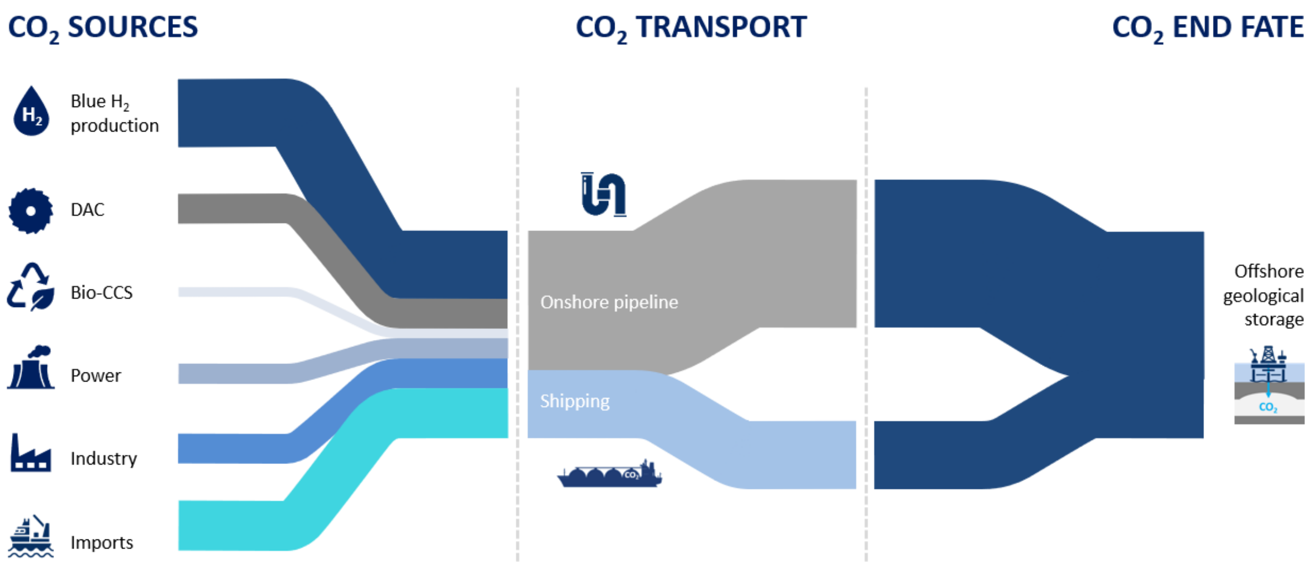
CCUS Economics Impacts Study

Delivering a roadmap for growth and emissions reductions for Scotland

November 2021



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This study was led by Element Energy (an ERM company).

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 80 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work.

Vivid Economics conducted the economic analysis of this study.

