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Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions

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Study summary

Current thinking on climate change mitigation generally suggests that, in the mid- to long-term, large-scale methods of removing carbon dioxide (CO_2) from the atmosphere and preventing it from returning there will be required. Such methods are often termed negative emission technologies (NETs) as they reduce the net anthropogenic CO_2 emission.

This summary outlines the findings of a study carried out by Scottish Carbon Capture & Storage (SCCS) into the potential for achieving negative emissions in Scotland in the near- to mid-term.

The purpose of the study is to inform policy makers on the potential scope for negative CO_2 emissions in Scotland and suggest how that might practically be achieved. This is to allow opportunities for policy support and incentives to be considered in the context of Scotland's Climate Change Plan and Energy Strategy, including the Bioenergy Action Plan currently under development. The draft Climate Change Plan, for instance, aspired to the achievement of negative emissions in the Scottish electricity sector of 1.3 million tonnes of CO_2 equivalent (Mt-CO_2e) in 2031.

The study included a review of all identified NETs, reported separately, and then focused on the combination of existing Scottish industries that have biogenic CO_2 emissions, with the technologies of carbon capture and storage (CCS). This is considered a practical and achievable route to securing a meaningful level of negative emissions in Scotland in the timescale.

The study analysis covers bioenergy systems for heat and/or electricity generation, which may be combined with CCS – known as bioenergy with carbon capture and storage, or BECCS. Bioenergy systems were segmented into two groups: biomass combustion for heat or combined heat and power (CHP), and anaerobic digestion (AD) to produce biogas and/or biomethane, including AD in landfills, sewage treatment works, wet-waste processing and crop residue treatment.

The analysis also covers the fermentation industry, which is not used to produce biofuels/bioenergy to any extent in Scotland but was included due to its scale of biogenic CO_2 emission and the potential for lower-cost capture from concentrated CO_2 streams.

For each industry included, the current scale of CO_2 emissions was estimated for the sector, facilities with larger emissions were identified and the way in which CO_2 capture at these sites might be linked to a developing CO_2 transport infrastructure (as part of a more general development of CCS) was considered.

The main findings of the study are summarised below.

- The total emission in Scotland of biogenic CO_2 from the sectors considered is estimated to be in the order of 3.6 million tonnes of CO_2 per year (Mt-CO_2/yr) in recent years, see Table Ex1 below.

- From biomass combustion (for heat only or for CHP) emissions are estimated at 2.44 Mt-CO_2/yr.

- From AD processes of all types (landfill, sewage treatment, wet-waste and crop residue) emissions are estimated at 0.56 Mt-CO_2/yr, mostly from landfill gas operations.

- From fermentation to produce alcohol (beer, grain spirit, malt whisky) emissions are estimated at 0.47 Mt-CO_2/yr.

- Around 60% of the total biogenic emission (2.1 Mt-CO_2/yr) is from 32 facilities at 29 locations, each with biogenic CO_2 emission ranging from over 10,000 t-CO_2/yr to over 400,000 t-CO_2/yr; these facilities are listed in the report Appendices 6.9 to 6.13.

- Available CO_2 capture and liquefaction equipment suitable for these scales has been identified from a number of suppliers; it is available at scales smaller than the 10,000 t-CO_2/yr threshold chosen in this study.

- Of the 32 facilities, most are in Scotland's Central Belt and 23 are within 40 km of the Feeder 10 pipeline, identified as potentially forming a trunk route for a developing CO_2 transport infrastructure in Scotland; see Figure Ex1 below.

- Technical options for CO_2 transport are available for all these identified emitters; by road transport for smaller-scale emitters, by rail for medium to larger-scale emitters, which are not close to other emitters or to Feeder 10, or by a pipeline collection network.

- A CO_2 transport consolidation hub could be located in Grangemouth, or west or northwest of Falkirk. The ideal location would depend on the involvement of other major industries and on the long-term trunk transport method, which could potentially be by onshore or offshore pipeline or by shipping.

In conducting the study, it became apparent that data on biogenic CO_2 emissions in Scotland is not available in a consistent manner. It is not clear whether biogenic CO_2 emissions are reported fully or consistently in the Scottish Pollution Release Inventory maintained by Scottish Environment Protection Agency; in addition, many sites are below the reporting threshold. This required estimates to be made from output or capacity data, with assumptions where necessary.

Table Ex1. Estimate of current biogenic CO_2 emissions in Scotland from bioenergy and fermentation industry

Source	**Emission estimate**	**Comments**
	Mt-CO_2/yr	
Biogas CHP (including landfill and sewage treatment)	0.56	18 sites with emissions >10,000 t-CO_2/yr (12 landfill, 1 sewage, 5 other wet-waste/crop AD)
Biomethane upgrading	0.05	High conc. CO_2 stream, 1 site >10,000 t-CO_2/yr
Biomethane combustion	0.06	Distributed through grid, emissions at user sites
Biomass combustion (power station or CHP)	1.37	Three sites emit two thirds of this (0.88 Mt-CO_2/yr), ~30 smaller sites
Biomass combustion (heat only)	1.07	Three sites emit half of this (0.54 Mt-CO_2/yr), thousands of smaller sites
Fermentation – beer	0.01	Many sites (>82), 1 site >5,000 t-CO_2/yr
Fermentation – grain whisky	0.25	From 7 sites all >10,000 t-CO_2/yr
Fermentation – malt whisky	0.21	From 113 sites, most small, 8 >5,000 t-CO_2/yr
Total	**3.59**	

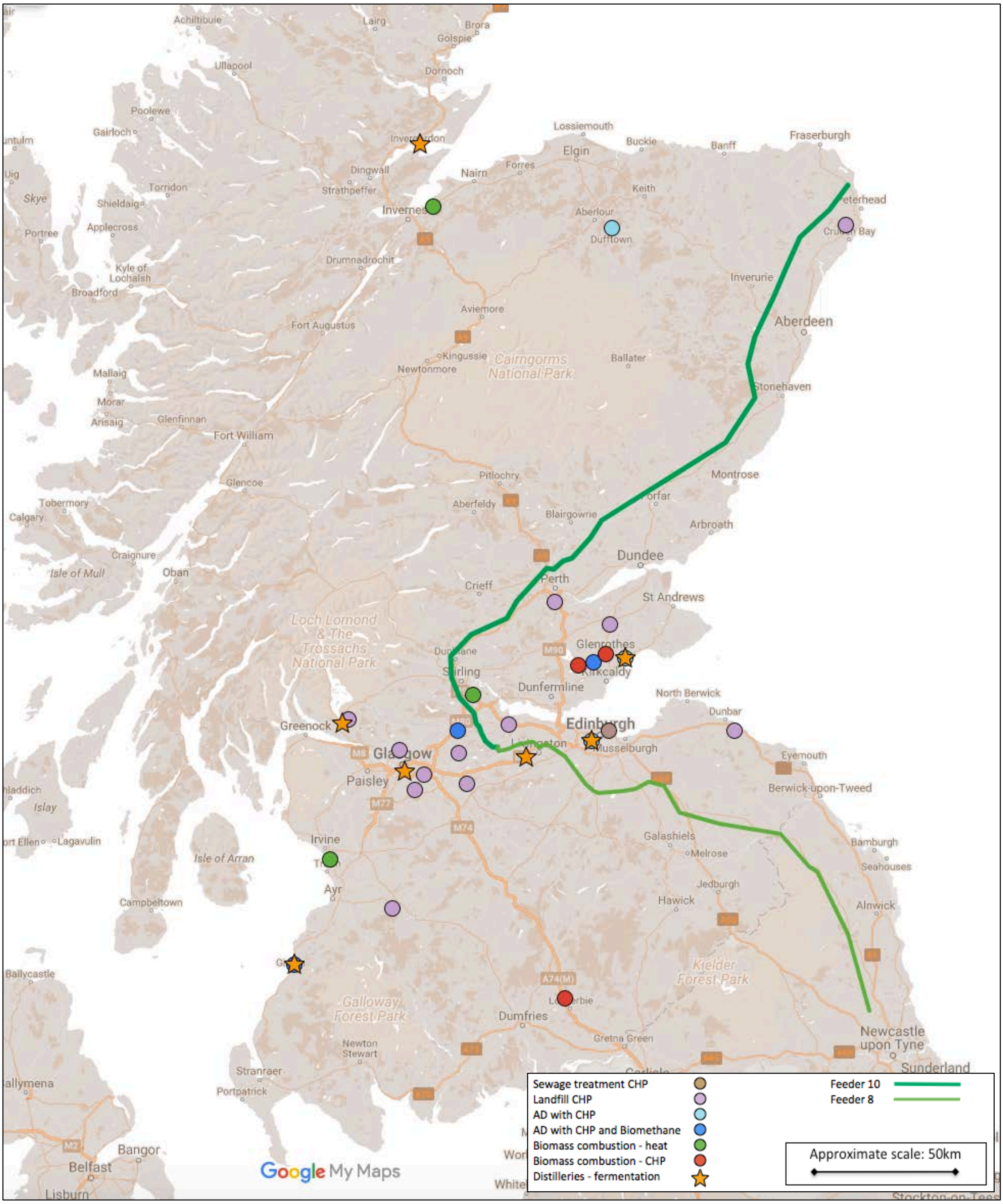


Figure Ex1. Locations of biogenic CO_2 emission sources >10,000 t-CO_2/yr in Scotland

Note: three distilleries also have AD with CHP facilities, symbols superimposed.

Negative Emission Technology in Scotland: Carbon capture and storage for biogenic CO_2 emissions

1 Introduction

1.1 Report focus

In 2017 the Scottish Government issued for consultation drafts of a new Climate Change Plan (Scottish Government, 2017b) and a new Energy Strategy (Scottish Government, 2017c) aimed to deliver revised emission reduction targets, consistent with the Paris Agreement, which will then be included in a revised Climate Change Act. The draft Plan and Strategy included reference to use of negative emission technologies (NETs), specifically forms of bioenergy with carbon capture and storage (BECCS), and proposed definition of a Bioenergy Action Plan. In response, the study reported here explored the potential for BECCS to contribute to achieving Scotland's climate change targets as part of the transition to a successful low-carbon economy.

Using new analysis of publicly available data, this study estimated the level of carbon dioxide (CO_2) emissions from biological sources (biogenic emissions) currently occurring in Scotland from industry and power generation. This allows a view of the degree of negative emissions that may be achieved through BECCS and related technologies in Scotland, from existing industries, and gives a basis for considering the potential to develop further negative emissions. The study considered the integration of BECCS with other potential developments of carbon capture and storage (CCS) on industry and power generation in Scotland. It also refers to a parallel review of the range of other NETs and their suitability to the Scottish context.

The aim of the report is to inform Scottish Government and help define policy emerging through the Bioenergy Action Plan. It suggests practical approaches to delivering negative emissions and sketches out the contribution that NETs may make to achieving Scotland's emission reduction targets. It does not attempt to provide a detailed discussion of the technologies involved or their issues but is more to show where there are opportunities that would be worth pursuing.

1.2 Report structure

The remainder of this introduction explains why NETs are considered critical in achieving global greenhouse gas emission reduction targets and the types of NET that have been identified to date. It introduces CCS briefly and bioenergy in more detail, with a description of the different forms of bioenergy and other biogenic CO_2 sources, and their relevance in the Scottish context.

Section 2 outlines the sources of data used in the study and the methods used to estimate current main contributions to biogenic CO_2 emission in Scotland. The resulting estimates are presented in Section 3 followed, in Section 4, by a discussion of the way these may be integrated into a practical vision of how CCS will develop in Scotland. Section 5 provides a brief concluding summary and some recommendations.

1.3 The need for negative emission technologies

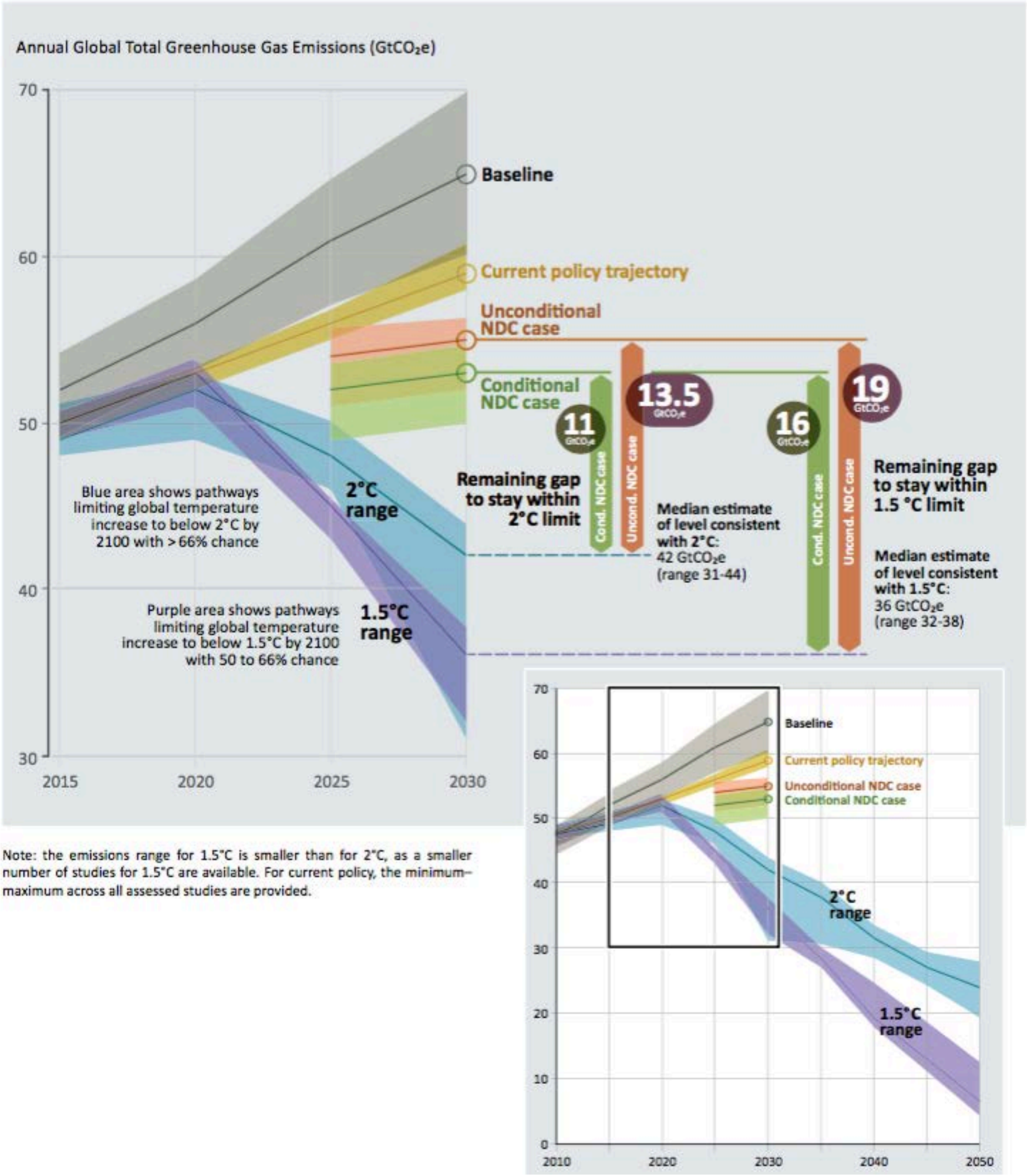
It is broadly accepted in discussions of climate change mitigation that some method of removing CO_2 already present in the atmosphere is likely to be needed in the mid- to long-term to achieve the greenhouse gas reductions necessary to control global warming. Methods of atmospheric carbon dioxide removal are often termed negative emission technologies as they reduce the net anthropogenic CO_2 emission, offsetting a proportion of "positive" emissions. In this sense negative is good and positive is bad.

