relevant literature resources and existing knowledge (see team list below).

Search terms (Table 11.1) were then used to identify other literature resources.

This allowed gaps in knowledge to be identified, and a list of stakeholders was drawn up to consult to provide evidence for these gaps.

Additional methodology is given below.

The project was then written up.

The project team was as follows:

**Lucy Hopwood**, NNFCC, Director and Lead Consultant for Bioenergy & Anaerobic Digestion. Lucy is widely regarded as an expert on AD, having worked in AD for NNFCC for over 18 years and having delivered countless projects on AD technology, feedstocks, policy and markets to private and public clients. Lucy and NNFCC are both shortlisted for awards at the 2023 Anaerobic Digestion and Bioresources Association's (ADBA) AD & Biogas Industry Awards 2023[39].

**Lucy Montgomery**, NNFCC, Senior Consultant. Lucy manages NNFCC's AD Carbon Calculator[40], adapting it for different AD plant designs and different carbon accounting rules across the sector. In her 6 years at NNFCC, she has carried out several projects de-risking the AD and biomethane sector for new investors, as well as carrying out financial due diligence on new AD projects and sustainability reporting for 7 operational AD plants. Before joining NNFCC, Lucy spent 6 years as a researcher in AD.

**Thea Allary**, NNFCC, Senior Research Analyst. Thea manages NNFCC's UK AD database and maps[41], and a related AD resource library[42]. Thea has also worked on several large AD projects where she analysed current policy across Europe.

**Gillian Finnerty**, NNFCC, Consultant. Gillian has worked on several major AD projects since joining NNFCC 2 years ago, including interviewing over 50 AD plants to determine capital and operational costs, on behalf of BEIS, and a report for EIC on central injection hub biomethane models[43].

**Audrey Litterick**, Earthcare Technical, Director. Audrey is a practical crop and soil scientist who specialises in soil assessment, soil management and the use of fertilisers and organic materials (including digestates and composts) on land. She works with waste processors including compost and AD facilities to develop and optimise quality products and by-products. She also works with farmers and other land managers to ensure the safe, effective use of composts, digestates, animal manures and a range of organic wastes on farmland and in the restoration of land degraded through opencast mining.

---

[39] https://adbioresources.org/events/awards/shortlist-2023/
[40] https://www.nnfcc.co.uk/publications/tool-biomethane-carbon-calculator
[41] https://www.biogas-info.co.uk/resources/biogas-map/
[42] https://www.realresearchlibrary.org.uk/
[43] https://www.energynetworks.org/assets/images/Resource%20library/GGG%20Biomethane%20Injection%20Study%20-%20Phase%203.pdf

Table 11.1 Search terms used for this report.

| Anaerobic digestion | Digestate | $CO_2$ use |
|---|---|---|
| Manure/slurry arising | Digestate treatment | CO2 demand (consumption) |
| Manure/slurry availability | Digestate processing | CO2 Market Demand (Consumption) |
| Regional manure | Digestate valorisation | CO2 externalities |
| Manure utilisation (use) | Nutrient management (Scotland) | CO2 market externalities |
| On-farm AD (anaerobic digestion) / biogas | Digestate added value | Biogenic CO2 Demand (Consumption) |
| Livestock farm AD (anaerobic digestion) | Digestate challenges use | Biogenic CO2 e-fuel |
| Farm waste AD (anaerobic digestion) | Digestate barriers use | CO2 market |
| Crop residues AD (anaerobic digestion) | Digestate application | CO2 price |
| Vegetable waste AD (anaerobic digestion) | Digestate rules | CO2 utilisation |
| Barriers farm AD (anaerobic digestion) | Digestate ammonia | CCS |
| Natural gas use Scotland | Digestate ammonium | CCU |
| Biomethane for transport | Anaerobic Digestate Demand (consumption) | |
| Renewable Energy Directive biomethane emissions | Biomethane Demand (Consumption) | |
| Cost of AD (anaerobic digestion) | Anaerobic Digestate (Consumption) | |
| RTFO | Digestate ammonia demand (consumption) | |
| Biomethane externalities | Ammonia demand (consumption) | |
| | Anaerobic Digestate externalities | |
| | Ammonia externalities | |

## 11.2 Stakeholder engagement

Stakeholder engagement was used to address gaps in knowledge after internal stakeholder consultation and literature search. A semi-structured approach was used with some set questions for different types of stakeholder.

