Scotland's Net Zero Roadmap: D1.3.1 Report on Biogenic CO_2 Emissions Potential

Authors: Richard L Stevenson,

Dr Erika Palfi, Rebecca Bell

Organisation: The University of Edinburgh / SCCS

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About Scotland's Net Zero Roadmap and Partners

Scotland's Net Zero Roadmap (SNZR) is Innovate UK funded project number 75206. The aim of the project is to develop a roadmap that sets out how Scottish industry can move towards Net Zero by 2045, based on exploring a number of decarbonisation scenarios. The project focuses on a cluster of industrial activity on the East Coast of Scotland which covers many of the largest industrial sites across a range of sectors and 80% of Scotland's industrial CO_2 emissions.

SNZR is led by NECCUS and other project partners are Aker Solutions Limited, Costain Limited, Altrad Babcock Limited, Energy System Catapult Limited, Halliburton Manufacturing and Services Limited, Net Zero Technology Centre, Optimat Limited, Pale Blue Dot Energy Limited, The University of Edinburgh, The University of Strathclyde, and Wood Limited.

Executive Summary

The Scotland's Net Zero Roadmap (SNZR) project is one of six roadmap projects aimed at producing detailed plans to reduce carbon emissions from major industrial areas across the UK. Funded by the Industrial Strategy Challenge Fund (ISCF) as part of the UK Government Industrial Decarbonisation Challenge (IDC), the SNZR project brings together 11 partner organisations from industry and academia to map out industry's role in achieving Scotland's target of Net Zero by 2045.

This report summarises the findings of Work Package 1 Task 1.3, which was focused on conducting an assessment of the potential for achieving engineered greenhouse gas removals (GGRs) within the SNZR cluster boundary by attempting to quantify the total amount of biogenic carbon dioxide (CO_2) that is (i) available and (ii) capturable, assuming the most recent capture rates that research and current commercial activities have shown to be possible. The study includes a review of existing Scottish industries that have biogenic CO_2 emissions, covering bioenergy systems for heat and/or electricity generation, which may be combined with CCS – known as bioenergy with carbon capture and storage, or BECCS; and non-energy systems for the production of alcohol. Bioenergy systems were segmented into three groups: biomass combustion for heat and/or combined heat and power (CHP); anaerobic digestion (AD) to produce biogas and/or biomethane, including AD in landfills, sewage treatment works, wet-waste processing and crop residue treatment; and energy-from-waste (EfW) systems. Fermentation - which, for the purposes of this study, pertains only to large-scale grain whisky distilleries - is included due to its scale of biogenic CO_2 emissions and the potential for lower-cost capture from concentrated CO_2 streams.

In total, 46 individual sources with a biogenic CO_2 potential of over 5ktCO_2/yr are identified within the geographical boundary of the SNZR cluster for the period 2021-2045. This covers facilities already operational in 2021 and new developments projected to come online (and offline) in the intervening years. The 46 sources are comprised of 43 from bioenergy and 3 from fermentation, and represent facilities from 7 industrial sectors: Cement, Commercial/Institutional, Food & Drink, Iron & Steel, Wood Fibre/Board, Power and Waste.

Figure 1 presents a high-level overview of how the cluster looks now (2021) and how it could look in 2045, in terms of the quantity of capturable biogenic CO_2. This includes the current (2021) baseline, with sectoral breakdown, and the changes projected by the illustrative future scenarios. According to the projections, by 2045, and growing at a compound annual growth rate (CAGR) of 6.4% (central estimate), overall capturable quantities of biogenic CO_2 from across the cluster are projected to rise to between 5-10.2Mt/yr – representing an increase of between 3.3-8.5Mt/yr (or 199-508%), compared to 2021 levels.

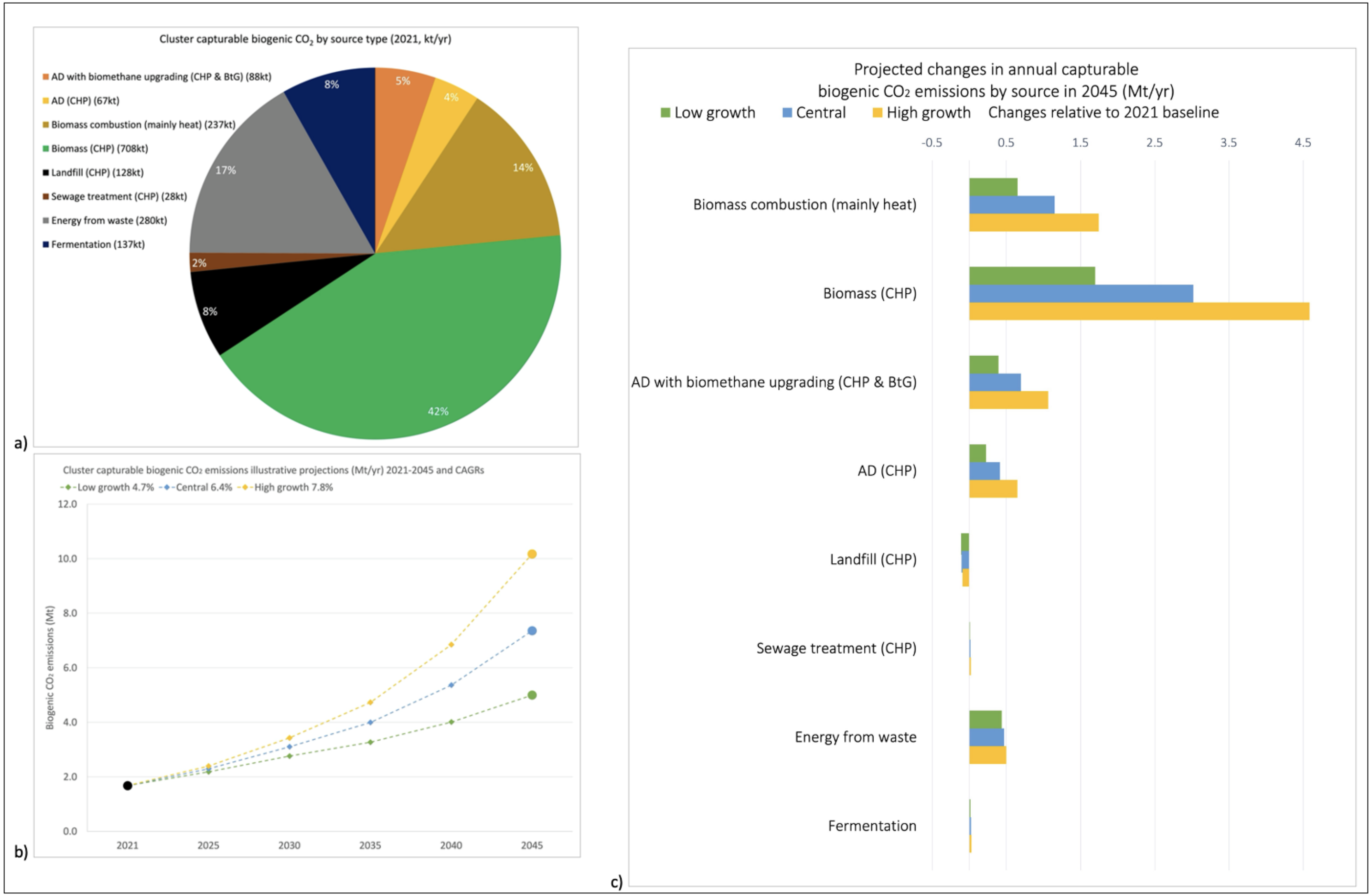

Figure 1: Overview of capturable biogenic CO_2 current (2021) baseline and cluster level illustrative projections (2021-2045) - a) current (2021) baseline broken down by sector: 1.7Mt/yr; b) illustrative future projections (2021-2045); c) projected changes by source (2021-2045)

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Acronyms

AD	Anaerobic Digestion
BECCS	Bioenergy with Carbon Capture & Storage
BEIS	Department for Business, Energy & Industrial Strategy
BtG	Biomethane to grid
CAGR	Compound Annual Growth Rate
CCPu	Climate Change Plan Update
CCS	Carbon Capture & Storage
CHP	Combined Heat & Power
CO_2/CO_2e	Carbon Dioxide/Carbon Dioxide equivalent
CH_4	Methane
DAC/DACCS	Direct Air Capture/Direct Air Capture & Carbon Storage
EfW	Energy from Waste
GHG/GHGs	Greenhouse gas(es)
GGR/GGRs	Greenhouse gas removal(s)
NNFCC	National Non-Food Crops Centre
REPD	Renewable Energy Planning Database
SEPA	Scottish Environment Protection Agency
SNZR	Scotland's Net Zero Roadmap
SPRI	Scottish Pollution Release Inventory

1 Introduction

1.1 SNZR background

The Scotland's Net Zero Roadmap (SNZR) project is one of six roadmap projects aimed at producing detailed plans to reduce carbon emissions[1] from major industrial areas across the UK[2]. Funded by the Industrial Strategy Challenge Fund (ISCF) as part of the UK Government Industrial Decarbonisation Challenge (IDC), the SNZR project brings together 11 partner organisations from industry and academia to map out industry's role in achieving Scotland's target of Net Zero by 2045[3].

The roadmap will consider multiple carbon reducing options such as electrification, the integration of renewable energy, fuel switching to clean sources (such as hydrogen), capture of carbon emissions from energy generation and industrial processes, and negative emissions opportunities (such as capturing carbon from biogenic energy sources). The project will create an energy system model covering key industrial sites along the Scottish East Coast, from the Lothians in the South to Aberdeenshire in the North. In total, 28 industrial sites will be assessed which collectively emit around 80%[4] of Scotland's industrial carbon dioxide (CO_2) emissions. It is therefore anticipated that any net zero solutions developed by the project can provide infrastructure plans and blueprints for the whole of Scotland. All of the data presented in this study is from publicly available sources.

1.2 Study aims

The purpose of this study is to inform policymakers, project developers and other key stakeholders of the potential scope for engineered greenhouse gas removals (GGRs) in Scotland, and thereby allow opportunities for policy support and incentives to be considered as part of the forthcoming Climate Change Plan, Energy Strategy and Just Transition Plan, and Bioenergy Action Plan as well as UK Government interventions.