The latest Emissions Gap Report from the United Nations Environment Programme (UNEP, 2017) suggests that a large gap exists between emissions projected for 2030 on the basis of current Nationally Determined Contributions under the Paris Agreement and the levels required to achieve either the 2°C or 1.5°C global warming goals (Figure 1). The gap is even larger when compared with the current policy trajectory. The report explores options for increasing mitigation efforts across all sectors concluding that, providing action is taken quickly enough, ways of closing the gap at 2030 at reasonable cost are available without CO_2 removal techniques. However, over the rest of the century the report suggests it will become "increasingly critical" to have methods of removing CO_2 from the atmosphere to address the likely overshoot of carbon budgets. Rapid scale-up to a negative emission rate ranging from 5 to 15 gigatonnes (Gt) of CO_2 per year is required to achieve integrated assessment model scenarios that achieve the 1.5°C warming goal in the second half of the century (UNEP, 2017).

1.4 Types of negative emission technology

There are a number of potential technologies for negative emissions including: bioenergy with CCS, direct air capture with CCS, enhanced weathering of minerals, afforestation and reforestation, soil carbon sequestration, biochar addition to soils and manipulation of carbon uptake in oceans (Pete Smith et al., 2015). These each have a different balance of advantages and disadvantages, benefits and challenges and different degrees of definition of their effects. In addition, there are other non-energy related biogenic emissions of CO_2, such as from fermentation for alcoholic beverages, which can be captured and stored to effect negative emissions.

A review of alternative NETs has been carried out by Scottish Carbon Capture & Storage (SCCS) in parallel to the present study (R Viguier, 2018). This suggests that the techniques of reforestation and afforestation, enhanced weathering of minerals in the ocean and peatland and wetland restoration may have relevance in Scotland alongside the techniques covered in the present study of capturing and permanently storing biogenic CO_2 biogenic emissions from bioenergy and other industrial processes.



Note: the emissions range for 1.5°C is smaller than for 2°C, as a smaller number of studies for 1.5°C are available. For current policy, the minimum–maximum across all assessed studies are provided.

Figure 1. Global greenhouse gas emissions under different scenarios and the emissions gap in 2030 (median estimate and 10th to 90th percentile range) (UNEP, 2017).

1.5 Carbon capture and storage

BECCS, Direct Air Capture and other NETs that involve storage of essentially pure CO_2 all rely on a chain of technologies in common with CCS to tackle emissions from industry or power stations. The elements of this chain include:

- Capture – a physical or chemical separation process to separate CO_2 from a mixture of gases (fuel gases, combustion flue gases, chemical or biological process off-gases, or directly from air);

- Transport – between capture and storage sites, usually by pipeline or ship, as established for fuel gases and industrial gases including CO_2;
- Storage – secure and permanent storage of CO_2 underground in carefully selected geological formations, which may be onshore or offshore.

Carbon capture and utilisation is a related technology chain where CO_2 is put to use rather than being stored. While potentially attractive commercially, many utilisation methods do not result in long-term removal of CO_2 from the carbon cycle and so have limited benefit for climate change mitigation (Niall Mac Dowell et al., 2017).

Scotland has been at the forefront of efforts to demonstrate CCS in the UK with a series of project proposals, some taken to advanced stages of design. However, so far none have progressed to construction for a variety of reasons, mostly related to finance and government support (Patrick Dixon and Theo Mitchell, 2016). Scotland is well placed to develop a CCS industry based on its ample CO_2 storage potential in the North Sea, with the required expertise and skills from the existing oil and gas industry and the potential to reuse existing pipeline infrastructure to reduce installation costs (this is discussed in more detail in Section 4). The Scottish Government recognises CCS as a critical element in its finalised new Energy Strategy (Scottish Government, 2017d) and Climate Change Plan (Scottish Government, 2018) required to achieve its mid-term emission targets, and it is also aware of the potential to develop a North Sea CCS industry providing a CO_2 management service to the rest of the UK and other European states.

1.6 Bioenergy

Bioenergy is energy made available from materials derived from biological sources. Bioenergy is inherently renewable, provided that materials can be regrown sustainably. Both plant-based and animal-based biological materials (biomass) can be used as a source for bioenergy. Carbon in biomass is fundamentally derived by photosynthesis of atmospheric CO_2 in plants; this carbon can be passed up the food chain into animal-derived materials. Conversion processes that make bioenergy available for use in society as electricity or heat generally result in release of carbon as CO_2. If returned to the atmosphere this emission is considered “carbon-neutral”; if it is captured and sequestered permanently, such that it does not return to the atmosphere, it can be considered “carbon-negative”.

There are several different forms of bioenergy conversion process and there are other non-energy biological conversion processes that give rise to CO_2 emissions; these different processes have different benefits and issues and different relevance for combination with CCS to effect negative emissions in Scotland. The following sections give a brief description of the main processes.

1.6.1 Biogas, landfill gas and biomethane

Biogas is a mixture of different gases produced by microbial breakdown of biological materials in the absence of oxygen. In such anaerobic conditions biological carbon is converted mostly to methane (CH_4) and CO_2, with other minor components depending on source material and process conditions. Biogas for bioenergy is produced in anaerobic digestion (AD) processes converting wet organic materials, such as sewage, manure, food waste, green waste, agricultural wastes or specially grown green crops. Landfill gas is a form of biogas where the biological conversion occurs under anaerobic conditions in a landfill site and the gas is collected at the surface. Although reported separately in UK national statistics, landfill gas and sewage gas are essentially the same as biogas from other AD processes for the purposes of this study and they are considered together.

“Raw” biogas, as produced, is generally a mixture of 50-70% methane and 25-45% CO_2 (Stephen Allen and Jonathan Wentworth, 2011). Raw biogas can be used directly to power a suitably specified turbine, gas engine or fuel cell to generate electricity, or in a combined heat and power (CHP) system to provide both electricity and heat. Many sites producing biogas integrate its use in a CHP system, using the heat on-site, including for the AD process itself, and exporting excess electricity. Technically, capture of CO_2 from combustion of raw biogas would be similar to capture from combustion of natural gas, with a possible advantage as (depending on air ratio used for combustion) the flue gas may have a higher concentration of CO_2 present due to the proportion in the raw biogas feed.

Biogas can also be upgraded to produce a gas, predominantly methane and termed biomethane, suitable for injection to the natural gas grid. The upgrading process involves removing CO_2 and other undesired impurities and, usually, adding small proportions of other hydrocarbon gases to match the combustion properties of natural gas. The process to remove CO_2 is essentially the same as that used to “sweeten” many “sour” natural gas supplies and can, depending on technique used, provide a concentrated stream of the separated CO_2 for capture. Globally, natural gas sweetening is the major source of CO_2 currently captured for storage, although much more is simply vented.

1.6.2 Biomass combustion

Combustion of solid biomass, mostly plant based, is the largest form of bioenergy globally, with much of it being in simple open combustion systems – fires – for heating or cooking in developing countries.

For the present context, three general categories can be identified for biomass combustion processes in Scotland.

- Small-scale, domestic combustion for space heating and hot water, ranging from open fires and wood-burning stoves to wood-pellet boilers.
- Intermediate-scale biomass boilers delivering heat (only) for commercial, institutional or small district heating schemes.
- Larger-scale biomass combustion plant producing heat for industry, electricity or, in most cases, a combination in a CHP configuration.

In the analysis for this study, only larger-scale plants were considered as potential candidates for CCS. The process options for CO_2 capture from biomass combustion are essentially the same as for fossil fuel combustion.

Combustion of process wastes and municipal wastes with high biomass content were grouped together with general biomass combustion for the purposes of the current study, while recognising that there are different issues with these feedstocks.

1.6.3 Alcohols for liquid biofuels

Fermentation processes are extensively used in some global regions to produce ethanol (or “bioethanol”) as a liquid biofuel for use as transport fuel. In Brazil sugar cane has been used as feedstock for decades non-contentiously while use of corn/maize in the USA and elsewhere has led to concerns over conflict between food and fuel use, food price increases and other sustainability issues. CO_2 is produced as a by-product of fermentation processes often in a high-concentration stream, which can be captured easily for use or for storage. This practice has been established as a source of CO_2 for use in the food and drink industry for decades and is being demonstrated as part of a full-chain BECCS project at industrial scale in Illinois, USA (Office of Fossil Energy, 2017).

Fermentation to produce ethanol as a biofuel does not occur to any extent in Scotland at present. However, an alternative fermentation process converting organic waste streams from the whisky industry to a mixture of acetone, butanol and ethanol is being developed in Scotland (Celtic Renewables, 2018). Butanol (or "biobutanol") can be used as a biofuel for diesel engines. This process also produces a CO_2 by-product stream, which could be suitable for capture if established at a relevant scale.

1.7 Non-energy biogenic CO_2 emissions

Important fermentation processes that are not part of the energy system also produce a biogenic CO_2 by-product that can be captured for use or for storage, which would result in a negative emission. The obvious main example in Scotland is the alcoholic beverage industry producing ethanol by fermentation of natural sugars derived mainly from barley.

Capture of CO_2 at breweries and distilleries has been practised extensively in the past with the CO_2 being re-used within the industry for carbonation, drinks delivery systems and other uses. This practice has declined over time with CO_2 supplies being outsourced instead from industrial gas suppliers; such CO_2 is mostly derived as by-product from hydrogen manufacture using natural gas. However, one distillery in Edinburgh still captures up to 20,000 tonnes of CO_2 per year (t-CO_2/yr), which it sells for reuse (North British Distillery, 2018).

Biotechnology processes being developed for pharmaceutical manufacture may also, in some cases, produce by-product CO_2 streams that might be captured and stored effecting a negative emission. However, at present, the scale of such developments is unlikely to justify investment in capture equipment.

2 Data sources and analysis methods

One focus of this study was to estimate the current quantity of biogenic CO_2 emission in Scotland in order to consider the potential for negative emissions by capturing and permanently storing this CO_2. The primary source of data on CO_2 emissions from industry and commerce in Scotland is the Scottish Pollution Release Inventory (SPRI), a database maintained by the Scottish Environment Protection Agency (SEPA, 2017). However, this was found to be insufficient for biogenic CO_2 emissions data and other sources of data have also been needed for this study.

Reasons for difficulty with using SPRI data include the following. Firstly, the scale of many biogenic CO_2 emissions is below the threshold for reporting, set at 10,000 t-CO_2/yr. Secondly, CO_2 emissions from fermentation in the alcoholic beverages sector appear not to be consistently included in the SPRI, presumably as they are clearly carbon neutral and may not be required for emissions inventory purposes.[1] Thirdly, allocation of emissions to biomass combustion in the paper and board sector appears to be inconsistent between years. In the absence of full reporting in the SPRI other approaches to estimating biogenic CO_2 emissions have been devised.

Data on electricity generated using bioenergy and on biomethane injected to the natural gas grid is available as this is the basis of subsidy payments; this was used to estimate associated biogenic CO_2 emissions by making certain assumptions. For biogas and biomass, combustion aggregate data and data for individual facilities was used to give both “top-down” and “bottom-up” estimates, although these do not tie up exactly due to limited data availability.

For CO_2 emitted by the fermentation industries, plant capacity data is available and was used in a “bottom-up” sense to estimate CO_2 emissions from alcohol production. Actual pure alcohol production volumes for individual breweries and distilleries were not found, possibly as they will be commercially sensitive. Neither was aggregate data for pure alcohol production easily found. Sales quantities as values and some sales volume data were found, but this was difficult to link back to production volume as pure alcohol due to varying alcoholic content and to significant time differences between production and sale, particularly in the whisky sector.

The sections below give the main sources of data used and outline the assumptions and calculations used to estimate the biogenic CO_2 emissions in Scotland from current operations in the sectors considered.

2.1 Biogas, landfill gas, sewage gas and biomethane

Statistics for electricity generation using biogas from AD, landfill and sewage treatment are available from UK Government National Statistics as Regional Renewable Statistics[2] (BEIS, 2017) compiled by the Department for Business, Energy & Industry (BEIS). This covers biogas use in CHP plant but not biomethane upgrading, which is treated separately below. Data on total generation in gigawatt hours (GWh), installed capacity in megawatts (MW) and number of generating sites in Scotland was extracted and used to estimate the actual total CO_2 arising from raw biogas combustion in CHP plant in 2016. The estimate

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[1] This situation is surprising and, despite enquiries to SEPA, has not been adequately clarified.

[2] Also referred to below as “the BEIS data”.

assumes a mid-range energy conversion efficiency to electricity (37.5%)[3] and a typical biogas composition (CH_4:CO_2 ratio 55:45 by volume) (Mike Goldsworthy, 2017). Methane energy content is taken as higher heating value (HHV) and literature values for gas densities are used (Engineering Toolbox, 2017b, 2017a). An example calculation in spreadsheet format is given in Appendix 6.1.

Two further data sources were used to obtain individual plant data for landfill gas, sewage gas and AD biogas.

For landfill gas and sewage gas, Ofgem data reproduced in the *Variable Pitch (2017)* website gave figures for installed capacity and average capacity factor for plants operating in the period October 2016 to September 2017. The data was used to estimate actual generation and CO_2 emission for each location as described above using a landfill gas composition of 50:50 by volume CH_4:CO_2.[4]

For AD biogas, plant capacity data as of June 2017 was obtained from the *Official Information Portal on Anaerobic Digestion* maintained for the UK Government by consultants NNFCC (originally the National Non-Food Crops Centre) (NNFCC, 2017). This gives details of both CHP generation capacity and biomethane injection capacity. Using the generation capacity data with an assumed capacity utilisation factor allows estimation (as outlined above) of the potential CO_2 arising from these sites if all were operating optimally. The modified calculation is shown in Appendix 6.2.

For biomethane upgrading, the AD Information Portal gives capacity data based on the maximum flow rate that each plant can inject to the gas grid (NNFCC, 2017). CO_2 emissions associated with this were estimated using the same assumptions and literature sources for capacity factor, biogas composition and physical data as detailed above. The estimate gives two values, one for the CO_2 separated from raw biogas, which would normally be emitted at the upgrading site, the second for the CO_2 resulting from eventual combustion of the upgraded biomethane, which would normally be emitted at a remote site where the biomethane is consumed. The calculation, with an example, is given in Appendix 6.3.

Data from the AD Information Portal was used to estimate CO_2 emissions from biogas CHP and from biomethane upgrading both on an aggregate basis, to compare with estimates based on the National Statistics data, and also for individual AD plants. Individual plant emission estimates were used to identify the most promising sites for capture of negative emissions from biogas production and to consider how these may be incorporated into a developing CCS infrastructure. This is discussed in Section 4.