**For stakeholders developing small-scale or manure-only AD solutions**

We understand that there is a particular challenge around farm-scale AD plants because they are too small to allow conventional biomethane upgrading, and because there is currently little incentive to build CHP-only AD plants. Furthermore, in the past, farm-based AD has had some reputational damage because some smaller operators have been left stranded with AD plants that they are unable to repair or run efficiently. Would you agree with this assessment? Have we failed to mention any other major issues facing agricultural AD plants?

Please tell us about your technology.

How does this address the financial or technical challenges faced by agricultural AD?

**For stakeholders handling a lot of slurry or feedstocks**

What volumes of feedstock are you dealing with?

What are the characteristics of the feedstock you are dealing with? If needed, prompt on dry matter content, energy content, etc.

How do you currently use or dispose of these materials?

Why are you interested in AD (or, if not, why are you not interested in AD)?

What could be the unintended consequences of using manures and slurries (or other feedstocks, if relevant) for AD?

**For stakeholders already operating farm-based or merchant AD plants**

What volumes of digestate (fractions) do you produce?

Do you have any trouble sourcing landbank for your products?

Are your products classed as waste or non-waste?

Do they go to agriculture or other land uses?

Would you consider expanding your portfolio of sites and if so why/why not?

**For stakeholders responsible for attempting to remove OR implement, maintain and police barriers to the land application of digestate**

Are you happy that the current regulatory regime combined with good practice guidance and assurance scheme/buy rules (if relevant) effectively controls the risk and maximises the benefits of recycling digestates to land?

If not, why not?

**For stakeholders who understand the practicalities of applying bulky organic fertilisers (including digestates) to land**

Are you happy that the current regulatory regime combined with good practice guidance and assurance scheme/buy rules (if relevant) effectively controls the risk and maximises the benefits of recycling digestates to land?

If not, why not?

Do you feel that farmers and other land managers fully understand how to get the most from digestates and how to minimise the risks?

Are you seeing or hearing of any problems in relation to environmental damage when digestates are being recycled to land.

Do you think there is potential to improve the financial value of digestate products through any (named) valorisation technique?

**For stakeholders who have developed or are developing digestate valorisation technologies**

Please tell us about your technology.

How “near to market” is this technology?

Will it be cost effective for all AD plants and if not, what size of plants would it be suitable for?

How does this address the financial or technical challenges faced by agricultural AD?

**The project team would like to thank the following people for giving their time:**

Gary Hague (Dairy Energy / Biolectric), Eoin Sharkey (Biofactory), Marc Mc Elhinney (Green Forty Development), Lucy Lewis (Marches Biogas), Tom Gill (Arla), Andy Bidston (Thyson), Mark Clayton and James Rundell (Qube Renewables), Chris Mann (Bennamann), Rahul Rajani (Powerblocks), Debbie Neely (Entrust Environmental), Tommy Dale (Forth Resource Management), Ross Forster (Peacehill Farming), Hamish Mellor/David Stirling (Keithick Farms and Biogas), William Rose (Mid Coul Farms and Renewables), David Finlay (Rainton Farm & Cream O' Galloway dairy), Fiona Donaldson (SEPA Waste Team), Claudia Erber (SEPA soils team), Teresa Dougall (SQC), Fiona Burnett (SQC/SRUC), NFUS (David Michie, Policy Manager), Alex Sinclair (SAC Consulting), John Williams (ADAS), David Tompkins (AquaEnviro), Matt Taylor (Grieve Strategic), Rachel Ramsay (SAC Consulting/Agrecalc), Caroline Rouffignac (Scotch Whisky Association), Hamish Walls (Scottish Agricultural Organisation Society)