1.3 Report focus

This report summarises the findings of Work Package 1 Task 1.3, which was focused on conducting an assessment of the potential for achieving engineered GGRs within the SNZR cluster boundary by attempting to quantify the total amount of biogenic[5] carbon dioxide (CO_2) that is (i) available and (ii) capturable, assuming the most recent capture rates that research and current commercial activities have shown to be possible. Within the context of the SNZR project, this study is focused on the collection and presentation of publicly available data that is relevant to understanding the current and

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[1] These roadmap projects are focused on carbon dioxide (CO_2) emissions only.
[2] BEIS (2021). Press Release. Available at: https://www.gov.uk/government/news/green-boost-for-regions-to-cut-industry-carbon-emissions
[3] Scottish Government (2019). Press Release. Available at: https://www.gov.scot/news/scotland-to-become-a-net-zero-society/
[4] SEPA (2020). SPRI dataset for 2019. Available at: https://www.sepa.org.uk/environment/environmental-data/spri/
[5] CO_2 emissions produced or brought about by living, or recently living, organisms, as opposed to CO_2 from petrochemical sources.

potential future biogenic CO_2 emissions profiles in the cluster. Where data is presented that is not publicly available, this is acknowledged, and the source is given.

This report presents a review of existing Scottish industries that emit biogenic CO_2 emissions, covering bioenergy systems for heat and/or electricity generation, which may be combined with CCS – known as bioenergy with carbon capture and storage, or BECCS; and non-energy systems for the production of alcohol that have CO_2 as a process emission. Bioenergy systems were segmented into three groups: biomass combustion for heat or combined heat and power (CHP); anaerobic digestion (AD) to produce biogas and/or biomethane, including AD in landfills, sewage treatment works, wet-waste processing and crop residue treatment; and energy-from-waste (EfW) systems for electricity and/or CHP. Emissions from EfW processes are currently accounted for in international reporting mechanisms under energy[6], not waste, and it is included here because the waste treated in these systems is from a mixture of biogenic and fossil origins, so a proportion of captured and stored CO_2 emissions will rate as GGR. Fermentation - which, for the purposes of this study, pertains only to large-scale grain whisky distilleries - is included due to its scale of biogenic CO_2 emissions and the potential for lower-cost capture from concentrated CO_2 streams. This covers facilities already operational in 2021 and new developments that are projected to come online in the intervening years.

The analysis and findings presented herein are exploratory in nature: these results did not feed into any other work package, either directly or indirectly, and are in that sense complementary to other activity undertaken across the SNZR project.

The remainder of this introduction outlines the Scottish context for engineered GGRs and gives an overview of the methodology and key assumptions that were made.

Section 2 presents the results of the assessment of total biogenic CO_2 available from facilities within the SNZR cluster area for the period 2021-2045. Section 3 is focused on the quantity of that biogenic CO_2 that is deemed capturable, according to the most recent capture rates that research and current commercial activities have shown to be possible. Section 4 is comprised of a case study to further outline the potential for near-term biogenic CO_2 capture in Scotland, and Section 5 summarises the key findings and conclusions.

1.4 Scottish context for engineered GGRs

This study represents a partial update of a study[7] carried out by Scottish Carbon Capture & Storage (SCCS) in 2018 into the potential for achieving negative emissions[8] in Scotland in the near- to mid-term. The context for that study was that "*Current thinking on climate change mitigation generally*

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[6] IPCC (2006). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 1 Chapter 8: Reporting Guidance and Tables. Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

[7] SCCS (2018). Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO2 emissions. Available at: https://www.sccs.org.uk/images/expertise/reports/working-papers/WP_SCCS_2018_08_Negative_Emission_Technology_in_Scotland.pdf

[8] In both the 2018 study and this one, only the potential for negative emissions is outlined via an assessment of the quantity of available/capturable biogenic CO_2. In order to assess and quantify which activities would qualify as effecting negative emissions, a full and proper lifecycle analysis would be required in each case to verify that net negative GGRs is achieved.

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."

At that time, the UK and Scotland both had targets of an 80% reduction in greenhouse gas (GHG) emissions by 2050. Then, in 2019, both the UK and Scottish Parliament legislated for net zero emissions targets by 2045 in Scotland and by 2050 in the UK as a whole. The existence of a net zero target makes the need for GGRs much more certain. Since emissions cannot be cut to zero, this implies the need to balance them by removing CO_2 from the atmosphere, whether using nature-based solutions (such as afforestation and peatland restoration) or engineered removals (such as capture and storage of biogenic CO_2 (BECCS or, more accurately, bio-CCS), or direct air CO_2 capture and storage (DACCS)), or, more likely, a combination of both.

Indeed, it is now generally accepted that GGRs will be needed to meet net zero targets, and this is reflected in subsequent UK and Scottish projections on the role of engineered GGRs and the potential demand for BECCS application. The UK's 6th Carbon Budget projects a UK-wide requirement for BECCS – BECCS power, BECCS EfW, BECCS in industry, BECCS hydrogen, BECCS biofuels, BECCS biomethane - of between 44-97MtCO_2/yr by 2050 and estimates that Scotland will need engineered GGRs in the range of 3-9MtCO_2/yr from the late 2020s to achieve its 2045 net zero target[9]. In line with that, the Scottish Government's Climate Change Plan update (CCPu)[10] proposes negative emissions interim targets of 3.8MtCO_2e and 5.7MtCO_2e by 2030 and 2032 respectively. Bioenergy market growth forecasts are also broadly aligned with these projections, suggesting annual growth of >8% during the period 2022-2027[11]. Beyond mid-century, it is likely that ambitions will be to keep emissions below net zero – that is, removing more GHGs than are released to the atmosphere, suggesting a longer-term role for engineered GGRs.

While the Scottish Government has not set targets for CCS, the CCPu acknowledges the essential role it will play in effecting negative emissions and envisages an established CCS industry by the end of this decade: "*technologies critical to further industrial emissions reduction (such as carbon capture and storage and production and injection of hydrogen into the gas grid) are operating at commercial scale by 2030*".

1.5 Methodology and key assumptions

This study is comprised of two key tasks. Firstly, a list of candidate facilities producing biogenic CO_2 emissions is compiled, including those currently operational and those in development. Secondly, CO_2 emissions profiles are calculated for those sites based on data collected from a range of publicly available sources. A set of three illustrative growth scenarios are then applied to the assessments of

[9] UK Climate Change Committee (2020). Sixth Carbon Budget. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/

[10] Scottish Government (2020). Securing a green recovery on a path to net zero: climate change plan 2018–2032 – update. Available at: https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

[11] Mordor Intelligence (2023). EUROPE BIOENERGY MARKET - GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2023 - 2028). Available at: https://www.mordorintelligence.com/industry-reports/europe-bioenergy-market

total available biogenic CO_2 and the portion that is deemed capturable, to allow some insight into how the cluster might evolve between now and 2045. The two key tasks are outlined below in Figure 2.

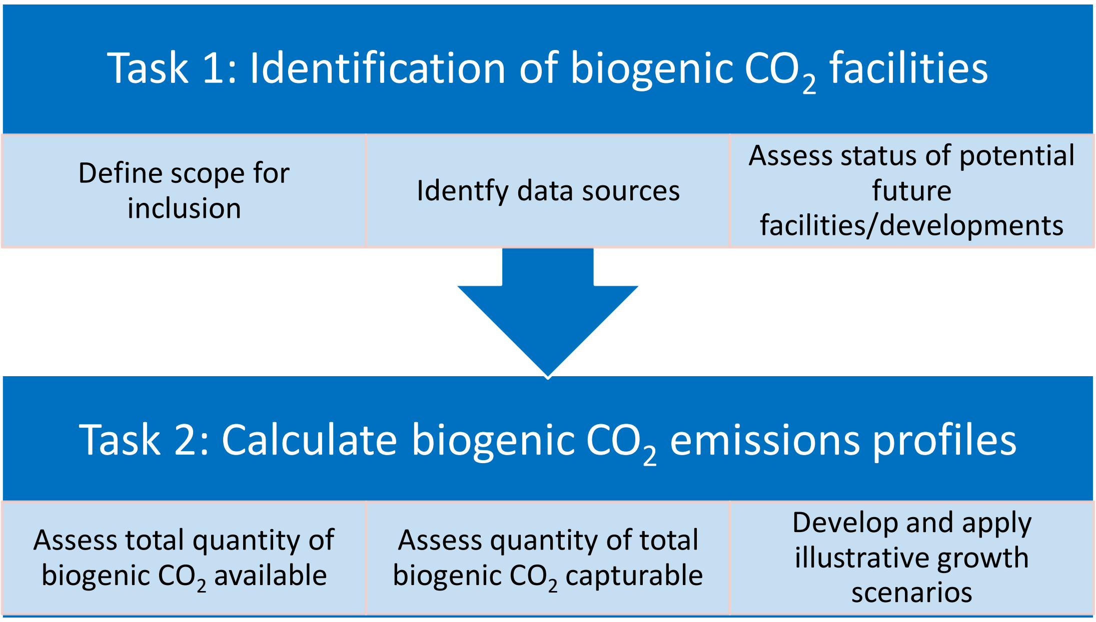

Figure 2: Task 1 and Task 2 overview

1.5.1 Facilities producing biogenic CO_2

Facilities from across the various sources and source types are identified from a combination of the following publicly available sources: The Official Information Portal on Anaerobic Digestion, which is maintained for the UK Government by NNFCC [12], Renewable Energy Planning Database (REPD), maintained by Barbour ABI on behalf of the Department of Business, Energy & Industrial Strategy (BEIS)[13], Ofgem Renewables Obligation Annual Report 2020-21[14], Scotch Whisky Industry Review 2021[15], Scottish Environment Protection Agency (SEPA) Scottish Pollution Release Inventory (SPRI) 2021[16], project/facility websites and local authority planning portals. Data for one plant – Norbord (Cowie), now West Fraser – comes directly from the company[17]. Inclusion of new developments during the period within scope are limited (somewhat conservatively) to those already under construction or in the commissioning phase. In this way, 7 new developments are identified, plus one facility scheduled for closure in 2030 (see 5Appendix A). With many more developments currently at various

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[12] NNFCC (2021). The Official Information Portal on Anaerobic Digestion. Available at: https://www.biogas-info.co.uk/resources/biogas-map/

[13] BEIS (2023). Renewable Energy Planning Database (REPD): January 2023. Available at: https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

[14] Ofgem Renewables and CHP Register (2021). Accredited Stations. Available at: https://renewablesandchp.ofgem.gov.uk/Public/ReportManager.aspx?ReportVisibility=1&ReportCategory=0

[15] Whisky Invest Direct (2023). Grain whisky distilleries in Scotland. Available at: https://www.whiskyinvestdirect.com/about-whisky/grain-whisky-distilleries-in-scotland

[16] SEPA (2021). Scottish Pollutant Release Inventory. Available at: https://www.sepa.org.uk/environment/environmental-data/spri/

[17] Personal communication with Nick Fedo, General Manager (West Fraser, Cowie) (March 2023)

stages of the planning process, It is highly likely that the number of new facilities coming online between 2021-2045 will be greater than this.

