NEGATIVE EMISSIONS TECHNOLOGIES (NETS): FEASIBILITY STUDY

Final Report

Report commissioned by the Scottish Government

Issue: 03

Scottish Government
Riaghaltas na h-Alba

Customer:
The Scottish Government

Customer reference:
CASE 582958

Confidentiality, copyright and reproduction:

Contact:
David Meek, 2nd Floor, 18 Blythswood Square, Glasgow G2 4BG

E: info@ricardo.com

Author:
Carwyn Williams Robbie Leishman, Amber Jenevizian, Sophia Zenon, David Meek, Richard Stevenson

Approved by:
Naser Odeh, David Meek

Signed

Ricardo reference:
ED16823

Date:
02/11/2023

Document History

Revision	Purpose Description	Prepared	Date Issued
1	Draft Final Report	DM, CW, RS, NO	07/07/2023
2	Revised Report	DM, CW, RS, NO	19/07/2023
3	Revised Report	DM, CW, RS, NO	24/07/2023
4	Final Report	DM, CW, RS, NO	27/07/2023
5	Revised Final Report	DM, CW,	18/10/2023
6	Final Report – Part 1	DM	30/10/2023
7	Final Report – Part 1 revised	DM, CW	02/11/2023

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ACRONYMS & UNITS USED

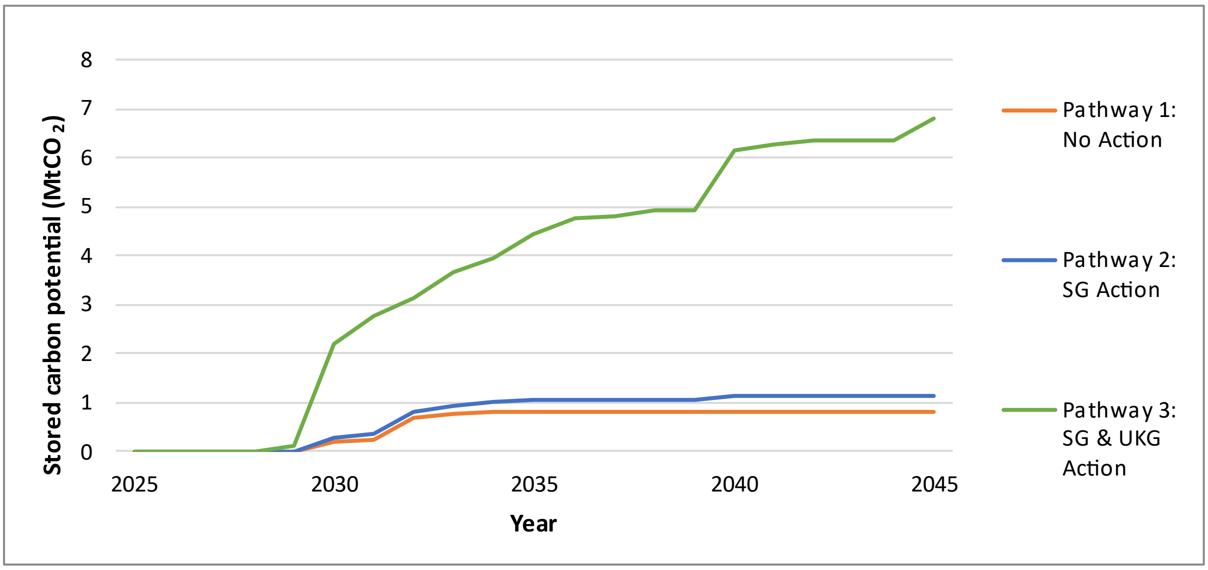
ACT	Advanced Conversion Technology
ATR	Auto thermal reforming
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CDRs	Carbon dioxide removals
CCC	Climate Change Committee
CCPu	Climate Change Plan Update
CXC	ClimateXChange
CfDs	Contracts for Difference
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
GJ	gigajoules
GWh	gigawatt-hours
GWP	Global warming potential
GGR	Greenhouse gas removal
ha	hectare
kWh	kilowatt-hours
LPG	Liquid petroleum gas
Mt	mega tonnes
MJ	megajoules
MWh	megawatt-hours
NETs	Negative emission technologies
RDF	Refuse Derived Fuel
SRC	Short Rotation Coppicing
SRW	Small Round Wood
SRF	Solid Recovered Fuel
SMR	Steam methane reforming
SAF	Sustainable Aviation Fuel
t	tonnes
yr	year

EXECUTIVE SUMMARY

KEY FINDINGS

This study estimates that **the maximum Negative Emissions Technologies (NETs) potential achievable in Scotland in 2030 is 2.2 MtCO_2/year** (60% of the available biogenic CO_2 emissions), based on existing and future potential sites and given technical, economic and other constraints. This is significantly lower than the stated NETs ambition in the CCPu of 5.7 MtCO_2/year by 2032. With additional policy interventions from both the UK and Scottish Governments, this figure could potentially reach 6.8 MtCO_2/year by 2045 with technologies such as direct air carbon capture and storage (DACCS), bioenergy CCS (BECCS), energy from waste (EfW) and biomethane and distillery sites all playing a role.

Figure 1: NETs potential for each pathway



- **Policies that introduce a negative emission trading element could have the greatest impact on NETs development in Scotland**, which we estimate could add ~5.7 MtCO_2 of additional carbon removals. This is because of the introduction of a revenue mechanism based on the negative emissions produced at each site, which we estimate could lead to an additional 50-60 sites being able to profitably deploy NETs.
- Sector specific funding could be used to deliver projects, in particular to the biomethane and fermentation sectors, to support the development of NETs in these sectors which have highly pure CO_2 streams. **We have estimated that a £40m investment by SG could contribute between 0.12 MtCO_2 and 0.36 MtCO_2 of additional emissions reduction depending on how it is targeted.**
- The deployment of CCS infrastructure is essential to ensure NETs targets are achieved. Scotland benefits from ample CO_2 storage capacity in the North Sea and a strong base in CCS R&D and engineering skills. In addition, companies such as Carbon Capture Scotland and Carbogenics are leading the way in Scotland in the deployment of NETs and can help facilitate early deployment which puts Scotland in a unique position to lead the way.
- Stakeholders consulted with during this project had an overall positive perception of NETs, but all highlighted that policy changes to incentivise NETs are needed, with most suggesting that long-term financial support is needed as well as up-front CAPEX support. The range of stakeholders were consulted with on this project were from a mixture of industries, higher education, research and trade associations.

- **The deployment of NETs in Scotland and its contribution to Net Zero targets is significantly dependent on the development of the Acorn Storage facility by 2030.** However, there are certain existing sites which can help initiate a NETs industry in Scotland prior to 2030. These are mainly biomethane and distillery sites where the capture of the CO_2 requires comparatively minimal investment.
- **Many existing biomethane and distillery sites in Scotland can have an attractive breakeven point for profitably installing NETs** and can act as 'low hanging fruits', contributing to the initiation of a NETs industry in Scotland, although at very small volumes (0.0001 $MtCO_2$ – 0.2 $MtCO_2$). Any feasibility studies for future biomethane sites should explore the option of adopting CO_2 capture and becoming net-negative.
- Biochar applications are emerging worldwide with several hundred thousand tonnes of carbon dioxide captured via biochar annually and contributing to carbon removal across Europe. This option can be deployed easily across Scotland where expertise already exists. However, the regulatory landscape to facilitate the use of biochar as well as Monitoring, Reporting and Verification (MRV) and certification procedures to ensure permanent storage of the carbon are needed for biochar as well as other NETs.
- A renewable source of electricity is essential for DACCS to ensure it contributes effectively to NETs targets. Strong competition for renewable electricity (e.g., with green hydrogen production) will exist and is very likely to affect the deployment of DACCS projects in Scotland. Taking this into account, **a modest DACCS deployment capacity of 0.5 $MtCO_2$/year is expected in 2030, doubling by 2040.**
- Carbon capture and storage is a key and important decarbonisation option for EfW sites and can contribute negative emissions. This feasibility study recommends that policy is developed to encourage the development of CCS on future EfW sites and to ensure such sites are carbon capture-ready. Furthermore, policies should prioritise the deployment of CCS on existing EfW sites which are also combined heating and power (CHP) and part of district heating (DH) schemes.
- **This study recommends that only domestic Scottish bioresources are included when estimating BECCS targets. Imported biomass is associated with higher life cycle emissions which are likely to negate the effect of carbon removals.** The available domestic dry biomass sources in Scotland limit the development of new biomass power plants to a small number of a few 50 MW plants and consequently limits the potential for BECCS power. The position in the UK Government's Biomass Strategy (published August 2023) on biomass imports will impact NETs developments in the UK as a whole and in Scotland. Nevertheless, any future MRV and NETs certification regime is expected to include emissions from biomass transport and is expected to reduce the negative emissions potential of power BECCS in Scotland.
- Our analysis suggests that in 2045, for future sites in the SG & UK Government Pathway:
    - Around 7.7 TWh of available bioresources are required for BECCS Power and BECCS Industry
    - Around 0.9 TWh of available bioresources are required for biochar
    - Around 0.15 TWh of available bioresources are required for BECCS Hydrogen
    - Around 4.3 M tonnes of waste is required for BECCS EfW
    - Around 1.9 M tonnes of feedstock are required for future biomethane sites
- **The development of the carbon removal or NETs industry in Scotland and across the UK requires the development of MRV and certification procedures to ensure that the captured CO_2 remains permanently stored** whether in geological formations or in emerging industrial applications. In addition, for biochar and BECCS applications, the MRV and certification guidelines need to ensure that the feedstock is sustainably-sourced and of biogenic origin.
- An important consideration for NETs in Scotland is whether the carbon captured in Scotland is traded in the UK under the UK ETS or internationally under Article 6 of the Paris Agreement.

This study assumes that the captured carbon would contribute to NETs targets for Scotland regardless of where it is stored irrespective of if or where any resulting credits were sold through the UK ETS. In reality, and particularly for DACCS, whether negative emission credits are sold/traded is a decision for an individual site/developer/organisation to make.

NETs have an important role to play in achieving Net Zero targets in Scotland.

Following the Paris Agreement, in 2015, NETs are a key element in many countries' Nationally-Determined Contributions (NDCs). For Scotland, the CCPu and the CCC's 6^{th} Carbon Budget highlighted the importance that NETs need to play in Scotland's climate change planning, including playing a key role in balancing residual emissions from hard-to-abate sectors such as aviation and agriculture.

The Climate Change Plan update (CCPu) for Scotland commits to undertaking a detailed feasibility study of opportunities for developing Negative Emission Technologies (NETs) or carbon removal projects in Scotland that would identify specific sites and applications of NETs, including developing work to support policy on technologies such as Direct Air Carbon Capture and Storage (DACCS) and Bioenergy Carbon Capture, Utilisation and Storage (BECCS). This NETs feasibility study referred to in the CCPu aims to help understand the NETs market and what technologies can realistically be deployed to meet the CCPu targets, and to develop deployment pathways and policy recommendations to help accelerate deployment of CCUS and NETs in Scotland.

This study considered a range of engineered NETs options including (i) direct air carbon capture and storage (DACCS), (ii) biochar produced from biomass pyrolysis, and (iii) various bioenergy CCS options including power and CHP BECCS, industrial BECCS, EfW BECCS, biomethane BECCS, hydrogen BECCS, biofuels BECCS and BECCS on distillery sites across Scotland. The study gathered evidence from the literature and through targeted stakeholder interviews on the feasibility, prospects and challenges for NETs deployment in Scotland. In addition, technology and cost data for the different NETs options was gathered to facilitate techno-economic analysis of existing and future sites which have potential to deploy carbon capture and to contribute to NETs targets in Scotland.

The study involved data gathering on existing sites which could potentially contribute to a NETs target in Scotland. Data for distillery and brewery sites, biomass CHP, biomethane sites and EfW (including both incineration and gasification sites) was collected. The amount of CO_2 available from existing sites which could potentially be captured was evaluated and the total NETs potential estimated.

The analysis shows that the total biogenic[1] CO_2 currently available from existing sites is around 3.3 $MtCO_2$/year, split across five main sectors (39% from biomass CHP and power sites, 26% industry, 14% EfW, 15% distilleries and 6% from biomethane sites). An additional 1 $MtCO_2$/year from these existing sites is attributed to feedstocks of fossil fuel origin (for example EfW feedstock containing high proportions of plastics, metals and glass). The total amount of biogenic CO_2 available for capture could increase if sites currently using fossil fuels switched to biogenic fuel inputs. Additionally, increasing the volume of biogenic waste entering EfW sites could in turn increase Scotland's negative emissions potential.

An economic feasibility analysis was undertaken on the basis of a Levelised Cost of Carbon (LCOC)[2] comparison in order to assess the feasibility of sites adopting NETs on a common basis and to identify the level of support that would be needed from the Scottish and UK Governments to make NETs viable. The economic and cost analysis assumes **permanent storage of CO_2** in the North Sea as part of the Acorn project utilising existing pipework infrastructure. Storage in the Liverpool Bay area for HyNet or storage in the coast of Humber and Teesside under the East Coast Cluster were also

[1] Biogenic carbon refers to carbon originating from plants and trees while anthropogenic carbon results mainly from fossil fuels.

[2] The LCOC is determined based on the total technology costs per tonne of CO_2 captured and permanently stored. The costs include CO_2 capture, transport and storage costs and consist of the sum of (i) the annualised capital costs, (ii) the operating costs and (iii) the loss of revenue due to the addition of CO_2 capture. The operating costs consist of both fixed and variable costs (for example, additional electricity and heat consumption). Further details of the LCOC calculation are given in Section 4 and the Technical Annexes.

assessed but associated transportation costs made it economically unfeasible to send captured CO_2 to these sites.

It should be noted that uses of the carbon dioxide from NETs are emerging as an alternative to geological storage. In any NET feasibility analysis, the permanence of the CO_2 needs to be considered. Some emerging applications such as sustainable aviation fuels (SAFs) are promising for CO_2 utilisation but cannot contribute to NETs or carbon removal targets as the CO_2 is released back into the atmosphere. Other emerging applications including concrete curing, mineral carbonation, green cement and polymers can offer CO_2 permanence. However, further work needs to be done on demonstrating these options in the future and developing the regulatory framework to allow these applications to be considered net-negative. This study assumes that the CO_2 captured from NETs remains permanently trapped regardless of whether it is stored in geological formations or via industrial applications thus contributing to NET targets. However, only permanent storage in geological formation was costed for the feasibility study, not utilisation options.

The economic feasibility analysis shows that **existing biomethane and distillery sites can act as 'low hanging fruits' and are considered early opportunities to deploy NETs in Scotland.** Despite the small volumes of CO_2 involved, these can help to demonstrate the NETs supply chain and identify opportunities for CO_2 utilisation in industries where the carbon can be permanently stored. **BECCS EfW** is also an opportunity in spite of the higher costs as CCUS is viewed as one of the very few solutions to allow EfW to continue to be deployed in Scotland. In addition, the combination of EfW with combined heat and power (CHP) and district heating (DH) operation is an option that helps improve efficiency and improve the financial viability of EfW BECCS. Several EfW BECCS plants with DH are currently in development in Scandinavian countries.

Three pathways of support were considered:

- **Pathway 1 – No Action** assumes minimal action or policies are promoted by the Scottish and UK Governments to influence the development of NETs in Scotland, and that there is no negative emission credit trading mechanism.
- **Pathway 2 – Scottish Government Action** represents a pathway that is made up of the 'low hanging fruit' sites that could adopt NETs for a relatively low investment cost and at the lowest levelised cost of carbon. Pathway 2 is bounded by specific policies and assumes no negative emission credit trading mechanism exists. This Pathway assumes only the Scottish Government will develop a policy package to support NETs deployment.
- **Pathway 3 – UK Government and Scottish Government Action** assumes a suite of policies and mechanisms are implemented from both the UK and Scottish Governments that result in high CCUS and NETs deployment. A negative emission credit trading mechanism is included in this pathway. The analysis shows that the maximum NETs potential achievable from existing sites in 2030 is around 2 $MtCO_2$/year (60% of the available biogenic CO_2 emissions).

A range of pathway-specific assumptions have been made, as outlined in Table 1. Some assumptions such as the deployment of the Scottish CCUS cluster were held constant for all pathways, while others were pathway dependent. These include a proxy to test whether or not a site may remain relatively profitable after including a NET facility **without** additional support and the scope for negative emissions credits trading through the UK ETS.

Table 1: Pathway Assumptions

	Pathway 1	Pathway 2	Pathway 3
Common Assumptions			
Acorn project	Active by 2030		
Feeder 10	Feeder 10 pipeline repurposed for CO_2 transportation between Bathgate and Peterhead, Garlogie and Kirriemuir compressor stations used as potential injection points		
Transportation	Combination of road and onshore pipeline using feeder 10 pipeline		
Storage	Storage in the North Sea either via the Acorn project, in the Liverpool Bay via the HyNet project or in the coast of Humber and Teesside under the East Coast Cluster.		
Bioenergy limitations	Bioenergy resource modelling to 2045 used for the analysis (Comparing Scottish Bioenergy supply and demand in the context of net zero, CXC, Report by Ricardo, 2022)[3]		
Imports	No biomass imports		
Capture performance	90-95% maximum capture rates (technology specific) Capture rate learning curves deployed such that sites can achieve the maximum CO_2 capture faster in later years of the modelling		
CAPEX & OPEX	Literature information used to develop the CAPEX & OPEX for sites. Learning rates for both CAPEX and OPEX introduced		
Pathway Specific	**Pathway 1**	**Pathway 2**	**Pathway 3**
Minimum tCO_2 for viability	2,500 tonnes	2,500 tonnes	1,000 tonnes
Relative Profitability Test	N/A	Yes	N/A – overwritten by NETs trading
Fiscal Policies	No additional fiscal support	Fiscal support of £40M allocated to NETs Sensitivities adjusting this allocation undertaken	
NETs trading scheme	N/A	N/A	Active - £80/tCO_2 in 2025

All pathways have been developed based on an assumption that the **Acorn storage facility** located in the north-east of Scotland is active by 2030. Realistically, biomethane and distillery sites in Scotland can start capturing CO_2 before 2030, and either export it for permanent storage globally (e.g., via The Northern Lights project) or for utilisation in industry (e.g., concrete curing or mineral carbonation) where it remains permanently stored. The relatively small volumes of CO_2 available from biomethane and distillery sites (i.e., in comparison to biomass CHP and EfW sites) make it possible for industrial utilisation to use most of the available carbon dioxide without the need for large and complex CO_2 storage infrastructure in the North Sea. This, however, requires these emerging CO_2 utilisation processes (e.g., concrete curing) to be recognised as permanent storage applications.

The analysis shows that the cumulative NETs potential between 2030 and 2045 ranges from 16 $MtCO_2$ (under the 'No Action' pathway) to 112 $MtCO_2$ (under the UKG and SG Action pathway), with a total investment requirement of £0.7–4.3 Bn over the 15-year period, as shown in Table 2 and Table 3. **Note**

[3] Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets (climatexchange.org.uk)

that these investment figures are contingent on the full range of policies envisioned in the respective pathways materialising.

Table 2: NETs potential, selected years including lifetime stored $MtCO_2$

Pathway	Annual stored Carbon, $MtCO_2$				Cumulative Stored Carbon $MtCO_2$
	2030	2035	2040	2045	
1 - No Action	0.6	0.8	0.8	0.8	**16**
2 – SG Action	0.8	1.2	1.3	1.3	**25**
3 – UKG & SG Action	2.2	4.5	6.1	6.8	**112**

Under the SG Action pathway, the total lifetime cumulative NETs potential is 25 $MtCO_2$ (0.4 $MtCO_2$/year in 2030 increasing to 1.3 $MtCO_2$/year in 2045). This includes existing biomethane and distillery sites as well as future EfW and biomethane sites. It also includes the planned Storegga DACCS project.

Under the UKG and SG Action pathway, the NETs potential increases from 2.2 $MtCO_2$/year in 2030 (which is significantly lower than the stated NETs target in the CCPu of 5.7$MtCO_2e$/year by 2032) to 6.8 $MtCO_2$/year in 2045 and includes all NETs technological options.

Table 3: CAPEX per pathway, selected years and total lifetime CAPEX

Pathway	Annual CAPEX (£M)				Lifetime CAPEX (£M)
	2030	2035	2040	2045	
1 - No Action	702	-	-	-	**708**
2 – SG Action	823	-	1	-	**824**
3 – UKG & SG Action	1,314	292	1,568	157	**4,320**

The study assumes that only domestic bioresources within Scotland are available for BECCS and biochar applications and that **there are no biomass imports for NETs in any pathway**, from either the rest of the UK or the rest of the world. The available domestic dry biomass sources limit the development of new biomass power plants in Scotland to a small number of 50 MW plants. This limits the potential for BECCS power, considering that not all of these sites will install CCS. Biomass imports could increase this potential, but it should be noted that any NETS Monitoring, Reporting and Verification (MRV) should take the source of biomass into account as the negative emissions potential is likely to reduce if upstream emissions from biomass transport are significant.

The study also assumes that if the carbon is captured in Scotland, then it would contribute to NETs targets for Scotland regardless of where it is stored. For all pathways, it was assumed that all sites that form part of a pathway (by meeting the LCOC and market requirement) where carbon is captured at site, will be counted – and not traded internationally. Trading of captured carbon credits is being negotiated under Article 6.4 of the UNFCC's Paris Agreement. It should also be noted that whether negative emission credits are sold/traded is a decision for an individual site/developer/organisation to make (in particular for DACCS). For the purposes of the negative emissions trading credits mechanism, it is assumed that this mechanism would operate as part of the UK ETS and that the apportionment of negative emission credits to be allocated to government greenhouse gas accounts would be based on the relative proportion of production. In other words, it is assumed that the negative emissions created in Scotland would be counted as part of Scotland's emission reduction targets irrespective of where in the UK the credits were sold through the ETS.

For NETs with a lower Technological Readiness Level (TRL) (e.g., DACCS, BECCS Power, BECCS hydrogen), it is expected that deployment will remain at very small scale without significant central support from either the Scottish or UK Governments. **Biochar applications already exist in Scotland,**

albeit at a small scale. Biomass pyrolysis is well-established already in several EU countries and already contributes to carbon removal in some countries. Certification schemes and MRV procedures are needed to ensure that biochar plays its role as a NET.

A renewable source of electricity is essential for DACCS to ensure it contributes effectively to NETs targets. Renewable electricity will be required to decarbonise the electricity grid, and by extension the electrification of energy demand such as heating or transport, and to establish a green hydrogen economy in Scotland. Thus, strong competition (i.e., for renewable electricity) could exist and, if so, affect the deployment of DACCS in Scotland. This study assumes a modest DACCS deployment of 0.5 Mt CO_2/year (based on existing stated commercial plans as part of the Scottish Cluster bid) in 2030 and assumes that this capacity will double by 2040, making only a small contribution of 0.1% of the required global DACCS targets by 2040 (according to the IEA).

The total NETs potential or the timeline at which NETs can be deployed was tested by varying the impact of fiscal, general and technical policies. Sensitivity analysis was undertaken to test the impact of the policy where this could be quantified.

Fiscal policies are those that either offer direct or indirect financial support to NETs while general policies and non-NETs specific policies are those which could impact the future of NETs through, for instance, public perception campaigning. Technical policies offer technical support to other related areas that could impact the development of NETs in Scotland, such as those related to improving transport infrastructure or planning policies.

At the time of analysis and reporting, the position in the UK Government's Biomass Strategy (subsequently published August 2023[4]) on biomass imports and supporting specific biomass technologies (e.g., biomass gasification) was unknown. If large amounts of biomass imports are included, this could in theory have a significant impact on the development of large NETs projects in Scotland due to a larger available bioresource volume. The emphasis on specific biomass feedstocks in the Bioenergy Action Plan will also be linked to which BECCS technologies can develop in the future.

The future feasibility of NETs in Scotland is also dependent on what NETs targets are introduced and whether emphasis is placed on specific technologies. Improvements in planning and consenting processes could lead to advancing NETs deployment. Policies to support the R&D and implementation of industrial processes which lead to permanent storage of CO_2 (e.g. concrete curing, mineral carbonation) could help accelerate early deployment. Furthermore, policies which facilitate supporting the development of CCUS infrastructure (including improving road conditions to facilitate road transport), addressing gaps in skills across the CCUS supply chain and addressing public concerns through public awareness campaigns can all lead to positive impacts on the development of NETs. Estimating the impact of such policies against a suite of emerging technologies is challenging due to the immature nature of the sector, with limited verified literature on existing and successful policies to draw upon.

The analysis of the various pathways shows that technology-specific funding can help early deployment of NETs. For example, the level of funding required to develop biomethane BECCS on existing sites is £20-70M. This only leads to a NETs potential of around 0.5Mt CO_2/year but can be seen as a way of kick-starting the NETs industry and infrastructure in Scotland, and of testing various CO_2 utilisation routes. Pathway analysis assumed a funding pot of £40M was available to support NETs in Scotland which is not linked to a specific NETs sector. Business model development is also essential to accelerate NETs deployment, allowing for more certainty in project viability throughout the development stage. **Finally, the expansion of the UK ETS to include NETs and negative emission credits, and a CfD mechanism to support NETs development, are also seen as key policies which could encourage the deployment of NETs in Scotland and the UK as a whole**.

[4] UK Government Biomass Strategy: https://www.gov.uk/government/publications/biomass-strategy

PART 1: NETS PATHWAYS DEVELOPMENT

1. INTRODUCTION

The purpose of this study is to help the Scottish Government better understand the NETs market, understand what NETs options can realistically be deployed in Scotland to support the transition to net-zero, and to subsequently develop NETs deployment pathways and policy recommendations for the Scottish Government to adopt. The objectives of this study are as follows:

- To review existing Negative Emission Technologies (NETs) and compare them in terms of their operating parameters and costs,
- To undertake stakeholder engagement to understand business development and investment plans in the private sector,
- To evaluate costs and benefits of different NETs options,
- To develop NETs pathways on the evidence gathered and to make suggestions on future policies for the Scottish Government in terms of NETs deployment.

Section 1 of this report discusses the importance of NETs in achieving Net Zero targets. **Section 2** outlines key considerations for NETs in Scotland based on the stakeholder consultation undertaken as part of the study. **Section 3** provides an assessment of the maximum NETS potential achievable in Scotland based on data gathered for existing and future sites and **Section 4** then undertakes an economic feasibility and estimates of the levelised cost of carbon (LCOC) for all sites within the database. **Section 5** introduces the set of NETs pathways developed for this study, outlining the assumptions and limiting factors, and describing the impact of certain policies on these pathways. A sensitivity analysis is also given in Section 5. Finally, **Section 6** provides conclusions and policy recommendations. The **Technical Appendices** at the end of this report provide a comprehensive summary of the literature reviewed, data gathered, and assumptions made in undertaking the economic feasibility and pathway development.

1.1 THE NEED FOR NETS TARGETS IN SCOTLAND

Negative emission technologies (NETs), also known as Greenhouse Gas Removal (GGR), Carbon Dioxide Removals (CDRs) or simply Carbon Removals, are vital for achieving domestic and global Net Zero targets[5]. They encompass both nature-based and engineered solutions, where atmospheric CO_2 is captured and sequestered in order to achieve a 'net removal' of carbon (whether permanently stored underground in depleted oil and gas fields or saline aquifers or in manufactured products such as concrete). Engineered solutions include options such as the thermal treatment of biomass through combustion, gasification, pyrolysis, anaerobic digestion, or fermentation (known as Bioenergy with Carbon Capture and Storage (BECCS). Other engineered solutions include the use of fanned capture units to capture atmospheric CO_2 using solvents and adsorbents (known as Direct Air Carbon Capture and Storage (DACCS)). Pyrolysis of biomass and waste to produce biochar where the carbon remains permanently stored is another engineered solution. See Figure 2 for further detail on the carbon flows of NETs.

While only engineered removals fall within the scope of this study, nature-based solutions, such as afforestation, enhanced weathering, ocean mineralisation, habitat restoration, and soil carbon sequestration, will play a vital role by increasing carbon storage in natural sinks. However, these alone cannot deliver removals at the pace and scale required to achieve UK climate goals and so engineered solutions will also be required.

[5] As stated by the CCC's 6th Carbon Budget and the Scottish Government's CCPu paper. These are discussed in depth and referenced to later in the report (see section 1.2).

NETs may play an important role in offsetting emissions from carbon intensive industries, such as aviation and agriculture, which are anticipated to continue to grow in carbon intensity and may emit circa 15 $MtCO_2$/year[6] in the UK in 2050. Under the UK's Net Zero Strategy, there is an ambition to deploy at least 5$MtCO_2$/year of engineered removals by 2030, in line with the National Infrastructure Commission's assessment, whilst the CCC[7] and Royal Society[8] estimate that 43.5-130 $MtCO_2$/year of NETs are needed by 2050. It is also expected that the UK's storage capacity will take around 10 years to be made ready, so work will need to begin now in anticipation of the quantity of captured CO_2 requiring permanent storage in the future[9,10]. On a global scale, to achieve Net Zero emissions by 2050 it is estimated that a total of 1.2 $GtCO_2$ of carbon capture is required by 2030 and 7.6 $GtCO_2$ is to be captured in 2050; 30% of which comes from BECCS and DACCS, 50% from fossil fuel combustion, and 20% from industrial processes[12]. Currently, there are approximately 35 commercial CCUS facilities in operation globally, with a collective CO_2 capture capacity of 45 $MtCO_2$/year.

Apart from their climate change benefits, NETs also provide an opportunity for the UK to export specialist skills. In addition, facilitated by Article 6 of the Paris Agreement, the UK could sell negative emissions to countries abroad (the UK has CO_2 storage capacities of ~78,000 $MtCO_2$, which is greater than domestic demands)[10]. This could lead to co-benefits of increased employment, innovation through start-up industries and creation of new value chains[11]. In the near future, NETs capacities are expected to grow significantly. Analysis by Element Energy[12] indicates that Scottish BECCS and DACCS capacities could reach 5-6 $MtCO_2$/year by 2050[6]. Furthermore, stakeholders predict even more optimistic deployments rates, with DACCS potentially operating at the megaton scale by the next decade[6].