## 11.3 Manure availability and gas yields: data and calculations

Manure availability data were taken from three references (Ricardo 2016, Ford *et al.* 2017, Freeman *et al.* 2020), all generated by the same consultancy. It is unclear from the reports how they came to these numbers, but a conventional approach is to calculate manure arisings from livestock numbers and manure estimates per head, and making assumptions about time livestock spend in housing (where manures can be collected).

To validate these numbers, livestock numbers were taken from UK national statistics (2022)[44] which uses agricultural census data. Manure tonnages and biogas yields were taken from an AD handbook[45].

[44] https://www.gov.uk/government/statistics/livestock-populations-in-the-united-kingdom
[45] KTBL (2013) Faustzahlen Biogas [Biogas rules of thumb], 3rd edition. ISBN 978-3-941583-85-6

Table 11.2: Data on cattle numbers and calculations for manure (slurry) arising.

| | No. of livestock | Manure generation (tpa/head/ year) | DM% | VS% | Manure (tpa) | Manure availability, if housed half the year (tpa) |
|---|---|---|---|---|---|---|
| Beef cows | 481,563 | 5.8 | 10% | 82% | 2,793,065 | 1,396,533 |
| Dairy cows | 200,975 | 17.2 | 10% | 75% | 3,456,770 | 1,728,385 |
| Beef cows 1-2 years | 190,996 | 4.35 | 10% | 82% | 830,833 | 415,416 |
| Beef cows under 1 year | 61,587 | 12.9 | 10% | 82% | 794,472 | 397,236 |
| Dairy cows 1-2 years | 223,451 | 2.9 | 10% | 75% | 648,008 | 324,004 |
| Dairy cows under 1 year | 64,325 | 8.6 | 10% | 75% | 553,195 | 276,598 |
| Male cattle | 51,651 | 5.8 | 10% | 82% | 299,576 | 149,788 |
| Male cattle 1-2 years | 185,177 | 4.35 | 10% | 82% | 805,520 | 402,760 |
| Male cattle under 1 year | 246,070 | 2.9 | 10% | 82% | 713,603 | 356,802 |
| SUM | **1,705,795** | | | | **10,895,042** | **5,447,521** |

Table 11.3: Data on pig numbers and calculations for manure arising.

| | No. of livestock | Manure generation (tpa/head/ year) | DM% | VS% | Manure (tpa) |
|---|---|---|---|---|---|
| Breeding pigs | 36,378 | 6.6 | 5% | 72% | 240,095 |
| Fattening pigs (incl. barren sows) | 302,603 | 1.6 | 7.5% | 71% | 484,165 |
| SUM | **338,981** | | | | **724,260** |

Table 11.4: Data on poultry numbers and calculations for manure arising.

| | No. of livestock | Manure generation (tpa/head/ year) | DM% | VS% | Manure (tpa) |
|---|---|---|---|---|---|
| Total poultry | 14,958,985 | 1.9 | 50.0% | 68% | 28,422,072 |

In Figure 3, data on animals/km² was converted to tpa/km². This was done by assuming each cow generated as much slurry as a dairy cow[46], which is 17.2 tpa slurry (Table 11.5).

Table 11.5: converting cow numbers to slurry generation.

| Cows | Slurry generated (tpa) |
|---|---|
| 0 | 0 |
| 10 | 172 |
| 50 | 860 |
| 150 | 2,580 |

NNFCC maintains a database of AD plants in the UK. The dataset comprises information about AD plants under the following statuses:

- Operational
- Under construction
- Abandoned
- Application submitted (for new builds)
- Application approved (for new builds)
- Application refused (for new builds)
- Application withdrawn (for new builds)

For each plant, qualitative and quantitative data is collected, such as:

- Developer
- Location
- Output
- Maximum energy capacities
- Feedstock tonnages
- Feedstock types

The database is updated on a monthly basis and an Annual AD Deployment report has been published in April of every year for the past nine years.