2.2 Biomass combustion

The scale of current biogenic CO_2 emissions resulting from biomass combustion in Scotland has been estimated from three different data sources giving both top-down and bottom-up estimates. The Regional Renewable Statistics for 2016 (BEIS, 2017) give data for total electricity generation from biomass and waste at 35 units in Scotland. From this an estimate of total CO_2 emission has been made based on two assumptions. An electrical conversion efficiency of 35% was assumed, based on data for the wood-burning Steven's Croft power station near Lockerbie (Mott MacDonald, 2017). It was assumed that all the fuel was wood with a specific CO_2 emission of 0.39 kg-CO_2/kWh (Volker Quaschning, 2015). The calculation

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[3] This is an arbitrary efficiency figure based on a range of values from a web search; efficiency depends on technology and scale, and ranges 30-45% or wider.

[4] A typical ratio for landfill and sewage biogas (Mike Goldsworthy, 2017).

is shown in Appendix 6.4. However, these data only relate to electricity generation and do not include biomass combustion for heat only.

The total renewable heat output produced in Scotland for 2015 is estimated in an Energy Saving Trust (EST) report (Fiona Flynn, 2016). Data covering biomass for heat only, biomass CHP and energy from waste (EfW) was used to estimate CO_2 arising from these sources. Heat energy conversion efficiencies of 80% for heat only and 45% for CHP and EfW were assumed, based on a spread of values from European plants (BASIS, 2015); the same specific CO_2 emission for wood as above was used. These estimates, shown in Appendix 6.5, overlap with the estimate based on renewable generation from the BEIS data, but the heat only portion is additional. In later analysis, the estimate based on the BEIS data for CHP and EfW in 2016 was used while data from the EST[5] for combustion of biomass in 2015 for heat only was used.

Reported emission data for individual biomass combustion plant has also been compiled from the SPRI database for 2016 (SEPA, 2017) allowing a partial bottom-up estimate based on the larger plants only, discussed below in Section 3.2.2.

2.3 Fermentation industries

The quantity of CO_2 released from fermentation processes in Scotland was estimated based on two factors: the production of pure alcohol for beverages and the ratio of CO_2 to alcohol produced by fermentation, with a number of assumptions relating to each factor.

For beer, an estimate of total beer production in 2013 was taken from the Circular Economy Sector Study on Beer, Whisky and Fish (Roland Arnison and Rupert Carrick, 2015). The quantity of pure alcohol produced was then calculated using the average alcohol content of beer brewed in the UK between 2012 and 2016 derived by calculation from HM Revenue & Customs information (HMRC, 2017).

Pure alcohol produced at grain whisky distilleries in Scotland (which includes the alcohol used for other spirits, such as gin and vodka) was estimated from distillery capacity data for 2014 (Whisky Invest Direct, 2017b) by applying a capacity factor of 90%. This high capacity factor is credible given the industrial scale of operations, a growing market and a recent history of capacity expansion.

Similarly for malt whisky distilleries, pure alcohol production was estimated from 2016 capacity data (Whisky Invest Direct, 2017a) with a capacity factor of 75% applied, reflecting the smaller scale and less industrial nature of this production.

The ratio of CO_2 to alcohol produced was estimated from first principles by assuming fermentation of one molecule of glucose gives rise to two molecules of alcohol (ethanol) and two molecules of CO_2, that is, a 1:1 molar ratio. Adjusting this for molecular weights of ethanol (46) and CO_2 (44), and for the density of ethanol (0.789 kg per litre) leads to a figure of 0.755 kg CO_2 being produced for every litre of pure alcohol. The calculation is shown in Appendix 6.6.

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[5] Referred to below as "the EST data".

3 Results: estimates of biogenic CO_2 emissions in Scotland

The current levels of biogenic CO_2 emissions arising in Scotland, estimated as described, are detailed in the following sections for the three sectors considered. The industries and plants producing these emissions differ considerably in type, scale and location, which means they are not all equal in terms of practicality to capture the CO_2 and effect negative emissions. This is discussed in Section 4, which brings together the estimates and considers what might be achievable in Scotland.

3.1 Emissions from biogas and biomethane

3.1.1 Biogas CHP

The Regional Renewable Statistics (BEIS, 2017) give aggregated data for installed capacity and actual electrical generation in 2016 for CHP plants at 46 landfill gas sites, 8 sewage treatment works and 27 AD plants in Scotland. These data are shown shaded in Table 1 together with derived values for theoretical annual generation, achieved capacity utilisation factor and the annual resulting CO_2 emission, estimated as described above at a total of around 560,000 t-CO_2/yr.

Table 1. Biogas in Scotland, 2016 – CHP generation and estimated CO_2 emission

	Unit	Landfill gas	Sewage gas	AD
Number of sites	#	46	8	27
Installed capacity of sites	MW	116.3	7.2	30.1
Generation	GWh	492.8	32.0	125.5
Annual theoretical capacity	GWh	1,019	63.5	263.3
Capacity factor achieved	%	48.4	50.4	47.7
Estimated CO_2 emission from CHP	t-CO_2/yr	426,508	27,683	108,594
Total estimated CO_2 emission	t-CO_2/yr	562,785		

These figures are based on actual electrical generation achieved from biogas in 2016. It is notable that the achieved capacity utilisation factor is quite modest, at around 50% for each type of biogas source. Also the number of AD plant included is lower than reported in the AD Information Portal, which lists 42 AD units in Scotland, of which 40 have CHP generation capacity (NNFCC, 2017).

An "upside" estimate for potential CO_2 emission has been made by modifying these two factors. The same installed capacity data as in Table 1 was used for landfill gas and sewage gas, while the CHP capacity for AD (43.7 MW) was taken from the AD Information Portal listing updated in June 2017 (NNFCC, 2017). For all biogas sources a high, but credible, capacity factor of 80% was applied, as suggested by the bioenergy consultants NNFCC (Mike Goldsworthy, 2017). The resulting "upside" estimate, shown in Table 2, suggests a total of just over one million tonnes of biogenic CO_2 might be produced from the existing installed capacity of biogas CHP plant in Scotland if a high level of plant utilisation could be achieved.

Table 2. Upside estimate of CO_2 emission from current (2017) biogas CHP in Scotland

	Unit	Landfill gas	Sewage gas	AD
Number of sites	#	46	8	42
Installed capacity of sites	MW	116.3	7.2	47.3
Upside estimate of generation at 80% capacity factor	GWh	815.3	50.8	306.2
Estimated CO_2 emission from CHP	t-CO_2/yr	705,579	43,960	265,034
Total estimated CO_2 emission	t-CO_2/yr	1,014,573		

3.1.2 Biomethane

The AD Information Portal lists twelve sites in Scotland in June 2017 with licences to inject upgraded biomethane to the gas grid (NNFCC, 2017). The total capacity listed was 8,315 Normal metres cubed per hour (Nm^3/h).[6] Using the method described in Section 2.1 with the achieved capacity factor from the BEIS (2017) data, the CO_2 associated with this biomethane upgrading and use is given in Table 3.

Table 3. CO_2 from biomethane upgrading and combustion in Scotland

	Unit	
Number of sites	#	12
Biomethane injection total capacity	Nm^3/h	8,315
Capacity factor	%	47.7
Annual biomethane production	t/yr	23,188
Co-produced CO_2, separated at upgrading site	t-CO_2/yr	52,315
CO_2 from biomethane use, at combustion site	t-CO_2/yr	63,767
Total CO_2 from biomethane upgrading and use	t-CO_2/yr	116,083

Although less than half of the CO_2 associated with biomethane is emitted at the upgrading sites, the separation processes used make it likely that this portion will be available as a concentrated stream making it easier to capture for storage or utilisation.

When the biomethane product is injected into the gas grid it mixes with, and becomes indistinguishable from natural gas in the distribution system. The CO_2 released on use – almost certainly by combustion – will also be indistinguishable from emissions from natural gas combustion. So, although this quantity can be calculated, it has no different relevance for CCS than emissions from natural gas. However, if emissions from grid-injected biomethane

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[6] "Normal" refers to conditions of 20°C and a pressure of one atmosphere.

were to be captured, for example at a natural gas-fuelled power station, these could be considered as negative emissions. Indeed, this is the conjectured source of 1.1 Mt-CO_2/yr of negative emissions modelled by Scottish Government as part of the draft Climate Change Plan (Scottish Government, 2017b; Andrew Mortimer, 2017).

3.1.3 Rationalisation with individual plant information – bottom-up estimate

Results of CO_2 emission estimates for individual landfill sites in the year to September 2017, grouped by location where there are multiple generating units at a site, are given in Appendix 6.7. The sum of these estimates is 409,038 t for this period, close to but slightly lower than the estimate of 426,508 t based on aggregated data for 2016. Both estimates are based on officially reported electricity outputs, the difference between them most likely due to the different period reported, perhaps indicating a decline in evolution of landfill gas as would be expected for this mature sector.

Twelve landfill gas sites had CO_2 emissions estimated at over 10,000 t in the year to September 2017, ranging up to nearly 60,000 t. The locations of these sites and options for integrating with CCS infrastructure are discussed in Section 4. The combined emission from these 12 sites was 345,535 t, or 84% of the total of all sites estimated, with the remainder spread over 17 sites with lower emissions. As the emission estimates depend on both installed capacity and how much the plant is used (achieved capacity factor) it is possible that in a different period different sites would have higher emissions.

For AD biogas, individual plant CO_2 emissions have been estimated for a selection of the 42 plants listed in the AD Information Portal (NNFCC, 2017). Plants selected were those with CHP capacity of 1 MWe or more, plus all sites with biomethane upgrading. These 22 sites and related data are shown in Appendix 6.8. Note that all biomethane upgrading sites also have CHP on site, of which three have capacity over 1 MWe.

The total on-site emission for these 22 sites with June 2017 data, estimated using the overall achieved capacity factor of 47.7% from the BEIS 2016 data, is 188,346 t for CHP and biomethane upgrading combined. Of this 136,031 t is from CHP emissions, which compares with the estimate based on all sites covered by the BEIS data of 108,594 t in 2016. Of these 22 sites, only six have total site emissions estimated at over 10,000 t-CO_2/yr.

3.1.4 Biogas and biomethane - summary

Anaerobic digestion processes for biogas production and the combustion of “raw” biogas in CHP units are well established in the UK with around 100 plants operational in Scotland, split between landfill sites, sewage treatment and wet-waste or crop AD plant. The number of such plant had been growing strongly until the last couple of years when changes to incentives have reduced the financial attractiveness (Mike Goldsworthy, 2017). The total CO_2 emissions from biogas CHP in Scotland are currently estimated at around 0.56 to 0.61 Mt-CO_2/yr with a potential upside to around 1.0 Mt-CO_2/yr for the current installed capacity.

A smaller number of, generally, the larger AD plants also upgrade a portion of biogas to biomethane for grid injection. Although requiring more investment and processing, this can give a higher value to the biogas product overall, depending on incentives and contracts available. From the twelve current biomethane upgrading sites in Scotland an estimated total of 52,315 t-CO_2/yr is emitted at the upgrading sites, with a further 63,767 t-CO_2/yr emission from combustion of the biomethane distributed to the point of use.

This suggests there are pros and cons of biomethane upgrading compared to use of biogas for CHP in terms of CO_2 capture for negative emissions. Upgrading can give a concentrated

CO_2 stream, likely to have lower capture costs but can only lead to capture of less than half the potential CO_2 at the upgrading sites, the remaining emission being distributed to consumer sites. In contrast, capture from CHP plant burning “raw” biogas is likely to have higher capture costs, due to the lower concentration of CO_2 in the flue gas, but allows capture of most of the CO_2 produced.

3.2 Emissions from biomass combustion

3.2.1 Top-down estimates

Using data from the Regional Renewable Statistics (BEIS, 2017) the method described above gives an estimate of total CO_2 emission arising from electricity generation from biomass and waste combustion in Scotland of around 1.37 Mt-CO_2/yr for 2016. The data imply an achieved capacity factor in 2016 of 63.2%, which is modest compared to what would be expected for the larger biomass power stations, although the 35 sites covered will include a variety of scales and purposes. For the larger plants the majority of the emissions are biomass derived (discussed below), but this may not be the case for the other plant; the BEIS data includes some adjustment for co-firing with fossil fuels and it is not know what proportion of waste is biomass derived.

The calculation method has been benchmarked against published data for the performance of and CO_2 emissions from Steven’s Croft biomass power station near Lockerbie (Mott MacDonald, 2017; SEPA, 2017). The performance data implies this plant operates at electrical conversion efficiency of 34.9% and, by applying a credible capacity factor for a large-scale plant of 90%, the calculation method predicts annual CO_2 emissions agreeing closely with reported values averaged over the last three years (within 1.2%). The conversion efficiency of 35% assumed in estimates here is based on the value for Steven’s Croft.

Applying this higher capacity factor of 90% to the total installed capacity of the 35 biomass and waste combustion sites reported in the statistics allows an upside estimate to be made. This suggests that up to 2 Mt-CO_2/yr might be emitted from these sites if all were operating optimally.

A second source used for high-level data on biomass combustion is from two EST reports (Fiona Flynn, 2016; Fiona Flynn et al., 2017), however, the data is not directly comparable. Figures in these reports for biomass combustion for CHP and EfW overlap with the BEIS data discussed above. The reports also give data for biomass combustion for heat only, which is additional to the BEIS data. The emissions from these three categories were estimated for 2015 totalling 2.56 Mt-CO_2, of which 1.48 Mt-CO_2 was from CHP and EfW, agreeing reasonably well with the estimate above based on the BEIS data (1.37 Mt-CO_2). The EfW figure in the EST data includes biogas from AD, which may explain the higher value estimated from this data. An additional 1.07 Mt-CO_2 was emitted from combustion of biomass for heat only. These data and derived estimates are shown in Table 4.

A similar comparison with the EST data for 2016 (Fiona Flynn et al., 2017) is complicated by the fact that renewable heat output from biomass CHP in 2016 was much lower than in 2015, despite slightly increased capacity. As the BEIS data for 2015 and 2016 indicate an increase in electricity generated from biomass over this period, this suggests that the quantity of biomass combusted also increased but that the beneficial use of co-produced heat decreased significantly. This highlights the uncertainties involved in making estimates of CO_2 emission by back calculation from energy output data.

Table 4. Comparison of estimates for CO_2 emission from biomass combustion

Emission source	Energy output, GWh	Output type	Conversion efficiency, %	Estimated feedstock energy, GWh	Estimated CO_2 emission, Mt
Based on BEIS data for 2016					
Combustion of biomass and waste for CHP	1,232	Electricity	35	3,521	1.37
Based on EST data for 2015					
Combustion of biomass for CHP	1,517	Heat	45	3,371	1.31
Energy from waste for CHP	192	Heat	45	427	0.17
Sub-totals for comparison				3,798	1.48
Combustion of biomass for heat only	2,203	Heat	80	2,754	1.07
Total (EST data)					2.55

3.2.2 Bottom-up estimate

The SPRI for 2016 (SEPA, 2017) includes CO_2 emission data for the larger biomass combustion and EfW plants in Scotland, which have been used to make partial bottom-up estimates. In the 2016 inventory there appears to be a difference from previous years in what has been attributed as biomass derived; some assumptions have been made to allow for this.