---

[6] Vivid economics (2019), 'Greenhouse Gas Removal (GGR) policy options – Final Report': Greenhouse gas removal policy options - GOV.UK (www.gov.uk)

[7] The Climate Change Committee (2020), 'The Sixth Carbon Budget – The UK's path to Net Zero': Sixth Carbon Budget - Climate Change Committee (theccc.org.uk)

[8] The Royal Society (2018), 'Greenhouse gas removal': https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

[9] The Royal Society (2018), 'Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments': https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5897820/

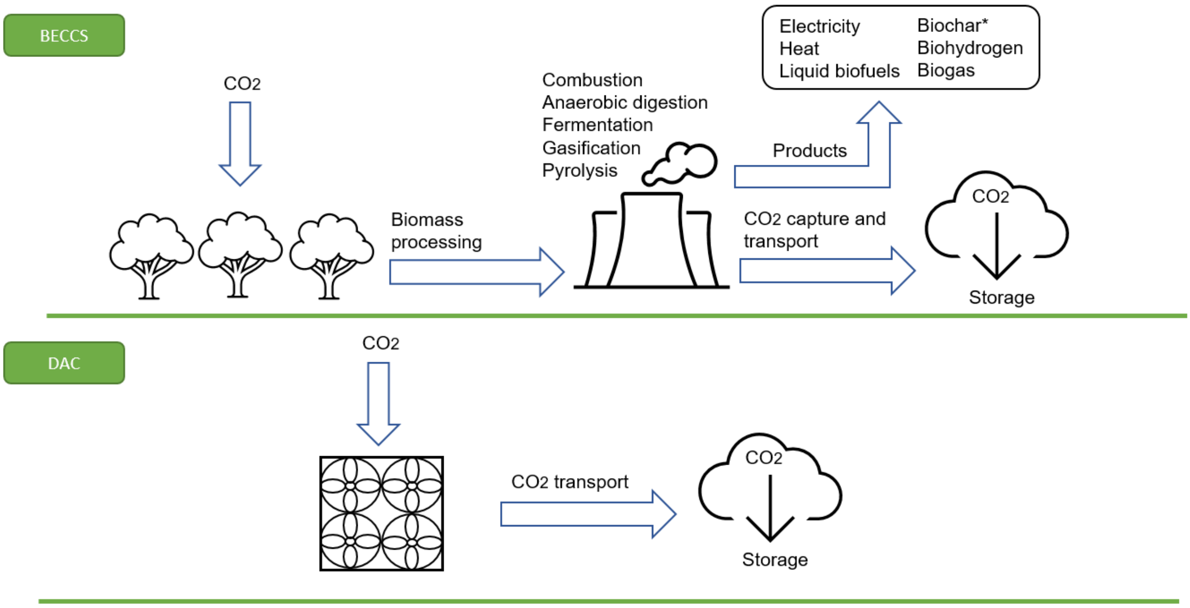
*Note that in 2021 the UK Government ran a consultation for introducing a Sustainable Aviation Fuel (SAF) mandate in order to reduce emissions in the aviation sector. The consultation aims to blend 10% SAF with fossil fuels by 2030 and up to 75% by 2050. Please see here: Mandating the use of sustainable aviation fuels in the UK - GOV.UK (www.gov.uk)

[10] National Infrastructure Commission (2021), 'Engineered greenhouse gas removals': Engineered greenhouse gas removals - NIC

[11] Haszeldine et al (2019), 'Greenhouse Gas Removal Technologies – approaches and implementation pathways in Scotland': Greenhouse Gas Removal Technologies – approaches and implementation pathways in Scotland

[12] Element Energy, 'Review of international delivery of negative emission technologies': Review of international delivery of negative emission technologies (climatexchange.org.uk)

Figure 2: Flowchart of the Negative Emission Technologies considered in this report**



**Majority of biochar production facilities do not utilise CCS. Instead, biogenic carbon is stored permanently within the biochar product and applied to soils; in the construction industry or for other emerging applications, hence enabling negative emissions.*

***Flowchart adapted from work completed by the IEAGHG[13].*

1.2 EXISTING SCOTTISH NETS AMBITIONS

The **Climate Change Plan Update (CCPu)**[14], published in December 2020, provided a detailed overview of Scotland's existing trajectory towards Net Zero and suggestions for improvement. A section was dedicated to NETs, which highlighted the need for negative emissions to offset hard-to-abate carbon-intensive sectors (e.g., aviation and agriculture). The CCPu considered both BECCS and DACCS as the engineered GGR options for Scotland, with BECCS categorised into BECCS Power, BECCS Gasification, BECCS Industry and BECCS Biofuels. The CCPu concluded that NETs will need to be implemented in 2029 at 0.5 $MtCO_2e$/year and scaled up to 5.7 $MtCO_2e$/year by 2032. This would be achieved by developing and commercialising the St Fergus gas terminal by 2024 (capturing 10 $MtCO_2$/year by 2030 of non-biogenic emissions), having the Acorn hydrogen site operational by 2025, and developing the St Fergus DACCS facility by 2026. The captured CO_2 can then be stored in depleted oil and gas reservoirs in the North Sea, which have a capacity of circa 46 $GtCO_2$[15].

The Scottish Government reviewed the update in May 2022[16], and concluded that the proposed NETs ambitions are unrealistic. This is due in large part to the UK Government's announcement that the Scottish CCUS Cluster would not be granted Phase 1 status for the CCUS Fund[17]. However, the

[13] IEAGHG, 'Biomass with carbon capture and storage (BECCS/Bio-CCS)': Microsoft PowerPoint - 2017-03-10 Bioenergy lecture 2 [Read-Only] (ieaghg.org)
[14] The CCPu (2018), 'Update to the Climate Change Plan 2018 - 2032: Securing a Green Recovery on a Path to Net Zero': Supporting documents - Securing a green recovery on a path to Net Zero: climate change plan 2018–2032 - update - gov.scot (www.gov.scot)
[15] Dennis Gramer (2017), 'Taking Stock of UK CO_2 Storage': Taking Stock of UK CO_2 Storage | The ETI
[16] The CabiNETs Secretary for Net Zero, Energy and Transport (2022), 'Climate Change Plan: monitoring reports 2022': Climate Change Plan: monitoring reports 2022 - gov.scot (www.gov.scot)
[17] BEIS (2021), 'October 2021 update: Track-1 clusters confirmed': October 2021 update: Track-1 clusters confirmed - GOV.UK (www.gov.uk)

development of a Scottish Cluster is still possible, due to £425,000 of direct financial support for the St Fergus site and the launch of the £5M CO_2 Utilisation Challenge Fund[18] in 2022. The Scottish Government also accepts that these BECCS ambitions are unrealistic, as a 2022 paper by Ricardo[19] highlighted a lack of available home-grown sustainable biomass within Scotland to meet future BECCS demands (according to the TIMES and 6CB pathways), resulting in a heavy reliance on biomass imports.

The CCPu also detailed actions for the Scottish Government to undertake, some of which have been completed, including: feasibility studies on biomass feedstock availability[19] and a horizon scan of international NETs deployment[20]. A draft Bioenergy Action Plan will be published in 2023, which will identify the most appropriate and sustainable use for bioenergy resources across Scotland. In addition, a proportion of the £80M from the Emerging Energy Technologies Fund will be provided to NETs partners[16]. The Scottish Government also acknowledges suggestions to use CfDs and the UK ETS to reward negative emissions (both of which are outlined in section 1.3 of the technical appendices document), in a bid to develop a NETs market, and develop a cross-sectoral approach towards the sustainable biomass use. One of the primary outcomes from this report will be to supply up-to-date, industry-specific information on future demand for NETs, to allow a more accurate assessment of the future implementation of NETs technologies for Scottish Government ministers and analysts.

The Committee on Climate Change (CCC)'s 6th Carbon Budget[21], published in December 2020, provided detailed Net Zero targets for the UK, which were partitioned out to all respective UK countries (including Scottish specific targets). Similar to the CCPu, a chapter was dedicated to NETs deployment, which stressed the importance of adopting engineered NETs early on, and modelled 5 different scenario pathways: Headwinds, Widespread Engagement, Widespread Innovation, Balanced Net Zero Pathway, and Tailwinds.

The CCC's target for the UK is to reduce emissions by 78% by 2035 (relative to 1990), which is significantly more ambitious than the UN's targets of 68%. This will build on the current investment of around £10Bn per year to around £50Bn by 2030[7]. In the 2023 Spring budget, a further £20Bn of UK Government support for CCUS was announced.[22]

According to the 'balanced' pathway, emissions fall rapidly in the electricity supply sector due to further adoption of renewables, whilst the heating and transport sectors decarbonise in the mid-2030s due to heat pumps and electric vehicles. Emissions from manufacturing and construction drop in the late 2020s, because of electrification and low carbon hydrogen, whilst emissions from agriculture and aviation stagnate and/or increase. These latter emissions must be offset using NETs.

Based on the GHG removal sector scenarios modelled in the 6th Carbon budget, the scale of UK NETs deployment via BECCS by 2050 ranges from 44-97 $MtCO_2$/year. This figure is composed of BECCS Power (16-39 $MtCO_2$/year), BECCS EfW (1-10 $MtCO_2$/year), BECCS Industry (3-4 $MtCO_2$/year), BECCS Hydrogen (0-36 $MtCO_2$/year), BECCS Biomethane (0.5-0.6 $MtCO_2$/year), and 0-15 $MtCO_2$/year for DACCS. The resulting demand for biomass increases to around 190-360 TWh, the UK domestic resource supply varies from 95-195 TWh[23] – indicating that imported biomass would be highly likely to be required to meet these future demands.

According to the 6th Carbon Budget, Scotland has more ambitious targets of achieving Net Zero by 2045, which will require 3-9 $MtCO_2$/year of engineered NETs by 2050. Interestingly, the 'balanced'

---

[18] Scottish Government (2022), '£5 million to develop carbon dioxide utilisation technology': £5 million to develop carbon dioxide utilisation technology - gov.scot (www.gov.scot)

[19] Ricardo, Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets: Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets (climatexchange.org.uk)

[20] Element Energy and E4Tech (2022), Review of International Delivery of Negative Emission Technologies climatexchange.org.uk/media/5132/cxc-review-of-international-delivery-of-negative-emission-technologies-february-2022.pdf

[21] The Climate Change Committee (2020), 'Policies for the Sixth Carbon Budget and Net Zero': Sixth Carbon Budget - Climate Change Committee (theccc.org.uk)

[22] https://www.gov.uk/government/publications/spring-budget-2023/spring-budget-2023-html

[23] The Climate Change Committee (2018), 'Biomass in a low-carbon economy', https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

pathway is simulated to reduce Scottish emissions by 64% by 2035 and 99% by 2050 (compared to 1990 levels) without using NETs.

The requirements for NETs are often linked back to the targets for carbon emissions. A high emphasis can sometimes be placed on NETs to meet national targets. This study used a bottom-up approach in determining the NETs potential in Scotland to provide a more realistic assessment of NETs possible contribution. The policies required to enable NETs varies in the pathways, showing that there is considerable variation in NETs deployment possible.

1.3 NEGATIVE EMISSIONS TECHNOLOGIES

The negative emissions technologies covered in this report are separated into the sectors they broadly relate to. The sectors considered were Power, Energy from Waste (EfW), Industry, Hydrogen, Biomethane, Direct Air Carbon Capture and Storage (DACCS), Biochar and Biofuel. The capture equipment used may be applicable across multiple sectors. For example, if it is assumed biogenic CO_2 emissions from Power, EfW and Industry arise from combustion, a number of capture methods may be equally applicable to these sectors. Capture equipment and NETs (as defined in this report) are discussed in greater detail within sections1 and 2 of the technical appendices document, but a brief summary is given in this section.

1.3.1 Technologies included in this study

Table 4 provides the technologies that were considered in and out of scope in this report. The out of scope/non-engineered NETs are outlined in summary form in Appendix 9 of the technical appendices document.

Table 4: Technologies considered in this study

In scope	Out of scope
DACCS	Reforestation and afforestation
BECCS Power (including Combined Heat and Power (CHP))	Soil Carbon Sequestration
BECCS Hydrogen	Enhanced Weathering
BECCS Energy from Waste (EfW)	Ocean Alkalinisation
BECCS Biogas (e.g., biomethane)	Ocean Fertilisation
BECCS Biofuels (e.g., bioethanol)	Embodied carbon practices (e.g., using wood in construction or creating concrete via DACCS)
BECCS for Fermentation	
BECCS Industry	
Biochar	

1.3.2 Technology readiness levels (TRL)

Throughout sections 1 and 2 of the technical appendices, reference is made to the technology readiness level (TRL) of NETs. This is a method of categorising the state of development of a technology. Technologies are assigned a TRL of 1 to 9 depending on their maturity, with 1 being the least developed and 9 the most. TRL was originally developed by NASA and the terminology used in definitions of each TRL level often reflect this, in the context of NETs, TRLs may be defined as shown in Table 5.

After reaching a TRL of 9, the focus shifts to full commercial deployment, driven by factors like profitability and competition with alternative technologies. This study explicitly addresses this next step in the pathways section.

Table 5: Categorisation of technologies by technology readiness level (TRL)[24]

Technology readiness levels	
Research and development	
TRL 1	Basic Research
TRL 2	Applied Research
Applied research and development	
TRL 3	Critical Function or Proof of Concept Established
TRL 4	Laboratory Testing/Validation of Component(s)/Process(es)
TRL 5	Laboratory Testing of Integrated/Semi-Integrated System
Demonstration	
TRL 6	Prototype System Verified
TRL 7	Integrated Pilot System Demonstrated
Pre-commercial deployment	
TRL 8	System Incorporated in Commercial Design
TRL 9	System Proven and Ready for Full Commercial Deployment

1.3.3 BECCS Power

The archetypical bioenergy power facility could be a solid biomass fuel (e.g., wood pellet or wood chip) boiler supplying steam to a steam turbine. The site may be power generation only or make use of waste heat from the process and be classed as combined heat and power (CHP). To such sites, amine post-combustion capture equipment may be fitted to capture bio-derived CO_2 from the flue gas. This briefly describes a system currently at TRL 8-9, however, attaching post-combustion capture to generating stations comes with an energy penalty as heat is required to regenerate the CO_2 capturing solvent.

An alternative method is oxy-fuel combustion. This broadly refers to a system where a stream of oxygen (rather than air) is provided for combustion. The advantage of this method is a higher CO_2 concentration in the flue gas, making CO_2 capture easier. The disadvantage is the requirement to run an air separation unit (ASU) to provide the oxygen stream. This combustion method, providing steam to a steam turbine, has been demonstrated at pilot level but not at commercial scale, so has a TRL of 7.

Existing at lower TRLs is pre-combustion capture. Biomass is gasified to produce syngas, CO_2 can be removed from syngas before combustion via physical absorption, reducing capture costs. Disadvantages of this system are high capital and operating costs, a system incorporating both integrated gasification combined cycle (IGCC) power generation and carbon capture is also yet to be demonstrated.

1.3.4 BECCS Energy from Waste

Energy from waste (EfW) plants typically comprise a boiler and steam turbine, similar to a BECCS power site. Where EfW differs is the fuel input, which may include municipal solid waste (MSW), commercial or industrial waste. The fuel may therefore vary widely in moisture content, calorific value and biogenic fraction. The latter is estimated to be between 40% and 60% of waste utilised in EfW plants. As such, the NETs potential from EfW is included within this study.

[24] BEIS (2021), Direct Air Capture and Greenhouse Gas Removal Programme – Phase 2: Competition Guidance Notes, Annex 3

Similarly, to BECCS power, post-combustion capture technology can be retrofitted to existing EfW plants (accepting that similar energy penalties will apply). Whilst post-combustion capture has been demonstrated commercially in other applications, it has yet to be integrated at a commercial scale with EfW, leading to a TRL of 7 in this case.

1.3.5 BECCS Industry

The BECCS industry category spans a range of activities. These encompass manufacturing of wood-based products such as paper mills, wood panel (orientated strand board and medium-density fibreboard) and wood pellet production, where wastage from processing provides an integral source of fuel. Such sites are similar to BECCS power and the same TRLs are assumed.

Cement production was also considered for its NETs potential. As part of the production process, clinker is produced in kilns at operating temperatures between 1400degC and 1500degC. This is traditionally achieved using fossil fuels, however, a limited amount of fuel switching (using waste derived fuel called solid renewable fuel (SRF)) has been demonstrated, with co-firing of up to 30-40% biomass is possible. Post-combustion capture may be applied to this process. Biomass kilns with CCS is at TRL 7, whilst co-firing kilns with CCS may be considered to be higher, with some commercial scale facilities planned[25].

In comparison to industries incorporating combustion process, CO_2 capture from the brewing and whisky industry is relatively simple. Fermentation of the grain or malt input results in a high purity stream of CO_2 that may be readily captured. This could constitute an early opportunity to achieve around 0.5MtCO_2/year of negative emissions.

1.3.6 BECCS Biomethane

Biomethane can be produced by the upgrading or methanation of other biomass derived gases (such as biogas or syngas). Thermochemical routes, such as gasification and pyrolysis may be used to produce syngas from a range of solid biomass feedstocks, including MSW, energy crops and forest residues. Alternatively, biogas can be produced by anaerobic digestion (AD) of wet biomass, such as manure, sewage sludge and food waste. The resulting biogas or syngas has a methane content ranging from 40-60% (depending on feedstock used), with CO_2 comprising the majority of the remaining volume. Upgrading of these gases increases the methane concentration to 93-97% by removal of the CO_2.

Upgrading of biogas from AD is an established process (TRL 9), with the resulting biomethane often mixed with natural gas in the grid. The upgrading process presents an opportunity to capture and store a highly concentrated stream of biogenic CO_2.

1.3.7 BECCS Hydrogen

Production of biohydrogen is a further process of the biomethane production described in section 1.3.6. Carbon is removed from the biomethane using processes that may be employed for natural gas, steam methane reforming (SMR) and auto thermal reformation (ATR). Following these processes, CO_2 is separated from the Hydrogen stream using amine based (MDEA) or vacuum pressure swing adsorption (VSPA) capture, resulting in a CO_2 offtake of 22gCO_2 to 71gCO_2 per MJ of Hydrogen for SMR and ATR respectively. TRLs for these processes range between 4 and 9.

1.3.8 Direct Air Carbon Capture and Storage (DACCS)

Direct air carbon capture and storage (DACCS) refers to various means of removing CO_2 directly from the atmosphere and storing it. TRLs for these technologies range from 4 to 7, with some pilot scale plants in operation. Methods that have been demonstrated can be split into liquid solvent DACCS and solid adsorbent DACCS. The former method may use a potassium hydroxide solution, which reacts with the CO_2 in the air, producing potassium carbonate. The solution is then reacted with calcium hydroxide, producing calcium carbonate and potassium hydroxide (which may be reused in the air contactor to capture CO_2). The resulting calcium carbonate is then heated in an oxy-fuel calciner to

[25] Bioenergy with carbon capture and storage, Technology deep dive, IEA, 2022

release the CO_2 and is later reformed into calcium hydroxide for reuse. Whilst it is assumed that the potassium carbonate is regenerated and reused, the system must be replenished with calcium carbonate at a rate of 0.03t per tCO_2. The solid adsorbent process uses a solid material filter to capture CO_2, the filter is then heated to a relatively low temperature (80degC to 120degC) to release the CO_2. This process degrades the sorbent material overs time, an average depletion rate of 7.5kg/tCO_2 gives the sorbent a lifetime of less than 1 year. Supply chains for adsorbent material will need to expand substantially to employ this technology at scale.

DACCS has advantages in that there are few restrictions to deployment locations (other than a means of storing the captured CO_2). The high energy demand of these systems, particularly with regards to heat (with demand between 1.46-2.45 MWh/tCO_2, see section 1.2.2 in the technical appendices document), mean that they would be ideally deployed near sources of waste heat. This would be most useful for solid adsorbent DACCS, where temperature demands are lower. Liquid solvent, however, requires temperatures in excess of 900degC in the calciner. Providing this by natural gas (as is currently the case) reduces the NETs CO_2 removal per tonnes of CO_2 captures, as the CO_2 released to fuel the process must be discounted.

Unlike other forms of NETs, the primary output of DACCS is the captured CO_2 (as opposed to generated power or heat). The potential to sell the captured CO_2 for utilisation purposes may be considered in the future, once the storage infrastructure is fully operational. Accordingly, capture costs for DACCS are potentially greater. Estimates for this range from as low as £67/tCO_2 up to £507/tCO_2. With no other associated revenue streams, the technology will be reliant on a negative emissions market emerging.

1.3.9 Biochar

Biochar is a charcoal-like product formed when biomass is thermally decomposed in very low or zero oxygen levels. This process is known as pyrolysis, which may be further categorised into fast and slow pyrolysis. Slow pyrolysis is favoured when biochar (as opposed to biofuel) production is prioritised. Applicable feedstock can vary greatly, with the process able to use most forms of dry biomass or waste material, with the feedstock providing most of the energy for the process. The resulting biochar retains carbon in the feedstock is a stable form and, applied to soil, may be considered a form of carbon capture and storage. Applying biochar to soil has further benefits in improving soil condition by absorbing heavy metals (e.g., arsenic and copper), increasing water and nutrient retention, and stabilising pH and microbial populations. By-products of biochar production include syngas and bio-oil, which may be combusted to provide heat and power.

The application rate of biochar must be limited to 30-60 t/ha, to ensure soil surface reflectivity does not decrease significantly and damage crops. Therefore, the deployment of biochar is also limited. The maturity of the technology is also debateable, with conflicting estimates for TRL between 3 to 6, or 5 to 7.

1.3.10 Common barriers

Although the deployment of NETs is accelerating, there are still a number of challenges and barriers that need to be overcome. These can be broadly categorised into economic, technical, infrastructure, supply chain, environmental, social and regulatory barriers.

Section 2.1 in the technical appendices document provides a more detailed overview of the common barriers to NETs implementation.

1.3.10.1 Technical

The most cited barrier for NETs is the need to develop CO_2 transport and storage infrastructure; there could be competition for storage capacity once this infrastructure is online. The high energy requirements of NETs are another common limitation, with oxy-combustion capture and DACCS being particularly energy intensive. Pre-combustion capture has an advantage over post-combustion capture in that physical absorption instead of chemical absorption can be used for the capture process due to the higher pressures involved. As a result, pre-combustion capture is associated with lower energy penalties due to the lower energy needed for physical solvent regeneration. Finally, engineered NETs have not yet been shown to operate at scale, and hence there is a knowledge constraint associated with operating these facilities.

1.3.10.2 Economic

Economic barriers to NETs exist due to the high capital cost associated with upfront investment. As an example, constructing a 1 $MtCO_2$/yr liquid solvent DACCS plant would cost £951.4M (see section 2.7 in the technical appendices document). Additionally, several NETs technologies possess high operating costs. This is most prevalent for DACCS, which requires the construction of large capture units to process and extract the diluted concentrations of CO_2 in the air (~400 ppm) and consumes significant heat and power.

1.3.10.3 Policy and Regulatory

Currently the costs of NETs are prohibitively high unless additional financial support is provided, resulting in economic barriers to their widescale deployment. The UK Government are proactively considering the most appropriate support to limit such barriers; however, support has been limited to date. Therefore, further financial incentives are necessary in order to provide stakeholders with greater long-term clarity and revenue certainty.

Additionally, the requirement to have effective monitoring, reporting and verification (MRV) standards in place is another key challenge. The high resource requirements (bioresources for BECCS and biochar & electricity/heat for DACCS), lack of CO_2 T&S infrastructure, and lack of policy incentives for GGRs are some of the main constraints towards deployment. Most notably, without a price or reward for negative emissions, GGR deployment may not be financially viable for the private sector[6].

1.3.10.4 Environmental

A major environmental challenge relates to the changes in land use to accommodate the large amounts of feedstock required for BECCS and biochar, which may result in species loss and reduced biodiversity. **The future availability of bioresources for BECCS and biochar have been used in this report**. Furthermore, land use changes may affect the price of agricultural commodities, such as food, which will negatively impact the poorest households.

1.3.10.5 Social

Public perception is an important aspect to ensure the successful wide-scale deployment of NETs; however, the unfamiliar nature of novel technologies may pose as a risk to gaining public support. To date, prior studies have shown that public acceptance varies across different NETs, with nature-based solutions having higher acceptance rates and engineering NETs being seen as a risk. A study on the perception of BECCS was recently undertaken in the UK, where a large majority (79%) of participants stated that prior to the experiment they knew little to nothing about BECCS[26].

1.3.10.6 Supply chain

The increased demand for negative emissions will result in an increase in the demand for carbon capture equipment. It can therefore be expected that the number of suppliers will need to increase to meet this demand in order to avoid significant supply chain barriers.

1.4 NON-ENGINEERED NETS

GGRs can be divided into two categories, nature-based and engineered removals – this report focusses on engineered solutions. A brief summary of nature-based/non-engineered NETs is presented in Appendix 9 of the technical appendices document.

There are four main categories of nature-based NETs:

1. Forests and forestry management

[26] Perceptions of bioenergy with carbon capture and storage in different policy scenarios, Perceptions of bioenergy with carbon capture and storage in different policy scenarios | Nature Communications

- Afforestation, reforestation, and forest management are various land-based GGRs that consider carbon removals through woodland expansion and forest management.
- The maximum technical potential of this GGR in the UK is 26.5 $MtCO_2$/year by 2050, which is the highest of the land-based GGRs, however, still notably lower than engineered GGRs[27].
- It should be noted that carbon can move from this GGR to others, due to biomass supply for biochar, BECCS and wood in construction. Additionally, GGR afforestation competes with biochar and bioenergy feedstock (for BECCS) for land.

2. Peatland/ peatland restoration
   - Peatland habitat restoration as a GGR method involves the re-establishment of functional, and hence carbon-accumulating, peatland ecosystems in areas that have been degraded to the extent they no longer sequester CO_2.
   - The maximum technical potential of this GGR in 2050 is 4.7$MtCO_2$/year; this figure is based on restoration of 750 kha of the most degraded peatlands in the UK[27]
3. Soil carbon sequestration
   - Soil carbon sequestration is a GGR method that considers how the carbon content of soil can be increased through land-use or land-management change. It is more relevant to agricultural land use, and hence has greater impact on cropland and grassland.
   - The maximum technical potential of this GGR is 15.7 $MtCO_2$/year by 2050, which again is considerably lower than engineered GGRs[27]
4. Wood in construction
   - Wood in construction as a GGR method is defined as the increased use of domestically produced wood in buildings to permanently store carbon. This has the potential to increase the amount of biogenic carbon stored in harvested wood products (HWP).
   - Due to several limitations, the maximum technical potential in the UK of this land-based GGR is 3.3 $MtCO_2$/year by 2050, which is significantly less than any other engineered GGR[27].

[27] Greenhouse gas removal methods and their potential UK deployment, Element Energy, Accessed at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1026988/ggr-methods-potential-deployment.pdf

2. THE RELEVANCE OF NETS FOR SCOTLAND

2.1 INTRODUCTION

This section highlights the issues which need to be considered when developing NETs pathways for Scotland. Important considerations include availability of bioresources, availability of CO_2 storage, future demand for NETs, improvements over time in the performance of CO_2 capture systems, future demand for power and renewables, GHG accounting, MRV and certification procedures. Each of these considerations and their relevance to Scotland are discussed below.

It should be noted that this information is gathered from a review of the latest literature sources and publications and from the stakeholder consultation (see Appendix 3 of the technical appendices document for a summary of the stakeholder consultation which was undertaken as part of this study).

The considerations highlighted in the section below are combined with the methodology described in Section 3 and 4 to develop the pathways described in Section 5.

2.1.1 Key Findings

- **Current support for biogenic carbon emitting sites:** Existing support is provided to current biogenic carbon emitters through the Renewable Obligations (RO) and Renewable Heat Incentive (RHI) schemes. New incentives will be necessary once these schemes end to ensure their continued operation.
- **Transition of biogas sites:** Biogas sites constructed after November 2021 will lose support after the RO scheme concludes. To maintain fiscal support, these sites may need to transition to biomethane production if a GGR support scheme is established. This transition can contribute to NETs if carbon is captured and stored during the AD upgrading process.
- **BECCS Biomethane sites:** To prevent operational disruptions at BECCS biomethane sites, grid agreements must be in place to minimise curtailment.
- **BECCS EfW sites:** It is likely that CCS will be installed onto EfW sites, regardless of whether additional fiscal support is provided by the government. This is out of necessity, to ensure that these sites are awarded planning permission and meet revised emission regulatory requirements.
- **Deployment challenges for NETs:** BECCS Power, BECCS Industry, DACCS, and BECCS Hydrogen all face challenges due to higher costs and lower technical maturity, making deployment at large scale unlikely without significant government support.
- **BECCS Industry sites:** Industrial sites emitting biogenic carbon, like pulp and paper manufacturers, will be compelled by regulations to implement carbon capture to meet planning permission requirements and comply with new emission regulations.
- **Carbon capture in brewing and distilling:** Breweries and distilleries might adopt carbon capture due to demand for captured carbon in their operations, such as carbonating drinks. This would not be considered NETs.
- **Interest in Biochar:** Stakeholders are expressing significant interest in biochar due to its versatility across various sectors. Deployment could be substantial, even without additional support.
- **Availability of bioresources:** The availability of future bioenergy resources could be a limiting factor behind the deployment of BECCS and biochar technologies. In order to maximise the total bioenergy available in Scotland (13.2 TWh for dry and 3.1 TWh for wet bioresources by 2045), the growth in bioenergy crops must be supported in the Bioenergy Action Plan, Biomass Strategy or potentially an agriculture and land use strategy.
- **MRV framework for NETs:** To qualify as a NET, captured CO_2 must either be permanently stored underground or used in industries where CO_2 becomes a permanent part of the product, such as concrete curing or green polymers. To account for this carbon, an appropriate MRV framework must be developed. This is ongoing and should consider the entire life cycle of a

NET process, including biomass sources, electricity and heat sources, and the fate of captured CO_2.

- **Competition and Market Demand:** Industry discussions reveal that existing biomethane and fermentation sites could implement CCS, but CO_2 is likely to be utilised rather than stored. Additional incentives are required to shift this carbon to permanent storage. Competition between BECCS Power and other low-carbon electricity sources is also possible.
- **CCS as an enabler of NETs:** The development of CCS industry and infrastructure is considered the cornerstone on which the NETs industry depends upon. Therefore, establishing CCS demonstration projects now is crucial to making the technology available in time.
- See section 2.3 for a summary of the key findings form the stakeholder feedback.

2.2 IMPORTANT CONSIDERATIONS AND ASSUMPTIONS

This section presents key assumptions in the NETs pathway development for Scotland.

2.2.1 Future viability of biogenic sites without fiscal support

Many large sites that emit biogenic CO_2 currently have some fiscal support via either the Renewables Obligation (RO) Scheme or Renewable Heat Incentive (RHI) schemes. Once this subsidy support ends, such sites will be forced into fundamental decisions over whether it is financially beneficial to continue operating. Many of these sites are owned by global companies which will likely have similar decisions to make across a number of sites.

Once the RO scheme ends, several biogas sites may be forced to switch to producing biomethane to ensure they receive continued financial support through a future GGR scheme[28]. This creates a significant opportunity for NETs through BECCS Biomethane if sites decide to capture the carbon from the biogas upgrade process and invest in infrastructure to allow its permanent storage (e.g., via transporting to other parts of the UK or global storage hubs or utilising it in specific industrial applications where it remains permanently trapped, e.g., concrete curing or green cement). Regarding EfW, it is unlikely that CCS will be installed because of fiscal incentives alone, but rather as a necessity of obtaining planning permission and as a regulatory requirement. **This is likely to fundamentally impact whether an EfW site is a profitable installation or not.**

For NETs that are more expensive and less mature (e.g., DACCS, BECCS Power, BECCS hydrogen), it is expected that deployment will remain at very small scale without significant central support from either the Scottish or UK Governments. Existing UK Government support schemes/competitions such as the GGR Competition, the Hydrogen Innovation Scheme, and Hydrogen Investment Fund could support this. Finally, discussions with stakeholders indicate great interest in biochar, due to its applicability in various sectors such as agriculture, wastewater treatment, and even the construction industry and several test-scale plants are planned in Scotland. Biochar deployment could therefore be significant in terms of number of sites (although in small volumes of NETs) even without additional support.