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Disclaimer

Executive Summary

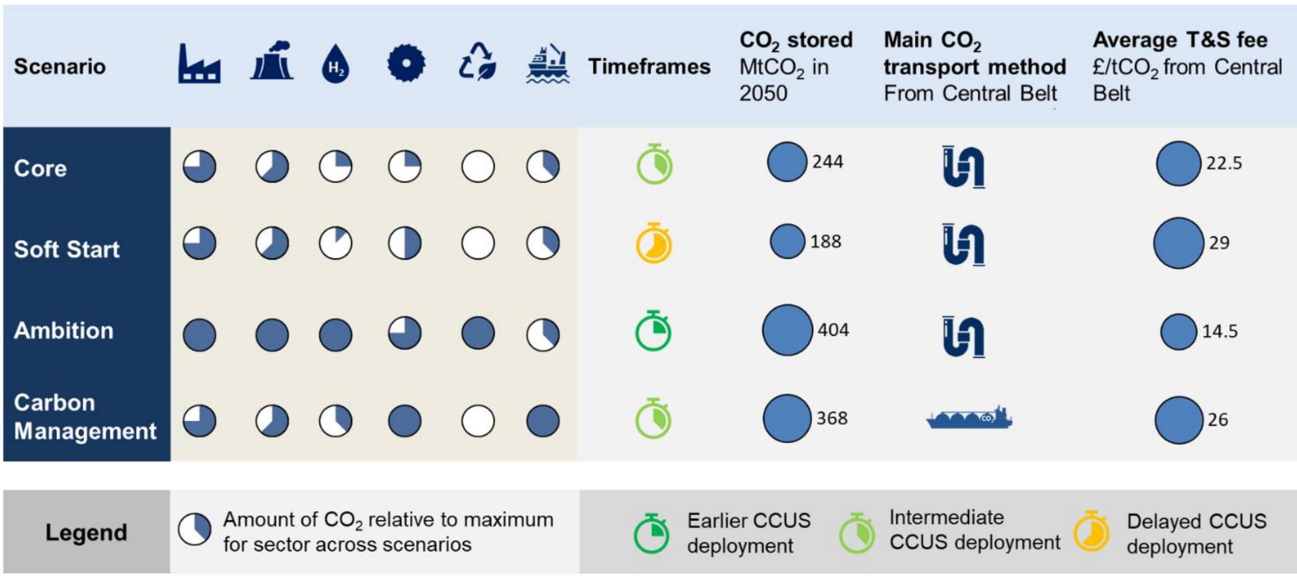
Introduction

In 2019, Scottish Government legislated new reduction targets for all greenhouse gas emissions to Net Zero by 2045. Scottish Government also set interim targets for reductions of at least 56% by 2020, 75% by 2030 and 90% by 2040, relative to a 1990 baseline. The next steps in this pathway for a Net Zero Scotland have been defined in Scottish Government's 2018-2032 Update to the Climate Change Plan. The document sets objectives for continuing greenhouse gas (GHG) emissions reduction across all sectors of economic activity. Meeting these targets will be transformative for some of Scotland's most important sectors, and the Just Transition Commission is engaging with Scottish stakeholders to advise Scottish Government on how to maximise the economic and social opportunities of the transition to Net Zero.

As documented in "Reducing emissions in Scotland – Progress Report to Parliament", the Committee on Climate Change noted that rapid action in Scotland will be required to meet the 2030 greenhouse gas reduction target[1], and Carbon Capture, Utilisation and Storage (CCUS) is a key technology which can enable deep decarbonisation of key Scottish emitters. Scotland's offshore oil and gas (O&G) legacy and access to some of the most extensive potential CO_2 storage capacities in Europe - with potential for over 50,000 $MtCO_2$ in the North Sea - means that CCUS can bring advantageous synergies for Scotland on its journey to a Just Transition, helping safeguard and create new jobs[2].

For all these reasons, CCUS can create environmental, social and economic value for the Scottish economy. There are a number of emerging projects and initiatives led by the private sector and looking to advance work on CCUS deployment in Scotland, such as the Acorn CCS and Acorn Hydrogen projects, Scotland's Net Zero Roadmap and Scotland's Net Zero Infrastructure. These projects are all evidence of the work industry is taking forward, the success of which will require cooperation of both UK Government and Scottish Government.

Four CCUS scenarios to help Scotland reach Net Zero by 2045



Summary of key technical findings for each of the four scenarios

CCUS is a versatile technology which can be adopted in multiple existing sectors, namely industry and power. In addition, CCUS can help new emerging low-carbon markets to grow, such as enabling blue hydrogen production, generation of negative emissions, and imports of CO_2 to Scotland. All these components of

[1] Committee on Climate Change, Reducing emissions in Scotland – Progress Report to Parliament (2020)
[2] Bentham, Michelle, et al. "CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas." *Energy Procedia* 63 (2014): 5103-5113.

economic activity have different techno-economic characteristics and thus different drivers and levers for their potential adoption of CCUS. As a result, this study has produced four scenarios investigating different hypothetical levels of CCUS uptake in each of these sectors. Each aims to represent a series of future growth opportunities within Scotland.

The **Core scenario** considers the uptake of CCUS in key industrial applications, in particular at large industrial sites in high-emitting areas of Scotland, in the power sector and for regional blue hydrogen production. Hydrogen is used extensively around the St Fergus/Peterhead region and in industrial sites around the Central Belt: Grangemouth, Fife/East Coast and Upper Forth, with likely supply hotspots expected in the North East and around Grangemouth. Most of the captured CO_2 is transported via onshore pipeline and intra-Scotland shipping plays a limited role but provides resilience. Some CO_2 is shipped to Scotland from UK and EU clusters.