The inventory lists three large biomass combustion plants that are primarily electricity generating facilities: Markinch CHP Biomass Plant, Steven's Croft Power Station and Westfield Biomass Plant; in 2016 these emitted 0.92 Mt-CO_2 of which 0.88 Mt-CO_2 was attributed as biomass derived. Two EfW plants, also generating electricity, are listed (Lerwick Energy Recovery Plant and Dundee Energy Recycling), which emitted 0.10 Mt-CO_2 between them. The combined reported emissions from these five sites, 1.02 Mt-CO_2 in 2016, can be compared to the estimates above based on the BEIS 2016 data and the EST 2015 data, accounting for 74.0% or 68.6% of the estimated emissions, respectively. The remainder of the estimated emissions will be from the remaining 30 smaller plants in Scotland generating electricity from biomass or waste. The comparison for the large biomass power stations is shown against the EST 2015 data in Figure 2(a)

However, a sizeable proportion of biomass combustion in Scotland is not used for electricity generation but for heat, and so will not be included in the BEIS data. The SPRI inventory lists three large and two smaller paper or board mills in Scotland. The larger plants (Norbord Morayhill Mill, Norbord Cowie Board Mill, UPM-Kymmene Caledonian Paper Mill) have been listed in several of the last few years of the inventory as having biomass derived emissions that will result from raising large quantities of process heat from biomass combustion. In 2016 only the Morayhill Mill is listed with biomass-derived emissions, however, it is assumed here that emissions from all three are predominantly biomass derived (with 2016 rates for Morayhill, 2014 rates for the others). The smaller plants have not been listed as having biomass derived emissions and are not included in this analysis.

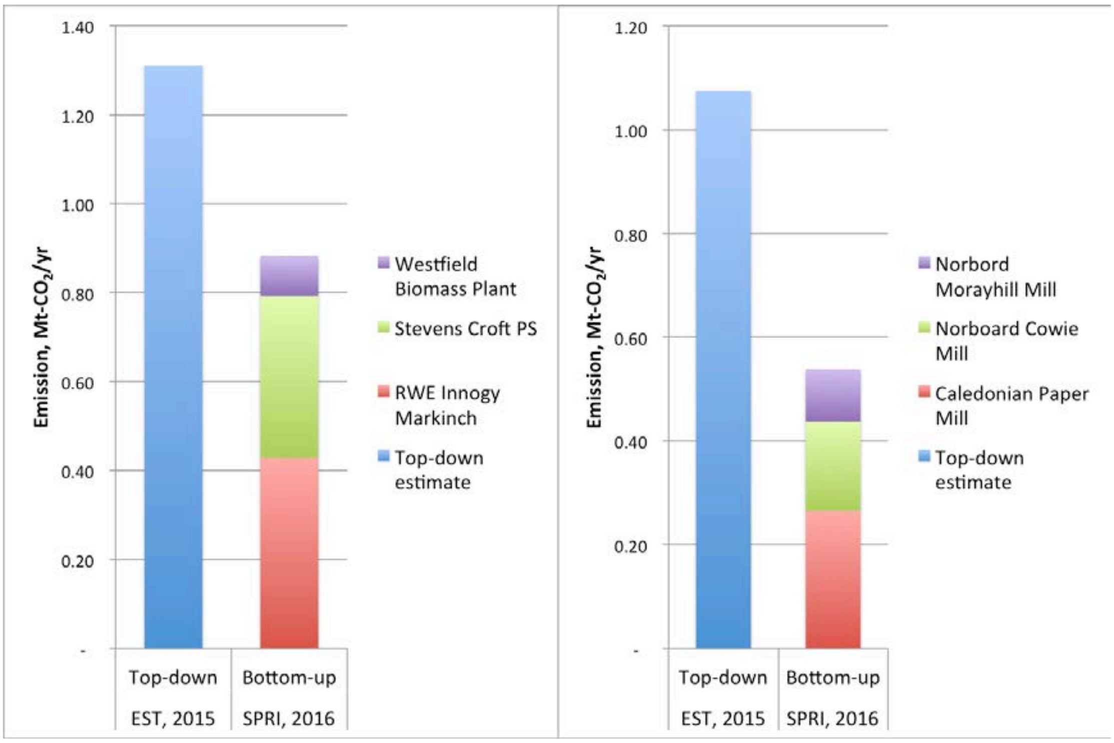


Figure 2. Comparison of top-down and bottom-up estimates of biogenic CO_2 emissions for (a) left, large biomass CHP and (b) right, large biomass process heat facilities

With this assumption, the three large mills emitted a total of 0.65 Mt-CO_2 in 2016 of which 0.54 Mt-CO_2 was biomass derived, representing 50% of the heat-only emission estimated from the EST 2015 data. The comparison for these process heat facilities is shown against the EST 2015 data in Figure 2(b).

Across these partial bottom-up estimates for 2016 a total emission derived from biomass of 1.42 Mt-CO_2 was released from just six plants in Scotland, representing 59.5% of the total estimated from the EST 2015 data (noting inconsistent year data); this does not include the emissions from EfW, which have an unknown biomass content.

3.2.3 Biomass combustion – summary

Estimates for total CO_2 emissions from biomass combustion in Scotland are difficult to make confidently owing to a lack of direct reporting for smaller emission sources and inconsistent coverage of available data that can be used to back-calculate emissions.

The total emission from biomass combustion based on 2015 data and with typical capacity utilisation is estimated in the region of 2.5 Mt-CO_2/yr with more than half of this being emitted at just six major sites – three biomass power stations or CHP sites and three large industrial sites using biomass combustion primarily for process heat.

3.3 Emissions from fermentation processes

3.3.1 Beer

The Circular Economy Sector Study on Beer, Whisky and Fish (Roland Arnison and Rupert Carrick, 2015) describes beer production in Scotland as coming from one large brewery (Tennent Caledonian), one medium brewery (Belhaven) and over eighty smaller, mostly "craft" breweries. It estimates total Scottish beer production at 2,435,000 hectolitres, or 243.5 million litres (ML) in 2013, made up as shown in Table 5. Average alcohol content of beer brewed in the UK between 2012 and 2016 was calculated from HMRC (2017) data as 4.18% alcohol by volume. This was used with the method described (Section 2.3) to estimate the pure alcohol quantity and hence the associated biogenic CO_2 produced through fermentation; results are also shown in Table 5. The total is perhaps surprisingly small reflecting the centralisation of large-scale brewing elsewhere in the UK over the past few decades.

Table 5. Scottish beer production and resulting CO_2 emissions in 2013

Source	Beer production, ML	Pure alcohol, ML	CO_2 emissions, t-CO_2/yr
Tennent Caledonian	200	8.36	6,310
Belhaven	12.3	0.51	390
Independent breweries (>80)	31.2	1.30	980
Total	243.5	10.18	7,680

3.3.2 Whisky

For whisky, and other spirits, the fermentation to produce a "wash" containing alcohol and releasing CO_2 is an intermediate process stage and production data for this is not easily available. The quantity of CO_2 released can be estimated by assuming that all the alcohol produced by fermentation is carried through the distillation process to the final product; in reality there will some losses on distillation, although these are likely to be small. However, the actual production volumes of final spirit products, or the pure alcohol produced are also difficult to find; this is partly because much spirit produced for whisky is stored for several years, maturing before release, meaning sales volumes in any year are not necessarily related to production volumes. The annual production of alcohol for whisky and other spirits has, instead, been estimated from published distillery capacity data.

Published grain distillery capacity figures for 2014 and malt distillery capacities for 2016 were taken from the Whisky Invest Direct website (2017b, 2017a). This lists seven grain whisky distilleries in Scotland and 113 malt whisky distilleries; the grain distilleries are all larger than the largest malt distillery. Table 6 lists the grain distillery capacities, together with estimated pure alcohol production, assuming a capacity factor of 90%, and calculated CO_2 emissions from fermentation for each distillery.

Table 6. Estimated alcohol production and resulting CO_2 emissions from grain whisky distilleries in 2014

Distillery	**Location**	**Owner**	**Quoted capacity, pure alcohol**	**Estimated production, pure alcohol**	**Estimated CO_2 from fermentation**
			ML/yr	ML/yr	t-CO_2/yr
Cameronbridge	Fife	Diageo	105	94.5	71,319
Girvan	Ayrshire	William Grant & Sons	87	78.3	50,942
North British	Edinburgh	Lothian Distillers	72	64.8	48,904
Invergordon	Easter Ross	Whyte & MacKay	40	36.0	27,169
Strathclyde	Glasgow	Chivas Brothers	40	36.0	27,169
Starlaw	Bathgate	La Martiniquaise	25	22.5	16,981
Loch Lomond	Alexandria	Loch Lomond Group	18	16.2	12,226
		Totals	375	337.5	254,710

Table 7 gives the same data for the eight largest malt whisky distilleries, having estimated CO_2 emissions over 5,000 t-CO_2/yr, and aggregated estimates of production capacity and CO_2 emission from the remaining 105 smaller distilleries; a capacity factor of 75% was assumed for the malt distilleries.

A point to note is that William Grant & Sons' Ailsa Bay malt distillery is on the same site as their Girvan grain distillery, taking the total fermentation emission at that site up to around 57,700 t-CO_2/yr.

Table 7. Estimated alcohol production and resulting CO_2 emissions from malt whisky distilleries in 2016

Distillery	Location	Owner	Quoted capacity, pure alcohol	Estimated production, pure alcohol	Estimated CO_2 from fermentation
			ML/yr	ML/yr	t-CO_2/yr
Glenfiddich	Speyside	William Grant & Sons	14.0	10.5	7,924
Roseisle	Highlands	Diageo	12.5	9.4	7,075
Ailsa Bay	Lowlands	William Grant & Sons	12.0	9.0	6,792
Glen Ord	Highlands	Diageo	11.0	8.3	6,226
Macallan	Speyside	The Edrington Group	11.0	8.3	6,226
Glenlivet	Speyside	Chivas Brothers Ltd	10.5	7.9	5,943
Dalmunach	Speyside	Chivas Brothers Ltd	10.0	7.5	5,660
Teaninich	Highlands	Diageo	9.8	7.4	5,547
		Sub total	91	68.1	51,395
105 smaller distilleries		Sub total	286.6	215.0	162,244
		Grand total	377.4	283.1	213,639

3.3.3 Fermentation emissions – summary

These estimates of biogenic CO_2 emission from the production of alcohol by fermentation for beer, whisky and other spirits in Scotland suggest a sizeable total emission of around 0.48 Mt-CO_2/yr, summarised by sector in Table 8. Although the sector estimates are for different years and by different methods, they give the general picture that a majority of the emissions are from a relatively small number of sites, mostly from seven grain distilleries with emissions ranging from 12,000 to 71,000 t-CO_2/yr plus eight malt distilleries and one brewery having fermentation emissions ranging from 5,000 to 8,000 t-CO_2/yr.

The estimate for alcohol production in whisky made here agrees reasonably well with that made in the Circular Economy Sector Study on Beer, Whisky and Fish (Roland Arnison and Rupert Carrick, 2015). This took base data from a different source and extrapolated it to estimate a total production of 625 ML pure alcohol in whisky in 2013. The derived figure for CO_2 emission also agrees well with a report for Scottish Enterprise (Grant Wilson et al., 2016), which estimated a total biogenic emission of 500,000 t-CO_2/yr from fermentation processes in Scotland.

Table 8. Estimated biogenic CO_2 emissions from fermentation industries in Scotland

Source (year)	Estimated production, pure alcohol	Estimated CO_2 from fermentation
	ML/year	t-CO_2/yr
Breweries (2013)	10.18	7,680
Grain distilleries (2014)	337.5	254,710
Malt distilleries (2016)	283.1	213,639
Total	630.76	476,029

3.4 Estimate of total biogenic CO_2 emission in Scotland from energy and industry

Within the scope of the data sources as described above, and accepting that the data available are not for consistent years, an approximate total of around 3.6 Mt-CO_2/yr of biogenic emissions is estimated for Scotland in recent times, shown by industry sector and source type in Table 9. This suggests that there are CO_2 emissions of biogenic origin in Scotland equivalent to about 10% of total reported Scottish CO_2 emissions, which were 36.2 Mt in 2015 (Scottish Government, 2017a). However, this is not to say that this entire emission quantity would be suitable for capturing and storing to effect negative emissions. Analysis of what may be practical to capture is presented in the following section.

Table 9. Estimate of current biogenic emissions in Scotland from energy and industry

Source	Emission estimate	Comments
	Mt-CO_2/yr	
Biogas CHP (including landfill and sewage treatment)	0.56	18 sites with emissions >10,000 t-CO_2/yr (12 landfill, 1 sewage, 5 other wet-waste/crop AD)
Biomethane upgrading	0.05	High conc. CO_2 stream, 1 site >10,000 t-CO_2/yr
Biomethane combustion	0.06	Distributed through grid, emissions at user sites
Biomass combustion (power station or CHP)	1.37	Three sites emit two thirds of this (0.88 Mt-CO_2/yr), ~30 smaller sites
Biomass combustion (heat only)	1.07	Three sites emit half of this (0.54 Mt-CO_2/yr), thousands of smaller sites
Fermentation – beer	0.01	Many sites (>82), 1 site >5,000 t-CO_2/yr
Fermentation – grain whisky	0.25	From 7 sites all >10,000 t-CO_2/yr
Fermentation – malt whisky	0.21	From 113 sites, most small, 8 >5,000 t-CO_2/yr
Total	**3.59**	(Difference in sum due to rounding)

4 Integration of biogenic emissions with CCS

This section addresses the question of how the capture of biogenic CO_2 to effect negative emissions in Scotland might be developed and to what extent this might be practical. It considers two main factors that are suggested as largely determining the practicality: the scale of emissions at an individual site and the location of the site. In this analysis economic factors are not considered, although clearly they are important and are affected by scale and location. Neither is CO_2 capture efficiency considered; scale is considered here in terms of current emissions, whereas typical capture plant designs target around 90% capture efficiency.

Scale is considered first, drawing on the preceding section to identify a list of currently operating plant of an appropriate scale to consider applying CO_2 capture. The context of how CCS infrastructure may be developed in Scotland is then briefly described, assuming this is based on existing proposals and projects, before discussion of the options for transport relevant to different scales and locations. A brief discussion of what this means for trunk CO_2 transport and CO_2 transport hubs in Scotland follows.

4.1 Relevant scale for capture of biogenic emissions

There is no hard and fast threshold of scale below which CO_2 capture is impossible, it can be done at laboratory scale, but clearly below a certain scale higher costs per unit CO_2 captured and declining net CO_2 abatement will make the process less effective. Commercially available CO_2 capture and liquefaction plant is listed by several suppliers down to a scale of 20 t-CO_2/day, or 7,300 t-CO_2/yr (Cryostar, 2018; GE Oil & Gas, 2018), and one supplier lists equipment of 3.5 t-CO_2/day capacity, or 1,300 t-CO_2/yr (Union Engineering, 2018).

For the present study an arbitrary emission threshold of 10,000 t-CO_2/yr has been chosen to include a site in the analysis. This is in line with, but not related to, the threshold used by SEPA for reporting CO_2 emissions in the SPRI. Using the estimates discussed above, 32 facilities have emissions above the threshold at 29 individual sites (three large grain distilleries also have large AD plants on site). The estimated biogenic emission from these 29 sites totals over 2.1 Mt-CO_2/yr, representing some 60% of the total estimated from all biogenic emission sources examined. Table 10 summarises these facilities and their emissions by type and all facilities are listed in Appendices 6.9 to 6.13. Note that emissions due to biomethane combustion after distribution through the gas grid are not included in these figures, only the emissions at site due to the upgrading process.