2.2.2 Availability of bioresource

The impact that NETs may have on the availability of bioenergy resources in the future could be a limiting factor in the development and capacity of sites that may be developed. This is particularly relevant given that the analysis excluded biomass imports and only considered domestic bioresources in estimating the NETs potential of each pathway. Thus, the availability of bioresources is a limiting factor for the development of BECCS and biochar technologies. Table 6 shows the split of dry (for power/industry/biochar & hydrogen) and wet bioresources (those that are more suited to anaerobic

[28] Sites producing biogas before the Green Gas Support Scheme came into effect in November 2021 are not eligible for the scheme.

digestion), the information in this table is taken from the CXC report "Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets"[29].

Table 6: Bioresource availability, adapted from CXC report[29].

Bioresource Availability	TWh		
	2022	2030	2045
Dry			
Currently Used	8.0		
Potential unused resource	1.7	2.9	5.3
Total available resource	9.7	10.8*	13.2*
Wet			
Currently Used	0.9		
Potential unused resource	1.9	2.1	2.2
Total available resource	2.9	3.0	3.1*

*Totals do not match due to rounding

Table 6 shows that there are currently 1.7 TWh of dry bioresources in Scotland that are available but unused. These are predominantly forestry residues and offcuts/brash that could be used in a high capacity[30] biomass boiler/power station. The increase in the available but unused dry bioresources (up to 5.3 TWh in 2045) comes predominantly from short rotation forestry and short rotation coppice as well as increase in forestry offcuts and sawmill residues, which are often used in the power industry. This increased availability increases the potential for power BECCS although it should be noted that increased future domestic demand could also lead to higher feedstock prices thus reducing the benefit for future power BECCS plants.

If it is assumed that a BECCS power station with a 50MWe gross capacity has a 31% efficiency with carbon capture technology installed, an availability of 90% and a capture rate of 90% this would require approximately 1 TWh of fuel per year. This means that in 2045 the available bioresource could support ~ 5 x 50 MWe BECCS Power stations or BECCS CHP plants – and could potentially result in around 1.5 $MtCO_2$ of negative emission if 90% of CO_2 captured and permanently stored. The 50 MWe figure has been chosen based on was taken as an arbitrary figure as this is the capacity of EON's Steven's Croft Power station in Lockerbie.

Several NETs options will compete for the available bioresources. The assumption above would rely on **all** bioresources being diverted to BECCS Power and none to Industry, Hydrogen, biochar or any other industry, which is unrealistic. The assumptions for Pathway 3 (UK Government & Scottish Government Action) take the available bioresources into consideration when evaluating future BECCS systems that could be supported. The UKG Action Pathway includes 5 x 50 MWe plants and a future penetration of CCS deployment rate of 50% (i.e., the model essentially has 125 MWe of BECCS Power included for the future scenario). Note that a sensitivity increasing this penetration rate to 100% was included, see section 5.6.6, page 91. The Decarbonisation Readiness consultation[31] proposes to update the 2009 carbon capture readiness (CCR) criteria by removing the 300 MWe threshold and expanding the scope of generation technologies to also include biomass and EfW. This means that any new biomass CHP plant in the UK will need to be capture-ready by leaving space to install carbon

[29] Ricardo for CXC (2022), 'Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets': Comparing Scottish bioenergy supply and demand in the context of Net-Zero targets (climatexchange.org.uk)

[30] The higher the capacity of the combustion system, the greater the ability that combustion system will typically have in using higher moisture content/less valuable bioresources. A biomass power station can be expected to combust fuels of up to 55-60%, whereas a smaller capacity system would typically be 30-40% moisture content.

[31] Decarbonisation Readiness: Joint call for evidence on the expansion of the 2009 Carbon Capture Readiness requirements (publishing.service.gov.uk)

capture when the technology becomes feasible. On that basis, all new biomass plants are expected to be capture-ready but to not necessarily install CO_2 capture until it becomes feasible to do so under specific circumstances. As TRLs improve, CAPEX and consequently LCOC will reduce in the future, making it more attractive to install CCS on biomass power and CHP plants. The 50% deployment rate is estimated based on the expectation that carbon capture will become economically feasible for half of the biomass capacity installed in Scotland in the future. The consultation applied to England only meaning that the current CCR requirements would still apply in Scotland – a similar policy or approach to that taken in England is needed for Scotland to incentivise NETs in the future.

The 2045 future bioresources have a significant short rotation coppice element – this needs to be supported in the Bioenergy Action Plan, Biomass Strategy or potentially an agriculture and land use strategy in order for that to be achieved. Without these additional energy crops, the future available bioenergy resources would be similar to the current estimates, which would only be able to support around 84 MWe of capacity (approx. 1.7 x 50 MWe capacity plant).

There is also 1.9 TWh of wet bioresources that are available but unused. This rises to an estimated 2.2 TWh in 2045. This capacity of available bioresources can support the pathway assumptions, with 20 biomethane plants with carbon capture installed with a penetration of 50% (based on trends in existing biomethane sites which shows that for half of these, it is economically feasible to install CCS). Future biomethane plants are assumed to be carbon capture-ready – but ultimately the demand for biomethane and incentives made available by the UK Government (e.g., as replacement to the existing Green Gas Support Scheme (GGSS)) will be the governing factor as to how many new biomethane plants come online.

The demand for biomethane on an hourly/daily basis can also lead to biomethane plants being curtailed. If these periods are only a matter of a few hours, then plants can typically deal with diverting the biomethane away from grid injection. If the curtailment periods are longer, this can have a knock-on impact on the generation of biomethane. When considering the additional equipment that would be included on a biomethane plant which was carbon capture ready, this curtailment in output would have an additional knock-on impact onto the running of the CO_2 capture plant – which could be detrimental to the overall operation and maintenance of the entire facility if curtailment occurred frequently. **Thus, any biomethane site that would want to implement NETs would likely need to have necessary grid agreements in place to minimise this curtailment <u>or</u> potentially the associated on-going OPEX associated with the site/plant could be higher than estimated in this report.**

2.2.2.1 Biomass imports

Imported biomass is associated with high upstream emissions (such as from shipping) which are likely to negate the effect of carbon removals, increasing the levelised cost of capture. **We have assumed that there are no biomass imports for use in any NETs project. This means that the future demand for bioenergy/biomass/biogenic CO_2 is limited to the available domestic resource[29].**

2.2.3 Future power demand

As with future biomass demand, there will be a huge competition for available power with the main uses being:

- Powering the national grid
  - Electrification of heat and transport will lead to a significant increase in power demand in the future, in line with both the CCC's 6th carbon budget[7] and National Grid's Future Energy Scenarios[32]
  - The 2030 renewable energy target has 50% of Scotland's energy consumption to be supplied by renewable sources[33]
- Green hydrogen production via electrolysis plants
- As an energy source for future DACCS plants

[32] National Grid's Future Energy Scenarios: https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[33] Scottish Government 2030 renewable energy target: https://www.gov.scot/policies/renewable-and-low-carbon-energy/

It is expected that renewable electricity will continue to play an important role in decarbonising the energy sector in Scotland. In addition, blue hydrogen is viewed as a transition fuel to a green hydrogen-based economy and so it is expected that green hydrogen targets will increase in the future. This means that a cautious approach should be taken when considering future DACCS in Scotland, as competition for available renewable power means that there may be more effective uses for the renewable power available to achieve net-zero and decarbonisation targets, rather than diverting this to removals.

This is a conservative approach but is included in all pathways. The purpose of this is to project a more realistic impact that DACCS can have based on this available power, rather than assume that high volumes of DACCS can be implemented in Scotland resulting in high NETs.

2.2.4 Improvements in carbon capture process performance and costs over time

2.2.4.1 Availability of the CO_2 capture plant

A typical assumption for carbon capture rates in CCS feasibility studies is 90%. In reality, instantaneous CO_2 capture rates can exceed 99%. The 90% capture rate assumption means that over a given period (typically one year of operation), ninety percent of the carbon dioxide produced is captured from the generation plant. This percentage is affected by the chemical process (which in theory can capture all of the carbon dioxide produced in a given moment) as well as by the plant performance parameters including for example whether the CO_2 capture plant is shut down for maintenance or for other reasons. Experience from CCS demonstrations in recent years shows that, due to optimisation and snagging issues, the availability of the CO_2 capture plant during initial operation for the first few years was low and improved to over 90% over time[34]. Improvement in the CO_2 capture rate was applied to provide a more accurate representation of the actual captured carbon at a potential site. These rates vary depending on the implementation year (early adopters will have a steeper learning curve than sites implementing CCS into the 2030s).

The following availability assumptions were adopted (in all cases the example is based on a maximum capture rate of 90%.)

Short term / Early Years 2023-2030

- 70% in year 1 = 0.7 * 90% > 63%
- 80% in year 2 = 0.8 * 90% > 72%
- 90% in year 3 = 0.9 * 90% > 81%
- 100% in subsequent years 90%

Medium term 2030 - 2035

- 80% in year 1 = 0.8 * 90% > 72%
- 90% in year 2 = 0.9 * 90% > 81%
- 100% in subsequent years 90%

Mid-late term 2035 - 2040

- 85% in year 1 = 0.85 * 90% 77%
- 95% in year 2 = 0.95 * 90% 86%
- 100% in subsequent years 90%

Late term 2040 onwards

- 90% in year 1 = 0.9 * 90% 81%
- 95% in year 2 = 0.95 * 90% 86%
- 100% in subsequent years 90%

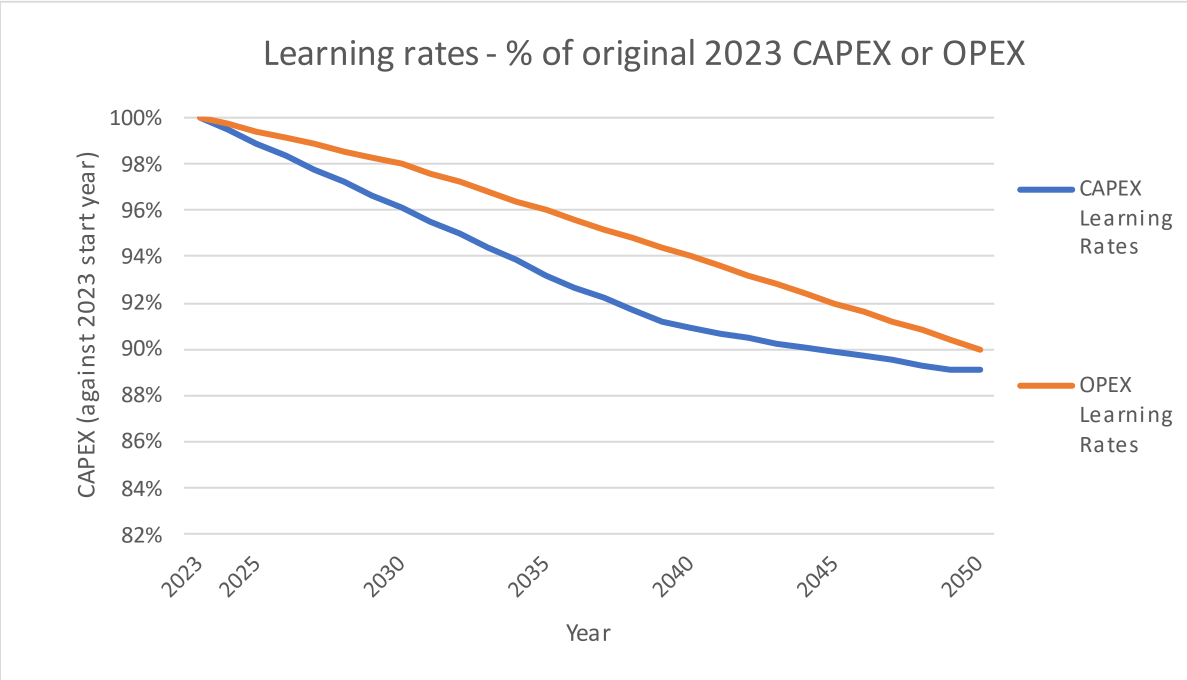
[34] IEA, Energy Technology Perspectives 2020: Energy Technology Perspectives 2020 – Analysis - IEA

These assumptions mean that the carbon capture plant shows improved availability with time and reaches higher carbon capture rates (>90%) in fewer years from initial operation.

2.2.4.2 Cost learning curves

We have included both CAPEX & OPEX learning rates against our calculated 2023 CAPEX/OPEX for CCS. This is shown in Figure 3. There is a moderate decrease to around 10-11% depreciation in original CAPEX-OPEX in 2023. This is applied to the CAPEX & OPEX rates for each site, varying on the year in which this site can implement NETs. This has the impact of reducing the LCOC for each site depending on which year it is implemented.

Figure 3: CAPEX & OPEX learning rates 2023 – 2050



2.2.5 Carbon accounting, utilisation & storage capacity

In order for the CCUS to contribute to NETs targets, the captured carbon needs to be permanently stored. This includes the trapping of CO_2 in saline aquifers (for example as the case with the Sleipner CCS project in Norway) or in depleted oil and gas fields. Carbon dioxide has many applications in industry but the majority of the these (e.g., urea and fertiliser manufacturing, greenhouses, food & drink) lead to the release of the CO_2 back into the atmosphere at some point and so cannot be considered as NETs. Emerging applications such as the use of CO_2 in producing sustainable aviation fuels (SAF) substitute for fossil-based aviation fuel rather than lead to negative emissions. However, some emerging industrial applications such as concrete curing, manufacturing of green cement and green polymers will lead to CO_2 permanence (i.e., permanent storage). Such processes are still at the early stage and require demonstration before they are deployed at a large scale cost-effectively.

The carbon accounting methodology used may influence whether a site may implement NETs. Monitoring, Reporting and Verification (MRV) methodologies and certification of negative emissions to ensure the permanence of CO_2 storage are still in development worldwide. While CCS is included in some emission trading schemes, currently CO_2 utilisation is still not included. It should be noted that any NETs MRV methodology should consider the full life cycle of the process including sources of the biomass, the source of electricity and heat as well as the fate of the CO_2 captured.

Other considerations for NETs accounting in Scotland are whether the carbon that is captured is stored domestically in Scotland or transported and stored elsewhere (i.e., to HyNet, the East Coast Cluster or shipped to the Northern Lights project in Norway). **For this study, it has been assumed that if the carbon is captured in Scotland, then it would contribute to NETs targets for Scotland regardless of where it is stored.**

2.2.6 Competition for NETs Deployment

2.2.6.1 Implementing NETs in Scotland versus other parts of the world

Many sites/operators are owned by global companies. The decision to implement NETs at any specific site will often be a decision based on the relative benefits offered for implementing based on the specific country where the site is based. Thus, organisations that may look to implement NETs in Scotland are likely looking at other countries where they have active sites where carbon capture technologies could be implemented. This is particularly relevant for BECCS Power / CHP and BECCS Industry (including the cement industry – noting that there is only one cement factory in Scotland). If Scotland had an incentive for businesses to invest in NETs in Scotland through either fiscal CAPEX support or a revenue stream for NETs through trading, then this could significantly increase deployment. For the purpose of this study, we assume that other countries do not have this type of mechanism which would make it relatively more attractive to implement a NETs project elsewhere.

2.2.6.2 Competing technologies and uses for stored carbon

If an existing site meets the criteria to be included as part of the suite of sites that eventually form the pathway, it is important to consider the alternatives to the technologies or industries where carbon can be captured. The specific competing uses for stored carbon (i.e., via utilisations streams as opposed to permanent storage) should also be considered.

As highlighted above, stored carbon may not end up being permanently stored – indeed there are many current uses for CO_2 that could be captured – particularly before any storage facility is available. Certain industries are optimistic over the potential for capturing biogenic CO_2 but uncertain over whether this captured CO_2 would end up permanently stored. Ultimately, if carbon is captured at a site, the end-use of the captured carbon is expected to be dominated by the financial benefit offered.

Common alternatives to permanent storage include use in producing SAF and synthetic fuels, use in the food and drink industry, chemical synthesis, producing micro algae and use in enhanced oil and gas recovery operations. Some industry-specific applications are also being trialled for example, methanisation of hydrogen in the whisky industry to produce methane that can be combusted as an alternative to direct hydrogen combustion, this instance, the captured carbon reduces the requirement to upgrade all plant equipment to be hydrogen ready. Both existing and new sites will face competition

Discussions with industry reveals that existing sites that could implement CCS now (biomethane & fermentation) currently have alternative uses for the stored carbon (food & drink industry – Renewable Transport Fuel Obligation (RTFO)). Such practice will not contribute to NETs in the early stages but in the future, when the right incentives are available, the captured carbon would be for permanent storage thus resulting in such sites contributing to NETs targets.

There may be competition between future BECCS & DACCS sites for CO_2 transport infrastructure and storage sites. However, this is not expected to be significant as Scotland benefits from the availability of large storage capacity in the North Sea. DACCS and BECCS could be complementary in the sense that low carbon electricity for DACCS can be provided via BECCS power or CHP sites.

BECCS power will also have competition from other sources of electricity including large scale renewable power, fossil-generated power with CCS, increased imported power from interconnectors or nuclear (noting that the Scottish Government is opposed to new nuclear power).

There is a need for a diverse energy mix in the future and combustion plants producing power (and heat) with carbon capture will form a part of that future energy mix. Torness nuclear power plant has a nameplate capacity of 1,290 MW_e, leaving a considerable gap in power generation when it comes offline. Note that this gap will be plugged by a variety of renewable and low carbon technologies – and BECCS Power is considered to be one of these.

Industrial sites that already have biogenic emissions typically use biogenic fuels as these are by-products from their production (wood/paper and pulp industries). Implementing carbon capture at these sites is again likely to be driven by regulatory reasons (i.e., they have been forced into implementing carbon capture via planning or consenting requirements). Organisations with net-zero targets will be forced away from traditional fossil-based systems without CCUS.

Breweries and distilleries that might implement carbon capture from fermentation processes have so far been driven by demand for the captured carbon for use in processes (for use in carbonation of drinks – or methanisation as outlined above). The alternatives to capturing carbon as a means to reduce emissions at these sites is the same as other industrial sites (biogenic fuels, electrification and hydrogen).

2.2.7 Future market demand for NETs and market penetration rates

NETs and carbon removals in general are seen worldwide as a way of balancing residual emissions from sectors which are hard to abate (such as aviation, agriculture and construction). On the route to Net Zero, it is essential that countries meet their interim carbon reduction targets; if they are not, the demand for NETs will only increase. The development of CCS industry and infrastructure is also seen as the enabler and cornerstone on which the NETs industry must rely on. It is thus important that CCS demonstration projects are established now with innovation to allow the technology to be available in time. Note that enhanced oil recovery (EOR) which uses carbon dioxide to improve the viability of oil production has so far been the major driver of the carbon capture industry.

The penetration and deployment rate of CCS projects in various sectors depends on various factors including: the current readiness of the technology, the willingness of various sectors to adopt CCS and their role in demonstration projects as well as the availability of support from government. The current study established projections for the growth of future industries which could be contributors to NETs and applied CCS deployment rates for each of the sectors to estimate future NETs potential. These penetration rates were estimated based on economic feasibility analysis for existing sites which showed the percentage of existing sites which could implement CCS and achieve a sufficiently low levelized cost of carbon (LCOC) below the threshold. It should be noted that this is a rough estimate and so a sensitivity analysis is undertaken on penetration rates.

The pathway model developed has a market penetration rate function to allow for sensitivities to be applied. Penetration rates can be applied to existing or future sites. The purpose of this function was to provide a "what if" into the modelling. If a site meets the LCOC threshold and is included in the pathway – this does not necessarily mean that it will inevitably implement NETs – the site may not have the capital to implement NETs, or there may be viable alternative uses for any captured carbon at that site. The penetration rate works in the following way:

1. Sites are chosen in each pathway based on the specific assumptions as outlined in sections 2.1 and 5.2
    - This provides a long list of existing, future & fuel switch sites in each of the technology categories
2. Penetration rates can theoretically vary from 0% to 100%
    - The higher the penetration rate the greater the anticipated impact of that specific NETs technology
        - This is useful in particular for sensitivity analysis as the number of sites that could deploy NETs could be easily varied.
3. For existing sites – the market penetration has been set to 100%
    - Ultimately this means that if the sites have been selected from the original list of ~300 into the pathway modelling process then it will adopt NETs.
        - E.g., if we assume a 10% penetration rate then for every 10 BECCS sites from the long list, one will be included in the final pathway.
4. The market penetration rate operates differently for future sites
    - As we cannot predict the number of future sites beyond what is currently planned, the boundaries for future NETs sites have been set by available bioresources (BECCS & biochar) and competition for available power (DACCS).

- Future biomass and EfW plants will receive permitting only if they are carbon capture-ready (Decarbonisation Readiness consultation, 2022). This means sites will need to leave enough space to install CCS in the future when it is feasible to do so. Sites need to submit a feasibility study as part of the planning and permitting process. However, **being carbon capture ready (CCR) does not necessarily mean that sites will install CO_2 capture and be carbon removals from the start. Our assumptions on penetration rates are based on the economic feasibility of sites in the future (learning curves, cost reduction and improved performance).** Options where CO_2 capture is currently more established (e.g., biomethane) are expected to have higher penetration rates in the future where CO_2 capture in the power sector is currently less established and so while there will be improvement in performance and costs in the future, we do not expect each biomass power and CHP site will install CO_2 capture from the start.
- The assumed penetration rates for future sites are as follows:

Table 7: Penetration rates for future sites

NET sector	Future penetration rates
BECCS Power	50%
BECCS Industry	50%
BECCS Fermentation*	N/A
BECCS Biomethane	20%
BECCS EfW**	50%
DACCS***	100%
Biochar****	100%
BECCS Hydrogen	100%

*No new fermentation sites included in any pathway as to the best of our knowledge there are no new large-scale sites planned (arbitrarily; any new fermentation sites constructed in recent years have been smaller-scale artisan sites).

** The number of EfW sites in each pathway varies from 1 in pathway 1, 2 in pathway 2 to 10 in pathway 3

*** The number of DACCS sites in each pathway varies from one in pathways 1 and 2 to 3 in pathway 3

**** The number of biochar sites in each pathway varies from 1 in pathway 1, 2 in pathway 2 to 10 in pathway 3

These market penetration rates have not been applied to future sites that could fuel switch to biogenic CO_2 – sites that are included in this part of the pathway have been estimated based on stakeholder commentary and existing biogenic CO_2 sites.

Fuel-switching sites have been applied only in the maximum NETs pathway and are assumed to be industry sites, most likely in the wood-based industry (i.e., sites that would have easier access to significantly cheaper biomass resources, that may be implementing biomass heat or biomass CHP systems without the historic fiscal support that would have been on offer from the RHI or ROC schemes).

The penetration rates were also used to produce the variability in the figures presented in the results section (section 5.4). Adjusting the penetration rates +/- 20% for each technology input was undertaken to show some high-level variance in results for each pathway. This method of adjusting the inputs rather than the results of the pathway modelling by +/- 20% was done to test the impact that future CCS deployment rates in the various NET sectors on the pathways.

2.3 KEY FINDINGS FROM STAKEHOLDER FEEDBACK

1. The development of the Acorn Storage Facility is seen as a necessity for NETs to develop on a large scale in Scotland.
2. Biomethane BECCS is already an option that many sites are considering in the UK. While several projects are currently financially viable, wide scale deployment of biomethane BECCS is not seen as realistic until the late 2020s. In parallel to this NETs option developing, focus needs to also be on creating and incentivising industrial CO_2 utilisation options where CO_2 remains permanently stored (these include concrete curing, green cement and mineral carbonation for example)
3. Power / CHP BECCS and EfW BECCS were seen as important options for achieving NETs targets due to the large volumes involved. However, these are not seen as viable options before the 2030s. Combining BECCS with CHP and / or DH applications provides the benefit of higher efficiencies and should be prioritised over power-only BECCS.
4. EfW BECCS were seen as an attractive option to focus on as CCS is the only option for EfW sites to decarbonise. Deployment of NETs for EfW plants was projected to be a credible option from around 2030 onwards, with the Acorn CCS CO_2 transport and storage infrastructure project cited as a key enabler. Projects installing CCS on EfW facilities are, however, planned in Scandinavian countries prior to 2030.
5. Sustainable aviation fuels (SAF) are seen by stakeholders as a better use for DAC-CO_2. Permanent storage of DAC-CO_2, which is the key driver for NETs, is unlikely to become feasible unless the right incentives are available to facilitate this approach. Future NETs policy should aim to prioritise geological storage of NETs over the use of CO_2 in the production of SAF which is a focus for the aviation industry.
6. Several barriers exist which need to be overcome if wide scale deployment of NETs is to be achieved in the next decade. These include financial barriers as well as non-financial barriers (supply chain and skills development, policy to encourage capture and permanent storage of CO_2 from specific sectors, planning and permitting, long-term environmental impacts, for example air and water emissions from wide scale deployment of CCS, etc.). NETs deployment is not seen as viable in the absence of incentives for the permanent storage of the carbon, whether in geological formations or via industrial applications. Scotland has a strong R&D base which can be utilised and supported to improve innovation in solvents, process design and optimisation, minimise environmental impacts from CCS deployment.
7. Previous work on supply and demand of bioenergy sources in Scotland shows that by 2045, short rotation coppice will be key. This means that the Bioenergy Action Plan, the Biomass Strategy or any agricultural and land use strategy should support this type of feedstock.

A summary of stakeholder engagement is provided in Appendix 3 of the technical appendices document. The following are key messages from the stakeholder consultation. Stakeholders included biomass power generators (including CHP), energy from waste sites and biomethane producers. Also included were industries such as distilleries, water and sewage, cement production, fuel and wood-based products (such as panel boards and paper).

3. ASSESSMENT OF NETS POTENTIAL IN SCOTLAND

3.1 INTRODUCTION

The analysis for this study considered the NETs potential and costs for:

i. **converting existing sites** to become carbon removal projects (e.g., existing biomethane, distillery, biomass CHP and EfW sites),

ii. the **development of future** NETs in Scotland (e.g., DACCS, biochar, hydrogen from biomass, biofuels and new biomass CHP and EfW sites), and

iii. **fuel switching** (e.g., fossil fuel sites converting to biomass).

A preliminary list of fossil fuel sites which could potentially fuel-switch to biomass as the fuel source was developed. However, due to lack of data, the prohibitive costs and the lack of appetite of such sites to convert to biomass and ultimately to become carbon removals, this option (iii above) was excluded from further analysis. In addition, it is expected that many industrial sites that currently consume fossil fuels are likely to consider converting to hydrogen rather than a bioenergy alternative.

The analysis relied heavily on data and evidence gathering through a comprehensive review of literature sources, recent studies and a stakeholder questionnaire combined with targeted interviews.

The section below outlines the methodology used to assess the total NETs potential for each of the NETs categories. This total potential represents the maximum achievable negative emissions without considering policy and economic constraints.

3.1.1 Key findings

- The maximum biogenic carbon available from existing sites in Scotland is currently 3.3 $MtCO_2$/year. This falls short of the benchmark set by the CCPu (5.7 $MtCO_2$/year in 2032 consisting of 5.2$MtCO_2$/yr of BECCS and 0.5$MtCO_2$/yr from DACCS)[14] by 2032. The maximum projected NETs potential for both existing and future sites (5.3 $MtCO_2$/year) would not be achieved before 2032, falling below the 2032 benchmark set by the CCPu.
- NETs in the BECCS Power and BECCS Industry sectors accounts for 69% of the total NETs potential.
- EfW emerged as the predominant technology in terms of carbon removal potential, being able to capture 83% of the total carbon emitted (including non-biogenic CO_2 originating from the non-biogenic part of the feedstock) but only accounted for 55% of the total NET potential, as not all EfW emissions are biogenic.
- The flexibility (e.g., municipal solid waste, MSW vs. refuse derived fuel, RDF) in feedstock selection means that EfW sites have greater variability in capture potential and costs. Whilst the composition can vary greatly, in general RDF has lower biogenic content and a higher calorific value than MSW. This difference in properties means that the design of CO_2 capture processes can change from site to another leading to variation in performance and costs.

3.2 NET POTENTIAL FOR EXISTING AND PLANNED SITES

A comprehensive list of existing and future planned sites in Scotland which emit biogenic carbon potentially contributing to NETs targets was developed. The list includes new DACCS and biochar developments, the deployment of BECCS on future biomass power and CHP, industry, EfW, biomass-based hydrogen and other potential BECCS sites. For each of the sites identified, the maximum NETs potential (considering the biogenic content of the fuel) was then calculated. Projections for future industries (e.g., power, cogeneration, EfW, hydrogen, biomethane and other industries) were developed based on historic trends and future demand estimates of the expected deployment and penetration rates of CCUS in each of these industries in order to predict the future potential of NETs in Scotland.

Data was obtained from publicly available sources including the Renewable Energy Planning Database (REPD), National Non-Food Crops Centre (NNFCC), Heat Networks Planning Database (HNPD), and Scottish Pollutant Release Inventory (SPRI). In addition, relevant CCUS papers and websites, news articles, and blog posts related to specific sites were also reviewed. These sources yielded valuable information about specific sites, including biomass/waste utilisation rates, heat and power outputs, production rates (such as biomethane, biogas, alcohol), and year of initial operation. Table 8 below shows a breakdown in the source of data used. The data collected was complemented and gaps addressed by engaging with key stakeholders, as discussed in Section 0. Finally, planning permission documents were also consulted to fill any knowledge gaps or cross-reference existing literature.

Note that the REPD is only applicable for sites that are currently in some form of planning, and therefore is only applicable until circa 2030. Beyond that, future sites across all technology categories are likely to be implemented depending on the specific political landscape and whether it is supportive of NETs. Therefore, penetration rates based on historic evidence, technology readiness and likely future policies which could encourage or discourage certain technological options were developed.

Table 8: Summary of data sources used to inform the CO_2 capture calculations

NET	Data sources
Existing sites	
BECCS Biomethane	NNFCC*[35]
BECCS Power	REPD[36]
BECCS Industry	REPD**, HNPD[37], SPRI[38], CHPQA***, and websites
BECCS AD	NNFCC and REPD
BECCS Fermentation	Whisky Invest Direct[39,40] and Scottish Carbon Capture Storage (SCCS)[47]
BECCS EfW/ACT	REPD
Future sites in planning	
BECCS Biomethane	REPD and planning documents
BECCS Power	REPD
BECCS AD	REPD
BECCS EfW/ACT	REPD and relevant websites/blog posts

*An amendment had to be made against the data quoted in the NNFCC and that stated in the planning application. See notes in Appendix 2 of the technical appendices document, for further information.