The **Soft Start scenario** is similar to Core, with carbon capture technology being adopted with the same geographic scope and scale in large industrial sites and in the power sector. However, this scenario considers a **delayed roll-out of key onshore pipeline CO_2 infrastructure**. This delay in availability results in a faster penetration of green hydrogen around the Central Belt of Scotland, higher intra-Scotland CO_2 shipping volumes and delayed growth of CO_2 imports by shipping.

The **Ambition scenario** increases the geographical outreach of the Core scenario and sees the uptake of CCUS in a wider range of industrial applications throughout Scotland, such as bio-CCS and smaller industrial sites. The increased ambition allows for an accelerated repurposing of onshore pipeline infrastructure. Similarly, this scenario sees a major role for hydrogen throughout Scotland, with the residential sector converting to run on hydrogen. This also allows for hydrogen fuel switching in smaller industrial sites around Scotland. As a result, the production of blue and green hydrogen is geographically distributed across Scotland.

The **Carbon Management scenario** sees the same level of deployment of CCUS and hydrogen as in the Core scenario. However, in this scenario Scotland leverages its CCUS value chain to help other regions of the UK and Europe decarbonise. In addition, Scotland utilises its abundant renewable energy resources to support an ambitious deployment of Direct Air Capture with CCS (DACCS) and to grow a market for hydrogen exports, mostly green. Shipping plays a key role to support imports of CO_2, and the lack of onshore pipeline infrastructure in Scotland means that increased shipping is also used to move CO_2 from the Central Belt of Scotland to the North East.

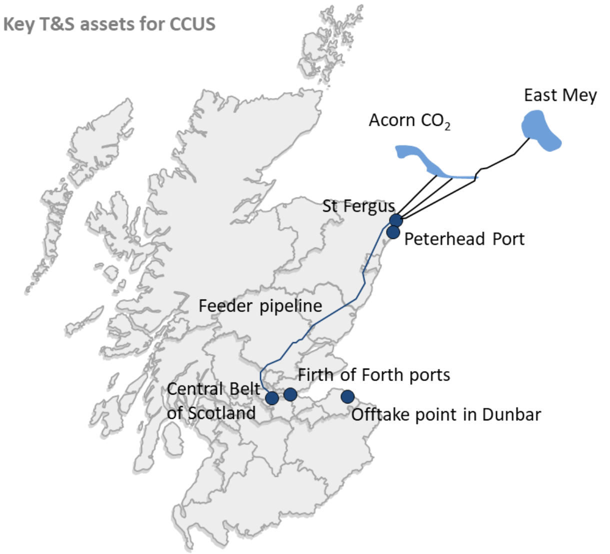
UK Government Cluster Sequencing Process

This report, and the underlying analysis supporting it, was prepared before the outcome of the UK Government's Cluster Sequencing process was announced.[3] Therefore, this report does not provide an assessment of the negative implications of the decision not to award the Scottish Cluster full Track 1 status. Such an assessment is not yet possible due to the lack of certainty over the practical implications of being a reserve cluster.

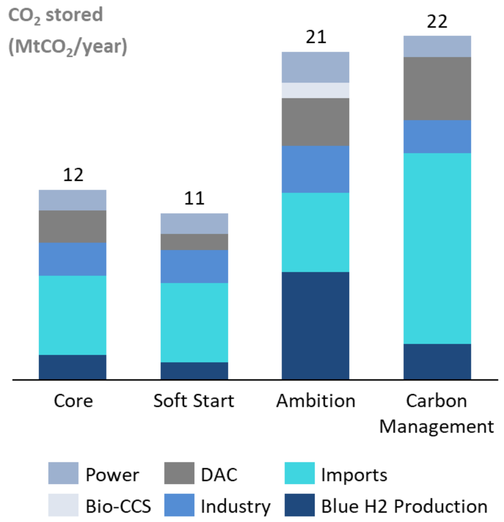
[3] Details of the UK Government's announcement are available at [Written statements - Written questions, answers and statements - UK Parliament]

Scottish CCUS value chains could offer both pipeline and CO_2 shipping transport options

Scotland's core CCUS value chains would be spread around the Central Belt of Scotland, St Fergus and offshore CO_2 stores



Scotland could store between 10.5 and 22MtCO₂/year, with a large contribution from CO_2 imports.