For the purpose of this analysis, plants with the following criteria where considered:

- Scottish plants [Region]

[46] KTBL (2013) Faustzahlen Biogas [Biogas rules of thumb], 3rd edition. ISBN 978-3-941583-85-6

- Operational or Under Construction [Status]
- Include Manure/Slurry [Feedstock type] (for Task 1 only)

The search returned 47 plants (biomethane to grid, as well as CHP & BtG plants), all using a total of 257,530 tonnes per annum of manure/slurry usage.

In order to determine the spatial variation of manure arisings, manure arising by local authority was taken from the BRMT. To determine current demand for manure, AD sites from the NNFCC AD database (2022) were categorised by local authority and the tonnage manure use was estimated by assuming all feedstock used was manure. This was subtracted from the values for manure arising for each local authority (Table 11.6).

Table 11.6: Manure arising and density by local authority (BRMT 2016).

| Local authority | Manure arising (tpa) | Area of LA ($km^2$) | Density ($tpa/km^2$) | AD manure demand (tpa) |
|---|---|---|---|---|
| Orkney Islands | 545,276 | 990 | 551 | 0 |
| East Ayrshire | 635,033 | 1,261 | 504 | 0 |
| East Renfrewshire | 86,884 | 174.3 | 498 | 0 |
| South Ayrshire | 565,755 | 1,222 | 463 | 8,000 |
| Aberdeenshire | 2,835,970 | 6,313 | 449 | 36,450 |
| South Lanarkshire | 755,025 | 1,772 | 426 | 0 |
| Falkirk | 121,875 | 297.4 | 410 | 0 |
| Renfrewshire | 102,558 | 261.6 | 392 | 0 |
| West Lothian | 161,735 | 427.6 | 378 | 0 |
| East Dunbartonshire | 66,019 | 174.6 | 378 | 0 |
| Aberdeen City | 65,215 | 185.7 | 351 | 0 |
| North Ayrshire | 308,396 | 885.5 | 348 | 670 |
| Dumfries & Galloway | 2,172,932 | 6,426 | 338 | 121,600 |
| North Lanarkshire | 158,152 | 469.8 | 337 | 0 |
| Fife | 407,466 | 1,325 | 308 | 6,900 |
| Scottish Borders | 1,436,298 | 4,732 | 304 | 31,260 |
| Moray | 646,773 | 2,238 | 289 | 15,000 |
| W Dunbartonshire | 45,315 | 158.8 | 285 | 0 |
| Inverclyde | 43,184 | 160.6 | 269 | 0 |
| East Lothian | 178,824 | 679.2 | 263 | 0 |
| Clackmannanshire | 38,640 | 159 | 243 | 2,000 |
| Stirling | 403,677 | 2,187 | 185 | 13,500 |
| Angus | 366,435 | 2,181 | 168 | 12,500 |
| Perth and Kinross | 511,430 | 5,286 | 97 | 6,000 |
| Shetland Islands | 116,545 | 1,466 | 79 | 0 |
| Argyll and Bute | 505,354 | 6,910 | 73 | 0 |
| Midlothian | 99,576 | 1,466 | 68 | 0 |
| Highland | 1,012,589 | 25,657 | 39 | 3,650 |
| Edinburgh, City of | 6,610 | 264 | 25 | 0 |
| Eilean Siar | 8,148 | 3,071 | 3 | 0 |
| Glasgow City | 5 | 175 | 0 | 0 |
| Dundee City | 0 | 60 | 0 | 0 |

Table 1.6 continued: Manure arising and density by local authority (BRMT 2016).