1.5.2 Estimating the amount of biogenic CO_2

The SEPA SPRI is the main source of data on CO_2 emissions from industry and commerce in Scotland. The SPRI reporting threshold for CO_2 is 10kt/yr. Reporting of biogenic CO_2 emissions in Scotland is not, however, a mandatory requirement, and while some data can be found in the SPRI, it is neither comprehensive nor consistent, although it is understood that efforts are underway to change this[18].

The threshold for inclusion in this study is 5kt/yr, some 50% lower than that of the SPRI. This is based on, and in consultation with, current commercial biogenic CO_2 capture operations in Scotland[19]. Therefore, for this study, additional sources of data[20] are required to calculate biogenic CO_2 emissions for the facilities within scope. The methodology employed herein is based on a combination of installed/generating capacity and uses a number of calculations following the earlier SCCS negative emissions study[7] with some updated figures and assumptions (noted where relevant). Sample calculations for every emission source can be found in the appendix section of that original report. Plant capacity data is obtained from the same sources as in 1.5.1 above, which is then used to estimate the total CO_2 emissions arising from biogenic sources. The following sections outline the methodology and key assumptions for each source type.

1.5.2.1 Biomass combustion

The projected scale of current biogenic CO_2 emissions arising from biomass combustion is determined from two different data sources and subsequently categorised into two distinct groups: biomass combustion primarily for heat and biomass combustion CHP.

The REPD[13] includes data on installed capacity for all UK renewable electricity and CHP projects and is updated quarterly. To estimate biogenic CO_2 emissions for biomass combustion CHP, capacity factors of 68% and 54.4% for plant and animal biomass respectively[21] and an electrical conversion efficiency of 35% were used. For biomass combustion mainly for heat provision, a UK capacity factor of 68%[20] and a heat efficiency of 80% are used. All biomass feedstock is assumed to be wood with a specific CO_2 emission of 0.39kg/kW, despite chicken litter being the main feedstock for one site – Westfield Biomass CHP.

1.5.2.2 Biogas, landfill gas, sewage gas and biomethane

Plant capacity data for AD biogas and biomethane upgrading, as of March 2021, are acquired from the AD portal[12], providing comprehensive information on both the CHP generation capacity and biomethane injection capacity of AD biogas plants. By utilising generation capacity data, with a presumed capacity utilisation factor of 80% for AD plants it was feasible to estimate the potential CO_2 emissions that could arise from these plants if they were to operate at maximum capacity.

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[18] Personal communication with Bob Boyce, Senior Data Scientist (SEPA) (May 2021)
[19] Carbon Capture Scotland can technically capture 3.5kt/yr. 5kt/yr represents a more economically viable threshold.
[20] Due to the absence of alternative publicly available data, SPRI data was used for the Tarmac facility.
[21] BEIS (2022). Energy Trends: December 2022. ET_6.1_DEC_22. Available at: https://www.gov.uk/government/statistics/energy-trends-december-2022

For AD biogas combustion activity, emissions are projected based on an assumed mid-range energy conversion efficiency to electricity of 37.5% and a typical biogas composition with a CH_4:CO_2 ratio of 55:45 by volume. The energy content of methane is presumed to be the higher heating value (HHV), while gas densities were determined by utilising values reported in the literature[22] . Emissions from biomethane upgrading are projected using the same assumptions and sources as for biogas above, and a separate capacity factor of 47.7%. The calculations for biomethane upgrading provide two values: the first value is for the CO_2 that is separated from the raw biogas, which would typically be discharged at the upgrading site, and the second value is for the CO_2 from the combustion of the upgraded biomethane, which would usually be released at the site(s) where the biomethane is ultimately utilised. Only the CO_2 discharged at the upgrading site is within the scope of this study.

For landfill and sewage gas combustion activity, actual generation and CO_2 emissions for each location are projected based on installed capacity data for plants that were operational during the period of 2020 to 2021[14][23], and average Scottish capacity factors for landfill gas (37.5%) and sewage gas (61.6%)[21]. The same assumptions and methodology are then used as outlined for biogas above, but using a landfill gas composition ratio of 50:50 by volume of CH_4:CO_2[24].

1.5.2.3 Energy from waste

Biogenic CO_2 emissions for EfW facilities are projected based on plant waste processing capacity data collected from project or facility websites and (where necessary) local authority planning portals. Emissions arising from EfW are modelled on a ratio of 0.9:1 (tCO_2:t/waste processing capacity), i.e. $0.9tCO_2$ produced for every 1t of waste processed[25][26]. Plants are assumed to operate at 50% of plated capacity during the first year of operation and at 95%/yr for the rest of their operational lifetime. It is assumed that 50% of emissions arising from EfW is biogenic in origin, following the generally accepted UK industry baseline, though it is accepted that this figure could be conservative and is certainly subject to change[27].

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[22] The Engineering Toolbox (2023). Available at: https://www.engineeringtoolbox.com/

[23] Emissions from landfill gas were calculated based on modelled actual generation figures, which accounts for the fact that average rate of collection of the UK landfill methane resource since 2013 is approximately 61% - see BEIS (2022) UK Greenhouse Gas Inventory 1990 to 2020: Annual Report for submission under the Framework Convention on Climate Change. Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2206220830_ukghgi-90-20_Main_Issue1.pdf

[24] Agency for Toxic Substances and Disease Registry (2001). Chapter 2: Landfill Gas Basics. Available at: https://www.atsdr.cdc.gov/hac/landfill/html/ch2.html

[25] Eunomia (2021). CCUS Development Pathway for the EfW Sector. Available at: https://www.eunomia.co.uk/reports-tools/ccus-development-pathway-for-the-efw-sector/

[26] Energy Systems Catapult (2020). Energy from Waste Plants UK with Carbon Capture. Available at: https://es.catapult.org.uk/report/energy-from-waste-plants-uk-with-carbon-capture/

[27] While 50% is the current generally accepted figure in the UK, this can be as high as 70% in some European countries – see NEWEST-CCUS (2023). Webinar 2: Carbon Capture and Storage for Waste to Energy: Evaluating climate impacts and technologies. Available at: https://www.newestccus.eu/events/webinar-2-carbon-capture-and-storage-waste-energy-evaluating-climate-impacts-and-technologies. Also, the biogenic fraction of Scotland's waste is likely to change in future, owing to improved biological waste processing, which would act to reduce it, and recent recommendations to remove fossil-based plastics from the incineration waste stream by 2030 – see Scottish Government (2023). Decarbonisation of residual waste infrastructure: report. Available at:

(footnote continued)

1.5.2.4 Fermentation

To determine the amount of CO_2 emitted from fermentation processes, two main factors are considered: firstly, the production of pure alcohol intended for use in beverages; and secondly, the ratio of CO_2 to pure alcohol produced during fermentation.

Actual volumes of pure alcohol produced by specific breweries and distilleries are not publicly available, most likely for reasons of commercial sensitivity. Hence, plant capacity data from fermentation industries are used to estimate CO_2 emissions, all of which will be biogenic. Figures for the amount of pure alcohol produced at grain whisky distilleries in Scotland, including alcohol used in other spirits such as gin and vodka, is derived from distillery capacity data[15] and by applying a process capacity factor of 90%. Malt whisky production is similarly assessed, but found to be below the 5kt/yr threshold in all cases within scope.

To estimate the ratio of CO_2 to alcohol that is produced, the methodology assumes that fermentation of one molecule of glucose produces two molecules of ethanol and two molecules of CO_2 in a 1:1 molar ratio. By adjusting this ratio for the molecular weights of ethanol (46g/mol) and CO_2 (44g/mol), and for the density of ethanol (0.789kg/litre), it is determined that 0.755kgCO_2 is produced per litre of pure ethanol.

1.5.3 Development of future illustrative scenarios

In order to project how quantities of biogenic CO_2 might change over time, a set of three illustrative scenarios are developed: 'High growth', 'Central' and 'Low growth'. The scenarios assume continued general support for bioenergy, whether that be from successor incentive schemes, e.g. following on from the Green Gas Support Scheme (GGSS), or from buoyant market forces, both of which would align with projected demand and stated necessity of GGRs for achieving climate change targets[28][29] and current market growth forecasts. It should be noted that the scenarios are influenced by and are sensitive to several factors: firstly, they do not consider issues around the availability and provenance of sustainable biomass feedstock; secondly, new developments are limited to those either currently under construction or in the commissioning phase (see 1.5.1); and thirdly, uncertainties around EfW feedstock could act to either increase or decrease the resulting biogenic fraction of emissions (see 1.5.2.3).

Emissions from bioenergy are plotted using Compound Annual Growth Rates (CAGR) – see 5Appendix C - based on a combination of reported renewable electricity generation in the BEIS Energy Trends

https://www.gov.scot/publications/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-second-report-decarbonisation-residual-waste-infrastructure-scotland/pages/7/ - which could act to increase it.

[28] Ricardo Energy & Environment on behalf of ClimateXChange (2022). Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets. Available at: https://www.climatexchange.org.uk/media/5276/cxc-comparing-scottish-bioenergy-supply-and-demand-in-the-context-of-net-zero-targets-february-2022.pdf

[29] Scottish Government (2023). Draft Energy Strategy and Just Transition Plan. Available at: https://www.gov.scot/publications/draft-energy-strategy-transition-plan/

database[30][31] and energy and emissions projections in the BEIS EEP 2021 dataset[32]. Emissions from fermentation are projected using historical UK whisky production data[33]. This is because biogenic CO_2 arising from the fermentation process is (by definition) a process emission, rather than from combustion activities for the purpose of energy generation.