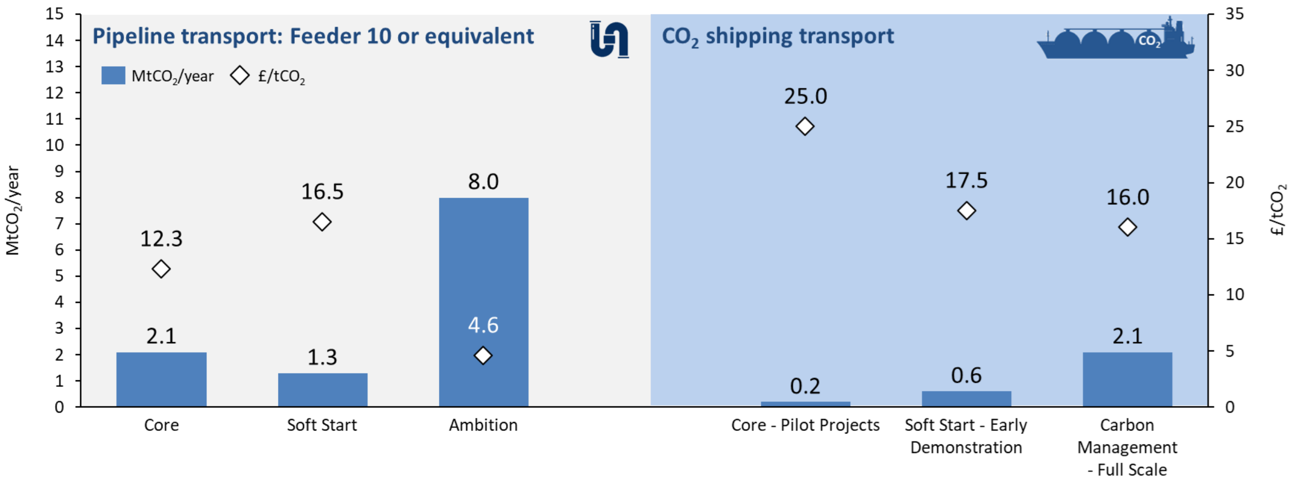
Map of key CCUS onshore and offshore T&S assets and summary of CO_2 volumes in 2050 per sector

As shown in the figure above, by 2050, the four scenarios envisage between 10.5 to 22 $MtCO_2$/year being stored in Scotland's Northern North Sea. Scotland can benefit from CCUS for the capture of its own CO_2 emissions; **however, the scenarios highlight the role which Scotland can play as a provider of carbon management services.** While CCUS would be deployed across multiple sectors, imports of CO_2 in Core, Soft Start and Carbon Management would constitute the largest sectoral proportion of CO_2 being stored (5-12 $MtCO_2$/year). In the Ambition scenario - representative of a Scottish hydrogen economy - CO_2 derived from blue hydrogen production would be the largest sector and deliver almost a quarter of all annual CO_2 volumes (around 7$MtCO_2$/year).

CCUS value chains for T&S in Scotland are likely to converge from the various CO_2 collection points in the Central Belt of Scotland and Peterhead into St Fergus, the CO_2 injection point for offshore storage. **Across the scenarios, transport of CO_2 to St Fergus can occur via pipeline or shipping** (the main transport mode for each scenario was illustrated above). The former would be via the repurposing of an existing Feeder pipeline whereas the latter would be by deploying shipping infrastructure to connect Firth of Forth ports to Peterhead Port.