4.2 Potential CCS landscape in Scotland

All realistic proposals for CCS in Scotland have suggested use of offshore geological structures for CO_2 storage, mostly considering areas under the North Sea where the exploration for oil and gas industries over past decades has led to a very good understanding of the geology. Several potential CO_2 storage sites in the Central North Sea have been extensively characterised and are considered ready for development (ETI, 2016).

Table 10. Summary of facilities with biogenic CO_2 emissions over 10,000 t-CO_2/yr

Type of facility	Number of facilities with estimated biogenic CO_2 emission >10,000 t-CO_2/yr	Estimated biogenic CO_2 emission, total by facility type, t-CO_2/yr
Sewage gas	1	17,882
Landfill gas	12	345,535
AD with CHP	3	44,802
AD with CHP and biomethane upgrading	3	69,809
Biomass combustion mainly for process heat	3	538,147
Biomass combustion with CHP	3	882,566
Fermentation, grain distilleries	7	254,710
Totals	32	2,153,451

Production of North Sea oil and gas has required transport of materials in bulk by pipeline and shipping. This has resulted in a network of pipeline routes from offshore production sites, through shoreline receiving points on the east coast, some including processing sites, connecting to onshore pipelines to deliver hydrocarbons to downstream processing sites and markets, generally in Central Scotland or further south. Tanker terminals have also been developed, generally for export of downstream hydrocarbon products by ship, but also for material imports.

As the North Sea oil and gas industry has matured and started to decline, some pipelines and some shipping facilities have become redundant or underutilised and may be available for alternative uses, such as CCS. In particular, certain offshore pipelines that have carried gas from North Sea fields to St Fergus gas processing terminal, and an onshore natural gas pipeline (Feeder 10) that runs from St Fergus to near Bathgate in central Scotland have been identified and studied as potential CO_2 transport pipelines (Scottish Power CCS Consortium, 2011; Element Energy, 2014).

Two significant CCS projects at different stages of development propose to reuse some of this existing hydrocarbon infrastructure to reduce initial capital costs.

The ACT Acorn Project (2017) proposes to capture emissions from the St Fergus gas processing terminal, north of Peterhead on the east coast, and reuse an existing offshore gas pipeline to transport CO_2 to a storage site in the Central North Sea. This initial phase of the project is proposed as the minimum viable full-chain CCS project. Further phases are proposed to build on this: using the Feeder 10 pipeline to bring captured CO_2 from Central Scotland; using Peterhead Port as a CO_2 ship-import terminal with connection by pipeline to St Fergus; and using further existing offshore pipelines to access other storage sites when required for additional CO_2 storage capacity. These expansion phases are indicated in

Figure 3; the name CO_2-SAPLING relates to the cross-border CO_2 transport elements of the ACT Acorn Project expansion, which form a proposed EU Project of Common Interest (Pale Blue Dot, 2017).

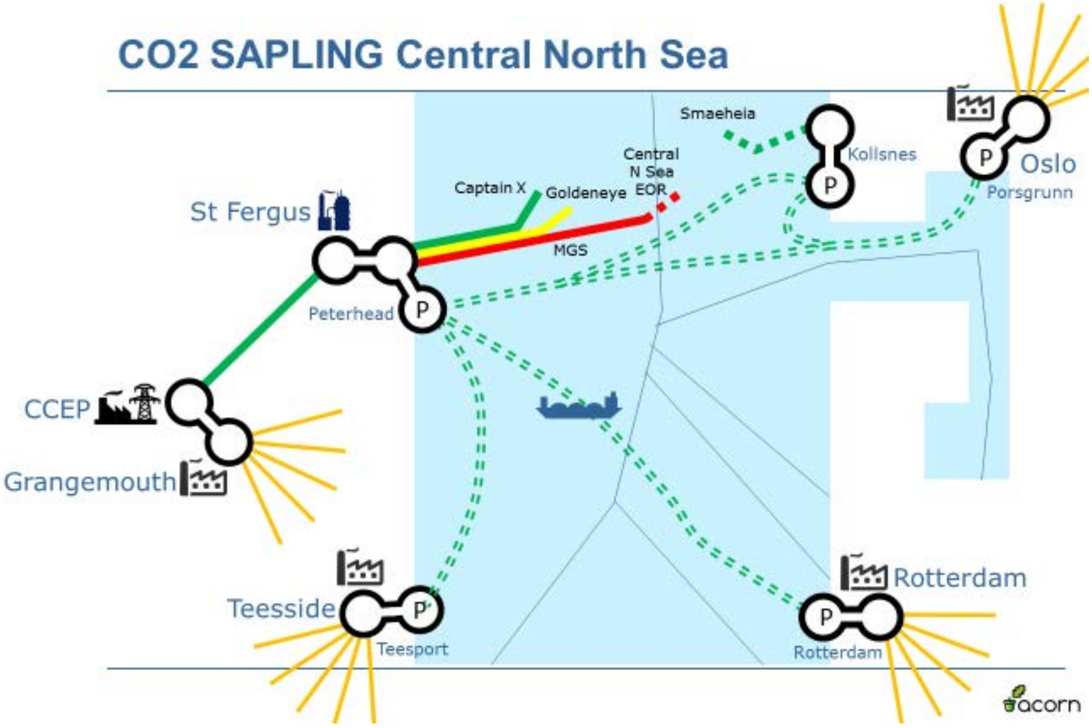


Figure 3. Potential expansion options for the ACT Acorn Project as the related CO_2 SAPLING Project (Pale Blue Dot, 2017)

The Caledonia Clean Energy Project (CCEP) proposes to build a large, gas-fed energy facility at Grangemouth, for either electricity generation or a combination of electricity generation with hydrogen production by steam methane reforming. It will include capture of CO_2 produced at a rate of around 3 Mt-CO_2/yr (Alan Simpson, 2018). The transport and storage of CO_2 will be integrated with the ACT Acorn Project infrastructure using the Feeder 10 pipeline for transport to St Fergus and the offshore pipeline and storage developed by that project, as also shown in Figure 3.

Conversion of Feeder 10 pipeline for CO_2 transport and provision of CO_2 storage in the Central North Sea through deployment of the two projects described would create the initial infrastructure that would allow other emitters to start capturing and storing their CO_2 emissions. Much of Scotland's heavy industry and its larger emission sources are located in Central Scotland, particularly around Grangemouth and in Fife. A previous study has estimated that more than three-quarters of emissions from large sources in Scotland are within 40 km of Feeder 10 and has identified emission sources that could form a CO_2 capture cluster in the area, with potential routes for CO_2 collection pipeline networks outlined (Peter Brownsort, Vivian Scott and R. Stuart Haszeldine, 2016). Depending on assumptions, a total practical CO_2 capture quantity in the region of 5 to 8 Mt-CO_2/yr was estimated (including CCEP), which would make effective use of Feeder 10 while leaving some spare capacity. The emitters covered in the previous study included four of the large biogenic CO_2 emitters identified above; how these and other biogenic CO_2 emitters may integrate with a developing CCS infrastructure is discussed in sections below.

In summary, most past and present proposals for development of CO_2 transport and storage infrastructure in Scotland suggest the formation of a transport trunk route from near Grangemouth to north-east Scotland then a further trunk route or routes to offshore storage areas in the Central North Sea. Initial developments might reuse existing pipelines, by connecting to the existing Feeder 10 pipeline running from Bathgate to St Fergus and then existing offshore pipelines. However, the capacity of Feeder 10 is limited to a maximum of 10 Mt-CO_2/yr (Element Energy, 2014) so beyond this capacity, or beyond the lifetime of Feeder 10, an alternative would be needed, either a new pipeline or (possibly and) a CO_2 shipping system.

4.3 Locations of relevant plant with biogenic CO_2 emissions

The locations of the 29 sites identified in the present study with biogenic emissions over 10,000 t-CO_2/yr are plotted on a "Google My Maps" shown as Figure 4.

Many are situated in the Central Belt of Scotland and 21 of the 29 sites are within 40 km of the Feeder 10 pipeline with others further scattered, up to 130 km from the pipeline.

4.4 Transport options for captured biogenic CO_2 emissions

The most effective option for the transport of CO_2 from any site to join a larger-scale CO_2 transport infrastructure will depend on the scale of CO_2 capture and on the distance to be transported. But there will always be a technically feasible option available. Globally, CO_2 is currently transported by road tanker, tank cars on trains, ships and pipelines (Worley Parsons, 2009).

For smaller operations (say up to 100,000 t-CO_2/yr), and those more distant from large-scale or fixed CO_2 transport infrastructure, road transport is likely to be most cost effective. Road tankers in the UK can carry around 20 t of liquefied CO_2, meaning that, at the threshold scale of 10,000 t-CO_2/yr, two tankers every three days would be sufficient. The existing CO_2 capture facility at the North British Distillery in Edinburgh is serviced by truck transport at a nominal scale of 20,000 t-CO_2/yr (North British Distillery, 2018).

For medium-scale operations close to existing railways, trains may provide an effective solution. Tank cars designed for CO_2 are available to charter in Europe (VTG, 2018), although it is not known what numbers are currently available or whether they are compatible with the UK railway system. The existing design carries around 60 t CO_2 and typical freight train lengths in the UK of 775m (Network Rail, 2017) would allow 50 tank cars, or 3,000 t, per train. A capture facility of 150,000 t-CO_2/yr scale could be serviced by one train every week.

It is envisaged that road or rail transport would be used to bring CO_2 destined for permanent storage to a transport hub where it would be consolidated with other shipments for onward transport, which could be either by pipeline or by ship. For road or rail transport, CO_2 would be compressed and refrigerated to a liquid state to minimise transport volume and a buffer storage capacity equal to at least one transport load would be needed at the liquefaction site, to minimise loading time. At the transport hub, for onward transport by pipeline, CO_2 would be reconditioned (warming and pumping to higher pressure) before injecting to the pipeline. For ship transport, CO_2 would be maintained as refrigerated liquid for loading to the ship. In either case it is likely that some buffer storage capacity would be needed at the transport hub. Such buffer stores would be standard designs for containing a liquefied gas, usually cylinders ("bullet tanks") for smaller quantities or spheres for larger amounts (Peter Brownsort, 2015b).

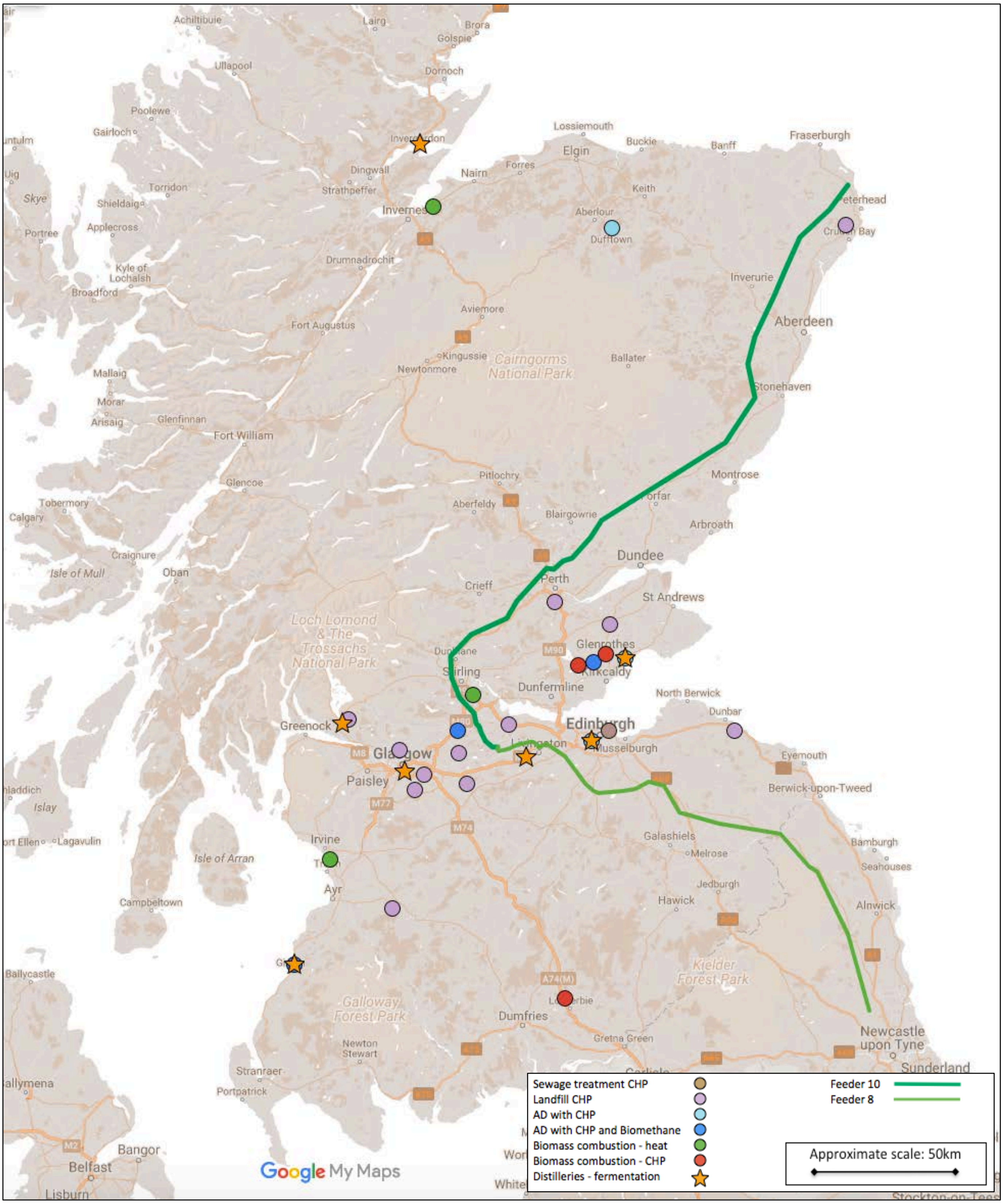


Figure 4. Locations of biogenic CO_2 emission sources >10,000 t-CO_2/yr in Scotland.

Note: three distilleries also have AD with CHP facilities, symbols superimposed

For most biogenic CO_2 capture operations, being generally of small or medium-scale, it is likely to be most effective to use road or rail transport to link to larger-scale CO_2 transport infrastructure at a collection hub. This is likely to be the case except in two circumstances: either where the emission source is very close to the larger-scale infrastructure, such as being close to the route of Feeder 10, or where several sources are located close together with an aggregate CO_2 volume that would justify a new pipeline connection serving the cluster.

Other than these exceptions, most of the smaller sites would probably be best served by road transport with a main collection hub in Central Scotland, either near the route of Feeder 10 or near a port facility for onward transport. Some of the medium-scale sites that are more distant from the Central Belt might be effectively served by rail transport. For instance, Steven's Croft power station at Lockerbie, the distillery site at Girvan, Caledonian Paper Mill at Irvine and Norbord Morayhill Mill near Inverness are all located on, or very close to, existing railways. Their CO_2 emissions ranging 100,000 to 360,000 t-CO_2/yr are estimated to require from 3 to 10 trains a month for transport.