| Local authority | AD manure demand (%) | Remaining manure (tpa) | Remaining manure (tpa/km$^2$) | Region |
|---|---|---|---|---|
| Orkney Islands | 0% | 545,276 | 551 | NW |
| East Ayrshire | 0% | 635,033 | 504 | SW |
| East Renfrewshire | 0% | 86,884 | 498 | SW |
| South Ayrshire | 1.41% | 557,755 | 456 | SW |
| Aberdeenshire | 1.29% | 2,799,520 | 443 | NE |
| South Lanarkshire | 0% | 755,025 | 426 | SW |
| Falkirk | 0% | 121,875 | 410 | SW |
| Renfrewshire | 0% | 102,558 | 392 | SW |
| West Lothian | 0% | 161,735 | 378 | SE |
| East Dunbartonshire | 0% | 66,019 | 378 | SW |
| Aberdeen City | 0% | 65,215 | 351 | NE |
| North Ayrshire | 0.22% | 307,726 | 348 | SW |
| Dumfries & Galloway | 5.60% | 2,051,332 | 319 | SW |
| North Lanarkshire | 0% | 158,152 | 337 | SW |
| Fife | 1.69% | 400,566 | 302 | SE |
| Scottish Borders | 2.18% | 1,405,038 | 297 | SE |
| Moray | 2.32% | 631,773 | 282 | NE |
| W Dunbartonshire | 0% | 45,315 | 285 | SW |
| Inverclyde | 0% | 43,184 | 269 | SW |
| East Lothian | 0% | 178,824 | 263 | SE |
| Clackmannanshire | 5.18% | 36,640 | 230 | SW |
| Stirling | 3.34% | 390,177 | 178 | SW |
| Angus | 3.41% | 353,935 | 162 | SE |
| Perth and Kinross | 1.17% | 505,430 | 96 | SE |
| Shetland Islands | 0% | 116,545 | 79 | NW |
| Argyll and Bute | 0% | 505,354 | 73 | SW |
| Midlothian | 0% | 99,576 | 68 | SE |
| Highland | 0.36% | 1,008,939 | 39 | NW |
| Edinburgh, City of | 0% | 6,610 | 25 | SE |
| Eilean Siar | 0% | 8,148 | 3 | NW |
| Glasgow City | 0% | 5 | 0 | SW |
| Dundee City | 0% | 0 | 0 | SE |

## 11.4 Biogas yield of manures

The biomethane potential, BMP (also called specific methane yield, SMY), is a measure of how much biomethane it is possible to get from a given feedstock for anaerobic digestion. It can be measured with a laboratory batch anaerobic digestion test or estimated using several other common laboratory techniques (Weinrich *et al.* 2018).

A very large number of studies exist on the BMP of various feedstocks for anaerobic digestion, but often results are very variable from laboratory to laboratory and cannot be compared across different studies. Few published resources exist with a large number of feedstocks analysed using the same methodology and large sample sizes. However, some German biogas initiatives have attempted this, summarised in a biogas handbook[47].

Indicative biomethane potentials of manures and some other popular feedstocks are listed in Table 11.7. It is worth noting that these are subject to considerable variation; the dry matter content (i.e. the inverse of the moisture content) is one of the main factors influencing biogas yield from manures, with higher dry matter contents leading to higher biogas yields, but animal diet, animal age and manure storage conditions can also have a large impact, as well as the presence of bedding or feed.

Table 11.7: Physical characteristics and biomethane potential of some key manures. For reference, feedstocks like maize silage or depackaged supermarket food waste have much higher gas yields.

| | Dry matter content (%) | Volatile solids (%) | Biomethane potential ($Nm^3/t_{VS}$) | Methane yield ($Nm^3/t$) |
|---|---|---|---|---|
| Beef cattle manure | 25% | 82% | 250 | 51 |
| Beef cattle slurry | 10% | 80% | 210 | 17 |
| Dairy cow manure | 25% | 75% | 250 | 47 |
| Dairy cow slurry | 10% | 75% | 210 | 16 |
| Pig manure | 22% | 83% | 240 | 45 |
| Pig slurry | 6% | 80% | 250 | 12 |
| Sheep manure | 30% | 80% | 250 | 60 |
| Poultry manure | 40% | 75% | 280 | 84 |
| LA food waste | 16% | 87% | 370 | 52 |
| Grass silage | 35% | 90% | 320 | 101 |
| Maize silage | 35% | 95% | 340 | 113 |