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[30] BEIS (2023). Energy Trends: December 2022. Available at: https://www.gov.uk/government/collections/energy-trends

[31] Bioenergy (not including EfW) CAGRs were calculated based on a 2016-2021 subset of the BEIS ET reported renewable electricity generation figures, to account for a more modest growth rate owing to the impact of incentive schemes such as the Renewables Obligation (RO), Non-domestic Renewable Heat Incentive (NDRHI) and Feed-in Tariffs (FIT)

[32] BEIS (2022). Energy and emissions projections: 2021 to 2040, Appendix C: Carbon dioxide emissions by IPCC category. Available at: https://www.gov.uk/government/publications/energy-and-emissions-projections-2021-to-2040

[33] Office for National Statistics (2022), UK Manufacturers' Sales by Product Survey (Prodcom). Available at: https://www.ons.gov.uk/file?uri=/businessindustryandtrade/manufacturingandproductionindustry/datasets/ukmanufacturerssalesbyproductprodcom/current/finalprodcomdata2021.xlsx

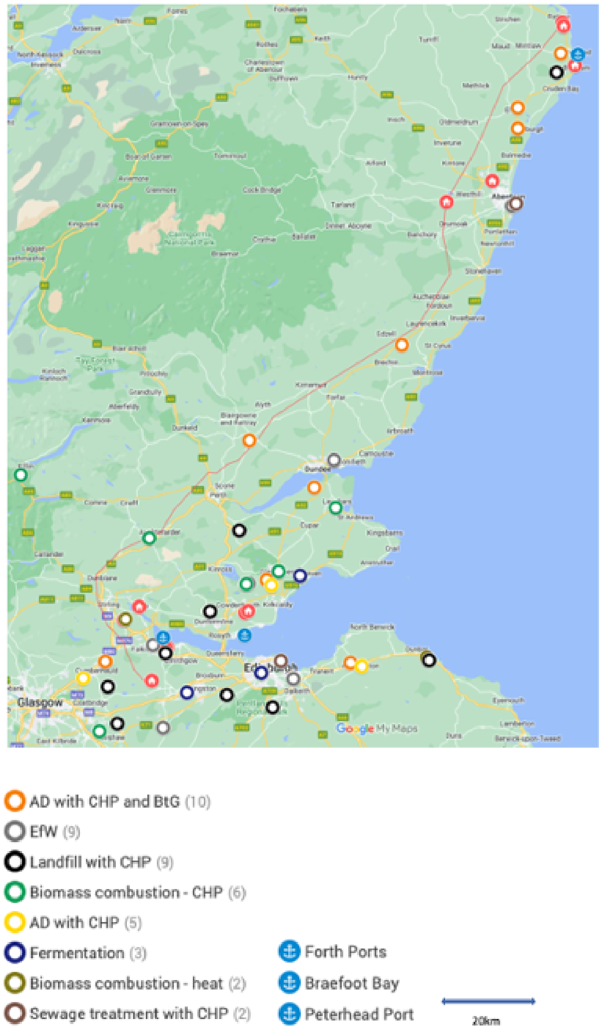
2 Assessment of total biogenic CO_2 available (2021-2045)

This section outlines the total quantity of biogenic CO_2 available within the geographical boundary of the SNZR cluster for the period 2021-2045. This includes an overview of where the cluster is now (2021) and a set of illustrative projections to 2045, which offer some insight as to how things might have changed by then.

2.1 Total biogenic CO_2 emission sources and profiles – cluster level (2021-2045)

In total, 46[34] individual sources of biogenic CO_2 are identified, covering facilities already operational in 2021 and new developments projected to come online in the intervening years. According to the central estimate, the total quantity of biogenic CO_2 being produced across the cluster goes from 1.7Mt/yr in 2021 to 7.8Mt/yr in 2045. Almost all facilities (45 out of 46) are within 20km of proposed CO_2 transport infrastructure (pipelines/shipping ports/rail terminals) and/or at least one of the SNZR 28 sites; 11 are existing SNZR 28 sites and 7 are new/significant (post-2021) developments. The 46 sources are comprised of 43 from bioenergy and 3 from fermentation, and represent facilities from 7 industrial sectors: Cement, Commercial/Institutional, Food & Drink, Iron & Steel, Wood Fibre/Board, Power and Waste. Figure 3 gives an overview of the geographical, industrial and emissions scope of the assessment of total biogenic CO_2 available.

[34] By 2045, there will be 45 operational facilities because one of them comes offline in 2030 – see 5Appendix A



Facilities in scope: **46**

Existing SNZR sites within scope: **11**

Facilities within 20km of proposed CO_2 transport infrastructure and/or at least one SNZR 28 site: **45**

Total biogenic CO_2 emissions within scope (≥5kt/yr, central estimate)
2021: **1.7Mt**
2045: **7.8Mt**

Sources of biogenic CO_2 within scope: **8**

Bioenergy sources

- Biomass combustion (mainly heat)
- Biomass combustion (CHP)
- AD with biomethane upgrading (CHP+BtG)
- AD (CHP)
- Landfill (CHP)
- Sewage treatment (CHP)
- Energy from Waste (EfW)

Non-energy sources

- Fermentation

Industrial sectors covered by biogenic CO_2 sources: **7**

- Cement
- Commercial/Institutional
- Food & Drink
- Iron & Steel
- Wood Fibre/Board
- Power
- Waste

Figure 3: Geographical, industrial and emissions scope of total biogenic CO_2 available - cluster level (2021-2045)

2.2 Current total biogenic CO_2 emission sources and profiles – source level (2021)

Of the 46 sites within scope, 39 are operational in 2021 producing a combined 1.7Mt biogenic CO_2/yr. Bioenergy sources accounted for 92% of the total, with the remaining 8% coming from fermentation. The absolute and percentage share of biogenic CO_2 for each source and source type are summarised in Figure 4 below.

CO_2 comes predominantly from three bioenergy sources, which, combined, account for 71% of all biogenic CO_2 within scope in 2021: Biomass (CHP) is the largest source (41% or 716kt); EfW the second largest (16% or 280kt); followed by Biomass combustion for mainly heat provision (14% or 240kt). The three next largest sources are Fermentation (8% or 142kt), AD with biomethane upgrading (CHP & BtG[35]) (8% or 137kt) and Landfill (CHP) (7% or 129kt).

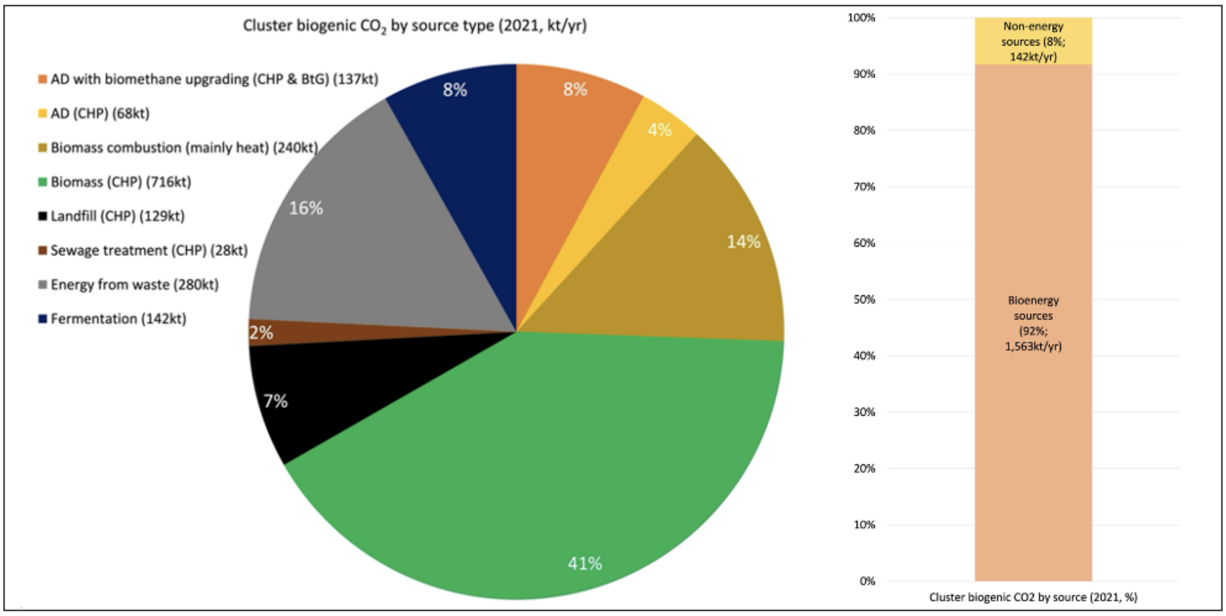


Figure 4: Cluster biogenic CO_2 by source and source type (2021)

NB: Figures may not add up exactly due to rounding

2.2.1 Current total biogenic CO_2 from bioenergy sources (2021)

Bioenergy systems are segmented into three groups: biomass combustion for heat or CHP; AD to produce biogas and/or biomethane, including AD in landfills, sewage treatment works, wet-waste processing and crop residue treatment; and EfW systems for electricity and/or CHP.

There were 36 bioenergy facilities (see **Error! Reference source not found.**) operational in 2021, accounting for 1.6Mt biogenic CO_2/yr. Table 1 provides an overview of the total projected biogenic CO_2 available from all bioenergy sources.

[35] Biomethane to grid (BtG)

Bioenergy source	Source type	No. of sites	Projected total biogenic CO_2 (kt/yr)
Biomass combustion	Mainly heat	2	240
	CHP	6	716
AD	Biomethane upgrading (CHP+BtG)	8	137
	AD (CHP)	5	68
	Landfill (CHP)	9	129
	Sewage treatment (CHP)	2	28
EfW	EfW	4	280
Total[36]		**36**	**1,598**

Table 1: Projected total biogenic CO_2 from all bioenergy sources (2021)

2.2.2 Current total biogenic CO_2 from non-energy sources (2021)

Non-energy sources of biogenic CO_2 are comprised of a single source: fermentation, which, for the purposes of this study, pertains only to large-scale grain whisky distilleries. It is included here due to the scale of its biogenic CO_2 emissions and the potential for lower-cost capture from concentrated and almost pure (98%) CO_2 streams.

There were 3 non-energy (fermentation) facilities (see 5Appendix B 5Appendix B) operational in 2021, accounting for 0.1Mt[37] biogenic CO_2/yr.

2.3 Future total biogenic CO_2 emission sources and profiles (2021-2045)

The scenarios incorporate seven newly operational, announced and/or projected developments meeting the 5kt/yr minimum threshold that have either come online since 2021 or have been assessed as certain[38] to do so during the period 2021-2045 plus one facility closure, in addition to the 39 facilities that were already operational in 2021. The projections are summarised at both the cluster and source level.

NB: These scenarios represent hypothetical futures that are broadly aligned with Scottish and UK climate change targets and market growth forecasts. As such, they offer some insight into how these sectors could develop. They are neither intended to represent pathways nor forecasts of what will happen.

[36] NB figures may not add up exactly due to rounding
[37] Rounded from 142 ktCO_2/yr
[38] Sites/facilities either currently under construction or in commissioning phase

2.3.1 Future total biogenic CO_2 emissions illustrative scenarios - cluster level

By 2045, and growing at a CAGR of 6.5% (central estimate), overall quantities of biogenic CO_2 available across the cluster are projected to rise to between 5.3-10.8Mt/yr, representing an increase of between 3.5-9.1Mt/yr (or 200-520%), compared to 2021 levels – see Figure 5 below.