By 2050, Feeder pipeline flows in the Core, Soft Start and Ambition scenarios would amount to 2.1 $MtCO_2$/year, 1.3 $MtCO_2$/year and 8.0 $MtCO_2$/year, respectively. The Core and Soft Start scenarios currently exhibit **annual CO_2 volumes below the throughput threshold below which Feeder 10 transport becomes less cost-competitive, due to underutilisation.** The Feeder 10 transport fee calculated for the three scenarios using the pipeline indicate that there is a threefold difference in the fee between the Soft Start **(£16.5/tCO_2)** and Ambition scenarios **(£4.6/tCO_2).** This highlights the benefit of economies of scale for pipeline transport and suggests that repurposing the pipeline would require strategic deployment of projects capturing CO_2 to materialise such benefit.

CO_2 shipping is likely to be used within Scotland as well as to import CO_2 from areas outside Scotland. In the case of intra-Scotland shipping, the extent to which this transport mode is used varies across scenarios, having CO_2 shipping to support pilot projects in the Core scenario, early demonstration projects in the Soft Scenario and a full-scale shipping scenario in Carbon Management. As the role of intra-Scotland CO_2 shipping grows in each scenario, the CO_2 shipping fees reduce from £25/tCO_2, £17.5/tCO_2 and £16/tCO_2, respectively.



Comparison of transport fees for onshore pipeline and CO_2 shipping for Scottish emitters

Comparing the estimated fees for pipeline and intra-Scotland shipping, **transport fees at full-scale CO_2 shipping would still be around £4/tCO_2 higher relative to pipeline fees for the same CO_2 transport volume**, as shown in the figure above. However, it is important to consider the value of system resiliency brought in by CO_2 shipping, as well as the key role it would play for isolated emitters, such as the Dunbar cement site.

In addition, regarding CO_2 imports, infrastructure associated with receiving CO_2 at the port of destination is significantly cheaper than infrastructure associated with exporting CO_2 deployed at origin ports. This suggests that **Scotland would be able to store more CO_2 at a lower cost (on a £/tCO_2 basis) by focussing investment on CO_2 imports rather than intra-Scottish shipments.**

In all scenarios, **CCUS value chains would require the commissioning of two CO_2 stores, namely Acorn CO_2 and East Mey** (part of the Acorn CCS project). All scenarios foresee the preferential repurposing of existing offshore transport pipelines, however the sequential nature of store commissioning assumed in this study implies that new pipelines would also be required to accommodate the envisaged CO_2 injectivities.

Scotland's competitiveness could be defined by low-cost CO_2 transport and storage options

Scotland has an enormous potential to offer cost-effective storage of CO_2, partially due to the plans to reuse offshore pipelines. This study suggests that, on a levelised cost basis and assuming full capacity, potential fees for the Acorn CO_2 site could be in the range of £11-12/tCO_2. Sequenced use of East Mey would lead to costs in the order of £8.2-9.5/tCO_2. This represents a cost reduction of around 30%, materialised by factors such as scale of emissions stored, storage capacity and synergies between the Acorn CO_2 and East Mey projects. When combining the estimated onshore and offshore fees for CO_2 T&S, **a generic emitter in the Central Belt of Scotland would be exposed to £15-29/tCO_2 when using the Feeder pipeline and injecting in Acorn CCS stores**. The variation results from different T&S economics across the scenarios.

A high-level comparison of the aforementioned CO_2 storage and transport fees with publicly available data on the T&S fees which domestic emitters would be exposed to in other CO_2 T&S projects - such as Porthos and Northern Lights - suggests that **Scotland can offer competitive CO_2 storage services, both within Scotland and as a carbon management provider through CO_2 shipping imports** (even though CO_2 imports would require adding the CO_2 shipping fee to the CO_2 storage fee presented above). This advantaged position to import CO_2 is possible in part due to Peterhead port's envisaged CO_2 infrastructure capacity and offshore pipeline infrastructure, both capable of accommodating high CCUS growth prospects in order to realise economies of scale and increased asset utilisation.

Realising CCUS competitiveness needs to be accompanied by supporting policy

Potential for CCUS competitiveness in Scotland would require support by a policy framework ensuring that the risks for CCUS growth are addressed throughout all sectors where CCUS is likely to be adopted. In particular, carbon leakage is an important risk sitting in the capture stage of CCUS. Carbon leakage refers to the relocation of industrial activity to jurisdictions with less stringent environmental regulations (in this case a lower carbon price). The prevalent carbon price is an important determinant of the risk of carbon leakage.