** Amendments had to be made against the data quoted in the REPD and that submitted under the CHPQA. See notes See notes in Appendix 2 of the technical appendices document, for further information.
*** Combined Heat and Power Quality Assurance

The database of potential sites was filtered, removing sites that lacked sufficient data or those sites that relied solely on fossil fuels for their heat and power demands. Sites located on islands were also excluded due to the small volumes of CO_2 involved in addition to the impractical logistical challenges and relatively high costs associated with transporting CO_2 by ship. Appendix 2 in the technical appendices document shows a detailed breakdown of all the sites included and disregarded in the analysis, along with the specific data related to each site and the sources from which the data was extracted.

[35] NNFCC, 'Anaerobic Digestion Deployment in the UK (2021)': Anaerobic Digestion deployment in the UK (nnfcc.co.uk)
[36] DESNZ, 'Renewable Energy Planning Database: quarterly extract': Renewable Energy Planning Database: quarterly extract - GOV.UK (www.gov.uk)
[37] BEIS, 'Heat Networks Planning Database': Heat Networks Planning Database - data.gov.uk
[38] SEPA, 'Scottish Pollutant Release Inventory': SPRI | Scottish Environment Protection Agency (SEPA)
[39] Whisky Invest Direct, 'Malt whisky distilleries in Scotland': Malt whisky distilleries in Scotland | WhiskyInvestDirect
[40] Whisky Invest Direct, 'Grain whisky distilleries in Scotland': Grain whisky distilleries in Scotland | WhiskyInvestDirect

A comprehensive list of sites which are currently in planning was developed and the potential for deploying BECCS on these sites estimated utilising penetration rates based on historic evidence, technology readiness and likely future policies which could encourage or discourage certain technological options. To create this list the REPD, planning permissions documents, and site-specific websites and blogs were reviewed.

To project capacity growth beyond 2030 a number of assumptions were made based on existing growth rates and demands for power, biomethane, and industry products. These were bounded by the available bioenergy resources (for BECCS & biochar) ensuring that the estimation of the NETs potential from future sites was not excessively ambitious.

NETs potential from new future industrial developments in Scotland was also considered. Data on such developments is limited as these are sites which are not currently in planning and include (for example) future developments of biomass CHP, biomethane or EfW sites. Projections of future power and heat demand, waste generation, and biomethane targets were used in combination with historic trends to estimate future demand and CO_2 available from such sites. CCS deployment rates on new future sites was based on the analysis of existing sites and on the expected technology readiness to capture CO_2 from specific sectors. For example, analysis, done for this study, on existing biomethane sites shows that 50% of existing sites are economically feasible to capture carbon dioxide and so it is estimated that at least 50% of future sites will also be equipped with CCS. A similar approach was also applied to future biomass CHP and EfW sites. This is all discussed in further detail in Section 5.

For hydrogen sites, it is expected that the majority of future targets in Scotland will be based on green hydrogen, with some blue hydrogen production. Biomass-based hydrogen production is expected to complement any future demand but is not expected to become a major contributor until the late 2030s. This assumption is based on the technology readiness and costs as well as competitiveness in the market. This is also supported by both Scottish Government's Hydrogen Action Plan and the UK Government's Hydrogen Strategy where the focus is mainly on green and blue hydrogen. Biomass gasification to produce hydrogen gas has several technical challenges to overcome through and so it is unlikely for hydrogen from biomass gasification to develop widely until the late 2030s.

3.2.1 NETs potential estimates: assumptions and methodology

The potential for NETs at each of the existing sites was estimated based on:

- The CO_2 available from each of the sites (determined based on data gathered from a review of literature sources as well as stakeholder engagement),
- A consideration of the biogenic content of the fuel,
- An application of typical CO_2 capture rates for each of the technology options

It should be noted that the NETs potential determined in this way is the maximum potential and assumes that the captured CO_2 remains permanently stored and that no CO_2 is lost during transportation. The sections below describe the specific methodology used for each of the NETs options, which is the same for existing and future potential sites.

A summary of the LCOC modelling parameters used are listed in Appendix 2 of the technical appendices document. An overview of the modelling parameters and assumptions used are:

- An assumed 90% **CO_2 capture efficiency** has been used for all sites where pre- or post-combustion capture may be used, as discussed in section 1.2 of the technical appendices document. Capture rates for CO_2 resulting from biogas to biomethane upgrading has been assumed to be 95%, based on Ricardo's knowledge of current site performance.
- Different **load factors** were used depending on the choice of NET, ranging from 68% to 90%. These factors differ based on Ricardo's industrial expertise as well referencing to the literature (see Appendix 2 of the technical appendices document).
- The gross **power efficiencies** for BECCS power and industrial sites were taken to be 38.7% and 35.7% when considering NETs capacities. Similarly, EfW/ACT sites have efficiencies of

22% (gross) and 19% (net).[41] These figures are taken directly from the literature (Appendix 2 of the technical appendices document).

- The **heat and power efficiencies for a reference CHP site** were estimated using the CHPQA Database. Regarding biomass powered CHPs, the power and heat efficiencies are taken to be 37.5% and 25% respectively, whilst waste powered CHPs exhibit efficiencies of 31% and 15% respectively.
- The **quantity of CO_2 produced** by each NET was estimated using mass/energy balances and applying emission conversion factors that are taken from the literature (see Appendices 5, 11 and 12 of the technical appendices document for more details).

Below is an overview of the methodology employed for each specific NETS to assess CO_2 capture potentials. A more comprehensive explanation and example calculations are given in chapter 2 and Appendix 2 of the technical appendices document.

3.2.1.1 BECCS Biomethane

In estimating the CO_2 capture potential of a biomethane site, a mass and energy balance was conducted. This involved utilising the biomethane production rate, either obtained from the literature or manually calculated, and applying specific modelling parameters to back-calculate the CO_2 produced during the biogas upgrade process. Key modelling parameters are the biomethane loss rate during the biogas upgrade process, the assumed biogas composition, and the assumed density of CO_2 exiting the upgrader.

The CO_2 production potentials determined through the mass balance were compared to benchmarks from the literature[42] and the values were found to be very close, deviating by +- 0.002 $MtCO_2$/year, validating the assumptions and calculations used. See Appendix 2 of the technical appendices document for comparison.

The study also considered conversion of existing biogas production (AD sites) to biomethane sites incorporating carbon capture. However, after preliminary analysis these sites were subsequently excluded, due to the small CO_2 volumes and high site conversion costs increasing the levelised cost of capture beyond economic feasibility. To see the list of existing biogas sites considered, see Appendix 2 of the technical appendices document.

3.2.1.2 BECCS Power and Industry

A similar methodology was implemented to estimate CO_2 capture potential for existing power and industrial sites. This is justified since the combustion technologies used in BECCS Industry sites, such as biomass-powered turbines, boilers, and CHPs, are equivalent to BECCS Power sites.

The negative emission potential for each of the sites was estimated based on carbon content of the fuel input (determined from the gathered power output and using a factor of 0.35 $kgCO_2/kWh$[43]) and applying the relevant CO_2 capture efficiency. The estimated CO_2 production potential for selected sites was compared to the SPRI Database where data was available. The comparison revealed a general alignment, as demonstrated in Appendix 2 of the technical appendices document, which supports the reasonableness of the assumptions and data sources used.

Due to limited data availability, the CO_2 emissions rate provided by the SPRI database was relied upon to calculate the negative emission potential of the Dunbar Cement site assuming 40% of cement emissions result from fossil fuel combustion[44]. Additionally, considering the planned fuel mix of 45%

---

[41] Coal can achieve higher (>40%) and gas CCGT can be >50%. Gross efficiency measures the overall efficiency of a heat-generating plant, accounting for the recovery of all heat in the fuel, including latent heat typically lost during combustion (i.e., moisture in the flue gas). In contrast, net efficiency focuses solely on the heat efficiency without recovering latent heat, resulting in a lower value compared to gross efficiency.

[42] Ardolino and Arena, 'Biowaste-to-Biomethane: An LCA study on biogas and syngas roads' (2019): Biowaste-to-Biomethane: An LCA study on biogas and syngas roads - ScienceDirect

[43] DESNZ and BEIS, 'Greenhouse gas reporting: conversion factors 2022': Greenhouse gas reporting: conversion factors 2022 - GOV.UK (www.gov.uk)

[44] CarbonBrief, 'Q&A: Why cement emissions matter for climate change': Q&A: Why cement emissions matter for climate change - Carbon Brief

RDF/SRF waste[45] with a biogenic content of 17%[46], the quantity of emissions classified as biogenic was able to be determined.

3.2.1.3 BECCS Distilleries and Breweries

For whisky distilleries and breweries, the negative emission potential was estimated by assuming that the sites operate like industrial bioethanol plants as these sites use the same process of fermentation where process CO_2 emissions result. From this, the litres of pure alcohol (LPA) quoted in the literature was used and the CO_2 production potential calculated using a conversion factor of 755 tonnes CO_2 / Million litres of alcohol produced[47]. The resulting negative emission potential was determined using a capture efficiency of 90%.

3.2.1.4 BECCS EfW including waste gasification sites with pre-combustion carbon capture

For EfW (including advanced conversion thermal (ACT) sites such as gasification with carbon capture), the same methodology as BECCS Power/Industry was applied, but with variations in efficiencies, utilisation factors, and emission conversion factors.

One key difference between BECCS EfW/ACT and BECCS Power/Industry was the flexibility in feedstock selection, with EfW sites having the option to use either municipal solid waste (MSW) or refuse derived fuel (RDF). In comparison to MSW, RDF undergoes additional pre-processing. Whilst the composition can vary greatly, in general RDF has lower biogenic content and a higher calorific value than MSW[48]. As a result, there is greater variability in carbon capture potential and, consequently, capture costs for EfW facilities.

To validate the calculations, the calculated CO_2 production rate was compared to literature benchmarks, observing a close alignment for MSW-powered sites (see Appendix 2 of the technical appendices document). This final finding reinforces confidence in the accuracy of the assumptions and methodology used.

3.3 NEGATIVE EMISSION POTENTIAL ESTIMATES: RESULTS

3.3.1 Existing sites

Figure 4, page 44 shows an overview of the carbon capture and hence NETs potential for existing sites which can potentially become carbon removal sites. It should be noted that the NETs potential corresponds to the capture and storage of biogenic emissions, whilst the total carbon captured accounts for both biogenic and fossil emissions. The maximum projected NETs potential of existing sites is 3.3 $MtCO_2$/year, compared to the target set out in the CCPu (5.7 $MtCO_2$/year by 2032)[14], confirming that whilst retrofitting of existing sites will contribute to this target, the development of future NETs sites is key. It also signifies that the target year of 2032 to achieve these NETs is unfeasible and a new, more realistic target and/or target year for NETs will be required.

3.3.1.1 BECCS Power and BECCS Industry

Figure 4, page 44 shows the NETs potential to be primarily concentrated in the BECCS Power and BECCS Industry sectors, accounting for 69% of the total NETs potential. Two-thirds of the NETs potential from the power sector is provided by the Markinch Biomass CHP Plant and Stevens Croft Power Station, due to their significant gross power capacities (combined 115.4 MWe) and utilisation of 100% biogenic feedstocks. This is clearly illustrated by the breakdown in capture potential for the five largest BECCS sites shown in Table 9 below.

---

[45] Tarmac, 'Tarmac boosts cement plant sustainability': Tarmac boosts cement plant sustainability | Dunbar Quarry

[46] IEA Bioenergy, 'Municipal Solid Waste and its Role in Sustainability': 40_IEAPositionPaperMSW.pdf (ieabioenergy.com)

[47] Scottish Carbon Capture & Storage (SCCS), 'Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions'

[48] IEAGHG, 'CCS on Waste to Energy': New IEAGHG report: 2020-06 CCS on Waste to Energy - BLOG

Table 9: Capture potential breakdown for key BECCS sites in the Power and Industrial sectors

Site	NET	Carbon capture potential (MtCO$_2$/year)[49]	Percentage of capture potential (sector specific)[50]	Percentage of capture potential (total)[51]
BECCS Power				
Markinch Biomass CHP Plant	BECCS Power (CHP)	0.65	44%	15%
Stevens Croft	BECCS Power	0.32	22%	7%
Speyside Biomass CHP Plant	BECCS Power (CHP)	0.12	9%	3%
Rothes Bio-Plant	BECCS Power (CHP)	0.08	6%	2%
Westfield Biomass Power Station	BECCS Power	0.08	6%	2%
BECCS Industry				
Dunbar Cement	BECCS Industry (Cement)	0.44	35%	10%
Morayhill Mill	BECCS Industry (Oriented Strand Board)	0.31	25%	7%
Caledonian Papermill	BECCS Industry CHP (paper - coated magazine)	0.26	21%	6%
Cowie Biomass Facility	BECCS Industry CHP (Particle & MDF)	0.15	12%	3%
Barony Road, Auchinleck	BECCS Industry CHP (Chipboard and wood recycling)	0.05	4%	1%

Regarding BECCS Industry, Dunbar Cement is a significant potential contributor of captured carbon, representing 35% of the capture potential. However, the site's NETs potential is low due to the use of solid recovered fuel (SRF). Consequently, the negative emissions potential of BECCS industry is only 0.85 MtCO$_2$/year, from a total capture potential (biogenic and fossil CO_2) of 1.26 MtCO$_2$/year. When only biogenic emissions are considered, Norbord Morayhill (wood panel producer) and Caledonian Paper Mill account for the majority of the BECCS Industry NETs potential (67% when combined).

Regarding BECCS Industry, Dunbar Cement is a significant potential contributor of captured carbon, representing 35% of the capture potential. However, the site's NETs potential is low due to the use of solid recovered fuel (SRF). Consequently, the negative emissions potential of BECCS industry is only 0.85 MtCO$_2$/year, from a total capture potential (biogenic and fossil CO_2) of 1.26 MtCO$_2$/year. When

[49] Carbon capture potential relates to the maximum quantity of carbon that can be captured from a particular site.

[50] Percentage of capture potential (sector specific) is the measure of a site's ability to capture carbon compared to the total CO_2 that can be potentially captured within its sector.

[51] Percentage of capture potential (total) is the measure of a site's ability to capture carbon compared to the total CO_2 that can be captured by all sites. When referring to all sites, this is dependent on whether the table is considering existing or future sites.

only biogenic emissions are considered, Norbord Morayhill (wood panel producer) and Caledonian Paper Mill account for the majority of the BECCS Industry NETs potential (67% when combined).

3.3.1.2 BECCS EfW

Among EfW sites, the NETs potential is distributed evenly between sites, with Dunbar EfW being the most significant because of its a large gross power capacity of 25.6 MWe. This is clearly illustrated by the breakdown in capture potential for key EfW sites shown in Table 10 below.

Table 10: A breakdown in capture potential for key BECCS sites within the existing EfW sector

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Dunbar EfW (previously Oxwellmains EfW)	BECCS EfW	0.28	29%	6%
Charlesfield Biomass CHP Plant	BECCS EfW ACT (CHP)	0.16	17%	4%
Glasgow Renewable Energy and Recycling Centre (ACT)	BECCS EfW ACT (CHP)	0.16	17%	4%
Millerhill EfW	BECCS EfW	0.14	14%	3%
Levenseat EfW	BECCS EfW ACT	0.12	12%	3%

Note that the NETs potential of EfW sites is reduced by over half when biogenic emissions are accounted for, due to the utilisation of both MSW and SRF waste, which have varying biogenic contents of 50% to 17% on a wet weight (w/w) basis.

3.3.1.3 BECCS Fermentation

The four largest grain distilleries (Strathclyde, Cameronbridge, Girvan, and Invergordon) account for 40% of NETs potential from breweries/distilleries out of 141 sites in total (see the breakdown in capture potential for the largest alcohol producing sites in Table 11 below). These large distilleries are spatially far from one another, but there are some clusters of smaller distilleries – most notably in Speyside.

Table 11: A breakdown in capture potential for key BECCS sites within the existing Fermentation sector

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Girvan	Grain whisky	0.07	15%	2%
Cameronbridge	Grain whisky	0.07	15%	2%
Strathclyde	Grain whisky	0.03	5%	1%
Invergordon	Grain whisky	0.02	5%	1%
Starlaw/Glen Turner Distillery	Grain whisky	0.02	4%	~0%

3.3.1.4 BECCS Biomethane

For BECCS Biomethane, the NETs potential is low and makes up only 4% of the total NETs potential. This is due to the small-scale and localised nature of these upgrading sites, as shown in Table 12 below.

Table 12: A breakdown in capture potential for key BECCS sites within the existing Biomethane sector

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Girvan Distillery	BECCS Biomethane (grid injection & CHP)	0.02	20%	1%
Glenfiddich Distillery	BECCS Biomethane (grid injection)	0.02	15%	~0%
Portgordon Maltings Beyside	BECCS Biomethane (grid injection & CHP)	0.01	6%	~0%
Lockerbie Creamery	BECCS Biomethane (grid injectioN)	0.01	6%	~0%
Keithick Farm	BECCS Biomethane (grid injection & CHP)	0.01	4%	~0%

3.3.2 Future potential sites planned

Figure 4 provides an overview of the carbon capture and NETs potentials for future sites. The maximum projected NETs potential from future sites is an additional 2 $MtCO_2$/year giving a total NET potential (for both existing and future sites) of 5.3 $MtCO_2$/year). Again, falls below the target set by the CCPu (5.7 $MtCO_2$/year)[14].

The main components of the future planned sites are outlined below.

3.3.2.1 BECCS EfW

EfW emerged as the predominant technology of future sites, due in part to the quantity of EfW sites that are currently in some stage of planning. The potential was distributed reasonably evenly across multiple sites, with Thainstone Energy Park Project ERF, Coatbridge Material Recovery and Renewable Energy Facility, Earlsgate Energy Centre, and Drumgray Energy Recovery Centre (DERC) as the major potential contributors (see Table 13 below). These sites are fuelled by MSW rather than RDF, which has a higher biogenic content, representing the highest negative emission potential, accounting for approximately 55% of the total negative emissions from BECCS EfW.

Table 13: A breakdown in capture potential for key BECCS sites within the future EfW sector

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Drumgray Energy Recovery Centre (DERC)	BECCS EfW (CHP)	0.41	13%	11%
Coatbridge Material Recovery and Renewable Energy Facility	BECCS EfW ACT (CHP)	0.40	13%	11%
Thainstone Energy Park Project ERF	BECCS EfW	0.38	12%	10%
CalaChem Fine Chemicals (Grangemouth) - Earlsgate Energy Centre	BECCS EfW (CHP)	0.35	11%	9%
Westfield (former Opencast Coal Mine)	BECCS EfW	0.26	8%	7%

3.3.2.2 Direct Air Carbon Capture and Storage (DACCS)

The future NETs potential from DACCS was accounted for by the single Storegga Carbon Engineering project, which is proposed to be built in the late 2020s with assumed minimum capture rate of 0.5 $MtCO_2$/year. The development of future DACCS projects is location-dependent and, as discussions with stakeholders indicated, relies significantly on the available incentives and financial support as well as the development of international carbon markets. Additional future capacity in Scotland was estimated based on what is considered feasible as highlighted by stakeholder discussions and global DACCS targets.

3.3.2.3 BECCS Power

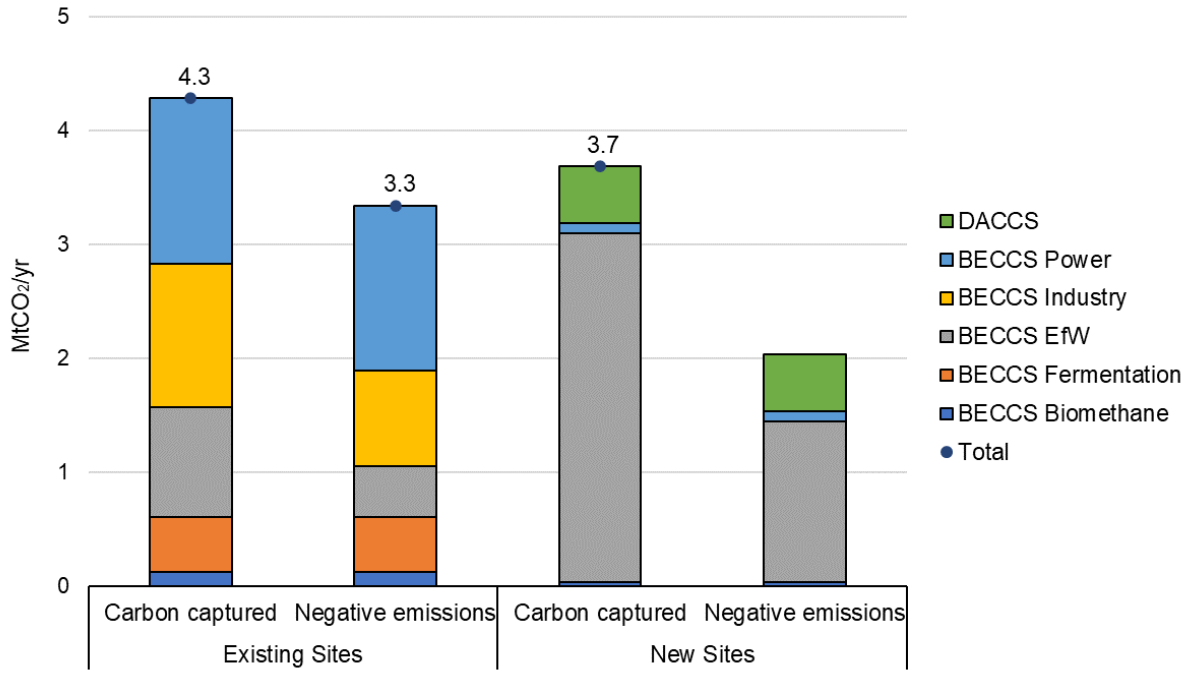
The carbon capture and NETs potential for BECCS Power was very low, with only 4 sites expecting to be installed from the planning databases reviewed (total combined gross capacity of 6.41 MWe). See Table 14 below for a breakdown. These sites are expected to be commissioned between 2030-2035, given the fact that planning permission has been granted but no construction work has begun. The largest of which was the ‘Achnabreck’ site, which plans to gasify wood pellets, and has an estimated NETs potential of 0.088 $MtCO_2$/year.

Table 14: A breakdown in capture potential for all BECCS sites within the future Power sector

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Achnabreck	BECCS Power ACT (CHP)	0.09	94%	2%
Co-Op, Polwarth Street - Biomass boilers	BECCS Power	0.00	3.0%	~0%

Site	NET	Carbon capture potential ($MtCO_2$/year)	Percentage of capture potential (sector specific)	Percentage of capture potential (total)
Hillhead Of Coldwells, Longhaven - Biomass Boilers	BECCS Power	0.00	2%	~0%
Little Broomfield - Biomass boiler	BECCS Power	0.00	1%	~0%

Figure 4: Breakdown in carbon capture and negative emission potential of existing and new sites



3.4 SUMMARY

The analysis described above (and as detailed in Appendix 2 of the technical appendices document) highlighted where the majority of the NETs potential in Scotland is expected to come from. The suite of existing, operational sites gives a mixture of potential NETs projects – predominantly focussed in BECCS Power & BECCS Industry. Sites that are not yet constructed offer a different range of NETs potential – focussed predominantly in BECCS EfW and a moderate contribution from the planned Storegga DACCS installation at St Fergus.

The analysis shows that the total CO_2 available from existing biogenic sources in Scotland is around 3.3 Mt CO_2/year. Not all of this CO_2 can be a contributor to NETs targets and so the next section of the report will evaluate the economic feasibility of sites to evaluate this potential. Also, permanent storage of the CO_2 captured is essential in order to ensure that a site contributes to NETs targets. This is discussed in more detail in Section 5.

4. ECONOMIC FEASIBILITY OF NETS AT EXISTING AND NEW SITES

This section outlines the methodology used to assess the investment and operating costs of converting a site to deliver negative emissions based on a Levelised Cost of Carbon (LCOC) parameter. The LCOC, along with other factors like site location, stakeholder feedback on technologies, and site age, was then used to determine the likelihood a candidate site would convert to a carbon removal or NETs project. This enabled sites to be compared and categorised into the various pathways described later in Section 5.

4.1 LCOC METHODOLOGY

The LCOC served as a filtering mechanism to determine whether a site would likely convert to a NETs and hence be included in the subsequent pathways, as the higher the LCOC the less economically attractive the site. Note that the LCOC for a site varied depending on the choice of pathway, with revenues associated from negative emission trading being included in pathway 3, whilst pathways 1 and 2 only included revenue streams from the site itself. For existing sites, no revenue streams were accounted for within Pathways 1 and 2, whilst they were for future sites.

The LCOC of a site was calculated using:

- the investment cost of retrofitting a site with CCS (CAPEX),
- the Capital Recovery Factor (CRF), a figure used to annualise the investment cost,
- the variable and fixed OPEX, which accounts for the annual operating and maintenance costs of CCS,
- the annual cost of transporting and storing the carbon; and
- the annual NETs potential including both biogenic and fossil emissions.

See Appendix 2 of the technical appendices document for the definitions of each parameter involved.

<u>LCOC calculation</u>

$$LCOC = \frac{(CAPEX \times CRF) + OPEX_{fix} + OPEX_{var} + C_{transport} + C_{storage} - Revenue\ specific\ to\ NETs}{CO2_{captured}}$$

The LCOC threshold (i.e., the LCOC that a site had to achieve to be included in the pathway was £80/tCO_2 in 2025 – this value was chosen as it was broadly in-line with current EU ETS trading prices. The LCOC threshold price had an inflation added such the LCOC threshold increases year on year (see Figure 6, page 52).

4.1.1 Cost analysis

This section provides an overview of the methodology used to determine the CAPEX, OPEX, and CO_2 transport and storage costs. A thorough breakdown of the specific methodologies and assumptions used for each NET, as well as example calculations, are provided in Appendix 2 of the technical appendices document.

CAPEX: In estimating the CAPEX, the widely used sixth-tenths rule was employed[52], which is a method for approximating a project's costs by taking the cost of a comparable completed project and scaling it by the exponent 0.6, based on the capacity of the reference plant. This scaling can be done by

[52] The sixth-tenths rule is an estimate of economies of scale stating that if the capital cost for a given sized piece of equipment is known, changing the size will change the capital cost by the 0.6 power of the capacity ratio: https://msuweb.montclair.edu/~lebelp/MooreEcsScaleQJE1959.pdf

considering various factors such as CO_2 capture potential, heat/power production, and biomethane production. An example calculation is provided below.

$$CAPEX = Cost\ (M£) \times \left(\frac{Capacity\ site\ of\ NET}{Reference\ capacity}\right)^{0.6}$$

This methodology was used for both existing and potential future sites. For existing sites, the cost analysis focused solely on CCS retrofit expenses. In contrast, future sites factored in additional costs associated with constructing the NET site itself. Specifically, BECCS Power and EfW sites accounted for the construction of the energy centre, while BECCS Biomethane sites considered the construction of both the AD Plant and AD Upgrading facility. Refer to Appendix 2 of the technical appendices document for a thorough breakdown of the specific methodologies and assumptions used for each NET, as well as example calculations.

It's important to note that this method provides a quick and rough estimate of costs. However, it should be used with caution, as it may not encompass all the unique aspects and complexities of a project. Since a detailed cost analysis for each NET site would not have been feasible due to resource and time constraints of this project, using this method was deemed the most economical approach to this task.

OPEX: OPEX is divided into two categories: fixed and variable costs. Fixed OPEX encompasses ongoing expenses that remain consistent regardless of the production or operational level. Examples include salaries, equipment maintenance, and insurance. Variable OPEX includes costs that fluctuate based on the level of production or operation. These can include raw materials, fuel, and energy consumption.

Cost benchmarks were not used to determine fixed and variable OPEX of existing sites, due to significant variations in assumptions and parameters found in the literature. Utilising these benchmarks would lead to incomparable costs. Instead, fixed OPEX was estimated to be 5% of the CAPEX[53], and variable OPEX considered increases in electricity and heat usage only. The only exception was the Dunbar Cement site, where site specific data was unavailable. When evaluating future sites, it was necessary to consider the overall costs associated with both installing and operating a NET. To accomplish this, cost benchmarks were employed in their entirety and then scaled up using the sixth-tenths rule. Although this approach may lead to potential cost overestimation, this conservative cost approach was deemed to be the most appropriate given the time and resource constraints on the project.

To validate the assumptions, the respective costs were compared to industrial benchmarks (see Appendix 2 of the technical appendices document). The overall estimation was reasonably close, with costs falling within +- 39% of each other. As for variable OPEX, the assumption was supported by the fact that heat and power usage are the primary components of variable costs mentioned in the literature. However, in reality, the variable OPEX for a CCS facility is a complex component with very limited available published data. The variable OPEX was cross-referenced against the LCOC results to ensure consistency with literature.

The prices for heat and power used to determine variable OPEX were 14.6 p/kWh (power), based on Ofgem's wholesale market indicators[54], and 4p/kWh (heat), which was assumed, based on Ricardo's internal modelling and expert judgement and knowledge of recent DH schemes. The assumed low price of heat was justified by the fact that the heat price was being considered at the export point, rather than the price at which heat is sold directly to the customer. In this scenario, the generator sells heat to a third party at 4p/kWh.

The heat price assumption is relevant for biomass and EfW sites and is applied in calculating the loss of revenue due to the majority of heat recovered from the generation process being used to satisfy the CO_2 capture process. Increasing the heat price to 6p/kWh increases revenue in comparison to the reference case (i.e., based on 4p/kWh) and leads to a 13-20% increase in LCOC for the existing CHP and EfW sites and 0-4% for new sites. This relatively small change in LCOC did not have an impact in

[53] AECOM, 'Next Generation Carbon Capture Technology': Next generation carbon capture technology: technoeconomic analysis work package 6 (publishing.service.gov.uk)

[54] Ofgem, 'Wholesale market indicators': Wholesale market indicators | Ofgem

the total NET potential for the pathways as it did not lead to additional sites deemed feasible to include as a result of the additional heat revenue.

CAPEX and OPEX benchmarks: Table 15 lists the respective cost benchmarks used in the analysis. These were adjusted for inflation using indices provided by the World Bank[55], and subsequently converted to British pounds Sterling using OECD exchange rates[56]. This ensured a fair and consistent comparison across all NETs. The indexes and exchange rates used are detailed in Appendix 2 of the technical appendices document. The costs listed under the heading ‘CCS Costs’ account for existing sites, whilst those under ‘Plant Costs’ account for future sites.