Considering the potential exceptions to road or rail transport, the map of source locations shows there are a number of biogenic CO_2 sources within 10km of Feeder 10. These include smaller emitters at Stoneyhill, Avondale and Greengairs landfill sites, Starlaw Distillery and Shanks/Energen Biogas, each with emissions ranging 17,000 to 60,000 t-CO_2/yr, and one medium-scale emitter, Norbord Cowie Mill, with 171,000 t-CO_2/yr emissions. Cost comparisons between road transport and pipeline for these volumes of CO_2 are not available, however, it is thought likely that only the larger volume and shorter distance (c.5km) for the Norbord Cowie Mill might justify an individual pipeline connection.

The clearest opportunity for a cluster of biogenic CO_2 emission sources is located in Fife, including Westfield Biomass power station, Quila Energy AD plant, RWE Innogy Markinch CHP plant and Cameronbridge Distillery, which has fermentation, AD and biomass combustion emissions (Diageo, 2013). These sources total around 640,000 t-CO_2/yr, which is more likely to justify investment in a pipeline connection, particularly if combined with emissions captured from other large emitters in the area, specifically the Fife Ethylene Plant and Fife Natural Gas Liquids Plant, both situated at Mossmoran; these two plants emitted over 1 Mt-CO_2 between them in 2016 (SEPA, 2017). A CO_2 pipeline collection network taking in the Cameronbridge, Markinch and Mossmoran sites and linking to Feeder 10 at Dunipace, near Denny, has previously been suggested with indicative costing (Peter Brownsort et al., 2016). This could also connect the other Fife biogenic CO_2 sites, as well as the Norbord Cowie Mill and another industrial site in Alloa, giving a total emission volume of around 2 Mt-CO_2/yr, of which about 40% would be biogenic.

4.5 Trunk transport and hub options for CO_2

The bulk of Scottish CO_2 emissions, from biogenic and from fossil fuel or chemical processing sources, occur in the Central Belt; options for trunk transport using the Feeder 10 pipeline have been discussed in depth previously (Scottish Power CCS Consortium, 2011; Element Energy, 2014; Peter Brownsort et al., 2016). However, Feeder 10 has a limited capacity at around 10 Mt-CO_2/yr maximum (Element Energy, 2014) and will have a limited lifetime. Alternative options include a new pipeline or use of shipping; these are both considered briefly here.

A new pipeline would most likely be routed from close to the greatest concentration of emission sources, currently Grangemouth, direct to an offshore storage site, or via a shoreline booster station, such as may be developed at St Fergus. It would likely be designed for high pressure, dense phase CO_2 at a capacity suitable for all envisaged users. It could be routed offshore, or follow an existing pipeline corridor onshore. In either case the capital cost would be high. In the context of this study, the most relevant consideration is the likely starting point at or near Grangemouth.

Shipping of liquefied CO_2 is an alternative that may have lower capital costs than pipelines, particularly at smaller scales and for longer distances (Peter Brownsort, 2015b). Shipping is seen as advantageous at an early phase of development of large-scale CO_2 transport infrastructure from the flexibility it gives for collection from different locations. Several projects around the North Sea Basin are considering the use of CO_2 shipping, including the related ACT Acorn and CO_2-SAPLING projects that propose importing CO_2 into Peterhead Port in north-east Scotland for onward transport by pipeline to North Sea storage sites (Peter Brownsort and Sam Gomersall, 2018). This leads to the option for shipping CO_2 from Central Scotland to Peterhead as an alternative to using Feeder 10.

As with a new pipeline, a ship-transport route should serve the greatest concentration of emission sources, so again Grangemouth is the most obvious site for a CO_2 shipping terminal. Grangemouth Port has long experience of tanker traffic, including refrigerated liquids. It currently has eight tanker berths, with further unused quay space and development area. Ineos recently started importing liquefied ethane through a new facility at Grangemouth to supply its polymer production processes; this uses ships of 21,000 deadweight tonnes, with dimensions the largest that can currently be accommodated in the entry lock (Forth Ports, 2014; Marine Traffic, 2018). At this size of ship, one ship every two days would allow transport of about 3 Mt-CO_2/yr (Peter Brownsort and Sam Gomersall, 2018). This could be shipped to Peterhead for onward transport or direct to an offshore storage location if suitable mooring and offloading technology is developed (Peter Brownsort, 2015a).

In either of these forward scenarios that do not use Feeder 10, Grangemouth would appear to be a favourable site for a CO_2 transport hub; it has good road connections via the M9 motorway, a rail-freight line to the docks and is the largest cluster of industrial CO_2 emission sources in Scotland. If Feeder 10 is used, Grangemouth remains a good location for a CO_2 transport hub for the above reasons, but would require a connection to the trunk pipeline. Outline route options and costings for connection are available from previous studies (Peter Brownsort et al., 2016; Alan Simpson, 2018). However, for connection of road and rail CO_2 collection services to Feeder 10 only, other locations could be considered closer to the intersection of the pipeline with railway routes and still close to the motorways, to the west of Falkirk.

5 Concluding summary and recommendations

This study was carried out to help Scottish Government develop an understanding of the potential for achieving negative CO_2 emissions in Scotland, in order to help meet greenhouse gas emission reduction and climate change targets.

A review of alternative NETs confirmed the use of CCS technologies to capture and permanently store CO_2 released from biological sources as one of the most appropriate approaches to negative emissions in Scotland, building on existing support and momentum in CCS development, existing industry and natural assets.

The main part of the study focused on quantifying the level of current biogenic CO_2 emissions in Scotland from existing sources in the energy and industrial sectors, specifically emissions from all forms of biogas, biomass combustion and the fermentation industry for alcohol production. It is estimated that approximately 3.6 Mt-CO_2/yr is emitted from these sectors and, while it would not be possible to capture all of this efficiently, some 60% – 2.1 Mt-CO_2/yr – is emitted at 29 larger sites of a scale where CO_2 capture would be practical. At this level, negative emissions achieved by capturing and storing this CO_2 would provide a useful offset to continuing fossil fuel derived CO_2 emissions, most recently reported for Scotland at 36.2 Mt-CO_2 in 2015.

This estimate should be considered as indicative only; obtaining the data to compile it was challenging. It was found that biogenic CO_2 emissions are not consistently recorded or reported and the estimate was formed using different methods and timescales for different sectors. However, reasonable agreement with other studies was found, where these exist, and the use of different estimation methods, both top-down and bottom-up, lends credibility to the findings as an indicative estimate.

The study also considered the scale of capture equipment and the transport modes that would be required to integrate collection of this biogenic CO_2 into a wider CO_2 transport and storage infrastructure, such as is being considered under current proposals in Scotland. Technical options were found to exist for the scales and locations of all sites identified. Financial viability was not considered, and is likely to be challenging under current policy and fiscal conditions.

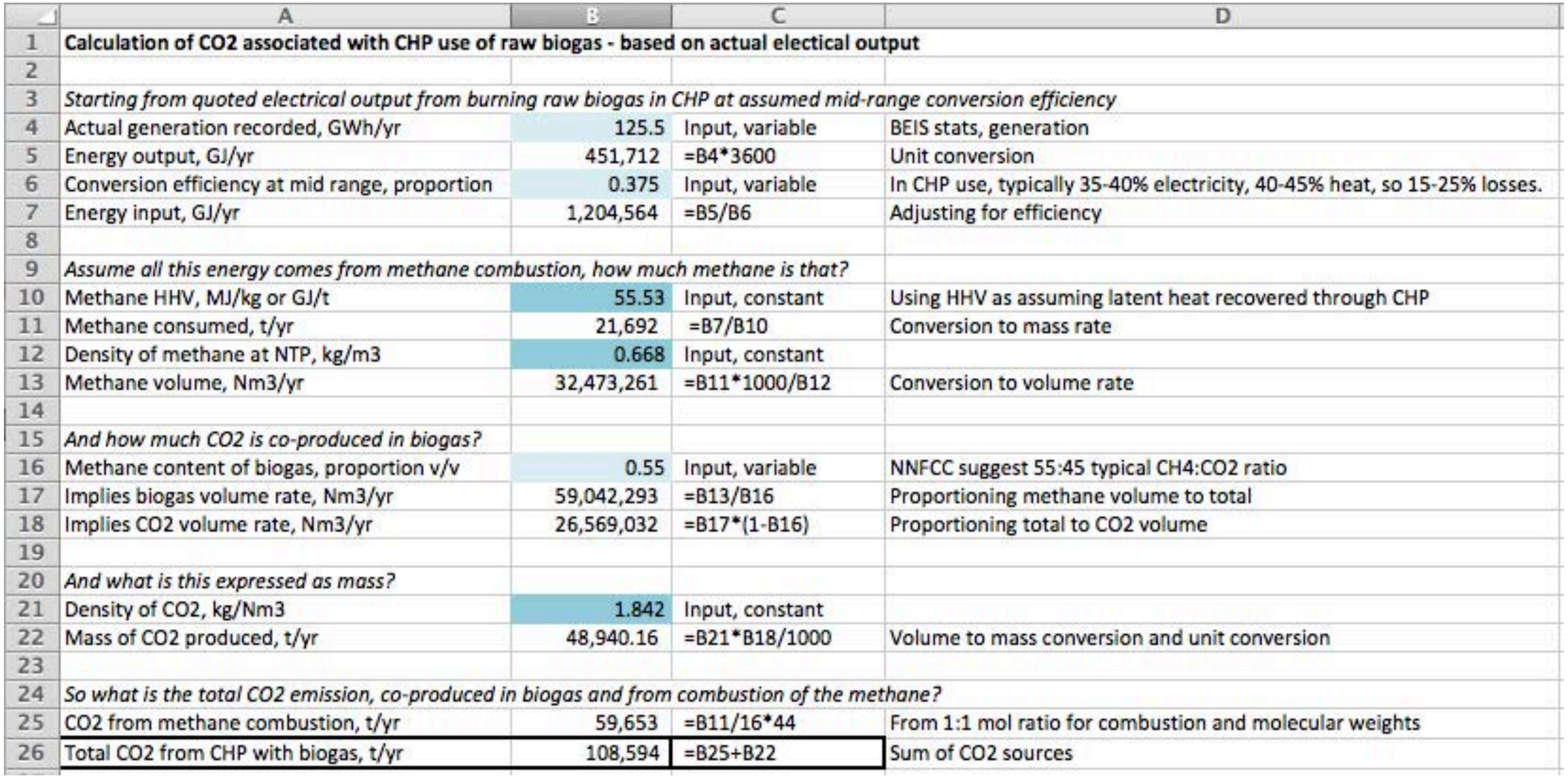
Overall, this work confirms a view that there is a sizeable potential to achieve negative CO_2 emissions in Scotland through the use of CCS technology on existing biogenic CO_2 emissions in energy and industrial sectors, and this would also be the case for new developments in these sectors. This approach would directly contribute to achieving the ambitions of the Climate Change Plan to decarbonise the economy. Fiscal and policy conditions and the absence of developed CO_2 transport and storage infrastructure currently prevent this potential from being realised; there is currently no incentive to reduce biogenic emissions as they are considered carbon-neutral. However, this potential provides an additional justification for progressing the provision of such infrastructure and highlights opportunities to introduce policies or incentives to facilitate project development. It is hoped that through its forthcoming Bioenergy Action Plan, and through other means, Scottish Government can create the conditions that encourage such developments to come forward.

The study leads to some specific recommendations, which may be considered by Scottish Government for action:

- Improve consistency and coverage of reporting of biogenic CO_2 emissions to allow better quantification of the opportunity for negative emissions.
- Consider incentives and/or policies specifically to encourage capture of biogenic CO_2 emissions.
- Support early project development to demonstrate CO_2 capture from biogenic sources at appropriate scales (smaller than previous CO_2 capture proposals).
- Initiate and/or support further work to define better the options for smaller-scale CO_2 transport modes, both technically and commercially, including the integration of such modes with trunk transport of CO_2.
- Maintain support for existing proposals that aim towards development of CO_2 transport and storage infrastructure in Scotland; such infrastructure is clearly a pre-requisite for achieving significant negative CO_2 emissions.