Risk and mitigation of carbon leakage

Price parity between average carbon price and full-chain CCUS costs would be reached in early 2030s, up to a third of Scotland's industrial carbon capture capacity is expected to be deployed before such date.

The various carbon leakage risk indicators evaluated (costs of capture, carbon price, change to production costs etc.) suggest that all industrial sectors investigated are, to a varying extent, exposed to the risk of carbon leakage, especially during initial stages.

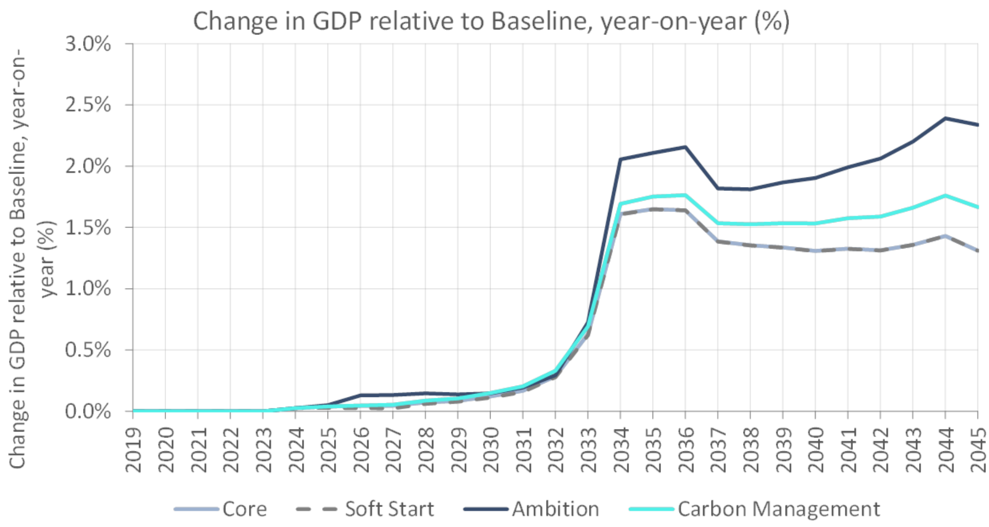
This implies that CCUS deployment in the short to medium term (up to 2030s) will require a strong supporting policy: direct subsidies, business models and other policy options described in Chapter 5.

Throughout the timeframes for CCUS deployment in Scotland, the risk of carbon leakage can be minimised with strong policy support

Unlocking economic growth: CCUS could create thousands of jobs

Bringing to reality **the CCUS value chains considered in the scenarios would require between £9bn and £30bn in total cumulative investment up to 2050**, with the Soft Start and the Ambition scenarios representing the lower and upper figures, respectively. In all scenarios largest capital investment is required around late 2020s and early 2030s, with the Ambition scenario exhibiting a maximum of around £1bn in 2030. Such total investment profiles would lead to different levels of GVA and job creation, which have also been explored.

Under the scenarios assessed in this study, CCUS uptake has a positive impact on the Scottish economy. In 2045, Scottish Gross Domestic Product (GDP) can be 1.3-2.3% (£3.8bn - £6.7bn) higher than hypothetical and generally not credible scenarios which meet Net Zero but do not have access to CCS; a significant additional increase in GDP, but relatively small compared to the 70% increase in the Scottish baseline GDP from under £170bn to £290bn over 2019 – 2045. These scenarios are not credible according to the CCC's 6th Carbon Budget, which states that ""*Scotland's 75% target for 2030 will be extremely challenging to meet, even if Scotland gets on track for Net Zero by 2045. Our Balanced Net Zero Pathway for the UK would not meet Scotland's 2030 target – reaching a 64% reduction by 2030 – while our most stretching Tailwinds scenario reaches a 69% reduction"* Relative to a more credible baseline that has a modest CCS uptake (Soft Start), GDP increase in 2045 can reach up to 1% (£2.9bn) depending on the scenario.