[55] The World Bank, ‘GDP deflator (base year varies by country)’: GDP deflator (base year varies by country) | Data (worldbank.org)
[56] OECD, ‘Exchange rates’: Conversion rates - Exchange rates - OECD Data

CAPEX and OPEX benchmarks

Table 15: Cost benchmarks used within the LCOC analysis

NET	CCS Costs					Plant Costs				
	Capacity	CAPEX (M£)	Fixed OPEX (M£/year)	Variable OPEX (M£/year)	Reference	Capacity	CAPEX (M£)	Fixed OPEX (M£/year)	Variable OPEX (M£/year)	Reference
BECCS Biomethane	0.0044 $MtCO_2$/year	0.86	0.03	0.17	Lars-Julian Vernersson[57]	230 m^3/hr	4.78	0.52 (total OPEX) *		Mattia De Rosa[58]
BECCS Power/Industry (Wood)	498 MWe	346.97	13.88	1.08	BEIS (2018)[59]	498 MWe	876.81	45.70	2.48**	BEIS (2018)[59]
BECCS Industry (Cement)	2328.77 t,clinker/day	192	8.6	72.7	AECOM (2022)[53]	N/A	N/A	N/A	N/A	N/A
BECCS Fermentation	0.13 $MtCO_2$/year	5.93	0.40	1.25	US Department of Energy (2014)[60]	N/A	N/A	N/A	N/A	N/A
BECCS EfW/ACT	0.3 $MtCO_2$/year	96.8	4.7	17.7	AECOM (2022)[53]	0.39 Mt,waste/year	247.17	5.52	20.97	Catapult Energy Systems (2020)[61]

*Units of £/m^3

**This benchmark does not include the cost of using biomass feedstocks. This additional cost of biomass feedstock is taken to be ~£25/MWh (used in BEIS CCS report)[62] and is applied later in the calculations

[57] Lars-Julian Vernersson, 'Bio-LNG and CO_2 liquefaction investment for a biomethane plant with an output of 350 Nm3/h': FULLTEXT01.pdf (diva-portal.org)
[58] Mattia De Rose, 'Economic assessment of producing and selling biomethane into a regional market': Economic assessment of producing and selling biomethane into a regional market (sagepub.com)
[59] BEIS, 'Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology': Benchmarking State-of-the-art and Next Generation Technologies (publishing.service.gov.uk)
[60] National Energy Technology Laboratory, 'Cost of Capturing CO_2 from Industrial Sources': Energy Analysis | netl.doe.gov
[61] Catapult Energy Systems, 'Energy from Waste Plants with Carbon Capture': 20200513-Energy-from-Waste-Plants-with-Carbon-Capture-Final.pdf (esc-production-2021.s3.eu-west-2.amazonaws.com)
[62] Analysis the potential of bioenergy with carbon capture in the UK to 2050, Ricardo, 2020

CO_2 Transport: It was assumed that the Feeder 10 pipeline would be re-purposed to transport CO_2 to Peterhead and to the St Fergus gas terminal, with the CO_2 stored permanently in the North Sea. It was assumed that the capture location was the factor that determined whether the emissions could be considered to be of Scottish origin. Alternative storage locations across the UK were also considered, such as the Liverpool Bay area for HyNet and the coast of Humber and Teesside under the East Coast Cluster. These alternative storage locations meant that captured CO_2 would be transported overground as there is no pipeline in place – this resulted in excessive costs for all sites, which tipped the LCOC analysis in a significantly unfavourable direction. Therefore, all captured emissions were assessed at being stored in the North Sea due to cost implications of transporting to other storage hubs. For more details on the transportation assumptions and associated costs, see section 1.6 of the technical appendices document.

The NET site locations were determined using X and Y coordinates found using a Grid Reference Finder[63] and mapped using GIS Mapping. The distances by road from these sites to the four injection points along the Feeder 10 pipeline were then calculated to estimate potential road transport costs. See Table 16 below for the list of pipeline injection points considered, and their respective distances to the St Fergus pipeline.

Table 16: CO_2 injection points along the Feeder 10 pipeline and their respective distances

Injection point	Location	Distance to St Fergus (km)
Bathgate	Start of Feeder 10 for injection into pipeline	278
Kirriemuir	Potential injection point on Feeder 10	214
Garlogie	Potential injection point on Feeder 10	64
St Fergus	End of Feeder 10 pipeline	0

To minimise these transportation costs, the shortest distance by road was assumed for the initial leg of the journey. The final transportation cost was the summation of road transport, the direct pipe distance from one of the injection points to the St Fergus site, and the direct pipe distance from St Fergus to the Acorn storage site (80km)[48].

There were a number of additional assumptions that needed to be considered:

1.) The method ruled out any sites that were located on islands.
2.) The method did not consider the potential construction of additional pipelines for transporting CO_2 from different locations to the feeder 10 pipeline. For instance, sites located in industrial clusters like Grangemouth may opt to transport captured CO_2 directly through pipelines to the feeder 10 pipeline in the future. Therefore, transportation costs for certain sites may have been overestimated in the analysis.
3.) The road transportation analysis also considered transporting CO_2 to other potential sites (i.e., HyNet and the East Coast Cluster). This was done to understand the effect not having an active storage facility in Scotland would have on costs.

CO_2 Storage: Storage costs were taken directly from the IEAGHG EfW CCS paper[48], where the high-end costs were utilised to ensure the final results remained conservative. As these costs were quoted in a £/tCO_2 basis, with no reference to plant size, then costs were linearly scaled up based on CO_2 capture capacity. See section 1.6 of the technical appendices document for further detail.

Revenues: When considering future sites, the proposed revenue streams that were non-CO_2 related had to be accounted for. Regarding BECCS Biomethane, revenue sales from biomethane were not considered as this fell outside of the established mass/energy balance boundary. However, for BECCS

[63] UK Grid Reference Finder, 'Batch Convert Tool': Batch Convert Tool (gridreferencefinder.com)

Power and EfW/ACT, revenue sales derived from the provision of both heat and power were considered. The same methodology and prices used to determine variable OPEX for existing sites were applied here, but instead of estimating the loss in heat and/or power revenues, the gain in heat/power revenues was considered. For further details, refer to the Cost Analysis section in Appendix 2 of the technical appendices document.

4.1.2 Relative profitability test for pathway

The relative profitability of a site was a test that was added to site inclusion in pathway 2: SG Action. It was applied to evaluate the potential product value uplift that would be required if a site was to implement NETs (and this was not applied in pathway 3 as there was a negative emission trading scheme included in this pathway, see 5.2.3.1, page 57).

The following parameters were tested

	Products/Parameters
• BECCS Power	Electricity & Heat
• BECCS EfW	Electricity & Heat
• BECCS Biomethane	Biomethane
• BECCS Fermentation	Whisky
• BECCS Industry	various products

The test calculated the impact of applying CCS at these sites and the impact on the mass/balance calculations was evaluated. The test involved keeping a constant output for the site and determining what the impact on input/throughput of product/raw materials was needed to maintain this output. The costs associated were then calculated and these were calculated as a % of product value. A low % uplift indicates that CCS could be applied at the site and there would not be a significant increase on product, a larger % indicates a higher uplift on costs (and thus less likely to remain profitable with CCS.

The result of this test was that high value products (Whisky) could remain profitable with CCS due to the high volumetric throughput. Similarly, biomethane can remain competitive as the impact of applying CCS at a biomethane site does not impact the inputs (as CO_2 is already produced in a high quality stream, it is just not captured) and so should be able to be implemented at relatively low cost. More detail on this interim test is provided in see 5.2.3.1, page 57.

4.2 LCOC RESULTS

4.2.1 Existing sites

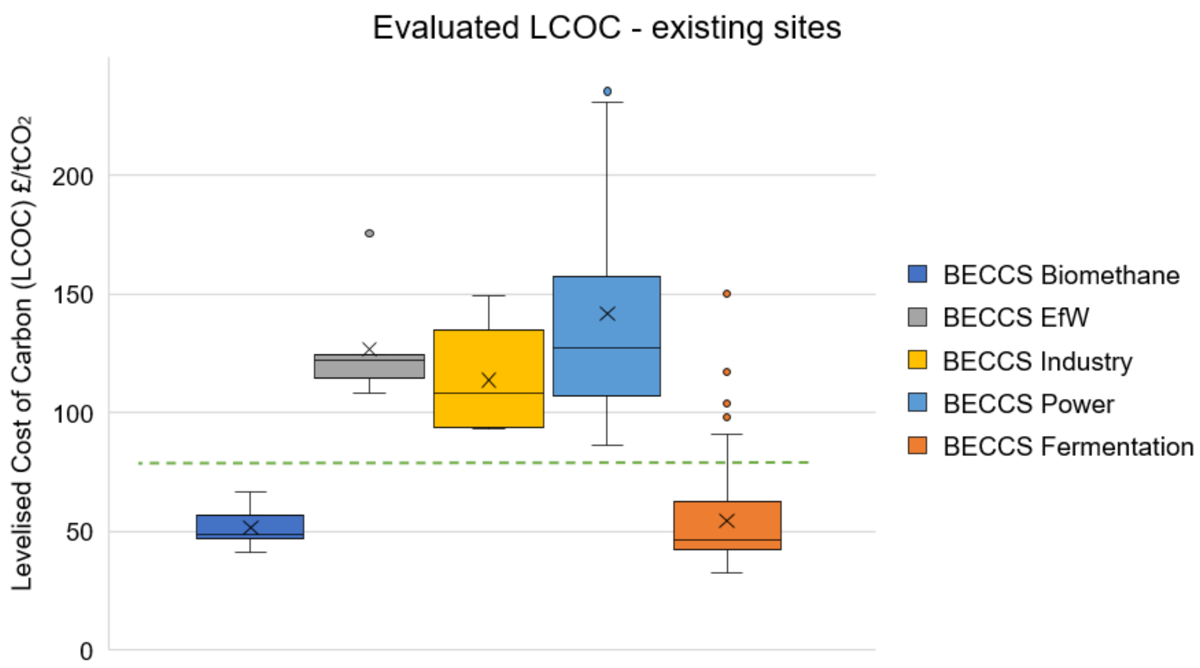
The LCOC of a site was used as the threshold point for whether or not it would be included in the various pathways (i.e., a site has to have an LCOC above the threshold in order for it to be included in the pathway). The LCOC calculation was based on the formula outlined in section 4.1. Revenue from trading of negative emissions (based on the UK ETS price) was considered only within Pathway 3 – UK Government and Scottish Government Action. Where the LCOC for a site was negative in this pathway, then it was included in the list of potential sites where NETs could be implemented.

Meeting this threshold did not mean that these sites would automatically be included in the final list of future sites that contribute to the NETs target for each pathway. Additional considerations were also taken into consideration as described in Section 5. There were several ways in which LCOC could be calculated, some of which are based on CO_2 avoided and some on CO_2 captured.

The approach adopted was based on CO_2 captured and considered the increase in energy costs associated with that captured CO_2, by fixing the fuel input rate and calculating the increase in heat or power demands of the site. This approach was applied to power generation in the Frontiers Economics paper[64], but was extended to other applications in this report. This method was justified given the fact that retrofitting existing sites was being considered rather than new builds, and focussing on the pathways analysis rather than the costings. The inputs and outputs are defined in section 2 of this report, whilst the various LCOC calculation methods employed, and their logic, are detailed in Appendix 2 of the technical appendices document.

The LCOC, which does not include any revenue from negative emissions trading for existing sites, are shown in Figure 5.

Figure 5: LCOC for existing sites - with no negative emission trading income



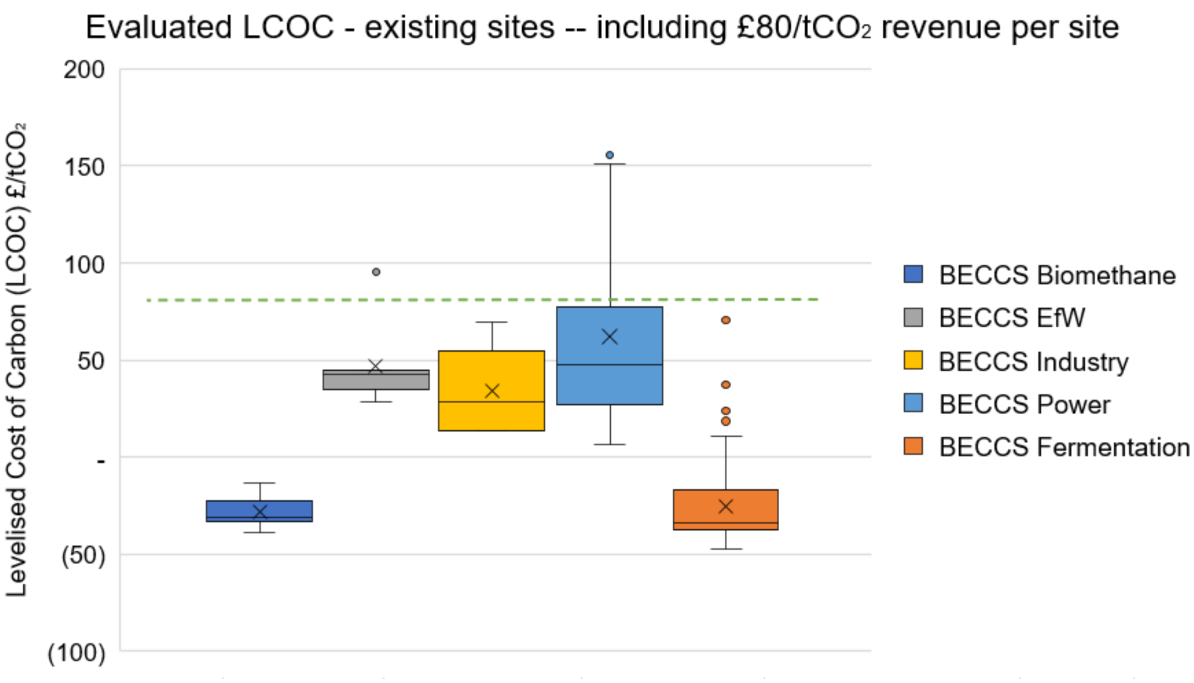
The X label indicates the exclusive median (i.e., the median is excluded from the calculation if the number of values in the dataset is odd), the horizontal lines indicate the upper and lower quartiles, and the dots are known as outliers (i.e., data points that are numerically distant from the rest of the data). The horizontal green line indicates a negative emission trading revenue of £80/tCO_2 that is excluded in the calculation of LCOC.

There is a large difference in the LCOC per site within a technology category, which highlights both the differences in emitted carbon per site as well as the differences in components that make up the LCOC calculation. In particular, transportation costs can vary considerably depending on where the site is physically located and the route that any captured carbon would need to take prior to being permanently stored.

Figure 5 shows the LCOC as per the formula presented in section 4.1 – but does not include any revenue from any negative emissions trading. Figure 6 includes a revenue stream equating to £80/tCO_2 for the negative emissions credits. The £80/tCO_2 figure was used in the analysis based on an estimation of the UK ETS trade price in 2025. More details of this are shown in 5.2.3.1, page 57.

[64] Power Generation, Frontiers Economics: https://www.frontiersin.org/articles/10.3389/fclim.2021.647276/full

Figure 6: LCOC for existing sites with £80/tCO_2 negative emission trading revenue included.



The X label indicates the exclusive median (i.e., the median is excluded from the calculation if the number of values in the dataset is odd), the horizontal lines indicate the upper and lower quartiles, and the dots are known as outliers (i.e., data points that are numerically distant from the rest of the data). The horizontal green line indicates a negative emission trading revenue of £80/tCO2 that is included in the calculation of LCOC.

Figure 6 replicates Figure 5 but includes the impact of revenue from potential negative emissions credits. For sites with a **negative LCOC,** this suggests that with the £80t/CO_2 revenue then this would be an advantageous site to implement NETs. The sites with the lowest LCOC (in either figure) are those that could implement NETs at the lowest additional cost. When NETs credits are introduced, those with a negative LCOC are those that could profit from introducing NETs at that site.

The policies that support each pathway are outlined in section 5; however, the negative emission credit revenue is only included in pathway 3.

4.2.2 Future sites

Data was also available for power, biomethane, and EfW sites currently in planning. An assessment of the LCOC for adding CCS to these new sites was undertaken. **Due to the high capital costs for CCS on power and EfW and due to the low volumes of CO_2 involved in CO_2 capture from biomethane, the analysis shows that none of these technologies can be economically attractive without a negative emission price.** The future threshold emission price used in the analysis is shown in Figure 7, page 57.

Key conclusions from this analysis are as follows:

- EfW benefits from lower variable OPEX due to the negligible cost of waste feedstocks compared to alternative biomass feedstocks.
- Sites operating as CHP benefit from the fact heat recovered can be utilised directly into the CO_2 capture process for solvent regeneration (typically required as low-pressure steam at 3 bar and temperature of around 120C) and so the energy penalty can be significantly reduced. It is thus advantageous for new EfW and power sites to consider operating as CHP and be part of DH systems if they also intend to install carbon capture in the future as this improves process efficiencies and reduces the energy penalty associated with CCS. Several EfW BECCS sites in Scandinavia are being developed as CHP and DH schemes which contributes to improving the overall economic feasibility.

- Advanced Conversion Thermal (ACT) technologies include waste gasification. Such systems can apply pre-combustion capture which is slightly less expensive than post-combustion capture.
- Several AD sites are being developed in Scotland. If these are developed as biomethane sites (i.e., to access the specific benefits and incentives applicable to biomethane available in the future), they provide an opportunity for CO_2 capture from the biogas upgrade process and subsequently can become potentially NETs sites. The small volumes and the high CAPEX involved in constructing the conversion equipment to make an AD site a biomethane producing facility means that these will have a high LCOC and will thus require incentivisation if they are to develop as NETs projects. There are additional non-financial reasons that any site may choose to not develop NETs; for AD in particular there are additional regulatory reasons for the management of wastes (manures and slurries) that any future AD sites need to comply with.

4.3 SUMMARY

Section 4 presented the results from the economic feasibility analysis. The purpose of the LCOC analysis was to compare sites on a common basis and to identify which sites fit into which pathway. When calculating the LCOC for existing sites, the cost of retrofitting CCS was only considered. The CAPEX was calculated using the sixth tenths rule, and OPEX was divided into fixed and variable costs; fixed OPEX was set at 5% of CAPEX, while variable OPEX was determined based on increases in electricity and heat demand. Regarding future sites, the LCOC included the additional costs of constructing the NET site itself, where CAPEX and OPEX benchmarks were fully applied and scaled up using the sixth tenths rule. Costs associated with CO_2 transport and storage assumed that the Feeder 10 pipeline would be repurposed, the CO_2 sent to the Acorn CCS Cluster, and the CO_2 stored in the North Sea.

When comparing the LCOC of existing sites, it's clear biomethane and distilleries can act as 'low hanging fruits' and can contribute to initiating and kick-starting a NET industry in Scotland, although at very small volumes. As will be discussed in the next section, this is subject to ensuring that the captured emissions are permanently stored. EfW can play a key role in achieving NET targets due to the regulations surrounding the incineration of waste, as well as CCUS being a key technology recommendation made in the independent review of the role of incineration in the waste hierarchy in Scotland[65]. On the other hand, BECCS Power and BECCS Industry both exhibit a high LCOC (averaging at £114/tCO_2 and £142/tCO_2), even when negative emission revenues are considered. This is an indication of additional government support being required if these sites are to become economical.

[65] Independent review of the role of incineration in the waste hierarchy in Scotland: https://www.gov.scot/publications/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/

5. PATHWAY MODELLING

5.1 PATHWAYS DEFINITION

Three pathways were evaluated in this study. For each of the pathways, the NETs potential and the associated CAPEX and OPEX were evaluated.

The pathways evaluated are:

- **Pathway 1 – No Action**
  - This pathway assumes minimal action and policies are promoted by the Scottish and UK Governments to influence the development of NETs in Scotland, other than those that have already been confirmed or assumed.
    - There is no negative emission credit trading mechanism in this pathway.

- **Pathway 2 – Scottish Government Action**
  - This pathway includes what has been considered to be the low hanging fruits (easiest to deploy) for NETs in Scotland. It represents a pathway that is made up of sites that could adopt NETs for a relatively low investment cost and at the lowest levelised cost of carbon. The pathway is bounded by specific policies as discussed in later sections.
    - There is no negative emission credit trading mechanism in this pathway.

- **Pathway 3 – UK and Scottish Government Action**
  - This pathway assumes high CCUS and NET deployment is possible with a suite of policies and mechanisms included to promote NETs in Scotland
    - A negative emission credit trading mechanism is included in this pathway.

Common assumptions amongst all pathways are outlined in section 2.1. Pathway-specific assumptions are discussed in section 5.2.

An impact assessment looking at various policy and funding mechanisms is contained in section 5.3, page 61.

5.2 PATHWAY-SPECIFIC ASSUMPTIONS

5.2.1 No Action pathway

Under this pathway it is assumed that there will be no additional support for NETs from the Scottish Government and UK Government, beyond what had already been confirmed publicly at the outset of this study. Therefore, the sites that are included in this pathway have either:

- Already received funding or are committed to adopting NETs.
  - Project dreamcatcher (DACCS) associated with the Acorn project.
  - Some biomethane and fermentation sites associated with project NEXUS.
- Those that may be forced into adopting NETs through regulatory reasons.
  - In particular this relates to potential EfW sites that are planned and would be expected to have to follow The National Planning Framework 4.[66]

[66] National Planning Framework 4: https://www.gov.scot/publications/national-planning-framework-4/

5.2.2 Scottish Government (SG) Action pathway

Under this pathway, CCS will be installed onto existing 'low-hanging fruit' (LHF) sites to achieve quick, easy, and affordable negative emission gains. Any sites included in the 'No Action' pathway are also included in this pathway. Whilst no revenue from negative emissions trading was included in this pathway, the sites in this pathway all had low LCOC (i.e., a LCOC of £30-60/tCO_2, as per the calculation in section 4.1). A relative profitability test was undertaken to check viability, which is outlined below.

- Sites were added into this pathway by means of applying various CAPEX funding mechanisms up to a value of £40M (note the value of this funding, and where it could be applied was tested in a sensitivity analysis).

5.2.2.1 Existing Sites

5.2.2.1.1 Relative Profitability Test for SG Action pathway

The relative profitability of a site that may implement a NET facility was tested in this pathway - it was assumed that there was no direct revenue from the CO_2 captured and instead assessed what uplift to the "products" would need to increase by to remain profitable. This is a somewhat crude estimation, used to test the theory that certain industries are best placed to offer potential routes to increasing the NETs capacity in Scotland at lower overall costs. Note that some substantial assumptions were needed to be added in order for this test to be applied to our list of existing sites:

- The values of power and heat (for CHP sites) had to be consistent across all sites – in reality in a competitive market for electricity, the price of electricity sold to the market fluctuates and on the other side of the spectrum – sites also enter long-term contracts for selling power, which will mean that the profitability of their power sold will vary against the market price.
- The value of biomethane across all sites had to be kept consistent – similarly to the market for electricity, the profitability of biomethane is determined by the market price and contracts that each site has entered into – thus we kept this consistent across the different sites in the pathways.
- The value of whisky produced had to be kept consistent. Clearly the price paid for a bottle or cask of whisky will vary depending on manufacturer and maturation period (i.e., how long the whisky stays in cask prior to bottling). The price/value of whisky has by far the greatest variance between single malt/single grain/blended malts and blended grain sites and between manufacturers that provide these whiskies. As whisky is a high value product manufactured throughout Scotland at vast volumes, the impact of implementing NETs on the profitability of whisky was found to have the lowest impact.
- This test could not be applied to industrial sites as these all have a variety of products that will vary in both type and value, and it was not possible to create a communal product that would be applied to a BECCS Industry site. We assumed that BECCS Industry would operate similarly to BECCS Power and as such these sites would not then pass the revenue test.

The calculation was undertaken in the following manner:

- The annual LCOC costs were established (LCOC (£/tCO_2 multiplied by NET potential (MtCO_2/year)
- The volume of products being sold (power/heat/biomethane/whisky/beer) were calculated
    - This was calculated for pre- and post-CCS
        - Note in some cases the CCS does not affect the outputs (fermentation processes & biomethane sites)
- The revenue from products being sold was then calculated
    - This was then calculated for pre- and post-CCS
- The % increase in price was then calculated to maintain the same level of revenue
    - A low % increase indicates that introducing CCS at the site could be implemented without having to increase the price of products substantially.

5.2.2.1.2 Pathway inclusion

For an existing site to be included in this pathway the following criteria was set that had to be met. Note that these criteria were able to be adjusted in the pathway analysis, based on the evidence reviewed and some sensitivities that were tested are included in section 5.6.

- Minimum negative capture potential had to be > 2,500 tCO_2
- The transportation costs associated with the overall OPEX had to be <50% of the total OPEX
    - This was again an arbitrary value that was used as a filter in this pathway – the impact of transportation costs on the OPEX then has a larger impact on more rural sites – often these rural sites have relatively low capture potential
- It is assumed that profitability is only impacted by additional costs and that that there are no additional revenues as a result of the investment in CCS.
- Profitability test had to have an impact that was < 20%
    - i.e., if the introduction of NETs to a site resulted in the “product” value needing to increase by more than 20% then it was not included.
        - 20% was included as an arbitrary value and agreed with the initial iterations of the pathway.
            - For BECCS Fermentation the increase on unit cost increased by 0.5 – 2%
            - For BECCS Biomethane the increase on unit cost increased by 9 -14%
            - For BECCS Power/EfW and by proxy, BECCS Industry – the price increases substantially to > 100% -- showing that NETs technologies in these industries cannot be expected to be implemented without additional external support or regulatory measures as would be expected.
- A maximum CAPEX value of £40M in government support was used to bound this pathway – this was again an arbitrary value and sensitivities on this value have been undertaken. This CAPEX funding was not sector specific but would apply to all technologies. When included with the sites with the lowest LCOC it resulted in BECCS fermentation and BECCS biomethane sites being included
    - This was not an unexpected result, due to the high concentration of CO_2 that is produced and the relatively low volumes meaning the overall CAPEX per site is low.

5.2.3 UK Government (UKG) & Scottish Government (SG) Action pathway

For a site to be included in this pathway the criteria requirements were reduced to produce a larger sub-set of potential sites that could contribute to the overall capacity of NET sites in Scotland. Various policy mechanisms were tested and, where possible, the impact of their inclusion was quantified, see Table 21, page 73. Note that these criteria can be flexed in the pathway analysis and some sensitivities that were tested are included in section 5.6.

- Minimum negative capture potential was dropped from 2,500 tCO_2 / year to 1,000 tCO_2 / year
- The transportation costs as a fraction of OPEX were removed – this ultimately led to an increase in rural BECCS biomethane and BECCS fermentation sites – but the impact this has on the overall NETs potential was relatively low.
- The Profitability test was included for this pathway due to the inclusion of NETs trading scheme revenues. However, it should be noted that under such a trading scheme, if the carbon price increases to a certain point, then sites with CCS can be more profitable than those without despite their higher costs.
- No upper boundary on CAPEX was placed. However, sensitivities around how much potential CO_2 may be possible to capture and permanently store against sectors-specific funding was tested and is shown in the results section.
- A negative emission tariff was introduced in this pathway, see section 5.2.3.1 for more details.

- It is assumed that this is built upon the UK ETS trading scheme and importantly applies to all potential NETs (UK ETS is only currently applicable to power generation and the aviation industry).

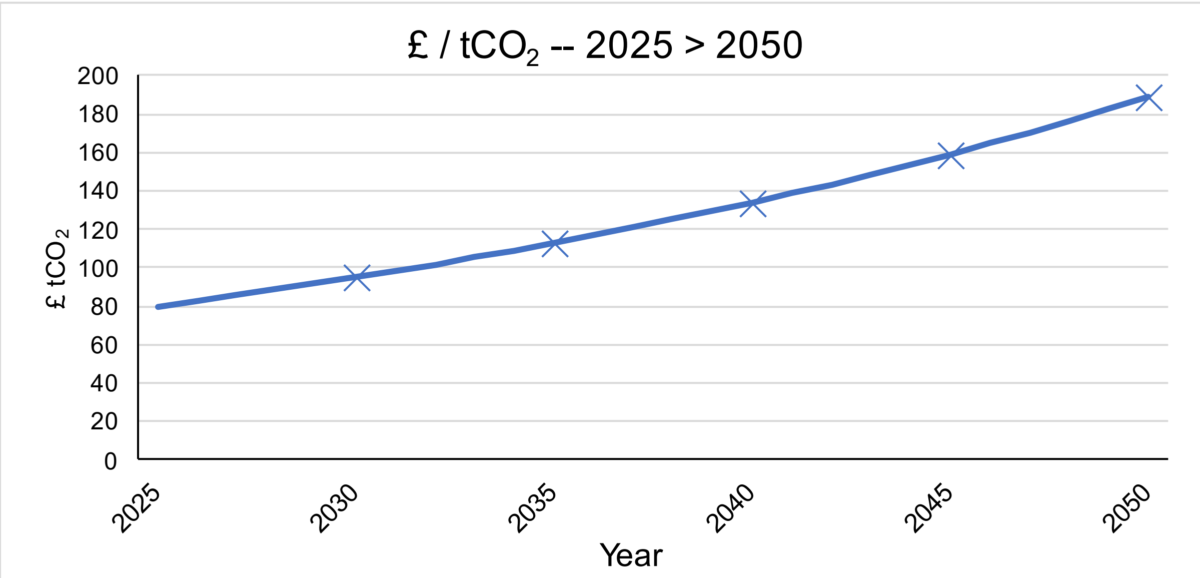
5.2.3.1 Negative Emission Trading Scheme

In pathway 3, a demand-based mechanism was introduced. See section 1.3 of the technical appendices document for a variety of potential demand-based mechanisms that are potentially being developed for the UK and some that are currently being developed throughout the world.

Our LCOC values are graphed against the assumed £/tCO_2 negative emission prices, starting at £80/tCO_2 in 2025. Where the LCOC is lower than the £/tCO_2 this indicates that the NET facility could be implemented and make a net-profit. This analysis was also used to determine the year of implementation.

Our base year £/tCO_2 was £80/tCO_2 in 2025. This is inflated by 3.5% through to 2045, giving a range of £/tCO_2 over the course of the analysis.

Figure 7: Carbon price (£/tCO2) 2025-2050



£/tCO_2 prices:

- 2025 £80
- 2030 £95
- 2035 £113
- 2040 £134
- 2045 £160

So, for example, if a site had an LCOC of £100 then it would have an implementation year of 2031-2032. Note that the LCOCs for each site are based on 2023 CAPEX rates and we have included learning rates for CAPEX which are calculated for each existing site based on a 2023 cost metric. The analysis does not vary the LCOC (which would reduce as CAPEX reduces over time – see below).

5.2.4 Future sites – all pathways

Future potential NETs sites (i.e., not those currently in planning) are complicated to estimate. Firstly, we evaluated the growth rates estimated across the specific industries, then we addressed the specific assumptions within each pathway as per the previous sections, lastly, we applied market penetration rates to get the best estimate of what could be a future NETs site. For example, simply using the biomethane growth rates required to meet the assumed biomethane percentage of gas on the grid would over-estimate the biomethane component as a) not all would necessarily come equipped with CCS equipment and b) not all captured carbon would end up being permanently stored.