To calculate the biogas yield based on herd size, the number of cows was multiplied by the amount of slurry from a dairy cow, 17.2 tpa, and multiplied by the methane yield, 16 $Nm^3/t$, and divided by the methane content of biogas, 55%.

To calculate the equivalent electrical capacity based on biogas yield, biogas is again converted to biomethane by multiplying by 55% (a conservative estimate of methane content of biogas, typically used by Ofgem), giving $Nm^3$ of biomethane. To convert $Nm^3$ of biomethane to kWh of biomethane, a conversion factor of 10.5 $kWh/Nm^3_{biomethane}$ (a conservative estimate of the energetic content of biomethane, typically used by Ofgem)

[47] KTBL (2013) Faustzahlen Biogas [Biogas rules of thumb], 3rd edition. ISBN 978-3-941583-85-6

is used. To convert from kWh of biomethane to kWh of electricity, a conversion efficiency of 35% is assumed (a conservative estimate of the electrical efficiency of a gas CHP[48]). To get from kWh electricity per year to kW capacity, it is then assumed a typical AD plant operates 8,000 hours a year, allowing for some maintenance downtime.

To calculate the biomethane capacity based on biogas yield, biogas is again converted to biomethane by multiplying by 55%, giving $Nm^3$ of biomethane. $Nm^3$ are converted to scm using 1.05 scm/ $Nm^3$. Finally, it is assumed that biogas upgrading to biomethane results in 5% losses[49] and that the AD plant operates for 8,000 hours a year.

Table 11.8: AD capacity based on dairy cow herd size.

| | Annual biogas yield ($Nm^3$) | Equivalent electrical capacity (kW) | Equivalent biomethane capacity (scm/h) |
|---|---|---|---|
| 150 cows | 75,000 | 18.9 | 5.1 |
| 1,000 cows | 500,000 | 126.3 | 34.3 |

48 https://energy.ec.europa.eu/publications/review-reference-values-high-efficiency-cogeneration_en

49 Several technologies for biogas upgrading are available, with losses ranging from less than 0.1% to losses of up to 10%, although the latter is rare, with most processes only losing 1-4%. 5% is a conservative estimate. See table 5 in Petersson & Wellinger (2009), available at https://www.ieabioenergy.com/wp-content/uploads/2009/10/upgrading_rz_low_final.pdf

## 11.5 Carbon dioxide calculations

The methane concentration of biogas varies between 50% and 70%, depending on feedstock used[50], and throughout this report has been assumed to be 55%[51]. This means that for every Nm³ of biomethane injected into the grid, roughly 0.82 Nm³ of $CO_2$ is generated.

To calculate $CO_2$ generation capacity from Scottish biomethane injection (estimated at around 0.8 TWh in 2021), TWh were converted into kWh using a conversion factor of 1,000,000 kWh/TWh and then into Nm³ using a factor of 10.5 kWh/Nm³. The volume of biomethane was multiplied by 0.82 (45% / 55%) to give an approximate volume of $CO_2$.

Volume of $CO_2$ was converted to moles using the gas molar volume 0.022414 Nm³ /mol. Moles of $CO_2$ were converted to mass using the molecular weight of 44.01 g/mol. Grams were converted to tonnes using the conversion factor of 1,000,000 g/t.

## 11.6 Scale of AD

Table 11.914 has been included to conveniently allow the reader to compare different scales of AD given in their different industry units.