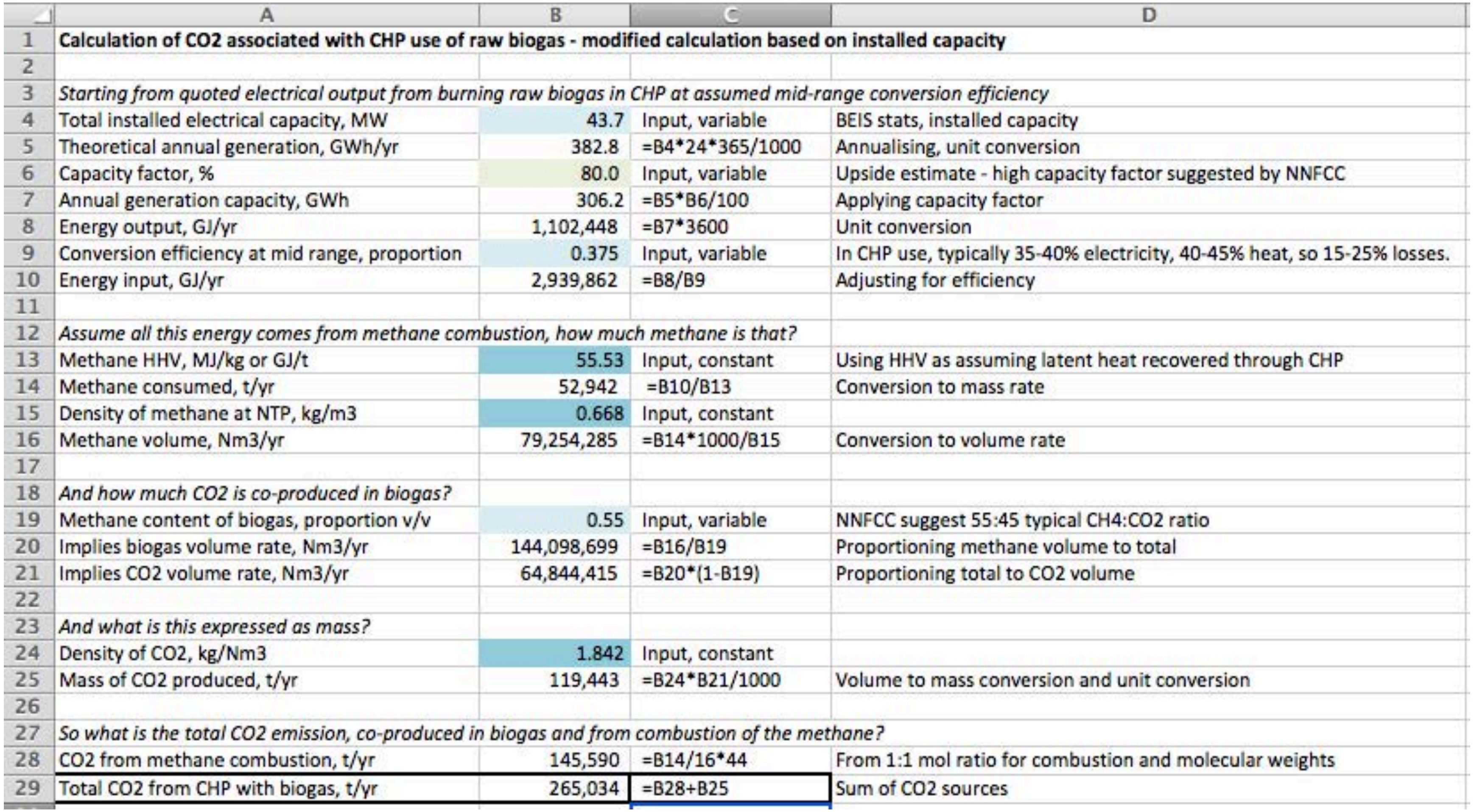
6 Appendix: methods and results

6.1 Calculation of CO_2 emission associated with CHP use of raw biogas



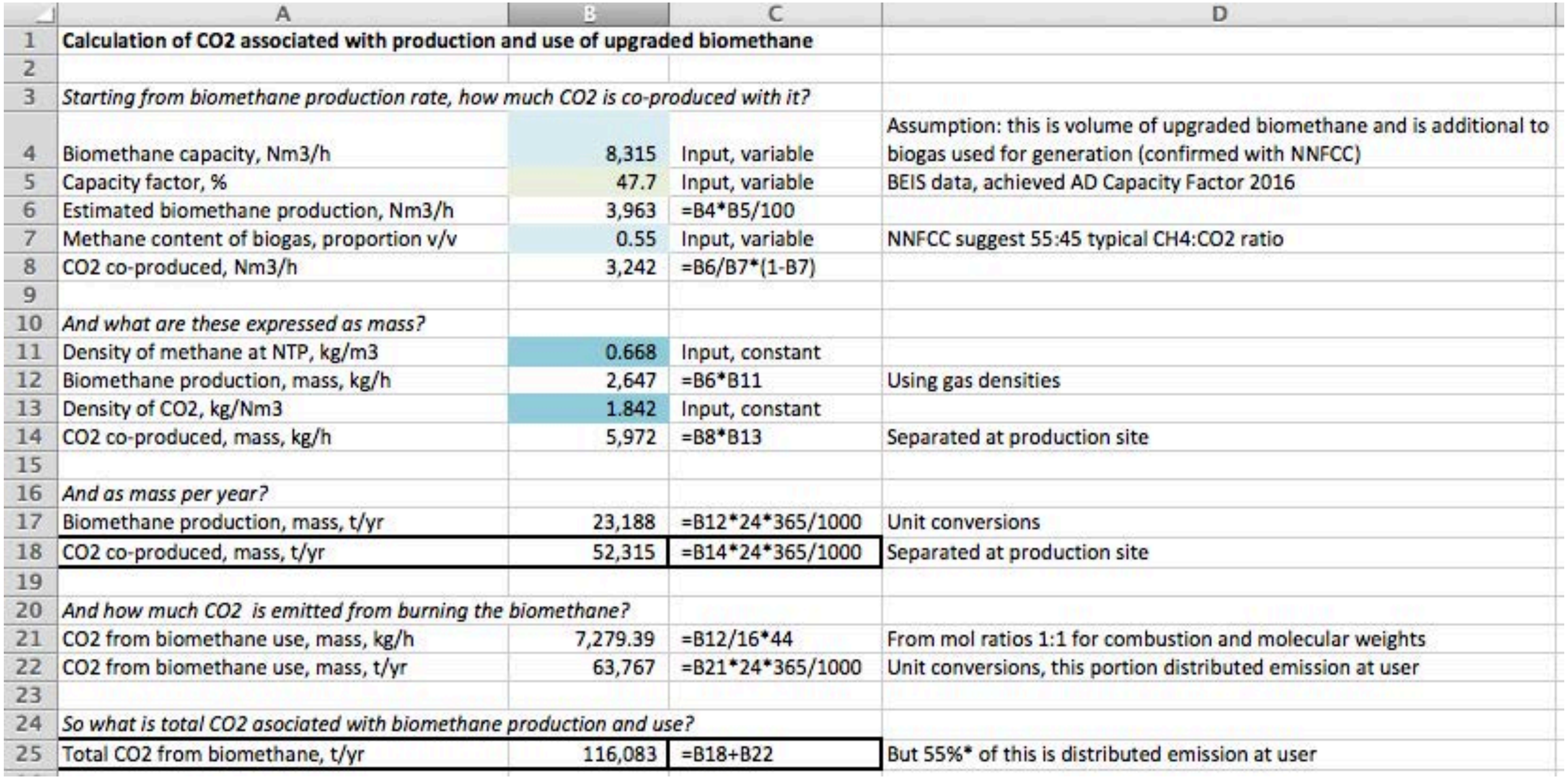
	A	B	C	D
1	**Calculation of CO2 associated with CHP use of raw biogas - based on actual electical output**			
2				
3	*Starting from quoted electrical output from burning raw biogas in CHP at assumed mid-range conversion efficiency*			
4	Actual generation recorded, GWh/yr	125.5	Input, variable	BEIS stats, generation
5	Energy output, GJ/yr	451,712	=B4*3600	Unit conversion
6	Conversion efficiency at mid range, proportion	0.375	Input, variable	In CHP use, typically 35-40% electricity, 40-45% heat, so 15-25% losses.
7	Energy input, GJ/yr	1,204,564	=B5/B6	Adjusting for efficiency
8				
9	*Assume all this energy comes from methane combustion, how much methane is that?*			
10	Methane HHV, MJ/kg or GJ/t	55.53	Input, constant	Using HHV as assuming latent heat recovered through CHP
11	Methane consumed, t/yr	21,692	=B7/B10	Conversion to mass rate
12	Density of methane at NTP, kg/m3	0.668	Input, constant	
13	Methane volume, Nm3/yr	32,473,261	=B11*1000/B12	Conversion to volume rate
14				
15	*And how much CO2 is co-produced in biogas?*			
16	Methane content of biogas, proportion v/v	0.55	Input, variable	NNFCC suggest 55:45 typical CH4:CO2 ratio
17	Implies biogas volume rate, Nm3/yr	59,042,293	=B13/B16	Proportioning methane volume to total
18	Implies CO2 volume rate, Nm3/yr	26,569,032	=B17*(1-B16)	Proportioning total to CO2 volume
19				
20	*And what is this expressed as mass?*			
21	Density of CO2, kg/Nm3	1.842	Input, constant	
22	Mass of CO2 produced, t/yr	48,940.16	=B21*B18/1000	Volume to mass conversion and unit conversion
23				
24	*So what is the total CO2 emission, co-produced in biogas and from combustion of the methane?*			
25	CO2 from methane combustion, t/yr	59,653	=B11/16*44	From 1:1 mol ratio for combustion and molecular weights
26	Total CO2 from CHP with biogas, t/yr	108,594	=B25+B22	Sum of CO2 sources

6.2 Calculation of CO_2 associated with CHP use of raw biogas - modified calculation based on installed capacity



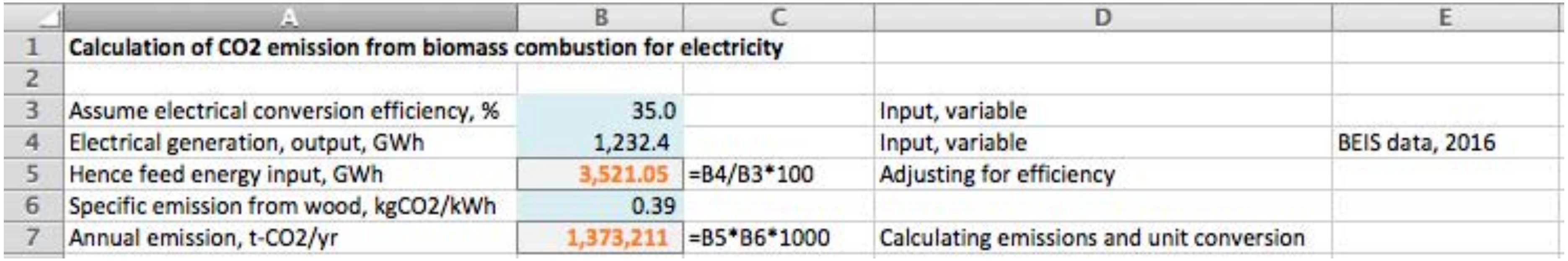
	A	B	C	D
1	**Calculation of CO2 associated with CHP use of raw biogas - modified calculation based on installed capacity**			
2				
3	*Starting from quoted electrical output from burning raw biogas in CHP at assumed mid-range conversion efficiency*			
4	Total installed electrical capacity, MW	43.7	Input, variable	BEIS stats, installed capacity
5	Theoretical annual generation, GWh/yr	382.8	=B4*24*365/1000	Annualising, unit conversion
6	Capacity factor, %	80.0	Input, variable	Upside estimate - high capacity factor suggested by NNFCC
7	Annual generation capacity, GWh	306.2	=B5*B6/100	Applying capacity factor
8	Energy output, GJ/yr	1,102,448	=B7*3600	Unit conversion
9	Conversion efficiency at mid range, proportion	0.375	Input, variable	In CHP use, typically 35-40% electricity, 40-45% heat, so 15-25% losses.
10	Energy input, GJ/yr	2,939,862	=B8/B9	Adjusting for efficiency
11				
12	*Assume all this energy comes from methane combustion, how much methane is that?*			
13	Methane HHV, MJ/kg or GJ/t	55.53	Input, constant	Using HHV as assuming latent heat recovered through CHP
14	Methane consumed, t/yr	52,942	=B10/B13	Conversion to mass rate
15	Density of methane at NTP, kg/m3	0.668	Input, constant	
16	Methane volume, Nm3/yr	79,254,285	=B14*1000/B15	Conversion to volume rate
17				
18	*And how much CO2 is co-produced in biogas?*			
19	Methane content of biogas, proportion v/v	0.55	Input, variable	NNFCC suggest 55:45 typical CH4:CO2 ratio
20	Implies biogas volume rate, Nm3/yr	144,098,699	=B16/B19	Proportioning methane volume to total
21	Implies CO2 volume rate, Nm3/yr	64,844,415	=B20*(1-B19)	Proportioning total to CO2 volume
22				
23	*And what is this expressed as mass?*			
24	Density of CO2, kg/Nm3	1.842	Input, constant	
25	Mass of CO2 produced, t/yr	119,443	=B24*B21/1000	Volume to mass conversion and unit conversion
26				
27	*So what is the total CO2 emission, co-produced in biogas and from combustion of the methane?*			
28	CO2 from methane combustion, t/yr	145,590	=B14/16*44	From 1:1 mol ratio for combustion and molecular weights
29	Total CO2 from CHP with biogas, t/yr	265,034	=B28+B25	Sum of CO2 sources

6.3 Calculation of CO_2 associated with production and use of upgraded biomethane



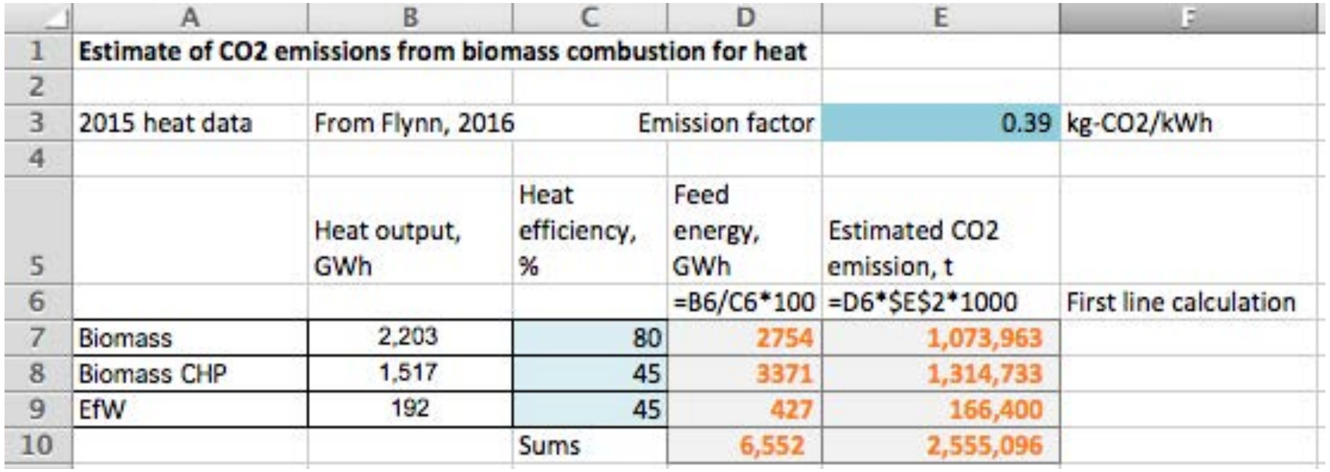
	A	B	C	D
1	**Calculation of CO2 associated with production and use of upgraded biomethane**			
2				
3	*Starting from biomethane production rate, how much CO2 is co-produced with it?*			
4	Biomethane capacity, Nm3/h	8,315	Input, variable	Assumption: this is volume of upgraded biomethane and is additional to biogas used for generation (confirmed with NNFCC)
5	Capacity factor, %	47.7	Input, variable	BEIS data, achieved AD Capacity Factor 2016
6	Estimated biomethane production, Nm3/h	3,963	=B4*B5/100	
7	Methane content of biogas, proportion v/v	0.55	Input, variable	NNFCC suggest 55:45 typical CH4:CO2 ratio
8	CO2 co-produced, Nm3/h	3,242	=B6/B7*(1-B7)	
9				
10	*And what are these expressed as mass?*			
11	Density of methane at NTP, kg/m3	0.668	Input, constant	
12	Biomethane production, mass, kg/h	2,647	=B6*B11	Using gas densities
13	Density of CO2, kg/Nm3	1.842	Input, constant	
14	CO2 co-produced, mass, kg/h	5,972	=B8*B13	Separated at production site
15				
16	*And as mass per year?*			
17	Biomethane production, mass, t/yr	23,188	=B12*24*365/1000	Unit conversions
18	CO2 co-produced, mass, t/yr	52,315	=B14*24*365/1000	Separated at production site
19				
20	*And how much CO2 is emitted from burning the biomethane?*			
21	CO2 from biomethane use, mass, kg/h	7,279.39	=B12/16*44	From mol ratios 1:1 for combustion and molecular weights
22	CO2 from biomethane use, mass, t/yr	63,767	=B21*24*365/1000	Unit conversions, this portion distributed emission at user
23				
24	*So what is total CO2 asociated with biomethane production and use?*			
25	Total CO2 from biomethane, t/yr	116,083	=B18+B22	But 55%* of this is distributed emission at user