In 2045, the impact of CCS and hydrogen on the Scottish economy can be 1.3-2.3% higher than scenarios which meet Net Zero but do not have access to CCS

The increase in Scottish GDP relative to the 2045 baseline is driven by three reasons:

- **Access to CCS and blue hydrogen as alternative technologies lowers the cost of reaching the Net Zero target for the Scottish economy and its sectors**. ViEW, the computable general equilibrium (CGE) model used in this analysis, estimates that CCS can decrease the carbon price, in other words the cost of emitting CO_2, in 2045 up to 90% relative to the baseline without access to CCS. A lower carbon price and hence energy costs benefit energy intensive industries such as chemicals, non-metallic minerals, paper, and iron & steel. The benefits accrue primarily in the safeguarding of existing jobs and economic activity in these sectors and their supply chains.
- **The increase in economic activity, application of CCS and demand for blue hydrogen drive the demand for now low carbon oil and natural gas**, enabling a managed and Just Transition in this sector through supporting GVA and employment in fossil fuel production, i.e., O&G extraction, oil refining and gas processing.
- The higher economic activity in energy intensive industry and fossil fuel production reverberates through the economy, further supporting demand for these sectors and other sectors that are lower emissions intensity, such as services.

Food production and manufacturing do not benefit from the lower carbon price, and high investment needs of CCS infrastructure and competition with energy intensive industry and services could increase its capital and labour costs. It could gain from CCS if savings from the lower energy and abatement costs exceed the increase in capital and labour costs, or in fact it could lose if the latter counters the former.

At the sector level, higher GVA growth does not necessarily translate to higher job creation. Energy intensive and lower emissions industries become more capital intensive over time and decrease their labour intensity, leading to displacement of jobs despite GVA gains, as evidenced by real world trends. In developed economies, industries increasingly invest to automate their production processes and hence decrease their labour costs and intensity. At the national level, driven by the modelling setup, decreases in employment in sectors with decreasing GVA are counterbalanced by employment gains in other sectors. This includes a counterbalancing between the electricity and fossil fuel production and services sectors. However, it is important to note that this result is driven primarily by the CCUS uptake scenarios imposing use of natural gas with CCS to generate electricity, lowering the share of renewables in the electricity mix.[4]

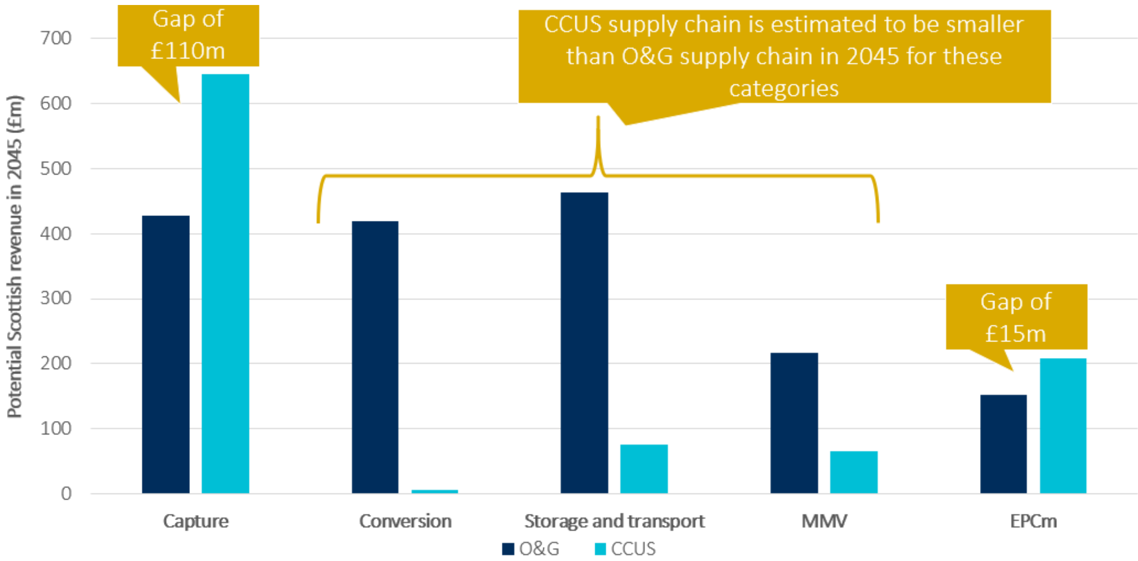
The impact of carbon management and DACCS on GVA and employment is positive but negligible in size when compared to the impact of energy intensive industries and fossil fuel production, as the CCS and DACCS infrastructures have low GVA and labour intensity. In other words, the CCS and DACCS infrastructures requires few workers per tonne CO_2 shipped, transported, and stored. This is largely driven by assumptions and calibration of the CGE model used in this assessment. Nevertheless, negative emissions technologies have wider benefits to environment and biodiversity which are not captured in this study.