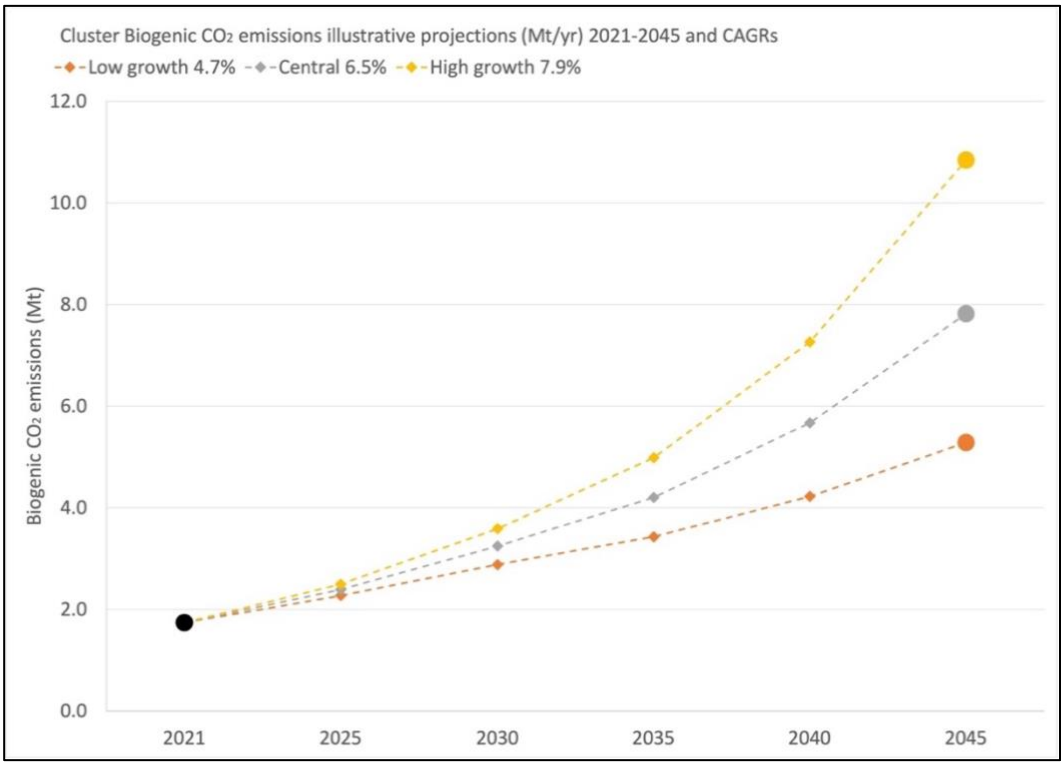


Figure 5: Future total biogenic CO_2 emissions illustrative scenarios – cluster level (2021-2045)

2.3.2 Future total biogenic CO_2 emissions illustrative scenarios – source level

There is considerable variation between the various source types in how the projections assume they will evolve. In 2045, and in line with anticipated market growth and demand profiles, most bioenergy source types are projected to see increases in biogenic CO_2 emissions, ranging from AD (CHP) at 230kt/yr (low growth) to Biomass (CHP) at 4.6Mt/yr (high growth), with Sewage treatment (CHP) showing only a very slight increase of around 17kt/yr that is broadly in line with incremental population increase. Landfill (CHP) is the only bioenergy source to see a decrease, attributable to the 'tailing off' of landfill emissions largely as a result of the imminent (near) ban on biodegradable waste to landfill in Scotland, due to take effect in 2025. EfW is projected to account for around an extra 0.5Mt/yr by 2045, attributable also (in part, at least) to the diversion of waste from landfill but also to new plants coming online post-2021. Fermentation is projected to see only a very marginal increase of around 25kt/yr, due to expected incremental growth. Figure 6 summarises the projected changes in total annual biogenic CO_2 emissions by source in 2045.

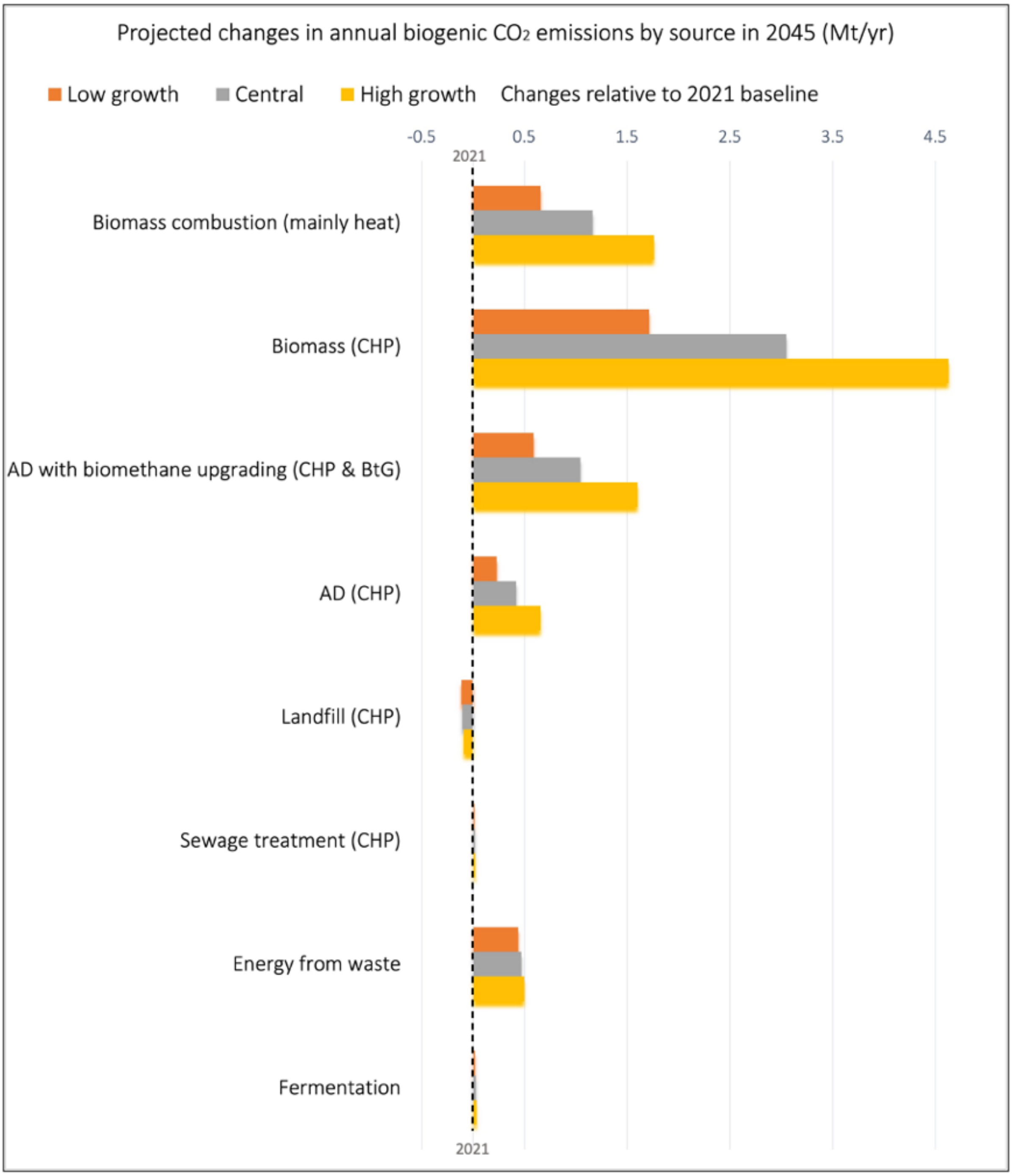


Figure 6: Projected changes in total annual biogenic CO_2 emissions by source in 2045

NB: Figures may not add up exactly due to rounding

2.3.3 Future total biogenic CO_2 emissions illustrative scenarios – bioenergy source profiles (2021-2045)

Table 2 shows the projected emissions profile (central estimate) for each bioenergy source type in 5-year intervals (2021-2045).

Bioenergy source	Source type	No. of sites	Projected total biogenic CO_2 (kt/yr)					
			2021	2025	2030	2035	2040	2045
Biomass combustion	Mainly heat	2	240	322	465	671	971	1,402
	CHP	6	716	928	1,302	1,843	2,629	3,764
AD	Biomethane upgrading (CHP+BtG)	10	137	228	342	518	783	1,181
	AD (CHP)	5	68	94	141	214	322	487
	Landfill (CHP)	9	129	97	69	49	34	24
	Sewage treatment (CHP)	2	28	30	33	36	41	45
EfW	EfW	9	280	515	735	710	727	749
Total[39]	-	**43**	**1,598**	**2,214**	**3,087**	**4,041**	**5,507**	**7,652**

Table 2: Projected total biogenic CO_2 from all bioenergy sources (2021-2045)

[39] NB figures may not add up exactly due to rounding

2.3.4 Future total biogenic CO_2 emissions illustrative scenarios – non-energy source profiles (2021-2045)

Table 3 shows the projected emissions profile (central estimate) for fermentation (the only non-energy source type covered in this study) in 5-year intervals (2021-2045).

Non-energy source	Source type	No. of sites	Projected total biogenic CO_2 (kt/yr)					
			2021	2025	2030	2035	2040	2045
Fermentation	Fermentation	3	142	146	150	156	160	166

Table 3: Projected total biogenic CO_2 from all non-energy sources (2021-2045)

3 Assessment of capturable biogenic CO_2 (2021-2045)

This section outlines the total quantity of biogenic CO_2 that is technically and economically capturable within the geographical boundary of the SNZR cluster for the period 2021-2045. The most up-to-date capture rates were applied to the various sources to be able to compare against the total amount of biogenic CO_2 available. These are aligned with UK Environment Agency best available technique (BAT) guidance[40] which stipulates a minimum rate of 95% for post-combustion capture plants, current commercial operating conditions and a projected premium for biogenic CO_2 in the context of negative emissions credits driving capture rates towards 100%. The capture rates are summarised in Table 4 with the remaining sub-sections outlining the capturable resource in more detail.