Additionally, we cannot apply the locational element of the analysis to future sites as we do not know where these sites might be placed. However, we can apply the same locational element to suggest that island-based future sites would not be included in our list of future sites.

Island sites are unlikely to have the required infrastructure to transport captured CO_2 at a cost-effective manner. This does not mean that an island site could not implement a CCS project, but the captured CO_2 is more likely to be a) of lower volume and b) higher cost to transport over longer distances meaning that alternative uses for the captured CO_2 are a more realistic assumption. The isle of Islay has 9 whisky distilleries, with an additional distillery on the adjacent isle of Jura. There could be a potential future NETs project that incorporates all of these distilleries - this would require agreement for communal transportation of captured CO_2 between the distilleries in order to make this a potential future viable solution.

Ultimately, evaluating the potential future NETs sites was a difficult aspect of the analysis (compared to the existing site list where we know, or can evaluate all the parameters that make up our LCOC analysis). This component of the site-based analysis has the highest level of uncertainty.

Some of the high-level growth rates used in the modelling are outlined below:

- **BECCS Biomethane**
    - CCC projections for biomethane sites in the UK were used and proportionately translated to a Scottish context. This represents growth of around 3.7 times based on 2020 > 2040 capacity in Scotland; Note that the majority of all biomethane production facilities in Scotland were driven by the RHI, with the current support scheme, the GGSS not resulting in any significant biomethane facilities being constructed. Therefore, a more conservative growth rate of 2 was used.
        - This equates to an estimated maximum of up to 0.24 $MtCO_2$ to 2045
- **BECCS Fermentation**
    - We did not assume any new whisky or beer brewing sites in the pathways but do note that clearly any new facilities in this industry would likely need to be built to be at least low carbon if not carbon-neutral or carbon-negative.
- **BECCS EfW**
    - Future list of EfW sites evaluated based on revised list presented in "Incineration and energy from waste" report by SPICe for the Scottish Government in 2022[67] – revised based on known modifications to this site list (some sites refused planning and others having had funding withdrawn).
        - A total of 10 new EfW sites are included in the analysis.
            - These equate to an estimated maximum of up to 1.88 $MtCO_2$ by 2045

BECCS Power, BECCS Industry, BECCS Hydrogen and biochar will all compete for the same available bioresources in the future, this is bounded by the analysis undertaken in the CXC report that estimates the future bioresources that are available and unused (see Table 6, page 27).

- **BECCS Power**
    - Linked to the demand for future power requirements in Scotland.
        - These equate to an estimated **maximum** of up to 1.62 $MtCO_2$ in 2045 (based on 5 plants of 50 MWe).

[67] SPICe (2022), 'Incineration and Energy from Waste': Incineration and Energy from Waste | Scottish Parliament

- **BECCS Industry**
    - As “industry” is a wide term, future BECCS Industry sites are assumed to be linked to wood and wood production facilities, which are linked to the growth in the wood and timber in construction industries in particular. Future non-biogenic CO_2 industrial sites that could in theory adopt a biogenic fuel source are not included.
        - Note that “fuel-switching” to a biogenic fuel source requires a vast amount of capital and technological expertise to implement. Whilst there has been a historic shift from non-biogenic to biogenic fuels used in industry for heat and power applications over the past 10-15 years – this has typically been linked to subsidy schemes. Changing a gas boiler/gas CHP to one that is fuelled on a biogenic fuel is typically a very large project for the scale of sites that are considered in this report**. In particular any site that uses natural gas in a gas turbine (which is compressed prior to combustion) cannot be replaced with a biomass fuelled alternative. On the contrary, gas CHP systems that use steam turbines to generate electricity could use biomass as a fuel source (biomass combustion to produce the steam which is then used in the turbine).**
            - This equates to a maximum of up to 0.32 $MtCO_2$ in 2045
- **Biochar**
    - Several pilot biochar projects currently being developed in Scotland, growth rates derived from this and from internal and external stakeholder discussions.
        - Total estimated NETs capacity of 0.018$MtCO_2$/year used (2030) up to a maximum of 0.32 $MtCO_2$/year in 2045.
        - In order for biochar to expand as a carbon removal option, additional work needs to be done on MRV and certification procedures and recognising applications for biochar where the CO_2 remains permanently trapped (e.g., soil re-construction, use in concrete blocks, etc.).
- **BECCS Hydrogen**
    - Linked to the Hydrogen action plan[68] and estimated demand for BECCS Hydrogen. Note that bio-hydrogen is not touted frequently in the hydrogen action plan, with most future green hydrogen expected to come from electrolysis.
        - This equates to a maximum of up to 0.04 $MtCO_2$ in 2040.

5.2.5 Site inclusion in each pathway

Table 17 shows the different NETs that have been included in each pathway, split by existing sites, future sites and fuel switch sites[69].

[68] Scottish Government’s Hydrogen Action Plan: https://www.gov.scot/publications/hydrogen-action-plan/

[69] Note that “fuel switching” for fermentation sites has been allocated as “not-applicable” – this is because the emissions that are captured from these sites are related to the process, and not any fuel combustion. These sites could well switch to a biogenic fuel source, but that does not impact the emissions we have assumed as capturable under our pathways.

Table 17: Site inclusion per pathway

	NET sectors	Pathway 1 - No action	Pathway 2 – SG Action	Pathway 3 – UKG Action
Existing sites	BECCS Power	Not included	Not included	Included
	BECCS Industry	Not included	Not included	Included
	BECCS EfW	Not included	Not included	Included
	BECCS Biomethane	Included	Included	Included
	BECCS Fermentation	Included	Included	Included
	Biochar	No existing sites	No existing sites	No existing sites
	BECCS Hydrogen	No existing sites	No existing sites	No existing sites
	DACCS	No existing sites	No existing sites	No existing sites
New Sites	BECCS Power	Not included	Not included	Included
	BECCS Industry	Not included	Not included	Included
	BECCS EfW	Included	Included	Included
	BECCS Biomethane	Not included	Included	Included
	BECCS Fermentation	Not included	Not included	Included
	Biochar	Included	Included	Included
	BECCS Hydrogen	Not included	Not included	Included
	DACCS	Included	Included	Included
Fuel Switch	BECCS Power	Not included	Not included	Not included
	BECCS Industry	Not included	Not included	Included
	BECCS EfW	Not included	Not included	Not included
	BECCS Biomethane	Not applicable	Not applicable	Not applicable
	BECCS Fermentation	Not applicable	Not applicable	Not applicable
	Biochar	Not applicable	Not applicable	Not applicable
	BECCS Hydrogen	Not applicable	Not applicable	Not applicable
	DACCS	Not applicable	Not applicable	Not applicable

5.3 POLICY & FUNDING IMPACT ASSESSMENT

The analysis also involved an assessment of the impact of different policies on NETs potential and feasibility in Scotland. It should be noted that the impact of many of these policies was difficult to quantify due to lack of information on how NETs will be influenced by introducing them and so the results are discussed qualitatively where this has been the case. Where quantification was possible, a sensitivity analysis was also undertaken on some of the parameters to test policy impacts.

There are a number of policies that have been considered in each of the pathways that can influence the future of NETs in Scotland. The impact can either be:

(i) by increasing the volume of CO_2 captured and permanently stored, or

(ii) by shifting the trajectory of when the option can be deployed (i.e., earlier timeline of deployment)

The policies and mechanisms have been split into those that:

(i) the Scottish Government have control over, and

(ii) those that are in the control of the UK Government.

These have been split into 3 broad categories, and a supplementary spreadsheet that outlines the inter-linking nature of the policies, their impact, and our assessment on quantifying the impact has been included, signpost here the categories are:

- **General policies:**
  - Non-NETs specific policies that could impact the future of NETs.
- **Fiscal policies:**
  - Policies that either offer direct or indirect financial support to NETs, these can be broad or sector specific.
- **Technical policies:**
  - Policies that offer technical support to other related areas that could impact the development of NETs in Scotland

The range of policies and levers that have been assessed varies amongst the three pathways.

- For the 'No Action' pathway, it was assumed that there are no fiscal policies in support of NETs.
- For the 'SG Action' pathway, it was assumed that some fiscal policies were available, devised to incentivise the sites with the lowest LCOC to implement NETs, and,
- For the "UKG Action" pathway, it was assumed that there is a wider range of fiscal support (including the adoption of the negative emission revenue).

We undertook a RAG review of the suitable policy areas to outline whether or not this policy would positively impact NETs (Green), negatively impact (Red) or where the policy area was not well enough defined, or the impact that this could have on NETs could not be verified or confirmed.

5.3.1 General policies

There are a range of broader policies beyond those specifically addressing the deployment of, that if developed to support NETs, could impact the volume and trajectory of NETs in Scotland. In particular, the following policy areas were reviewed:

5.3.1.1 Policies ensuring Acorn deployment

All pathways have been developed based on an assumption that the Acorn storage facility is developed and is active by 2030. Thus, in all pathways there are no stored biogenic CO_2 volumes until 2030. Realistically, sites (biomethane and distillery sites) in Scotland can start capturing CO_2 before 2030 and either exporting it for permanent storage globally (e.g., The Northern Lights project) or for utilisation in industry (e.g., concrete curing or carbonation) where it remains permanently stored (this is possible as the NETs volumes involved at this early stage of deployment are low). This also requires that such emerging applications are recognised as permanent storage applications.

5.3.1.2 Biomass Strategy (both for Scotland and wider of the UK)

The UK Bioenergy Strategy was published in August 2023. The position of the UK government regarding imported biomass and support for specific biomass technologies will impact NETs deployment in Scotland. This will also be impacted by the position of the Scottish Government regarding the use of imported biomass. The detailed procedures regarding monitoring, reporting and verification of the source and sustainability of biomass will also have an impact on NET development. For this study, it was assumed that there are no biomass imports for NETs in all pathways. Drax power station current combusts around 7 million tonnes of pellets per year that are imported[70], this is roughly equivalent to 33.6 TWh (assuming 1 tonne of pellets is equivalent to ~4,800 kWh) – this far outweighs all bioenergy resources in Scotland. Whilst implementing a BECCS plant at the scale of Drax in Scotland is highly unlikely, allowing biomass imports could have a large impact on future BECCS developments in Scotland as the upper limit on availability for biomass for bioenergy would be removed.

5.3.1.3 Bioenergy Action Plan

Previous research has indicated that Scotland's ability to increase biomass production from current levels is largely dependent on energy crops, miscanthus, and short rotation forestry. A greater emphasis on converting land to produce these resources would encourage greater feedstock production and allow deployment of BECCS technologies at a greater scale.

5.3.1.4 Statement of NETs targets

Any statement of future NETs targets is not itself a direct driver for NETs, but ultimately should have been formalised based on reports similar to this and other policy areas. The setting of NETs targets would send a signal to industries – but would need to be supported with some fiscal support mechanism to drive progress towards the target. Setting a target that is both ambitious and feasible will be challenging to achieve.

5.3.1.5 Economic licensing improvements

This could see projects/systems be more financially attractive, reducing overall LCOC with a reduction in transportation and storage licensing costs; this is currently being legislated by the UK Government.[71] This could in-theory increase the overall volume of CO_2 that is diverted to permanent storage. A licence will determine the allowed revenue which a transport and/or storage operator may receive, which may in turn result in reduced operating costs that would not be passed on to producers of emissions.

5.3.1.6 Planning and consenting policies

A key barrier to deployment of CCS projects in general and NETs is the planning (from the local authority or council) and permitting (from SEPA) requirements. This is because experience with permitting CO_2 capture projects is recent and so permitting takes a long time. One of the requirements of the permitting process is to prepare a detailed environmental impact assessment which needs to include air quality impact assessment. The understanding of air and water emissions associated with large scale CO_2 capture systems is solvent-dependent (e.g., amines or potassium carbonate used for capturing the carbon dioxide) and is still developing. Also, most of the available guidance is on amine systems. Better understanding and improved guidance for different solvents will help speed the permitting process in the future.

An important consideration for the permitting of future UK NET sites is that they will be required to be carbon capture-ready. This means that they will need to do a feasibility study on carbon capture and to leave sufficient space to install CO_2 capture when it becomes feasible to do so in the future. The Decarbonisation Readiness consultation in 2022 (for the whole of the UK) proposes to include biomass and EfW under this requirement and to remove the 300 MW threshold stated in the 2009 regulation. In order to speed up future permitting process, guidance on carbon capture-readiness needs to be clear. For example, this needs to include guidance on space requirements, and as biomass will be covered by the new rules, it also needs to include guidance on assessing the sustainability of the biomass, due to increase in demand as a result of adding carbon capture in

[70] Drax power station combustion mix: https://www.drax.com/wp-content/uploads/2021/03/Drax_AR2020.pdf

[71] Energy security bill: https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-carbon-dioxide-transport-and-storage-regulatory-investment-model

the future. If the Scottish Government was to implement similar requirements this would support the wider NETs agenda.

The planning process could also be time consuming depending on the location of the site. The National Planning Framework 4 (NPF4) is the national spatial strategy for Scotland, setting out national planning policy, regional priorities, and spatial principles. Guidance on CCS and NETs could be included as part of the NPF4 to help simplify the process.

If the planning and permitting processes are improved, then this could lead to an advancement of getting NETs projects online and could result in a lower LCOC if administrative charges are reduced. It should be noted that this study did not include administrative charges in our LCOC analysis but appreciate that for larger sites/systems then this could represent a substantive capital outlay.

5.3.1.7 Supply chain and skills gaps

One key barrier to NET and CCS in general is related to the supply chain. Scotland has well-established expertise in engineering design, construction and commissioning. Manufacturing of carbon capture equipment mostly comes from outside Scotland (e.g., amine and potassium carbonate systems for CO_2 capture). Detailed analysis is needed to identify gaps in the supply chain and in skill requirements which will be needed when wide scale deployment of NETs will happen (for example the need for process engineers with specific expertise). Policies needs to be established to help address gaps in the supply chain and training of new skills to prepare for this.

5.3.1.8 Public awareness campaigns

No direct impact on timescale or volume of NETs but could in theory incentivise other developers to implement in Scotland (if the campaign is positive and successful). A successful campaign would ensure the merit of BECCS, biochar and DACCS are outlined in relation to Scotland's communities, existing net-zero commitments, specific industry net-zero targets and should incorporate life-cycle analysis. This could also incorporate analysis on the bioresources that are involved in the various NETs – linking to the demand on bioenergy and impact on domestic forestry activities and imports (or lack thereof). Quantifying the impact that this may have on the demand for NETs in Scotland is difficult to do, however a positive campaign focussing on the need for NETs in-line with the current climate crisis could minimise objections to future site development.

5.3.1.9 Road improvement strategies

Road improvements could reduce the transportation cost component of overall OPEX, reducing the overall LCOC for the site. Several of the potential NETs sites are rural, meaning that transportation costs often represent the highest proportion of the total OPEX. Road improvement works such as dualling the A9 and the A96 would result in faster, more cost-effective road transport to either Peterhead or the grid injection points at Garlogie or Kirriemuir for some parts of the proposed routes. Ensuring roads remain open throughout winter via improvement management and gritting will ultimately help to keep all vehicles on the Scottish road infrastructure for longer periods. Large vehicle movement on smaller A or B roads can impact both the condition of the road surface significantly and in some cases the road width may be a limiting factor on the size of vehicle that is capable of using the road.

5.3.2 Financial policies

5.3.2.1 Sector-specific CAPEX funding

The impact that sector specific CAPEX funding could have on existing sites in Scotland is shown in Table 18 below. Note we have not assumed any sector-specific CAPEX funding is available in the 'No Action Pathway' and the SG Action pathway'. The figures presented in Table 18 are based on selected sites contained within the analysis.

Table 18: Potential sector specific funding and impact for existing sites

Sector-specific funding for existing sites	$MtCO_2$/year		CAPEX needed to achieve estimated CO_2 capture	
	Low value	High value	Low value	High value
BECCS Power	0.20	0.80	£93M	£300M
BECCS Industry	0.10	0.55	£45M	£131M
BECCS EfW	0.20	0.40	£160M	£333M
BECCS Biomethane	0.05	0.10	£4M	£15M
BECCS Fermentation	0.02	0.04	£16M	£56M
TOTAL	**0.57**	**1.89**	**£318M**	**£835M**

Table 18 shows that both the BECCS Biomethane and BECCS Fermentation sites, whilst representing the lowest CO_2 capture potential, are also the cheapest to implement. This pertains to these sites having the lowest LCOC (though is clearly not the only factor of the LCOC calculation). Both BECCS Power and in particular BECCS EfW require significant capital to achieve moderate to high CO_2 capture potential. If sector specific funding was provided by either the Scottish or UK Governments, then substantively different amounts of capital could be diverted to different sectors or technologies, resulting in a wide range of potential captured CO_2.

5.3.2.2 Other broad funding schemes (for all NETs technologies)

There are a variety of funding schemes that could be developed by both the Scottish and UK Governments. In pathways 2 & 3 we have used a funding pot of £40M being made available to support NETs in Scotland which is not specifically linked to a NETs sector. Note however, that significant funding is required in Power, Industry or EFW which would likely only advance a handful of potential sites. No external funding from the Scottish Government or the UK Government has been allocated in the No Action pathway.

5.3.2.3 Business model support

Business model support could push implementation of a NETs project forward, allowing for more certainty in project viability throughout the development stage. Business model support that advances NETs capacity prior to 2030 when the Acorn project is active could result in an increase in emissions being utilised rather than stored unless alternative storage facilities are present (East Coast Cluster or HyNET).

Our analysis showed that transporting to other UK clusters increased the transportation element of the LCOC calculation considerably, making this generally an unfeasible option for the majority of Scottish sites.

5.3.2.4 ETS Expansion (including NETs trading scheme revenues for UK Government Action pathway)

As outlined in 5.2.3.1, the expansion of the UK ETS to include a NETs trading scheme revenue is included in the UKG & SG Action pathway as a demand-based intervention has a significant impact on the results of the NETs modelling (see results in section 5.4, page 66).

5.3.3 Technical policies

5.3.3.1 CCUS cluster deployment

This is not a pre-requisite for specific sites to develop NETs technologies – but rather a requirement for any CCUS project in Scotland and the UK to develop and have permanent storage. In Scotland, the industrial cluster operating between Grangemouth and the north-east is being developed and is central to all CCUS and future NETs projects in Scotland. If this was not developed, then the impact would be felt on the Acorn project and ultimately any CCUS/NETs project in Scotland.

5.3.3.2 CCUS/GGR targets

Non-NETs targets for CCUS or GGRs will not lead to a direct impact on NETs in Scotland but would be considered to be a catalyst and could indirectly increase the development of NETs in Scotland. The CCUS/GGR targets would themselves need to be aligned with other developmental aspects of wider CCUS in order to be achieved. One key element, which we have included in our assumptions, is the use of the Feeder 10 pipeline for transportation of captured CO_2 to Acorn – this clearly would not be developed based on NETs alone.

5.3.4 Potential future policies and funding mechanisms that could be deployed to support NETs

A high-level summary of the potential future mechanisms that could be deployed to support NETs is shown below. More details are provided in section 1.3 of the technical appendices document.

- Expansion of the existing GGR removal programmes.
    - To further develop field experiments, pilots, and demonstration and commercialisation projects.
- Expansion of the CfD programme.
    - Expand to target BECCS specifically.
- Expansion of the UK ETS.
    - Allow offsets from NETs to be traded.
- GGR Obligation Scheme.
    - Alternative to expanding UK ETS.
- GGR tax credit/carbon levy.
    - energy intensive industries receive a reduction in tax if they adopt GGRs and/or CCS.
- Monitoring, verification and reporting (MVR).
    - Robust protocol that could be developed and implemented to ensure (amongst other things) that BECCS or biochar uses low carbon, locally sourced feedstocks.
- Other GGR subsidies.
    - To potentially incentivise a range of developers to develop NETs projects with up-front grants and sector-specific funding.

5.3.5 Existing International policies

In recent years, there have also been several global advancements in incentives that have been developed to promote the accelerated deployment of NETs. NETs policy support to date has predominantly focused on direct grant support. There are BECCS reverse auctions planned in Sweden; a NETs tariff planned for Luxembourg; front-end engineering design studies for DACCS in the USA and Bipartisan Infrastructure Law (BIL) (also in the USA) aimed to commercialise carbon management, industrial decarbonisation technologies – with specific regional support for DACCS. More detail is contained within section 1.3 of the technical appendices document.

5.4 POLICY QUANTIFICATION

Various policies and strategies were evaluated in a qualitative manner, where possible the impact was assessed qualitatively. The results and analysis from this process are provided below.

Key

Red Policy does not support the NETs pathway, modelled to not have a positive impact on the NET potential
Amber Policy area may impact the NETs pathway in a positive way – the impact will depend on the policy specifics
Green Policy has a positive impact on the pathway, increasing then NET potential

Period over which the policy could have an impact

5.4.1 Pathway 1 – No Action Pathway

Table 19: Pathway 1 – No Action, policy quantification estimates

Policy lead	Policy	Policy Area	R/A/ G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
UKG	Scottish Cluster active by 2030	General	Green	Link to Acorn/wider CCUS - so imperative to all scenarios - a requirement for CCUS & NETs	Yes	Yes - timelines of NETs deployment are tied to Acorn, so delaying/accelerating Acorn will delay/accelerate NETs deployment.	Linking to Acorn could result ~0.5 Mt CO_2 NETs potential				
UKG	ETS Expansion (with no negative emissions credits for engineered GGRs)	Fiscal	Amber	Without Negative emission credits, the expansion of UK ETS unlikely to have positive impact.	No	No					
UKG	UKG DAC competition proceeds as planned. No spill-overs to Scotland from UK projects. Scottish projects anchored to Acorn timings and do	Fiscal	Red	Competition also supports biochar and BECCS but only supports R&D currently and real project implementation	No	Yes					

Policy lead	Policy	Policy Area	R/A/ G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
	not proceed beyond Phase 2										
UKG	Biomass Strategy in 2023 (sets out criteria that applies to all biomass)	General	Amber	Entirely depends on what is contained in the strategy. Suggest that if this outlines an increase in biomass thinnings/brash for use then this may increase this utilisation. This will need to include a positive approach to SRF & miscanthus so that available bioresources in for future bioenergy projects can be realised	No	No					
UKG	CCUS Business models for transport & storage, industrial carbon capture, waste ICC and dispatchable power (link) support for Track-1 and Track-2 (as per current levels of funding set out in Budget 2023 of up to £20 billion "for early deployment")	General & Fiscal	Amber	Interlinked with overall CCUS strategy -- T&S improvements / funding key to future sites being cost-effective and transition to NETs	No	Yes					
UKG	Business models for BECCS, Power BECCS and DACCS as per UKG policy documents (support is limited and late)	General & Fiscal	Green	Limit on support the limiting factor to how impactful this could be. Business models could result in storage permits being granted earlier than anticipated.	No	Yes	Well-developed business models could encourage additional projects to develop in addition to the Storegga Acorn project. This can be up to 0.1 Mt CO_2/year of NETs capacity.				
SG	No explicit NETs target	General	Red	Could disincentivise industry	No	No					
SG	Existing pots of unallocated funding used predominantly for CCUS associated with	Fiscal	Red	Whilst still advances CCUS, the impact on NETs industry is limited	No	No					

Policy lead	Policy	Policy Area	R/A/ G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
	Track-2 projects rather than NETs projects										
SG	Baseline advances in capture rates to be compared to a high threshold in planning decisions under NPF 4 (link) for Industrial Green Transition Zones	Technological	Amber	Fully operational capture rates for all technologies already estimated at 90-95% (depending on the technology) - if planning requirements place too high an initial capture on sites, then this could disincentivise.	No	No					
SG	No pro-NETs social campaigning (so current attitudes towards NETs either persist or worsen in the face of anti-carbon capture campaigning).	General	Red	Disincentivise industry (lack of incentive, relative disincentive, same for below entries)	No	No					
SG	No financial grants towards research and development	Fiscal	Red	Disincentivise industry from developing NETs projects.	No	No					
SG	No expansion of offshore skills passport to onshore energy sector	General	Red	Disincentivise industry	No	No					
SG	Poor or no enforcement of monitoring, verification and reporting standards for biomass sources (especially from beyond the UK)	General	Red	Disincentivise industry	No	No					

5.4.2 Pathway 2 – Scottish Government Action

Table 20: Pathway 2 – Scottish Government Action, policy quantification estimates

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
UKG	Scottish Cluster active by 2030	General	Green	Link to Acorn/wider CCUS - so imperative to all scenarios	Yes	Yes - timelines of NETs deployment are tied to Acorn, so delaying/accelerating Acorn will delay/accelerate NETs deployment.	Linking to Acorn will encourage additional NETs capacity under the LHF pathway in the form of biomethane / distillery and EfW BECCS capacity. Approx 1.3 Mt CO_2/year				
UKG	ETS Expansion (with no negative emissions credits for engineered GGRs)	Fiscal	Amber	Without NETs credits, the expansion of UK ETS unlikely to have positive impact.	No	No					
UKG	UKG DAC competition proceeds as planned. No spill-overs to Scotland from UK projects. Scottish projects anchored to Acorn timings and do not proceed beyond Phase 2	Fiscal	Red	Competition also supports biochar and BECCS but only supports R&D currently and real project implementation	No	No					
UKG	Biomass Strategy in 2023	General	Amber	Entirely depends on what is contained in the strategy. If this outlines an increase in biomass thinnings/brash for use, then this may increase this utilisation. This will need to include a positive approach to SRF & miscanthus so that available bioresources in for future bioenergy projects can be realised	No	No					

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
UKG	Business model support (moderate, by 2032)	General & Fiscal	Green	Limit on support the limiting factor to how impactful this could be. Business models could result in storage permits being granted earlier than anticipated - but as we have the start year set for 2030 then the policy can't shift this any earlier due to technical storage reasons.	Yes	Yes	Well-developed business models could encourage additional projects to develop. This is likely to lead to around 0.05 Mt CO_2/year of biomethane / distillery NETs capacity				
UKG	Two non-Scottish CCUS clusters active by 2030 (HyNET and East Coast)	General	Red	Would advance entire industry throughout the UK - could be a storage location for some sites in the south of Scotland - though transportation and distances currently rule this out	No	No					
SG	Statement of NETs targets, beginning in 2032, based on latest gap identified in TIMES modelling (plus margin) for Climate Change Plan	General	Red		No	Yes - target could shift sites to adopt earlier					
SG	Sector specific CAPEX funding	Fiscal	Green	Impact will be linked to the value of the CAPEX - would be a sliding scale - - if more ££ available then this could have a bigger impact	Yes	Yes - depends on when the funding is available	Biomethane / distillery sites require low levels of CapEx support while EfW BECCS requires much higher CapEx support. Impact is expected to be around 0.5 Mt CO_2/year				
SG	Additional Funding Streams (aka NETs fund)	Fiscal	Amber	As CAPEX: impact would be linked directly to how much funding is made available. Assumed to be only moderate	No	Yes - depends on when the funding is available	up to 0.1 Mt CO_2				

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
SG	"SIETF – Low Carbon Manufacturing Challenge Fund un-paused with £1 million allocated for NETs R&D; £1 million of support towards studies into specific deployment of NETs for energy efficiency and/or deeper decarbonisation projects in industry. £1 million to help establish accounting standards for life cycle emissions assessment of DAC and BECCS in Scotland	Fiscal	Green	All will have positive impacts on NETs in Scotland and heighten the overall understanding around the current state of affairs	Yes	Yes - depends on when the funding is available	up to 0.1 Mt CO_2				
SG	Just Transition Fund – Skills Passport, £1 million extra award to expand the programme to include energy workers looking to transition to onshore CCUS or NETs	Fiscal	Red	Indirect impact on whole industry							
SG	Emerging Energies Technology Fund – 50% of the £80 million funding pot goes towards capex support for NETs	Fiscal	Green		Yes	Yes - depends on when the funding is available	This level of funding will lead to an increase of 0.5-0.7 Mt CO_2/year				
SG	Planning and Consenting policy supportive of NETs	General	Amber	Would shorten the planning process and in theory cost less for a prospective site to implement - reducing overall LCOC	No	Yes					
SG	Bioenergy Action Plan supportive of NETs	General	Amber	as with the biomass strategy > could incentivise more tech providers to implement in Scotland	No	Yes					

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
SG	Pro-NETs public awareness campaign as part of Climate Change Plan, Energy Strategy and Just Transition Plan		Red	Campaigning alone not modelled to have impact -- clearly there is a large cross-over with other policy levers	No	Yes					
SG	Planned road improvements/expansions to trunk roads and A-roads incorporate NETs requirements to bring down journey times for road transport from dispersed sites	General	Amber	Reduced journey times and costs would reduce LCOC, unlikely to push more marginal sites into implementation alone.	No	Yes					
SG	Programme of co-ordination and work with enterprise agencies and industry bodies to help raise line of sight on prospective NETs projects to the supply chain	General	Amber	Increase awareness and overall perception - especially with potential installers	No	Yes					

5.4.3 Pathway 3 – UK Government & Scottish Government Action

Table 21: Pathway 3 – UK Government & Scottish Government Action, policy quantification estimates

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
UKG	Scottish Cluster active by 2030	General	Green	Link to Acorn/wider CCUS - so imperative to all scenarios	Yes	Yes - timelines of NETs deployment are tied to Acorn, so delaying/accelerating Acorn will delay/accelerate NETs deployment.	Linking to Acorn will encourage additional NETs capacity under the Max pathway including additional EfW and power BECCS capacity, leading up to 6.8 Mt CO_2 by 2045.				
UKG	ETS Expansion - include NETs trading scheme	Fiscal	Green	Modelled as having a very large impact. Will depend on what areas it expands into. Currently only power & aviation >> would need to cover all other areas where NETs could be installed (biomethane / industry / waste etc)	Yes	Yes	Expanding the ETS to include a tariff for NETs is expected to be a main driver for developing NETs in Scotland. This leads to an additional NETs of capacity in the range ~ 5-7 Mt CO_2/year				
UKG	Biomass strategy in 2023	General	Amber	Entirely depends on what is contained in the strategy. Suggest that if this outlines an increase in biomass thinnings/brash for use then this may increase this utilisation. This will need to include a positive approach to SRF & miscanthus so that available bioresources in for future bioenergy projects can be realised	No	No					
UKG	Business model support (Maximum, supports can stack – i.e., bioenergy + CCUS + GGR etc) by 2030	Fiscal	Green	May bring forward implementation to late 2020s but with storage unavailable until 2030, this isn't seen as having a large impact	Yes	Yes	Well-developed business models could encourage additional projects to develop. This is likely to lead to around 0.1 Mt CO_2 by 2030 under the Max pathway				