Biomethane capacity is typically given as grid injection capacity in scm/h. A 5% loss of biomethane upon biogas upgrading was assumed[52], allowing the amount of methane going to the biogas upgrading unit (BUU) to be calculated. It was assumed that 15%[53] of biogas is needed to power a CHP or boiler providing process heat, so methane going to BUU was divided by 85%[54] to obtain methane generation needed. Biogas generation needed was obtained by assuming biogas is 55% methane. Equivalent CHP capacity was taken from the injection capacity assuming 37%[55] electrical efficiency of CHP.

Sizing of AD plant as micro, small, medium, large and very large reflect technical limits and subsidy limits.

---

[50] This range is the result of the biochemical reaction converting feedstock to biogas, as modelled in the Buswell equation. A useful overview of the Buswell equation is available from Professor Charles Banks' teching resources as part of the Valorgas EU project, available at https://www.valorgas.soton.ac.uk/Pub_docs/JyU%20SS%202011/CB%204.pdf

[51] 51 55% is the convention in Ofgem's UK Solid and Gaseous Biomass Carbon Calculator, available at https://www.ofgem.gov.uk/sites/default/files/docs/2016/08/renewables_obligation_-_uk_user_guide_for_the_solid_and_gaseous_biomass_carbon_calculator.pdf

[52] Several technologies for biogas upgrading are available, with losses ranging from less than 0.1% to losses of up to 10%, although the latter is rare, with most processes only losing 1-4%. 5% is a conservative estimate. See table 5 in Petersson & Wellinger (2009), available at https://www.ieabioenergy.com/wp-content/uploads/2009/10/upgrading_rz_low_final.pdf

[53] This is highly variable, depending on site size and set-up. 15% is a convention used in-house at NNFCC.

[54] 100%-15% = 85%

[55] This is variable, depending on CHP model and depending on whether the CHP is running at full capacity or below. 37% is an in-house convention at NNFCC.

Table 11.9: Quick comparison of AD at various scales. Note that biomethane injection does not currently take place below 200 scm/h.

| Injection capacity (scm/h) | Methane going to BUU ($Nm^3/h$) | Methane generation needed ($Nm^3/h$) | Biogas generation needed ($Nm^3/h$) | Equivalent CHP (kW) | Size |
|---|---|---|---|---|---|
| 25 | 26 | 31 | 56 | 102 | Micro |
| 50 | 53 | 62 | 113 | 204 | Small |
| 100 | 105 | 124 | 225 | 409 | Small |
| 122 | 128 | 151 | 275 | 499 | Small |
| 200 | 211 | 248 | 450 | 818 | Medium |
| 300 | 316 | 372 | 675 | 1,227 | Medium |
| 400 | 421 | 495 | 901 | 1,636 | Medium |
| 500 | 526 | 619 | 1,126 | 2,045 | Medium |
| 600 | 632 | 743 | 1,351 | 2,454 | Medium |
| 700 | 737 | 867 | 1,576 | 2,863 | Medium |
| 800 | 842 | 991 | 1,801 | 3,272 | Large |
| 900 | 947 | 1,115 | 2,026 | 3,681 | Large |
| 1000 | 1,053 | 1,238 | 2,252 | 4,089 | Large |
| 1100 | 1,158 | 1,362 | 2,477 | 4,498 | Large |
| 1200 | 1,263 | 1,486 | 2,702 | 4,907 | Large |
| 1300 | 1,368 | 1,610 | 2,927 | 5,316 | Very large |
| 1400 | 1,474 | 1,734 | 3,152 | 5,725 | Very large |
| 1500 | 1,579 | 1,858 | 3,377 | 6,134 | Very large |
| 1600 | 1,684 | 1,981 | 3,603 | 6,543 | Very large |
| 1700 | 1,789 | 2,105 | 3,828 | 6,952 | Very large |
| 1800 | 1,895 | 2,229 | 4,053 | 7,361 | Very large |
| 1900 | 2,000 | 2,353 | 4,278 | 7,770 | Very large |
| 2000 | 2,105 | 2,477 | 4,503 | 8,179 | Very large |