Source	Source type	Notes	Capture rate (%)
Biomass combustion	Mainly heat	Post-combustion	99[14]
	CHP		
AD	Biomethane upgrading (CHP+BtG)	Pre-combustion	95[41]
		Post-combustion	99[42]
	AD (CHP)		
	Landfill (CHP)		
	Sewage treatment (CHP)		
EfW	EfW		100[43]
Fermentation	Fermentation	Process	97[44]

Table 4: Bioenergy and non-energy biogenic CO_2 capture rates

[40] UK Environment Agency (2022). Post-combustion carbon dioxide capture: best available techniques (BAT). Available at: https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat

[41] 95-96% separating CH_4 and CO_2 from biogas using membrane separating technology and sending the CO_2 stream straight to the CO_2 recovery. The 4-5% loss occurs during the scrubbing and purification of the CO_2 in the recovery stage. Personal communication with Richard Nimmons, Carbon Capture Scotland (March 2023)

[42] Gibbins, J., Lucquiaud, M. (2022) BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass and for Post-Combustion Capture Using Amine-Based and Hot Potassium Carbonate Technologies on EfW Plants as Emerging Technologies under the IED for the UK, Ver.2.0, December 2022. Available at: https://ukccsrc.ac.uk/best-available-technology- bat-information-for-ccs/

[43] Su et al. (2023). Thermal integration of waste to energy plants with Post-combustion CO2 capture. Available at: https://www.sciencedirect.com/science/article/pii/S0016236122028289

[44] Richard Nimmons, Carbon Capture Scotland

3.1 Current capturable biogenic CO_2 emission sources and profiles – source level (2021)

The 39 facilities that were operational in 2021 are projected to produce a combined 1.7Mt capturable biogenic CO_2/yr, representing only a very marginal reduction from the total amount available. Bioenergy and non-energy (fermentation) sources still account for 92% and 8% respectively of the projected total. The absolute and percentage share of capturable biogenic CO_2 for each source and source type are summarised in Figure 7 below.

CO_2 comes predominantly from three bioenergy sources, which, combined, account for 73% of all capturable biogenic CO_2 within scope in 2021: Biomass (CHP) is the largest source (42% or 708kt); EfW the second largest (17% or 280kt); followed by Biomass combustion for mainly heat provision (14% or 237kt). The three next largest sources are Fermentation (8% or 137kt), Landfill (CHP) (8% or 128kt) and AD with biomethane upgrading (CHP & BtG[45]) (5% or 88kt).

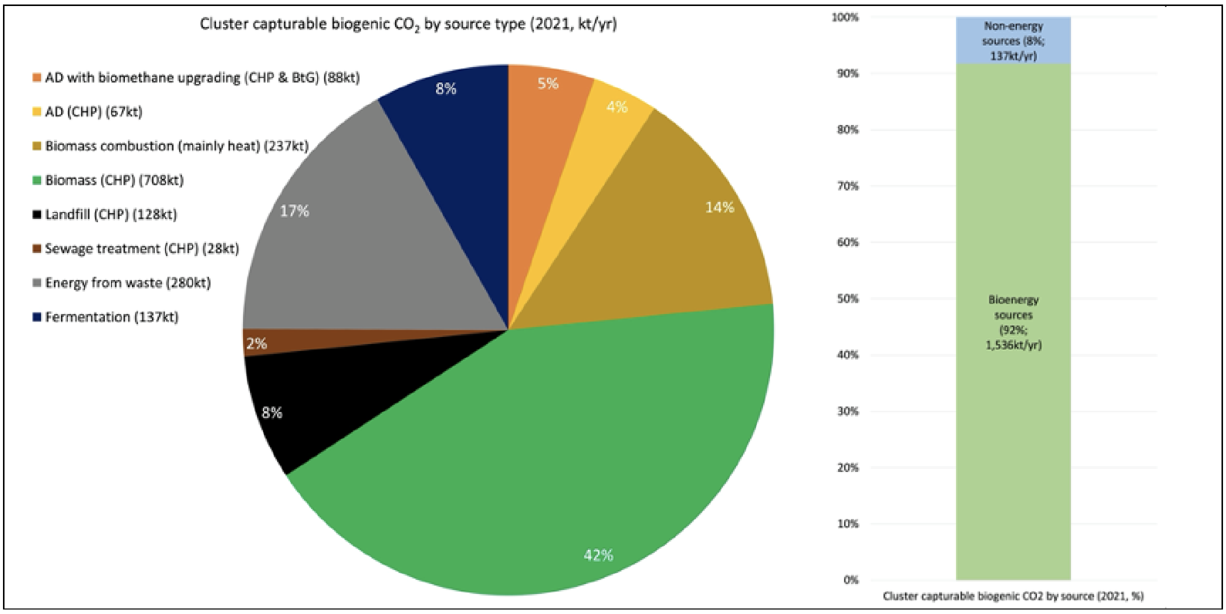


Figure 7: Cluster capturable biogenic CO_2 by source and source type (2021)

NB: Figures may not add up exactly due to rounding

3.1.1 Current capturable biogenic CO_2 from bioenergy sources (2021)

The 36 bioenergy facilities (see 5Appendix A) operational in 2021 account for a projected 1.5Mt capturable biogenic CO_2/yr. Table 5: Projected capturable biogenic CO_2 from all bioenergy sources (2021)5 provides an overview of the projected capturable biogenic CO_2 available from all bioenergy sources.

[45] Biomethane to grid (BtG)

Bioenergy source	Source type	No. of sites	Projected total capturable biogenic CO_2 (kt/yr)
Biomass combustion	mainly heat	2	237
	CHP	6	708
AD	biomethane upgrading (CHP+BtG)	8	88
	AD (CHP)	5	67
	Landfill (CHP)	9	128
	Sewage treatment (CHP)	2	28
EfW	EfW	4	280
Total[46]		**36**	**1,536**

Table 5: Projected capturable biogenic CO_2 from all bioenergy sources (2021)

3.1.2 Current capturable biogenic CO_2 from non-energy sources (2021)

The 3 non-energy (fermentation) facilities (see 5Appendix B) operational in 2021 account for a projected 0.1Mt[47] capturable biogenic CO_2/yr.

[46] NB figures may not add up exactly due to rounding
[47] Rounded from137 ktCO_2/yr

3.2 Future capturable biogenic CO_2 emission sources and profiles (2021-2045)

3.2.1 Future capturable biogenic CO_2 emissions illustrative scenarios - cluster level

By 2045, and growing at a CAGR of 6.4% (central estimate), capturable quantities of biogenic CO_2 available across the cluster are projected to rise to between 5-10.2Mt/yr, representing an increase of between 3.3-8.5Mt/yr (or 199-508%), compared to 2021 levels – see Figure 8 below.

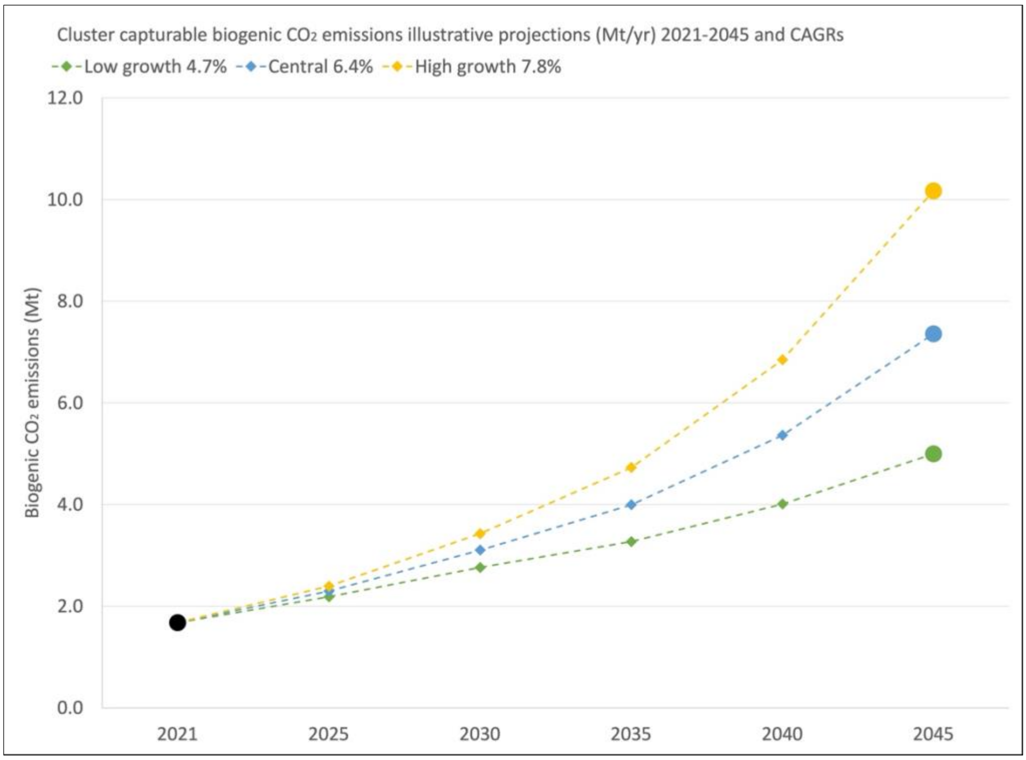


Figure 8: Future capturable biogenic CO_2 emissions illustrative scenarios – cluster level (2021-2045)

3.2.2 Future capturable biogenic CO_2 emissions illustrative scenarios – source level

The projected changes in annual capturable quantities of biogenic CO_2 between 2021-2045 mirror those outlined in section 2.3.2, and for the same reasons, with the only changes observed being the actual quantities projected. Figure 9 summarises the projected changes in annual capturable biogenic CO_2 emissions by source in 2045.