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
UKG	Three Non-Scottish CCUS clusters active by 2030 (Hynet and East Coast?)	General	Red	Would advance entire industry throughout the UK - could be a storage location for some sites in the south of Scotland - though transportation and distances currently rule this out	No	No					
UKG	Innovation Funding (similar to CCUS?)	Fiscal	Amber	Depends on the available capital to fund projects - could have a significant impact if there is a lot of capital available.	No	Yes	Depending on what types of sites are funded and whether it would be solely for new or used for both new AND existing sites, this policy could lead to additional NETs capacity of around 3-4 Mt CO_2 /year.				
UKG	High GGR targets set UK wide	General	Amber	Incentivise technology suppliers to implement in the UK (and Scotland)	No	Yes	Higher GGR targets could lead to additional NETs capacity but depending on the magnitude of the target and interlinking with other policies (e.g., development of business models, financial incentives, etc.). 1-1.5 $MtCO_2$/year additional NETs have been assumed to be possible.				
UKG	Economic licensing process simple and sped up	General	Red	Reduce overall upfront costs and reduces LCOC	No	Yes - could cut several years off licensing process					
SG	Large NETs targets, beginning in 2032	General	Amber	Incentivise technology suppliers to implement in Scotland specifically	Yes	Yes	This significantly depends on interlinking with other policies. A range of 1-1.5 Mt CO_2 is reasonable.				
SG	Sector specific CAPEX funding	Fiscal	Green	Impact will be linked to the value of the CAPEX - would be a sliding scale -- if more ££	Yes	Yes - depends on when funding is made available	CAPEX funding may choose to incentivise specific sites where the capture costs are				

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
				available then this could have a bigger impact			comparatively low (e.g., biomethane / distillery BECCS) or where large volumes of NETs can be achieved (e.g., EfW / power BECCS) or where CCS is almost the only solution (e.g., EfW sites not receiving permitting without CCS). This is policy impact is expected to be approximately 2 $MtCO_2$ (existing sites only) for approximately between £15M - £333M depending on the industry selected for priority funding.				
SG	Additional Funding Streams (aka NETs fund)	Fiscal	Green	As CAPEX: impact would be linked directly to how much funding is made available. Assumed to be only moderate. To be discussed qualitive in the report	Yes	Yes - depends on when funding is made available	Up to around 2 $MtCO_2$ for £800M (note all financial support mechanisms clash with one another -- there is an upper limit on the CO_2 that can be captured and stored and also an expected upper limit on how much funding either the SG or UKG can provide. Thus, we wouldn't expect high levels of sector specific funding AND high communal pots of money provided by SG and UKG all at the same time.				
SG	Planning and Consenting policy supportive of NETs	General	Amber	Reduce overall LCOC - This will lead to storage permits being granted and earlier deployment of projects	No	Yes					

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
SG	Bioenergy Action Plan supportive of NETs	General	Amber	Could incentivise technology suppliers to implement in Scotland specifically	No	Yes					
SG	Statement of NETs targets, beginning in 2032, based on latest gap identified in TIMES modelling (plus margin) for Climate Change Plan	General	Amber	Incentivise technology suppliers to implement in Scotland specifically	No	Yes					
SG	SIETF – Low Carbon Manufacturing Challenge Fund un-paused with £1 million allocated for NETs R&D; £1 million of support towards studies into specific deployment of NETs for energy efficiency and/or deeper decarbonisation projects in industry; £1 million to help establish accounting standards for life cycle emissions assessment of DAC and BECCS in Scotland	Fiscal	Green	All will have positive impacts on NETs in Scotland and heighten the overall understanding around the current state of affairs	Yes	Yes - depends on when funding is made available					
SG	Just Transition Fund – Skills Passport, £1 million extra award to expand the programme to include energy workers looking to transition to onshore CCUS or NETs	Fiscal	Red	Indirect impact on whole industry	No	No					
SG	Emerging Energies Technology Fund – 50% of the £80 million funding pot goes towards capex support for NETs	Fiscal	Green	Impact depends on value of fund – sensitivities have been run.	Yes	Yes - depends on when funding is made available	As per other financial policies, there is potential for overlap (also depends on where the communal funds are spent) - £40M could achieve 0.5-0.7 $MtCO_2$				

Policy lead	Policy	Policy Area	R/A/G	Impact	Can it be quantified	Could the policy change the implementation period of a NETs project	Mt CO_2 estimate - note these impacts are not cumulative	Year the policy impacts the pathway			
								2030	2035	2040	2045
SG	Pro-NETs public awareness campaign as part of Climate Change Plan, Energy Strategy and Just Transition Plan	General	Amber	Increase public awareness and acceptance. Could in turn reduce the number of objections to planning process?	No	No					
SG	Planned road improvements/expansions to trunk roads and A-roads incorporate NETs requirements to bring down journey times for road transport from dispersed sites	General	Amber	Reduced journey times and costs would reduce LCOC, unlikely to push more marginal sites into implementation alone.	No	Yes					
SG	Programme of co-ordination and work with enterprise agencies and industry bodies to help raise line of sight on prospective NETs projects to the supply chain	General & Technological	Amber	Increase awareness and overall perception - especially with potential installers	No	No					

5.5 PATHWAY RESULTS

5.5.1 Summary of results

The $MtCO_2$ results for the three pathways is shown in Figure 1 – note that sections 5.5.2 through to 5.5.4 show this in more detail and provide some sensitivity analysis around the central estimates.

Figure 1: NETs potential for each pathway

Note this is replicated from the executive summary

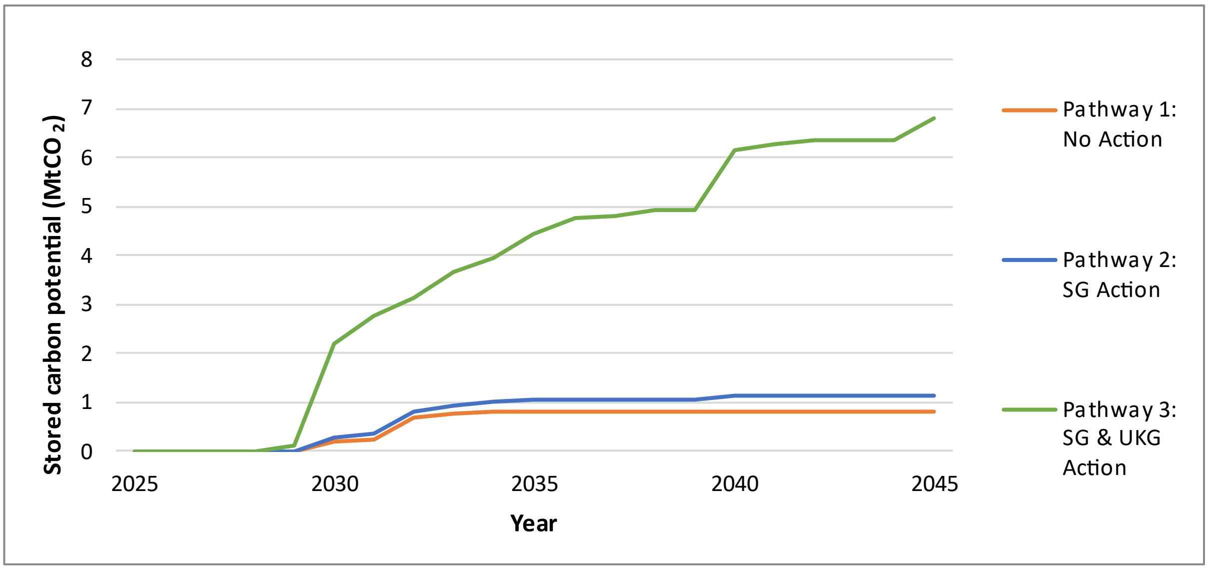


Figure 1 shows that without sustained support for NETs through a variety of policies and fiscal incentives, the total $MtCO_2$ for pathways 1 & 2 stabilize between 2030 and 2035, at moderately low volumes. Pathway 3 sees continued growth as a multitude of supportive policies in particular the NETs trading scheme revenue means that this continues to grow to around 6.8 $MtCO_2$ by 2045. The jump in 2040 is attributed mainly to additional DACCS projects.

Figure 1 shows that the potential CO_2 via NETs is significantly lower than the stated NETs targets presented in the CCPu of up to 5.7 $MtCO_2$/year by 2032.

Table 2 shows the yearly stored $MtCO_2$ per pathway up to 2045.

Table 2: NETs potential, selected years including lifetime stored $MtCO_2$

Note this is replicated from the executive summary

Pathway	Annual stored Carbon, $MtCO_2$				Cumulative Stored Carbon $MtCO_2$
	2030	2035	2040	2045	
1 - No Action	0.6	0.8	0.8	0.8	**16**
2 – SG Action	0.8	1.2	1.3	1.3	**25**
3 – UKG & SG Action	2.2	4.5	6.1	6.8	**112**

Table 3 shows the CAPEX per pathway in 5-year increments. The figures are shown as cumulative CAPEX (£M), this is replicated in Figure 8.

Table 3: CAPEX per pathway, selected years and total lifetime CAPEX

Note this is replicated from the executive summary

Pathway	Annual CAPEX (£M)				Lifetime CAPEX (£M)
	2030	2035	2040	2045	
1 - No Action	702	-	-	-	**708**
2 – SG Action	823	-	1	-	**824**
3 – UKG & SG Action	1,314	292	1,568	157	**4,320**

Figure 8: Cumulative CAPEX (£M) per pathway

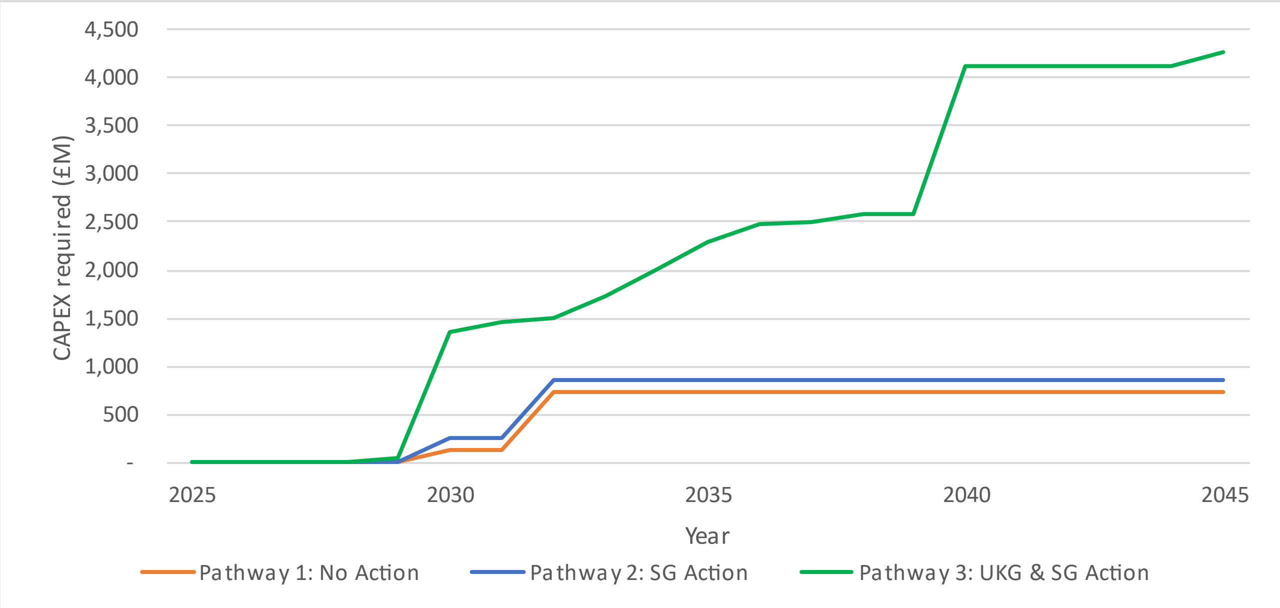
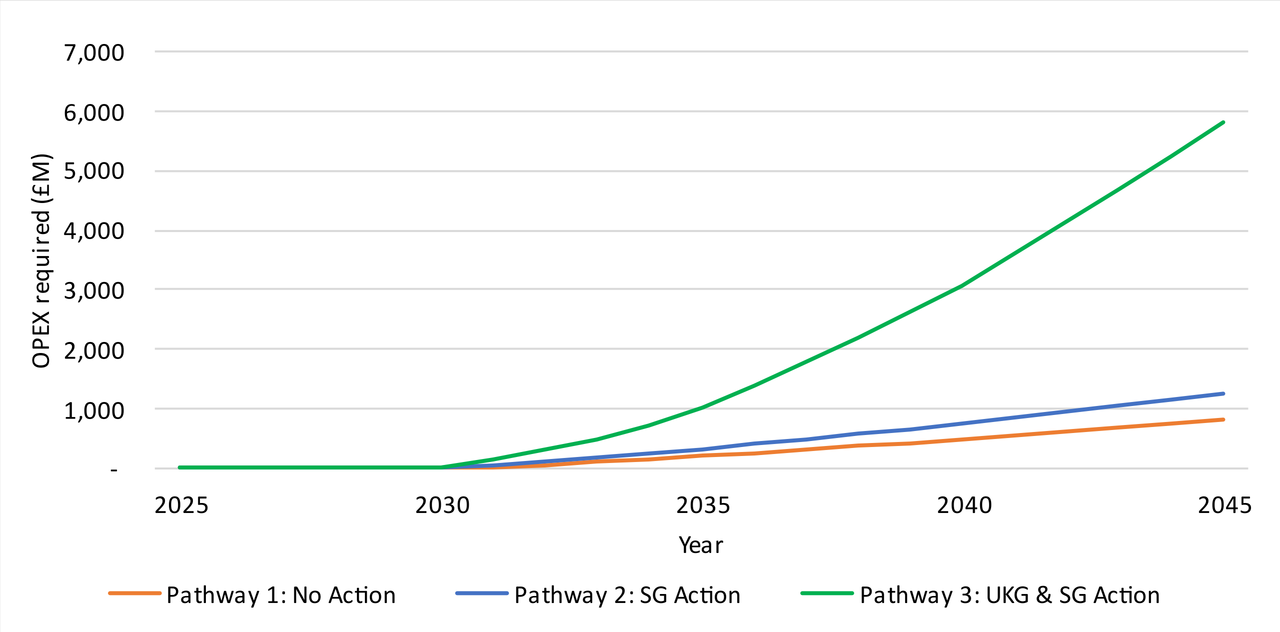


Table 22 shows the OPEX per pathway for operating a NETs facility. The figures presented in this table are annual, with the lifetime/cumulative total for 2045 also included. These are important to the overall narrative of NETs and indeed CCUS in general – none of the fiscal support policies that were evaluated and introduced across the pathways were strictly related to ongoing operation of a NETs site. Where revenue from a NETs tariff is included (pathway 3) it is assumed that this revenue would be used to cover the OPEX of the site (as with the revenue included the sites associated had negative LCOC (i.e., were sites that could implement NETs without being financially penalised. However, in pathways 2 & 3, these OPEX costs would be met by the site operator, and it is likely that this would lead to an increase in product costs irrespective of the technology.

Table 22: OPEX per pathway, selected years and total lifetime OPEX

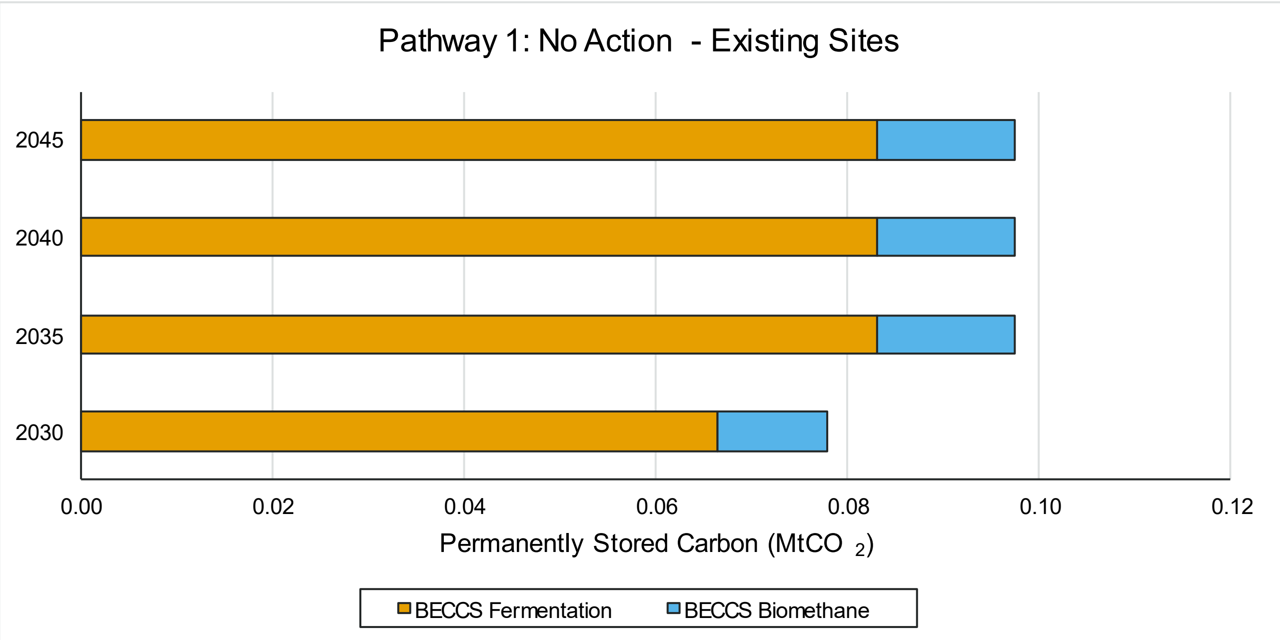
Pathway	Annual OPEX (£M)				Lifetime OPEX (£M)
	2030	2035	2040	2045	
1 - No Action	-	53	60	68	**854**
2 – SG Action	-	78	89	105	**1,294**
3 – UKG & SG Action	12	317	444	576	**5,812**

Figure 9: Cumulative OPEX (£M) per pathway



5.5.2 Pathway 1 – No Action

Figure 10: Pathway 1 – $MtCO_2$ stored potential – existing sites



The No Action pathway for existing sites is dominated by those that already have funding and a potential pathway to NETs – predominantly dominated by sites on project NEXUS. Note that due to confidentiality agreements, there have only been a select few sites that have confirmed they are part of project NEXUS, but conversations with the developer during the stakeholder engagement process outlined that there are several others signed on to the project that have yet to be named. Therefore, the sites are made up of those that have confirmed, and others that represent sites of an average tCO_2 output from our base list of sites.

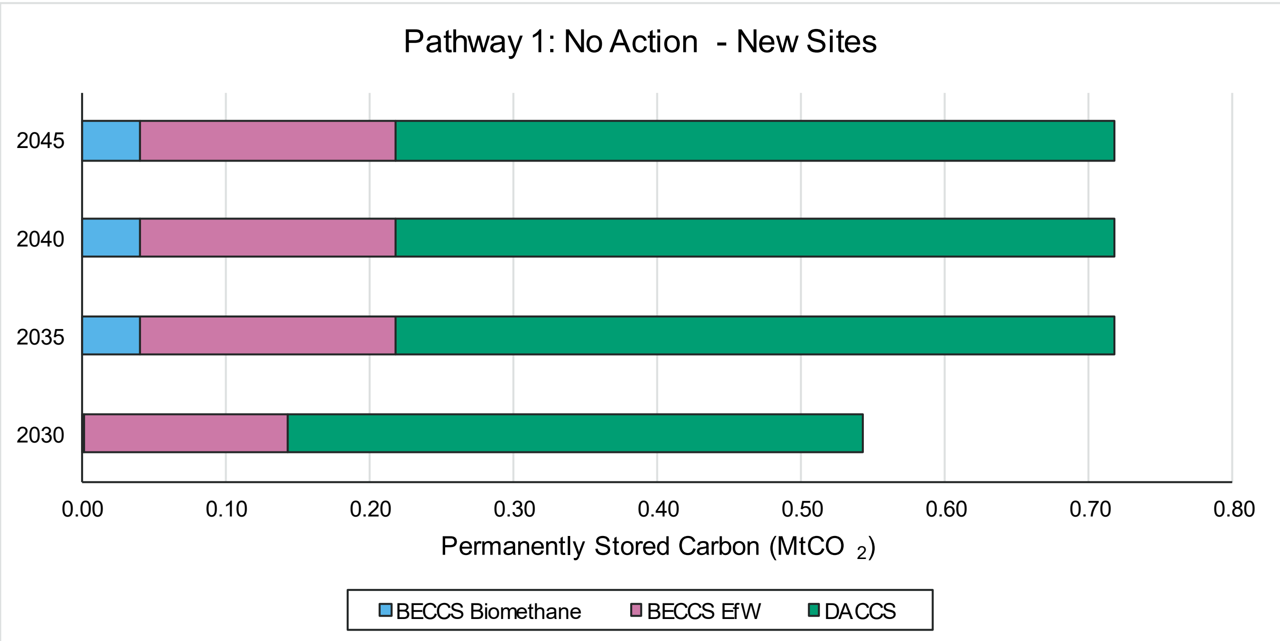
Table 23 shows the existing sites that were contained in this pathway:

Table 23: Existing Sites in pathway 1

NETs sector	Number of sites	CAPEX (£M)	Annual OPEX (£M) (year 1)
BECCS Fermentation	7	9.2	1.4
BECCS Biomethane	3	3.6	0.4
TOTAL	**10**	**12.8**	**1.8**

It must be noted that whilst project NEXUS has received funding and will go ahead, whether or not these negative emissions will be stored permanently or utilised in other industries is not confirmed. This is partly due to the uncertainty over the permanent storage solutions on offer, and, perhaps more pertinently, the other uses for the captured CO_2 can go to (see section 2.1). Discussions with a current biomethane site in Scotland which is not part of project NEXUS indicated that if they were to implement NETs at their site (a real consideration with proposals having been drawn up and decisions to be made in the coming years), the likely use of the stored CO_2 would be in food and drinks industries that are local. **Thus, whilst there may be many more sites associated with project NEXUS coming forward in the interim years through to 2030, whether or not these are permanently stored emissions remains to be seen.**

Figure 11: Pathway 1 – $MtCO_2$ stored potential – new sites



New sites in pathway 1 (and new sites in pathway 2 (Figure 14)) are dominated by the Storrega project dreamcatcher DACCS plant planned for deployment along with the Acorn project coming on-line at the end of the 2020s into 2030. This is assumed to capture and permanently store 0.5 $MtCO_2$/year **in all pathways** – this is a conservative assumption based on Storrega's public expectations. The sensitivity for DACCS ranges from 0.4 $MtCO_2$ (i.e. -20%) to 1.0 $MtCO_2$. This higher figure for the DACCS sensitivity relates to the potential maximum capture of the Storrega plant, which is stated as 1.0 $MtCO_2$.

The other CO_2 is derived from biomethane sites, linked to the future demand for green gas on the network and includes a single EfW site. A single EfW site was included as there are several in planning and our understanding is that rigid requirements on future EfW sites will be placed, one of these being carbon capture. The number of EfW sites included in the other pathways is increased, to test this assumption on future CCS-ready EfW sites.

Figure 12: Pathway 1 – $MtCO_2$ stored potential – all sites.

Includes sensitivity related to +/- 20% in input to pathway

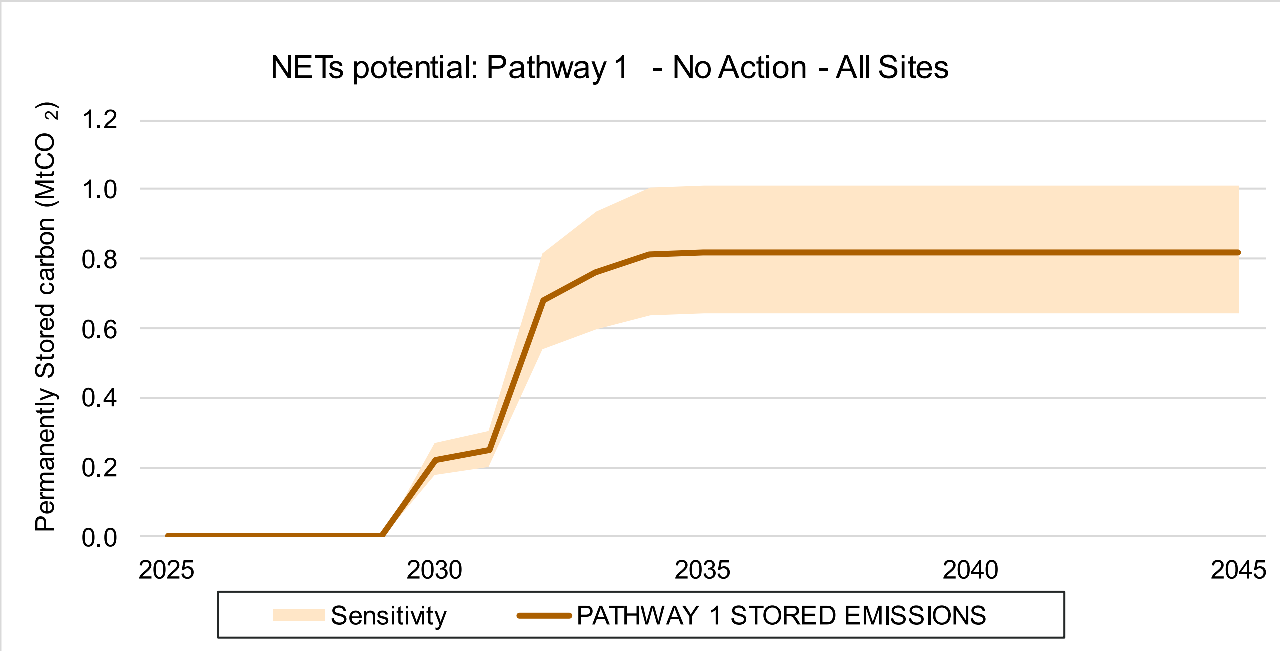


Figure 12 shows the combination of existing and new sites into the pathway, resulting in a NETs potential of around 0.2 $MtCO_2$ in 2030 rising to approximately 0.8 $MtCO_2$ in 2035, where this then stabilises.

Table 24: Pathway 1- No Action. Volumetric split of CO_2 stored by technology type

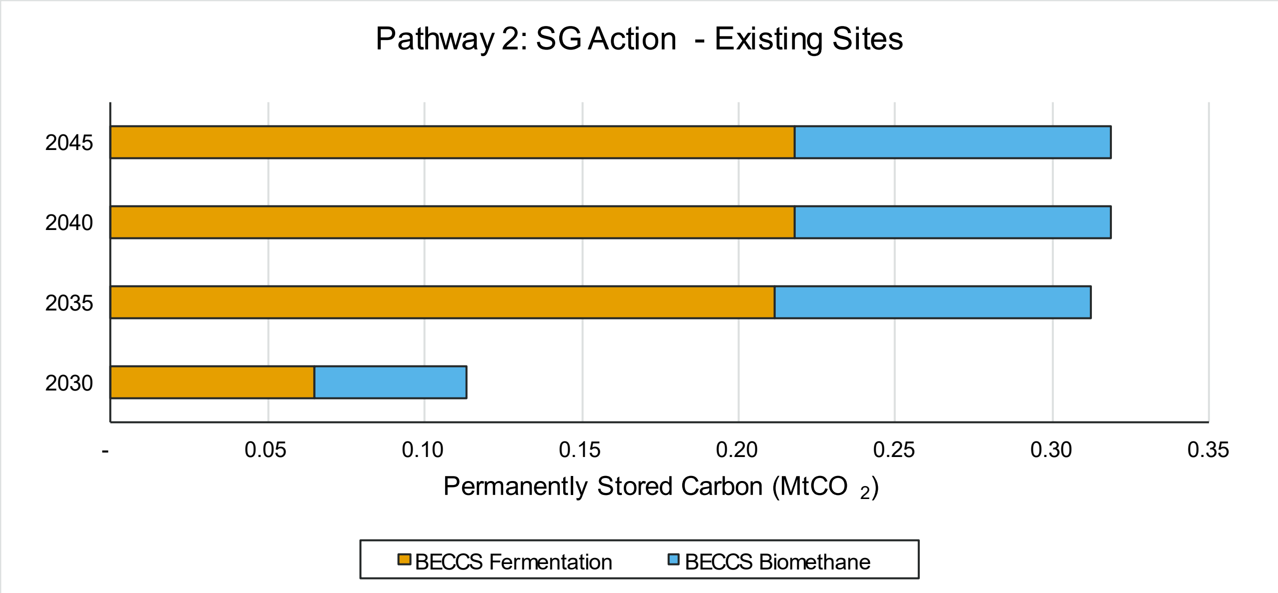
NETs sector	2030 $MtCO_2$	2035 $MtCO_2$	2040 $MtCO_2$	2045 $MtCO_2$
BECCS Power	-	-	-	-
BECCS Industry	-	-	-	-
BECCS Fermentation	0.07	0.08	0.08	0.08
BECCS Biomethane	0.01	0.05	0.05	0.05
BECCS EfW	0.14	0.18	0.18	0.18
DACCS	0.40	0.50	0.50	0.50
Biochar	-	-	-	-
BECCS Hydrogen	-	-	-	-
TOTAL	**0.62**	**0.82**	**0.82**	**0.82**

Table 25: Pathway 1- No Action. Percentage split of CO_2 stored by technology type

NETs sector	2030	2035	2040	2045
BECCS Power	0%	0%	0%	0%
BECCS Industry	0%	0%	0%	0%
BECCS Fermentation	11%	10%	10%	10%
BECCS Biomethane	2%	7%	7%	7%
BECCS EfW	23%	22%	22%	22%
DACCS	64%	61%	61%	61%
Biochar	0%	0%	0%	0%
BECCS Hydrogen	0%	0%	0%	0%
TOTAL	100%	100%	100%	100%

5.5.3 Pathway 2 – Scottish Government Action

Figure 13: Pathway 2 – $MtCO_2$ stored potential – existing sites

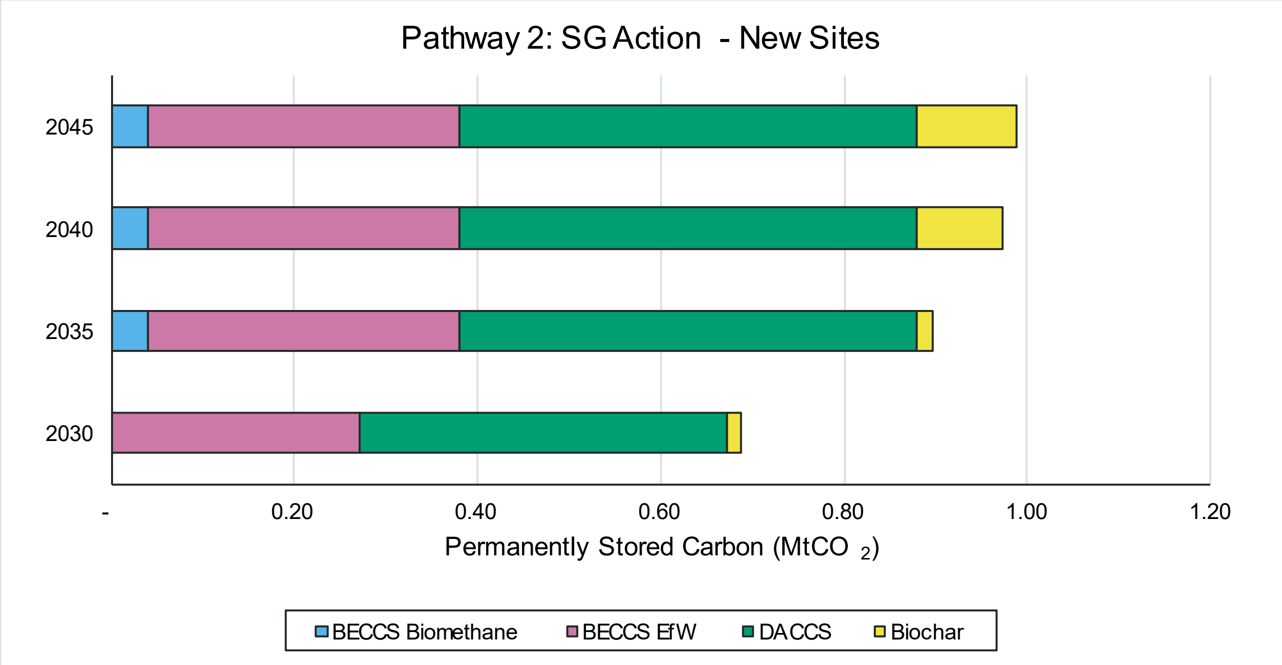


The Scottish Government Action pathway for existing sites is built up from , similar Pathway 1, sites that already have funding and a potential pathway to NETs – predominantly dominated by sites on project NEXUS – and then future sites that have been established based on our assumption of available CAPEX funding (non-sector specific but aimed at the lowest LCOC so this means that it ultimately is focussed on biomethane and fermentation sites) being made available in this pathway (£40M).