6.4 Calculation of CO_2 emission from biomass combustion for electricity



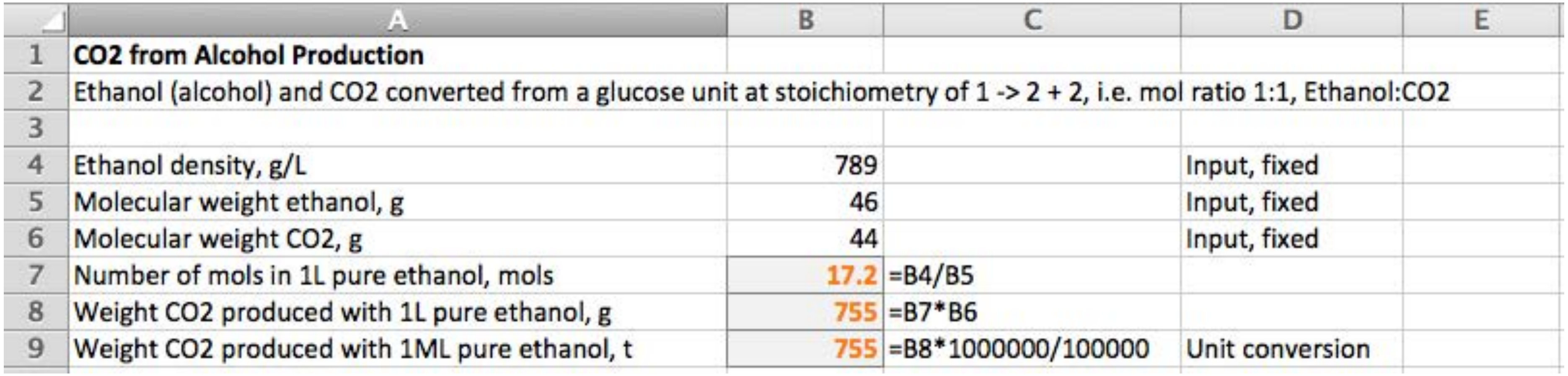
	A	B	C	D	E
1	**Calculation of CO2 emission from biomass combustion for electricity**				
2					
3	Assume electrical conversion efficiency, %	35.0		Input, variable	
4	Electrical generation, output, GWh	1,232.4		Input, variable	BEIS data, 2016
5	Hence feed energy input, GWh	3,521.05	=B4/B3*100	Adjusting for efficiency	
6	Specific emission from wood, kgCO2/kWh	0.39			
7	Annual emission, t-CO2/yr	1,373,211	=B5*B6*1000	Calculating emissions and unit conversion	

6.5 Estimate of CO_2 emission from biomass combustion for heat



	A	B	C	D	E	F
1	**Estimate of CO2 emissions from biomass combustion for heat**					
2						
3	2015 heat data	From Flynn, 2016		Emission factor	0.39	kg-CO2/kWh
4						
5		Heat output, GWh	Heat efficiency, %	Feed energy, GWh	Estimated CO2 emission, t	
6				=B6/C6*100	=D6*E2*1000	First line calculation
7	Biomass	2,203	80	2754	1,073,963	
8	Biomass CHP	1,517	45	3371	1,314,733	
9	EfW	192	45	427	166,400	
10			Sums	6,552	2,555,096	

6.6 Calculation of CO_2 arising from alcohol production



	A	B	C	D	E
1	**CO2 from Alcohol Production**				
2	Ethanol (alcohol) and CO2 converted from a glucose unit at stoichiometry of 1 -> 2 + 2, i.e. mol ratio 1:1, Ethanol:CO2				
3					
4	Ethanol density, g/L	789		Input, fixed	
5	Molecular weight ethanol, g	46		Input, fixed	
6	Molecular weight CO2, g	44		Input, fixed	
7	Number of mols in 1L pure ethanol, mols	17.2	=B4/B5		
8	Weight CO2 produced with 1L pure ethanol, g	755	=B7*B6		
9	Weight CO2 produced with 1ML pure ethanol, t	755	=B8*1000000/100000	Unit conversion	

6.7 Scottish landfill gas CHP: generation and estimated CO_2 emission

Source Variable Pitch (2017): https://www.variablepitch.co.uk/stations/technology/104/ and subsidiary tables; final column calculated

Site Name	Postcode	Capacity, kW	Average capacity factor, %	Generation 2016/17, GWh	Estimated emission, t-CO_2/yr
Greengairs Phases 1,3,5,6	ML6 7TY	12,552	69.65	62.8	59,749
Greenoakhill LF site and Patersons Quarries Generating Station – A	G32 8JF	8,264	69.95	50.6	48,210
Stoneyhill RO Generation - A,C	AB42 0PR	5,325	95.17	44.4	42,269
Avondale Power Station - A	FK2 0YG	11,376	39.34	39.2	37,327
Cathkin RO Generation - A,C	G74 4GY	7,396	49.71	30.3	28,814
Auchencarroch Original and #2 Landfill Site- A,C	G83 9LU	5,154	62.97	29.8	28,379
Dunbar Power Plant, D	EH42 1SW	6,790	45.87	27.3	25,978
Garlaff Landfill Gas Project	KA18 2RB	5,000	57.76	25.3	24,088
Auchinlea	ML1 5LR	2,272	85.65	17.0	16,231
Binn Landfill	PH2 2PX	3,333	51.12	14.9	14,211
Lochead Melville - A, C	KY15 7UL	1,431	85.34	10.7	10,186
Summerston	G23 5HD	2,850	42.46	10.6	10,093
Shewalton Landfill Site - A	KA11 5DF	1,836	56.25	9.0	8,614
Lochhead Fife Power - A	KY12 0RX	2,272	39.69	7.9	7,521
Tarbothill	AB23 8BT	1,100	60.29	5.8	5,531
Easter Langlee	TD1 2NT	760	85.34	5.7	5,410
Oatslie Generation - A (07/02/07)	EH25 9QN	2,630	23.56	5.4	5,168
Rigmuir	G75 0QZ	2,100	29.14	5.4	5,104
Nether Dallachy Renewable Energy	IV32 7TB	1,039	55.91	5.1	4,845
Locharmoss Landfill Site	DG1 1QS	800	68.78	4.8	4,589

Appendix 6.7 continued.

Site Name	**Postcode**	**Capacity, kW**	**Average capacity factor, %**	**Generation 2016/17, GWh**	**Estimated emission, t-CO_2/yr**
Hill of Tramaud Generating Station	AB23 8BQ	1,355	31.47	3.7	3,557
Levenseat Renewable Energy	ML11 8EB	910	35.44	2.8	2,690
Lochhead Landfill Site - A	DD8 2RL	1,136	27.14	2.7	2,572
Bonnyrigg Landfill (Melville)	EH18 1HN	1,150	26.4	2.7	2,532
Drummond Moor Generation - A (07/2/07)	EH26 8QF	1,150	22.64	2.3	2,172
Lower Polmaise Landfill Gas	FK7 7LU	575	28.84	1.5	1,383
Straid Farm - A	KA26 0JF	625	16.86	0.9	879
Kaimes Landfill Site	EH27 8EF	2,600	2.83	0.6	614
Knowehead Landfill	DD5 3QF	1,003	3.52	0.3	294

6.8 Larger Scottish AD biogas CHP and biomethane plant: estimated CO_2 emissions

Developer	**Site name**	**Near**	**CHP capacity**	**Biomethane**	**CO_2 from CHP**	**CO_2 co-produced with biomethane**	**Combined CO_2 emission at site**
			kW-e	Nm^3/h	t-CO_2/yr	t-CO_2/yr	t-CO_2/yr
Criterion: CHP plant with >=1000 kW-e capacity							
SSE	Barkip AD	Dalry	2,200		7,949		7,949
Scottish Water Horizons	Deerdykes composting and organics recycling facility	Cumbernauld	1,000		3,613		3,613
Fife Council	Lochhead Landfill	Dunfermline	1,400		5,058		5,058
Alauna Renewable Energy	Millerhill AD	Dalkeith	1,400		5,058		5,058
North British Distillery	North British Distillery	Edinburgh	3,400		12,284		12,284
Diageo	Cameronbridge Distillery	Methil	5,500		19,872		19,872
J Cunningham-Jardine	West Roucan Farm	Dumfries	1,200		4,336		4,336
GlaxoSmithKline	GSK Irvine	Irvine	1,000		3,613		3,613
Qila Energy	Wester Kerrowgair Farm	Inverness	1,000		3,613		3,613
Diageo	Glenfiddich Distillery	Dufftown	3,500		12,646		12,646
Subtotals			21,600		78,042		78,042

Appendix 6.8 continued.

Developer	**Site name**	**Near**	**CHP capacity**	**Biomethane**	**CO_2 from CHP**	**CO_2 co-produced with biomethane**	**Combined CO_2 emission at site**
			kW-e	Nm^3/h	t-CO_2/yr	t-CO_2/yr	t-CO_2/yr
Criterion: All plant with biomethane upgrading							
Shanks	Cumbernauld AD	Cumbernauld	3,600	495	13,007	3,114	16,121
William Grant & Sons	Girvan Distillery	Girvan	7,200	2,750	26,014	17,302	43,316
Keithick Biogas	Keithick Farm	Coupar Angus	500	605	1,807	3,806	5,613
TD Forster & Son	Peacehill Farm	Tayside	500	550	1,807	3,460	5,267
Charlesfield First	Cherlesfield Industrial Estate	St Boswells	500	550	1,807	3,460	5,267
Buchan Biogas	Downiehills Farm	Peterhead	500	550	1,807	3,460	5,267
Tambowie Biogas	Tambowie Farm	Milngavie	250	220	903	1,384	2,287
Qila Energy	Morayhill AD	Inverness	250	495	903	3,114	4,018
Qila Energy	Inchdairney Farm	Glenrothes	2,000	500	7,226	3,146	10,372
Qila Energy	Rosskeen Farm	Invergordon	250	450	903	2,831	3,735
Qila Energy	Brae of Pert Farm	Brechin	250	550	903	3,460	4,364
Qila Energy	Savock Farm	Ellon	250	600	903	3,775	4,678
Subtotals			16,050	8,315	57,989	52,315	110,305
Total t-CO_2/yr					136,031	52,315	188,346

6.9 Biogenic CO_2 emissions from sewage gas and landfill gas in Scotland

Estimates of biogenic CO_2 emissions in Scotland >10,000 t/yr; from sewage gas and landfill gas

	Postcode	Capacity, kW	Achieved capacity factor, year to 09/17, %	Theoretical output, GWh	Actual output year to 09/17, GWh	Estimated biogenic CO_2 emission, t/yr
Sewage gas sites						
Seafield - A, C, D	EH6 7RF	3542	60.53	31.03	18.78	17,882
Landfill gas sites						
Greengairs Landfill - combined entries (3)	ML6 7TY	10252	69.88	89.81	62.75	59,749
Greenoakhill Landfill/Paterson's Quarries - combined entries (2)	G32 8JF	8264	69.94	72.39	50.63	48,210
Stoneyhill RO Generation - A,C	AB42 0PR	5325	95.17	46.65	44.39	42,269
Avondale Power Station - A	FK2 0YG	11376	39.34	99.65	39.20	37,327
Cathkin RO Generation - A,C	G74 4GY	7396	49.71	64.79	32.21	28,814
Auchencarroch Landfill - combined entries (2)	G83 9LU	5154	66.02	45.15	29.81	28,379
Dunbar Power Plant, D	EH42 1SW	6790	45.87	59.48	27.28	25,978
Garlaff Landfill Gas Project	KA18 2RB	5000	57.76	43.80	25.30	24,088
Auchinlea	ML1 5LR	2272	85.65	19.90	17.05	16,231
Binn Landfill	PH2 2PX	3333	51.12	29.20	14.93	14,211
Lochead Melville - A, C	KY15 7UL	1431	85.34	12.54	10.70	10,186
Summerston	G23 5HD	2850	42.46	24.97	10.60	10,093

Input data source: Variable Pitch (2017)
Sewage gas - https://www.variablepitch.co.uk/stations/technology/128/
Landfill gas - https://www.variablepitch.co.uk/stations/technology/104/

6.10 Biogenic CO_2 emissions from AD sites with CHP in Scotland

Estimates of biogenic CO_2 emissions in Scotland >10,000 t/yr; AD sites with CHP

	Postcode	Capacity, kW	Theoretical output, GWh	Estimated biogenic CO_2 emission, t/yr
AD with CHP sites				
Diageo, Cameronbridge Distillery, Methil	KY8 5RL	5,500	48.18	19,872
Diageo, Glenfiddich Distillery, Speyside	AB55 4DH	3,500	30.66	12,646
North British Distillery, Edinburgh	EH11 2PX	3,400	29.78	12,284

Input data source: NNFCC (2017) AD Portal website http://www.biogas-info.co.uk/resources/biogas-map/

6.11 Biogenic CO_2 emissions from AD sites with CHP and biomethane in Scotland

Estimates of biogenic CO_2 emissions in Scotland >10,000 t/yr; AD sites with CHP and biomethane upgrading

	Postcode	Capacity, kW	Theoretical output, GWh	Biomethane injection capacity, Nm^3/h	CHP CO_2 emission, t/yr	Biomethane upgrading CO_2 emission, t/yr	Estimated combined biogenic CO_2 emission, t/yr
AD with CHP and biomethane sites							
William Grant & Sons, Girvan Distillery AD	KA26 9PT	7,200	63.07	2,750	26,014	17,302	43,316
Shanks, Cumbernauld AD	G67 3EN	3,600	31.54	495	13,007	3,114	16,121
Qila Energy, Inchdairney Farm, Glenrothes	KY5 0UL	2,000	17.52	500	7,226	3,146	10,372

Input data source: NNFCC (2017) AD Portal website http://www.biogas-info.co.uk/resources/biogas-map/

6.12 Biogenic CO_2 emissions from biomass combustion for heat or CHP in Scotland

Estimates of biogenic CO_2 emissions in Scotland >10,000 t/yr; biomass combustion for heat or CHP

	Postcode	Total CO_2 emission, t/yr	Estimated biogenic CO_2 emission, t/yr
Biomass combustion - mainly heat			
Caledonian Paper Mill	KA11 5AT	279,483	265,508
Norbord Cowie Board Mill	FK7 7BQ	268,160	171,622
Norbord Morayhill Mill	IV2 7JQ	106,333	101,017
Biomass - CHP			
RWE Innogy Markinch	KY7 6GU	438,000	429,240
Steven's Croft Power Station	DG11 2SQ	370,965	363,546
Westfield Biomass Plant	KY5 0HR	106,881	89,780

Input data source: SEPA (2017) Scottish Pollutant Release Inventory 2016 http://apps.sepa.org.uk/spripa/Search/ByPollutant/Criteria.aspx

6.13 Biogenic CO_2 emissions from fermentation industry in Scotland

Estimates of biogenic CO_2 emissions in Scotland >10,000 t/yr; fermentation industry

	Postcode	**Quoted Capacity / MLPA**	**Estimated production /MLPA**	**Estimated biogenic CO_2 emission, t/yr**
Fermentation - grain distilleries				
Diageo, Cameronbridge Distillery, Methil	KY8 5RL	105	94.5	71,319
William Grant & Sons, Girvan Distillery	KA26 9PT	75	67.5	50,942
North British Distillery, Edinburgh	EH11 2PX	72	64.8	48,904
Whyte & MacKay, Invergordon Distillery	IV18 0HP	40	36.0	27,169
Strathclyde Distillery, Glasgow	G5 0QB	40	36.0	27,169
Starlaw Distillery, Bathgate	EH47 7BW	25	22.5	16,981
Loch Lomond Distillery, Alexandria	G83 0TL	18	16.2	12,226

Input data source: Whisky Invest Direct (2017a) https://www.whiskyinvestdirect.com/about-whisky/grain-whisky-distilleries-in-scotland

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