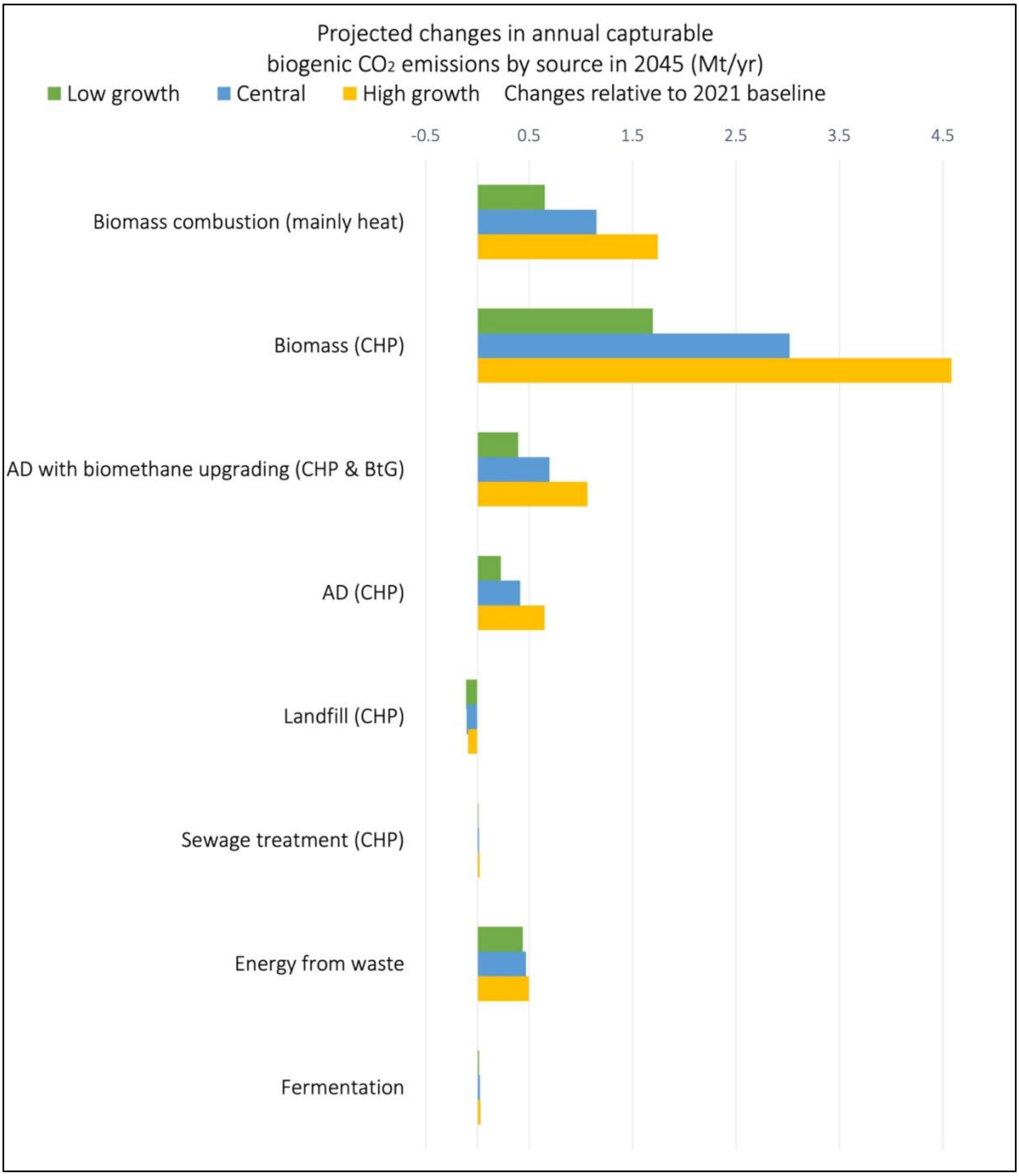


Figure 9: Projected changes in annual capturable biogenic CO_2 emissions by source in 2045

NB: Figures may not add up exactly due to rounding

3.2.3 Future capturable biogenic CO_2 emissions illustrative scenarios – bioenergy source profiles (2021-2045)

Table 6: Projected capturable biogenic CO_2 from all bioenergy sources (2021-2045)6 shows the projected capturable emissions profile (central estimate) for each bioenergy source type in 5-year intervals (2021-2045).

Bioenergy source	Source type	No. of sites	Projected capturable biogenic CO_2 (kt/yr)					
			2021	2025	2030	2035	2040	2045
Biomass combustion	Mainly heat	2	237	319	460	665	961	1389
	CHP	6	708	919	1289	1825	2602	3727
AD	Biomethane upgrading (CHP+BtG)	10	88	151	228	344	519	784
	AD (CHP)	5	67	93	140	212	319	482
	Landfill (CHP)	9	128	97	68	48	34	24
	Sewage treatment (CHP)	2	28	30	33	36	40	44
EfW	EfW	9	280	515	735	710	727	749
Total[48]	-	**43**	1536	2124	2953	3840	5202	7199

Table 6: Projected capturable biogenic CO_2 from all bioenergy sources (2021-2045)

[48] NB figures may not add up exactly due to rounding

3.2.4 Future capturable biogenic CO_2 emissions illustrative scenarios – non-energy source profiles (2021-2045)

Table 7: Projected capturable biogenic CO_2 from all non-energy sources (2021-2045)7 shows the projected capturable emissions profile (central estimate) for each non-energy source type in 5-year intervals (2021-2045).

Non-energy source	Source type	No. of sites	Projected capturable biogenic CO_2 (kt/yr)					
			2021	2025	2030	2035	2040	2045
Fermentation	Fermentation	3	137	141	146	151	156	161

Table 7: Projected capturable biogenic CO_2 from all non-energy sources (2021-2045)

4 Case study: Carbon Capture Scotland Limited

4.1 Company background

Carbon Capture Scotland Limited (CC Scotland)[49] is a Dumfries and Galloway-based company which is expanding from producing dry ice from its own captured CO_2, to providing CO_2 capture, transport and storage solutions for fermentation activities across Scotland.

The project in Dumfries and Galloway captures up to 10,000tCO_2/yr from a biomethane upgrader connected to an anaerobic digestion (AD) facility that processes waste from several farms. The plant also captures and processes a further 10,000t of vented CO_2 associated with the dry ice manufacturing process.

CC Scotland uses a compression, drying, purification and liquefaction process, which is most suited to applications where the CO_2 emitted is almost pure – such as whisky production, or anaerobic digestion of farm waste. It is suitable for AD processes that emit at least 0.5tCO_2/hour.

The SNZR project has found that there are 46 suitable sources of biogenic CO_2 within the SNZR cluster area, with many more likely to be found elsewhere in Scotland where agriculture is more predominant. If captured and permanently stored, this could account for between 2.9-3.8Mt/yr of negative emissions in 2032, equivalent to 51-67% of the Scottish Government's interim target of 5.7MtCO_2e for the same year.

4.2 Modular capture plant

CC Scotland has developed modular CO_2 capture plant: each module, which fits into an ISO shipping container, can capture 0.4-0.9tCO_2/hour, and more than one can be used together to capture CO_2 at higher flow rates. The process can be relatively intermittent – it does not require a continuous stream of CO_2. The size of the plant means that CO_2 capture can technically be carried out for fermentation processes producing as little as 3.5ktCO_2/yr. Since the threshold for considering suitability for CO_2 capture in the SNZR study is the slightly higher 5ktCO_2/yr, there are likely to be a number of additional sites – and thus an additional potential for negative emissions than has been reported.

The use of the ISO container reduces the noise levels from the capture process and makes the equipment less visually intrusive. The equipment is unique in that it is a true 'bolt-on' solution that can be disconnected and removed if required. The equipment is also substantially less energy intensive than traditional forms of CO_2 capture.

Currently, CC Scotland's operations, despite using biogenic CO_2, do not contribute to emissions reduction, as the CO_2 in dry ice is emitted to atmosphere when it is used. However, the process both proves the feasibility of the modular capture technology and produces a vital product that is used to transport chilled medical items such as vaccines, as well as fresh fruit and vegetables.

[49] Carbon Capture Scotland Limited. Available at: http://dryicescotland.co.uk

The next step is to keep captured CO_2 out of the atmosphere using secure geological storage: CC Scotland is considering a number of sequestration options, both domestic and international.

In addition, CC Scotland has plans to install its CO_2 capture equipment at several distilleries in Scotland, showing how Scotland's national drink can help reduce Scotland's greenhouse gas emissions: CC Scotland has estimated that there is 700kt of recoverable CO_2/yr from mainland distilleries.

4.3 Capture-as-a-service (CAAS)

CC Scotland's business model is to provide CO_2-capture-as-a-service (CAAS), initially to distilleries in Scotland: installing modular CO_2 capture equipment, which CC Scotland owns and operates: essentially taking the CO_2 off the hands of the emitters. CC Scotland proposes to use its experience of CO_2 handling to transport the CO_2 in tanks in ISO shipping containers – which are suitable for road, rail and ship transport. In this way, the proposal is to act like a waste disposal service, removing the CO_2 at source and managing it responsibly, so that the CO_2-producing company is assured that their CO_2 is kept out of the atmosphere without having to undertake any of the technical work to make it so. This model makes it easier for smaller and dispersed operations to contribute to greenhouse gas removal, without needing to connect to pipelines or develop their own expertise in CO_2 capture. Any credits generated for negative emissions will be owned by CC Scotland, and it has a business model that allows the CO2 source to use some or all of the negative emission credits.

The CC Scotland capture technology is best suited for fermentation emissions applications, but the CAAS model is one that could apply to any other CO_2-emitting industry, as long as suitable capture techniques are matched to each particular process. CC Scotland's development of this business model will be a crucial contribution to understanding how to deliver long-term CCS provision in Scotland, and an enduring negative emissions sector.

4.4 Nurturing a Scottish negative emissions market

Negative emissions are currently a voluntary activity: companies may pay for negative emissions generated elsewhere to offset their own residual emissions, but there is no legal requirement for them to do so. There are examples of voluntary initiatives emerging, such as the Science Based Targets Initiative[50], which specifically place carbon removal targets on participating companies. While CC Scotland is developing its business model to be self-sustaining in this context, there are interventions from government that would make the roll-out of CAAS easier. Firstly, the availability of CO_2 storage is crucial: accelerating the development of domestic sequestration projects (such as Acorn CCS[51]) so that they are operational as soon as possible and ideally before the 2027 target date. CC Scotland emphasises that this should be a priority, otherwise there is a likelihood that the CO_2 will be stored overseas, with Scotland missing out on the revenue from leasing its geological storage resource. Secondly, the role of negative emissions in compliance markets. The UK[52] and EU ETS[53], for example,

[50] Science Based Targets (2023). Available at: https://sciencebasedtargets.org
[51] Acorn (2023). Available at: https://www.theacornproject.uk
[52] The Scottish Government (2023). UK emissions trading scheme. Available at: https://www.gov.scot/policies/climate-change/emissions-trading-scheme/
[53] European Commission (2023). European Emissions Trading System (ETS). Available at: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

and the rules surrounding international emissions trading under Article 6 of the Paris Agreement[54], need to be agreed and finalised to give greater certainty to investors and enable the use of negative emissions to meet the UK and Scotland's climate change targets. In addition, decisions need to be made around government financial and risk-related support for CCS projects; measures to incentivise CCS such as carbon border adjustment mechanisms and public procurement requirements; and decarbonisation requirements in land use planning and environmental permitting.

CC Scotland would like to see government subsidising the cost of generating negative emissions – similar to the 45Q[55] credit in the USA. In their view, this would take out a huge portion of risk and allow for operators to sell negative emission credits within the range of normal carbon pricing (plus a reasonable premium). Their suggestion is that such a subsidy would be in the range of £40-£80 per ton and would be additional to any commercial gain for the negative emissions credits. As a protection, perhaps there would be a percentage reduction if commercial gain was realised over a certain threshold.