Table 26: Existing sites in pathway 2

NETs sector	Number of sites	CAPEX (£M)	Annual OPEX (£M) (year 1)
BECCS Fermentation	21	24.6	8.0
BECCS Biomethane	14	15.3	3.6
TOTAL	**35**	**39.9**	**11.6**

Figure 14: Pathway 2 – $MtCO_2$ stored potential – new sites



Similar to pathway 1, the future sites are made up from biomethane sites, the planned Storrega DACCS plant, two EfW sites and also two large scale biochar plants. Ultimately the capacity of biochar plants that could be implemented will depend on the available bioresources and how the current trial plants operate over the next 2-3 years.

Figure 15: Pathway 2 – $MtCO_2$ stored potential – all sites.

Includes sensitivity related to +/- 20% in input to pathway

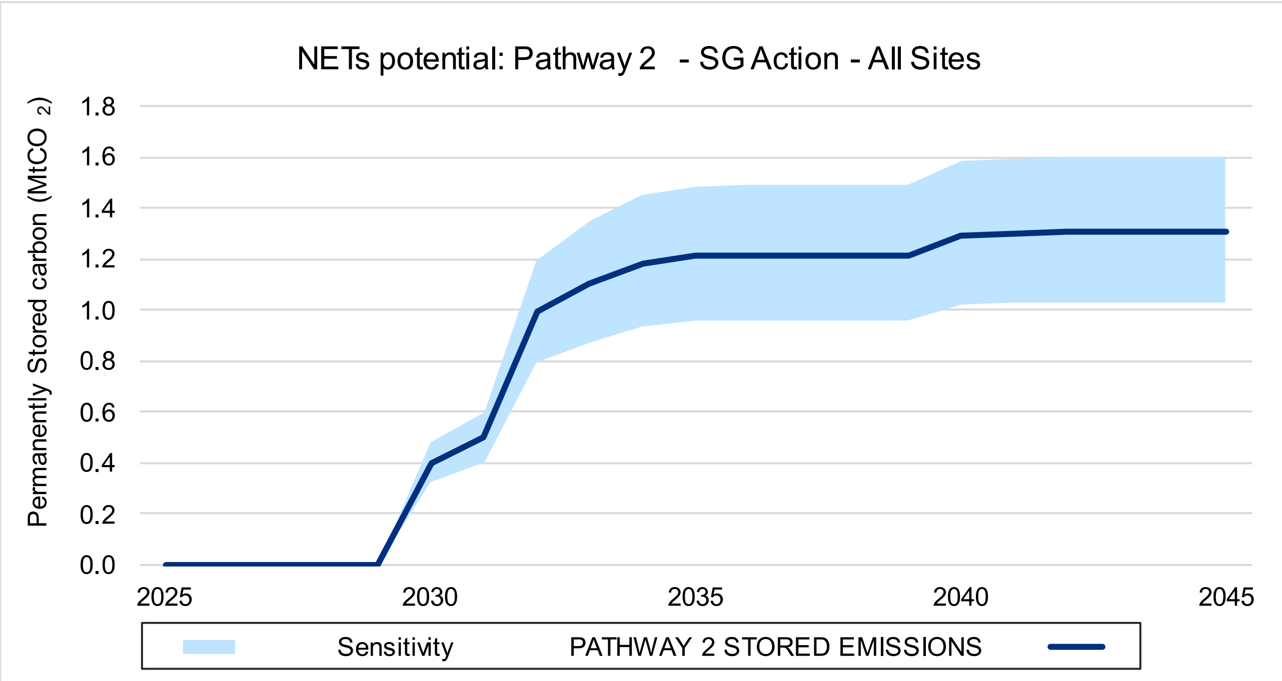


Table 27: Pathway 2- SG Action. Volumetric split of CO_2 stored by technology type

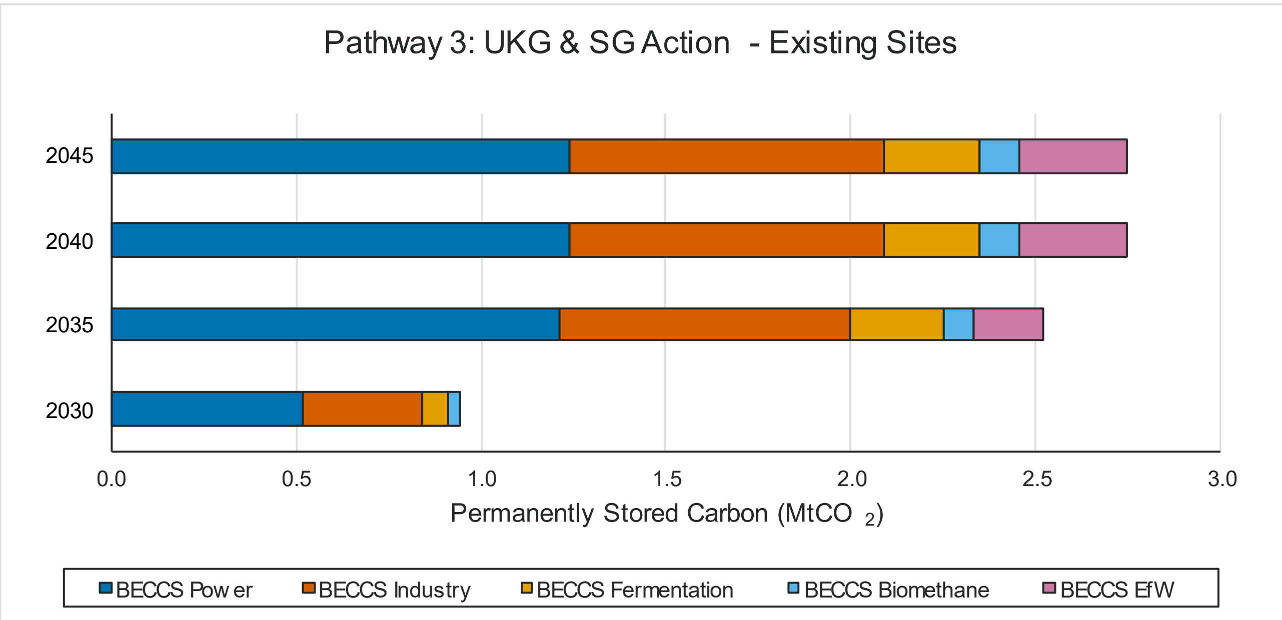
	2030 $MtCO_2$	2035 $MtCO_2$	2040 $MtCO_2$	2045 $MtCO_2$
BECCS Power	-	-	-	-
BECCS Industry	-	-	-	-
BECCS Fermentation	0.06	0.21	0.22	0.22
BECCS Biomethane	0.05	0.14	0.14	0.14
BECCS EfW	0.27	0.34	0.34	0.34
DACCS	0.40	0.50	0.50	0.50
Biochar	0.01	0.02	0.09	0.11
BECCS Hydrogen	-	-	-	-
TOTAL	**0.80**	**1.21**	**1.29**	**1.31**

Table 28: Pathway 2- SG Action. Percentage split of CO_2 stored by technology type

	2030	2035	2040	2045
BECCS Power	0%	0%	0%	0%
BECCS Industry	0%	0%	0%	0%
BECCS Fermentation	8%	18%	17%	17%
BECCS Biomethane	6%	12%	11%	11%
BECCS EfW	34%	28%	26%	26%
DACCS	50%	41%	39%	38%
Biochar	2%	1%	7%	8%
BECCS Hydrogen	0%	0%	0%	0%
TOTAL	**100%**	**100%**	**100%**	**100%**

5.5.4 Pathway 3 – UKG & SG Action

Figure 16: Pathway 3 – $MtCO_2$ stored potential – existing sites



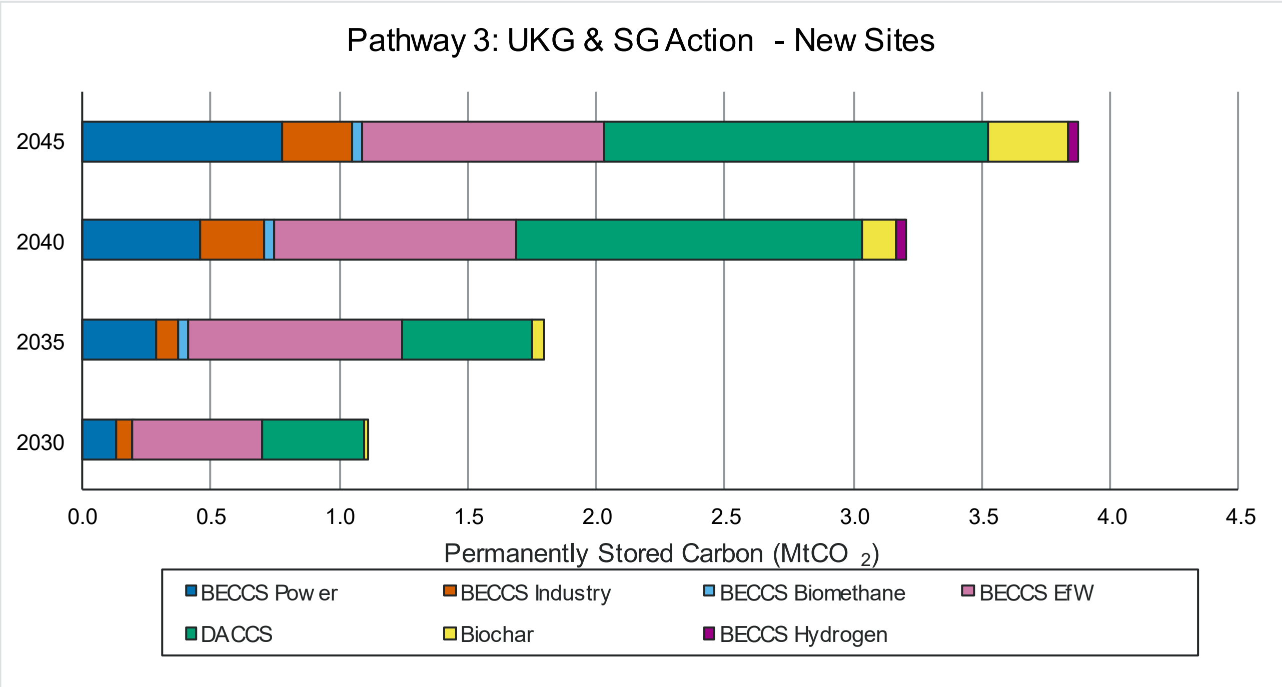
Pathway 3 is very differently constructed to pathways 1 & 2 with a significant increase in both existing and new sites being included in the pathway. The LCOC analysis outlined in sections 2.1 and 4.1 and the inclusion of the NETs trading scheme has meant that where the previous pathways were focussed on the maximum deployable NETs without UK Government intervention (which result in low CO_2 capture volumes), pathway 3 includes several BECCS Power, BECCS Industry and BECCS EfW sites, as these now meet the LCOC criteria required with the inclusion of the revenue from the NET tariff. This means that a substantially higher NET potential can be achieved, but ultimately this will come at significant cost both in terms of any up-front capital that may be supported (as either a sector specific or less-focussed funding mechanism) by either the Scottish or UK Governments – but also has high on-going cost through the credit revenue stream (this ultimately would be indirectly part-funded through government funds.)

Table 29 shows the existing sites that were contained in this pathway:

Table 29: Existing Sites in pathway 3

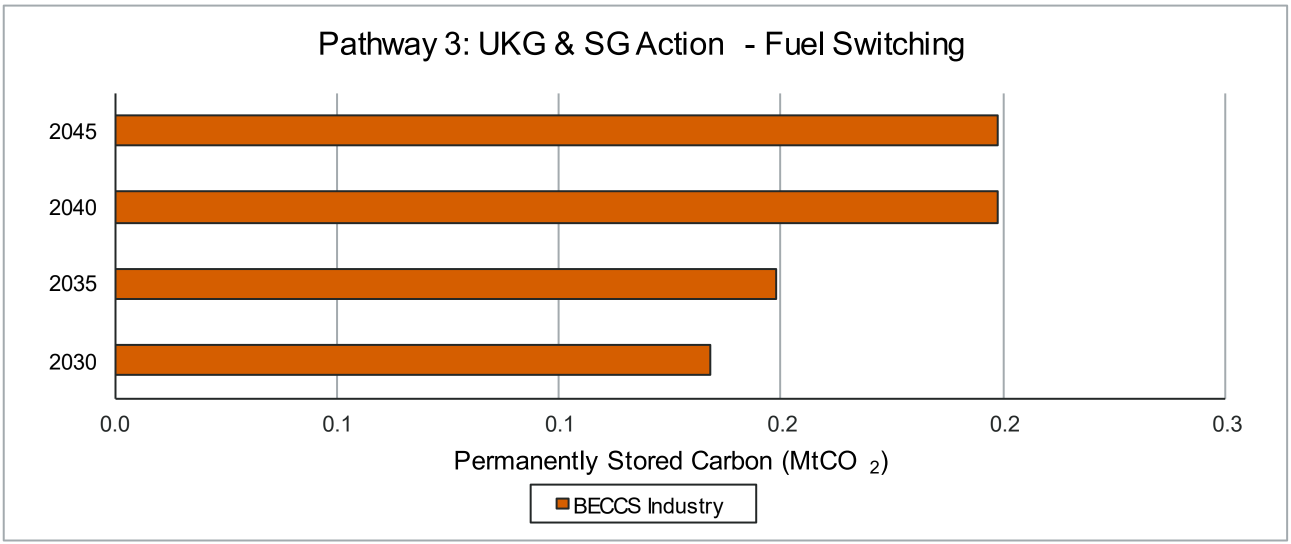
NETs sector	Number of sites	CAPEX (£M)	Annual OPEX (£M) (year 1)
BECCS Power	5	354.1	94.1
BECCS Industry	5	377.3	102.5
BECCS EFW	3	290.6	47.0
BECCS Biomethane	15	20.1	3.8
BECCS Fermentation	37	41.8	9.1
DACCS	0	0.0	0.0
Biochar	0	0.0	0.0
BECCS Hydrogen	0	0.0	0.0
TOTAL	**65**	**856.0**	**256.6**

Figure 17: Pathway 3 – $MtCO_2$ stored potential – new sites



New sites are no longer dominated by those that could implement NETs at the very lowest cost. BECCS Power, BECCS Industry, BECCS EfW and BECCS Hydrogen are all included in this pathway and are ultimately competing for the same bioresources. This means that a boundary can be placed on the “future” sites that may not have been considered if using at top-down approach to meeting net-zero targets.

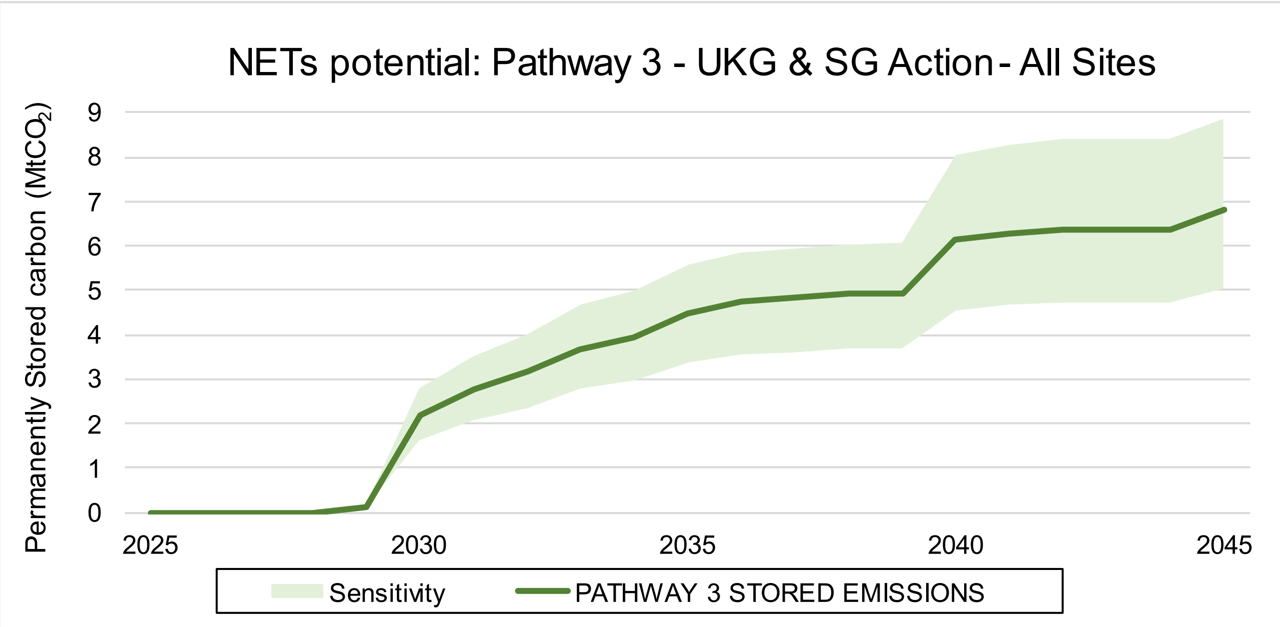
Figure 18: Pathway 3 – $MtCO_2$ stored potential – fuel-switching sites



Some fuel switching sites have been included in this pathway. It is assumed that these sites would be those that have a ready source of cheap biomass fuels - and are thus expected to be within the wood industry shifting from any residual conventional power/heat systems that may be installed at these sites. Fuel-switching is inherently difficult to estimate – there was **no indication** from any of the stakeholders approached during this project that they would consider moving to a biogenic fuel source unless there was some incentive there to do so.

Figure 19: Pathway 3 – $MtCO_2$ stored potential – all sites.

Includes sensitivity related to +/- 20% in input to pathway



6.8 $MtCO_2$ is estimated as being captured and permanently stored in this pathway, some high-level sensitivity shows that this could rise to ~8.5 $MtCO_2$.

Table 30: Pathway 3- UKG & SG Action. Volumetric split of CO_2 stored by technology type

	2030 $MtCO_2$	2035 $MtCO_2$	2040 $MtCO_2$	2045 $MtCO_2$
BECCS Power	0.6	1.5	1.7	2.0
BECCS Industry	0.5	1.0	1.2	1.2
BECCS Fermentation	0.1	0.2	0.3	0.3
BECCS Biomethane	0.0	0.2	0.2	0.2
BECCS EfW	0.5	1.0	1.2	1.2
DACCS	0.4	0.5	1.4	1.5
Biochar	0.0	0.0	0.1	0.3
BECCS Hydrogen	-	-	0.0	0.0
TOTAL	**2.2**	**4.5**	**6.1**	**6.8**

Table 31: Pathway 3- UKG & SG Action. Percentage split of CO_2 stored by technology type

	2030	2035	2040	2045
BECCS Power	29%	33%	28%	30%
BECCS Industry	24%	22%	20%	18%
BECCS Fermentation	3%	5%	4%	4%
BECCS Biomethane	1%	4%	4%	3%
BECCS EfW	23%	23%	20%	18%
DACCS	18%	11%	22%	22%
Biochar	1%	1%	2%	5%
BECCS Hydrogen	0%	0%	1%	1%
TOTAL	**100%**	**100%**	**100%**	**100%**

5.6 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to test the impact that certain parameters have on NETs potential and respective investment costs. Table 32 below provides a summary of the parameters tested and the resulting impact on NETs potential and associated costs.

Table 32: Pathway sensitivity analysis and the resulting impact on NETs potential and costs

Sensitivity	NETs Potential impact ($MtCO_2$/year)		CAPEX impact (£M)	
	Pathway 2	Pathway 3	Pathway 2	Pathway 3
Reduction in capture potential threshold from 2,500 tCO_2/year to 1,000 t/year	0.08	0	19.8	0
Remove threshold for transportation costs as a fraction of OPEX criteria	0.03	N/A	6.24	N/A
Increase CAPEX funding pool from £40M to £100M	0.82	0.27	135 100 from funding pool 35 separately funded (to fully convert the Markinch Biomass CHP Plant)	153 (100 from funding pool) 53 separately funded (to fully convert the Levenseat EfW plant)

5.6.1 Sensitivity 1: Minimum negative capture potential

The assumed lower bound criterion of a NET site requiring to provide at least 2,500 tCO_2 of negative emissions per year was tested. This analysis was applied to pathway 2 as the minimum threshold was already reduced for pathway 3.

Result: The reduction in the negative emission threshold led to 44 additional sites being considered within Pathway 2 – an almost doubling in sample size. These additional sites were categorised as one BECCS Biomethane and 43 BECCS Fermentation sites, where the negative emission potential increased from 0.36 $MtCO_2$/year to 0.44 $MtCO_2$/year at an investment cost of £19.8M.

5.6.2 Sensitivity 2: Transportation costs as a fraction of OPEX

The criterion of a NET site not being able to have a CO_2 transportation cost that is greater than 50% variable OPEX was challenged. This criterion was removed, which was tested for Pathway 2.

Result: The disregard of transportation costs as a criterion led to 11 additional sites being considered under Pathway 2. These additional sites were categorised as two BECCS Biomethane and 9 BECCS Fermentation sites, resulting in a small negative emission increase from 2.74 $MtCO_2$/year to 2.77 $MtCO_2$/year at an investment cost of £6.2M.

5.6.3 Sensitivity 3: Profitability test

The profitability test was removed once the NETs trading scheme revenue was included. The results of this sensitivity analysis are already considered within the LCOC results of Section 5.5.

5.6.4 Sensitivity 4: CAPEX boundary and sectors-specific funding

Under this sensitivity analysis, the upper boundary on CAPEX was removed and the assumed funding pool available to convert potential sites to NETs, which didn't meet the pathway criteria, was increased from £40M to £100M. The process behind allocating this funding was on a LCOC basis, with sites having the lowest LCOC being prioritised.

Result: Pathway 2

Initially, 48 existing sites met the criteria to be considered in Pathway 2. The pool funding increase to £100M enabled an additional 85 sites to be installed. The additional sites included were:

- x2 BECCS Biomethane sites (utilising £1.4M of the funding)
- x82 BECCS Fermentation sites (utilising £31.4M of the funding)
- x1 BECCS Power site (utilising £67.2M of the funding)
    - The site would need to have additional funding of £35M in order to cover the entire investment cost of CCS (the site chosen was Markinch Biomass CHP Plant).

The resulting increase in sites being considered led to the negative emission potential increasing considerably from 0.4 $MtCO_2$/year to 1.2 $MtCO_2$/year. This came at the cost of £135.M, where £100M was dedicated to the funding pool and £35.M dedicated to fully converting the Markinch Biomass CHP Plant using additional funds.

Result: Pathway 3

Initially, 65 existing sites met the criteria to be considered in Pathway 3. The pool funding increase to £100M enabled an additional 90 sites to be considered.

- x4 BECCS Biomethane sites (utilising ~£3.1M of the funding)
- x84 BECCS Fermentation sites (utilising ~£29M of the funding)
- x2 BECCS EfW sites (utilising ~£67.9M of the funding.)
- The Levenseat EfW site would need to self-fund £51.98M in order to cover the entire CCS investment cost).
    - The site would need to have additional funding of £52M in order to cover the entire investment cost of CCS (the site chosen was Levenseat EfW)

The resulting increase in sites being considered led to the negative emission potential increasing slightly from 2.7 $MtCO_2$/year to 3.0 $MtCO_2$/year. This came at the cost of £153.6M, where £100M was dedicated to the funding pool and £53.6M dedicated to fully converting the Levenseat EfW plant using additional funds. The reason behind the negative emission potential, despite the large investment required, is because the EfW sites are combusting/gasifying waste that has a biogenic content of 17-50% by weight.

5.6.5 Sensitivity 5: Introduction of a negative emission credit

This sensitivity analysis has already been considered within the LCOC results analysis. See Section 5.5 for the impact of including a negative emission price to all NETs.

5.6.6 Sensitivity 6: Improved future deployment rates of CCS in power / CHP BECCS and EfW sectors

This sensitivity tested the increase of CCS penetration rates for future biomass power and CHP and EfW sites from 50% to 100%. Currently it is expected that such sites will be required to be carbon capture ready from the start (in order to receive planning and permitting). However, whether such sites go ahead and install CCS will depend on whether this becomes economically feasible in the future. The analysis used penetration rates of 50% based on the fact that half of the sites will have their LCOC lowered (whether by reducing CapEx based on new learning, improving capture rates or reducing OpEx, etc.) to below the carbon price (which is also expected to rise in the future). This sensitivity assumes that the LCOC reduces further making it feasible for all future sites to install CCS and thus become NET contributors or carbon removals.

Adjusting the penetration rates of BECCS Power, BECCS Industry & BECCS EfW to 100% would increase the 2045 NET potential to 8.7 Mt CO_2.

6. CONCLUSIONS AND POLICY RECOMMENDATIONS

The NETs feasibility study for Scotland shows that the Maximum Feasible NET potential in 2030 is 2.2 Mt CO_2/year increasing to 6.8 Mt CO_2/year in 2045 (a total cumulative NET potential of 112 Mt CO_2 and corresponding total investment of £4.3Bn), this includes £40Mn CAPEX support from SG. The potential in the next decade is significantly lower than the potential of 5.7 Mt CO_2/year suggested by the CCPu. **Under a 'No Action' scenario, the achievable NETs potential of 0.2Mt CO_2/year in 2030 increases to 0.8 Mt CO_2/year in 2045.**

However, sensitivity analysis shows that increasing the public funding pool from £40M to £100M increases the NETs potential by only 0.8Mt CO_2/year for the SG Action pathway and by 0.3Mt CO_2/year for the UKG Pathway, with an additional 85-90 sites supported to become NET projects (approximately £1M per site). The small incremental volumes are due to the fact that these additional sites (under both pathways) are biomethane and distillery sites with relatively low CO_2 volumes. Supporting the development of NETs on these sites could help launch the NETs industry and infrastructure in Scotland, albeit at a small scale. Carbon Capture Scotland has a technology which is modular in nature meaning it can be more easily rolled out to lower volume sites like biomethane and distilleries thus helping to quickly contribute towards NETs deployment by 2030.

While the majority of NETs potential in 2030 is from existing BECCS EfW, Biomethane BECCS and Fermentation BECCS, in 2040-2045, most of the contribution to NETs is attributed to power BECCS and DACCS with contributions from BECCS industry, BECCS EfW and BECCS hydrogen. BECCS biofuels are expected to have a negligible role in carbon removal in Scotland based on discussions with stakeholders.

Achieving Net Zero targets in Scotland cannot be done without carbon removals and NETs. The deployment of NETs, and CCS facilities in Scotland rely heavily on the development of the Acorn project and the Grangemouth cluster. Due to the high investment costs, financial incentivisation is required to facilitate the deployment of all NETs options. It is recommended not to side-line or ignore any technologies but to prioritise deployment of certain options – including BECCS biomethane and BECCS Fermentation as although they provide low volumes of CO_2 - they provide the "low hanging fruits". Such options could receive CapEx and OpEx funding to help early deployment and preparing the stage for additional NETs to be demonstrated in a second phase of deployment.

It should also be noted that biomass pyrolysis and permanent storage of carbon in the produced biochar from the process can play a key role in Scotland -small scale cogeneration systems with biochar production can provide several benefits.

In order to facilitate short-term deployment of NETs, expected to be in low volumes, it is recommended that policies are introduced to encourage development of industrial processes which permanently store the CO_2 and can thus contribute to NETs targets – as NETs and CCS are high capital ventures, fiscal support, particularly that which is sector specific should be developed. Processes include for example concrete curing and mineral carbonation amongst others that could add to the NETs potential in the future.

Key policy areas that should be developed to maximise the NETs potential in Scotland:

- UK ETS expansion.
    - This should be expanded beyond electricity generation and aviation and consideration should be made as to how biogenic CO_2 is currently reported on (not currently required to pay for these emissions means there is currently no driver for sites with biogenic emissions to reduce the impact of these emissions.
    - Introduction of a NETs trading scheme.
        - The analysis in this report shows that introducing a NETs trading scheme could significantly enable NETs projects in Scotland.
            - The global ownership of many of the sites within this analysis means that NETs /CCS projects at large-scale sites will have competition across portfolios – Scotland must be an attractive location to develop NETs projects.
- Fiscal support mechanisms.
    - NETs sector specific funding should be prioritised – or if wider funding is made available, ensuring this can be distributed among specific sectors should be a focus.

- Bioenergy/biomass/agriculture strategies should be supportive of NETs.
    - If biomass imports are limited then these strategies need to support short rotation forestry, miscanthus and energy crops development.

The long-term deployment of NETs will involve large volumes of CO_2 being captured and permanently stored from biomass power / CHP and EfW sites. Evidence from countries across Europe show that the combination of biomass and EfW CHP sites with district heating and carbon capture provides an opportunity for improved efficiencies and lower costs, adding to overall greater system value. Future policies should consider prioritising the support of BECCS on CHP and DH sites. This can for example be done through allowing the heat used from the CHP plant and recovered from the CO_2 capture process to be considered as 'useful heat' under CHP Quality Assurance (CHPQA) definition. Other criteria which should be prioritised includes lower life cycle impacts (for example, discouraging NETs using imported biomass) and externalities which could arise from wide-scale deployment of NETs (e.g., increased air and water emissions).

Scottish Government
Riaghaltas na h-Alba

This publication is available at **www.gov.scot**

Any enquiries regarding this publication should be sent to us at

The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-83521-658-3 (web only)

Published by The Scottish Government, November 2023

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS1378074 (11/23)