[54] United Nations Development Programme (2023). What is Article 6 of the Paris Agreement, and why is it important?. Available at: https://www.undp.org/energy/blog/what-article-6-paris-agreement-and-why-it-important

[55] Global CCS Institute (2023). 45Q: The "Most Progressive CCS-Specific Incentive Globally" Is Now Open for Business. Available at: https://www.globalccsinstitute.com/news-media/insights/45q-the-most-progressive-ccs-specific-incentive-globally-is-now-open-for-business/

5 Key findings and conclusions

This report summarises the findings of Work Package 1 Task 1.3, which was focused on conducting an assessment of the potential for achieving engineered greenhouse gas removals (GGRs) within the SNZR cluster boundary by attempting to quantify the total amount of biogenic carbon dioxide (CO_2) that is (i) available and (ii) capturable, assuming the most recent capture rates that research and current commercial activities have shown to be possible. The study includes a review of existing Scottish industries that have biogenic CO_2 emissions, covering bioenergy systems for heat and/or electricity generation, which may be combined with CCS – known as bioenergy with carbon capture and storage, or BECCS; and non-energy systems for the production of alcohol.

In total, 46 individual sources with a biogenic CO_2 potential of over 5ktCO_2/yr are identified within the geographical boundary of the SNZR cluster for the period 2021-2045. This covers facilities already operational in 2021 and new developments projected to come online (and offline) in the intervening years.

The illustrative scenarios presented here project quantities of biogenic CO_2 that are influenced by and are sensitive to a number of factors, including issues around the availability and provenance of sustainable biomass feedstock, neither of which are considered here; new developments being limited to those either currently under construction or in the commissioning phase, which yields only a very conservative total of 6 facilities (plus one facility closure); and uncertainties around EfW feedstock, which could act to either increase or decrease the resulting biogenic fraction of emissions.

The key findings from the cluster level analysis are:

- 46 facilities producing biogenic CO_2 are identified for the period 2021-2045
- 45 of 46 facilities are within 20km of NTS Feeder 10, Grangemouth, Peterhead and Braefoot Bay shipping terminals and/or an existing SNZR 28 site

The key findings from the assessment of total biogenic CO_2 available are:

- In 2021, 39 operational facilities account for 1.7Mt
- In 2021, bioenergy sources account for 92% (1.6Mt) – 36 facilities; non-energy sources account for 8% (0.1Mt) – 3 facilities
- In 2021, the three largest contributors are all bioenergy sources:
  - Biomass (CHP): 716kt or 41%
  - EfW: 280kt or 16%
  - Biomass combustion (mainly heat): 240kt or 14%
- By 2045, overall quantities of biogenic CO_2 are projected to rise from 1.7Mt in 2021 as per 3 illustrative growth scenarios to:
  - Low growth (CAGR of 4.7%): 5.3Mt, representing an increase of 3.5Mt or 204%
  - Central (CAGR of 6.5%): 7.8Mt, representing an increase of 6.1Mt or 350%
  - High growth (CAGR of 7.9%): 10.8Mt, representing an increase of 9.1Mt or 524%
- In 2045, the three largest changes (all increases; central estimate) from the 2021 baseline are:
  - Biomass (CHP): 3Mt or 426%
  - Biomass combustion (mainly heat): 1.2Mt or 485%
  - AD with biomethane upgrading (CHP & BtG): 1Mt or 761%

The key findings from the assessment of capturable biogenic CO_2 available are:

- In 2021, 39 operational facilities account for just under 1.7Mt
- In 2021, bioenergy sources account for 92% (1.5Mt) – 36 facilities; non-energy sources account for 8% (0.1Mt) – 3 facilities
- In 2021, the three largest contributors are all bioenergy sources:
    - Biomass (CHP): 708kt or 42%
    - EfW: 280kt or 17%
    - Biomass combustion (mainly heat): 237kt or 14%
- By 2045, capturable quantities of biogenic CO_2 are projected to rise from just under 1.7Mt in 2021 as per 3 illustrative growth scenarios to:
    - **Low growth (CAGR of 4.7%): 5Mt**, representing an increase of 3.3Mt or 199%
    - **Central (CAGR of 6.4%): 7.4Mt[56]**, representing an increase of 5.7Mt or 340%
    - **High growth (CAGR of 7.8%): 10.2Mt**, representing an increase of 8.5Mt or 508%
- In 2045, the three largest changes (all increases; central estimate) from the 2021 baseline are:
    - Biomass (CHP): 3Mt or 426%
    - Biomass combustion (mainly heat): 1.2Mt or 485%
    - AD with biomethane upgrading (CHP & BtG): 0.7Mt or 790%

[56] For comparison, the residual emissions gap to net zero for the SNZR project (WP1 T1.1) under a business-as-usual 'do nothing' scenario was 6.1MtCO_2 in 2045.

Appendix A Bioenergy facility profiles 2021-2045 (5-year intervals)

Bioenergy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)						Notes
					2021	2025	2030	2035	2040	2045	
Biomass combustion	Mainly heat	2	Tarmac	East Lothian	60	80	116	167	242	349	
			Norbord (Cowie)	Stirling	180	242	349	504	729	1,053	
	CHP	6	Markinch Biomass CHP	Fife	431	579	837	1,209	1,747	2,524	
			Liberty Steel Dalzell CHP	North Lanarkshire	113	151	219	316	457	660	
			Gleneagles Hotel CHP	Perth & Kinross	8	11	15	22	32	47	
			University of St Andrews Biomass CHP	Fife	43	58	84	121	175	252	
			Acharn Forest Biomass CHP	Stirling	37	50	72	104	150	217	
			Westfield Biomass CHP	Fife	83	79	75	71	68	64	

Bioenergy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)						Notes
					2021	2025	2030	2035	2040	2045	
AD	Biomethane upgrading (CHP+BtG)	10	Millerhill AD (CHP & BtG)	Midlothian	9	13	19	29	43	66	
			Brae of Pert Farm AD (CHP & BtG)	Angus	15	22	32	49	74	111	
			Downiehills Farm AD (CHP & BtG)	Aberdeenshire	17	24	36	54	81	122	
			Inchdairnie Farm AD (CHP & BtG)	Fife	12	17	25	38	58	87	
			Keithick Farm AD (CHP & BtG)	Perth & Kinross	17	23	35	53	81	121	
			Peacehill Farm AD (CHP & BtG)	Fife	15	21	32	49	73	111	
			Savock Farm AD (CHP & BtG)	Aberdeenshire	17	23	35	53	81	122	
			Balmcassie Commercial Park AD (CHP & BtG)	Aberdeenshire	-	26	39	59	90	135	Comes online in 2023
			Bangley Quarry Biogas AD (CHP & BtG)	East Lothian	-	11	17	25	38	58	Comes online in 2024
			Energen Biogas AD (CHP)	North Lanarkshire	34	48	72	109	164	248	

Bioenergy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)						Notes
					2021	2025	2030	2035	2040	2045	
AD	AD (CHP)	5	Skeddoway Farm AD (CHP)	Fife	12	17	25	38	58	87	
			Lochhead Landfill AD (CHP)	Fife	7	10	14	22	33	50	
			Cameronbridge Distillery AD (CHP)	Fife	33	46	70	106	159	240	
			Pure Malt Products AD (CHP)	East Lothian	9	13	19	29	43	66	
			Deerdykes AD (CHP)	North Lanarkshire	6	8	13	19	29	44	
	Landfill (CHP)	9	Greengairs Landfill CHP	North Lanarkshire	22	17	12	8	6	4	
			Stoneyhill Landfill CHP	Aberdeenshire	13	10	7	5	3	2	
			Avondale Landfill CHP	Falkirk	36	27	19	13	9	7	
			Dunbar Landfill CHP	East Lothian	21	16	11	8	6	4	
			Auchinlea Landfill CHP	North Lanarkshire	7	5	4	3	2	1	
			Binn Landfill CHP	Perth & Kinross	7	5	4	3	2	1	

Bioenergy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)						Notes
					2021	2025	2030	2035	2040	2045	
			Lochhead Landfill CHP (Fife)	Fife	7	5	4	3	2	1	
			Oatslie Landfill CHP	Midlothian	8	6	4	3	2	2	
			Kaimes Landfill CHP	West Lothian	8	6	4	3	2	2	
	Sewage treatment (CHP)	2	Seafield WwTW CHP	City of Edinburgh	19	20	22	24	27	30	
			Nigg Bay WWTW CHP	Aberdeen City	9	10	11	12	14	15	
EfW	EfW	9	MVV Baldovie old (EfW)	Dundee City	42	43	44	-	-	-	Comes offline in 2030
			MVV Baldovie new (EfW)	Dundee City	-	48	49	50	51	53	Comes online in 2022
			Millerhill RERC (EfW)	Midlothian	66	68	69	71	73	75	
			Drumgray ERC (EfW)	North Lanarkshire	-	-	130	134	137	141	Comes online in 2026
			Dunbar ERF (EfW)	East Lothian	128	131	134	138	141	145	
			Earls Gate Energy Centre (EfW)	Falkirk		93	95	98	100	103	Comes online in 2023

Bioenergy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)						Notes
					2021	2025	2030	2035	2040	2045	
			Westfield Energy Recovery Facility (EfW)	Fife		54	105	107	110	113	Comes online in 2025
			NESS Energy Project (EfW)	Aberdeen City		34	64	66	68	70	Comes online in 2023
			Levenseat Phase 1 (EfW)	West Lothian	43	44	45	46	47	49	

Table 8: Bioenergy facility profiles 2021-2045

Appendix B Non-energy facility profiles 2021-2045 (5-year intervals)

Non-energy source	Source type	No. of sites	Site name	Site location (local authority)	Projected biogenic CO_2 (kt/yr)					
					2021	2025	2030	2035	2040	2045
Fermentation	Fermentation	3	Cameronbridge Distillery (fermentation)	Fife	75	77	80	83	85	88
			North British Distillery (fermentation)	City of Edinburgh	49	51	52	54	56	58
			Starlaw Distillery (fermentation)	West Lothian	17	18	18	19	19	20

Table 9: Non-energy facility profiles 2021-2045

Appendix C CAGRs applied to each biogenic CO_2 source and source type

Source	Sub-category	'Low growth'	'Central'	'High growth'
Biomass combustion	Plant biomass	5.65%	7.64%	9.24%
	Animal biomass (non-AD) (inc. poultry litter and meat and bone)	-1.29%	-1.06%	-0.79
AD	AD	6.35%	8.57%	10.37%
	Landfill gas	-8.19%	-6.77%	-5.01
	Sewage sludge digestion	1.44%	1.95%	2.36%
EfW	EfW (Biodegradable part only, which accounts for 50%)	0.32%	0.51%	0.69%
Fermentation	Grain whisky	0.50%	0.67%	0.81%

Table 10: CAGRs applied to each biogenic CO_2 source and source type

Scotland’s Net Zero Roadmap