Ensuring a Just Transition for skills, supply chains and capabilities

The analysis finds that the total gap in the Scottish CCUS supply chain in 2045 seems manageable relative to the supply chain's size in that year, but is significant when we zoom into individual supply chain categories: capture and pollution control, conversion and generation, T&S, measurement, monitoring and verification (MMV) and Engineering, Procurement and Construction Management (EPCm). To measure the supply chain gap, the top-down analysis compares the size of the 2045 Scottish CCUS supply chain to the size of the 2045 Scottish O&G supply chain. Specifically, the analysis concludes that:

- There is a gap of around £125mn in two out of five of the CCUS supply chain categories. These are capture equipment and EPCm. A number of Scottish companies are starting to operate in this space including Doosan Babcock, Wood Group and Petrofac. Indeed, a recent report by the Carbon Capture and Storage Association highlights the UK's export potential.
- In capture equipment, the gap that could be captured by Scottish companies in 2045 is around £110mn in potential revenue. It accounts for around 10% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 (around £1bn) or around 6% of total revenue able to be captured across the entire Scottish O&G industry today (around £1.8bn). There is therefore a potential investment gap in the design and manufacture of capture and compression equipment, which the Scottish Government could work with private finance to close. The fundamental skills in designing and manufacturing the capture equipment are likely to be the same as currently for O&G, but the skills may be applied differently. However, since there are gaps in only two out of the five CCUS categories, it is important to note that the gap in capture equipment represents 90% of the total gap of £125mn.
- In EPCm, there is a gap of £15mn in potential revenue that could be captured by Scottish companies in 2045, accounting for 2% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 or less than 1% of total revenue able to be captured across the entire Scottish O&G industry today.
- The analysis does not identify any gap in the other CCUS supply chain categories, such as conversion goods and services, storage and transport goods and services and MMV goods and services.

[4] Electricity generation from natural gas with CCS has lower GVA and job intensity compared to electricity generation from renewables, resulting in decreases in GVA and employment.



There is a gap of ~£110mn in potential Scottish revenue in capture equipment and ~£15mn in EPCm services between the O&G and CCUS sectors in 2045[5]

The stakeholder interviews confirm the findings from the top-down analysis - **many of the leading trade bodies recognise that the skills needed to enable Scotland to participate in the Net Zero transition exist today**. The key findings are:

- There are no major technical skills gaps. Scotland has many strengths which can be translated to the CCUS industry. The requisite skills, expertise, and capability to build a CCUS supply chain in Scotland already largely exist and the Industrial Strategy Challenge Fund should help some companies get off the ground.
- But there are barriers which will need to be overcome. These include the lack of a formal regulatory environment for CCUS; the potential to be outcompeted on scale as most of the CCUS clusters in the UK are not in Scotland; limited availability of high quality public datasets for companies to start evaluating potential CCUS storage sites; limited understanding of how plugging and abandonment of CO_2 wells will work.
- The key gap in skills is in specialist technical skills such as subsurface geological modelling. Additional investment in the UK's Centres for Doctoral Training was mentioned during stakeholder engagement, and it is clear that these are seen as an effective means to start to bridge the gap between academic R&D and solving technical challenges in industry.

There are a number of potential policy interventions which government could make to help overcome these barriers. These include making finance available for companies to invest in developing new capabilities; joint governmental procurement of CCUS equipment for Scottish CCUS projects; establishment of a CCUS regulator; publication of a policy statement and action plan for CCUS by the Scottish Government; increasing local content requirements; and increased investment in line with State Aid provisions.

[5] Vivid Economics, EIC Supply Map, BEIS Energy Innovation Needs Assessment for CCUS

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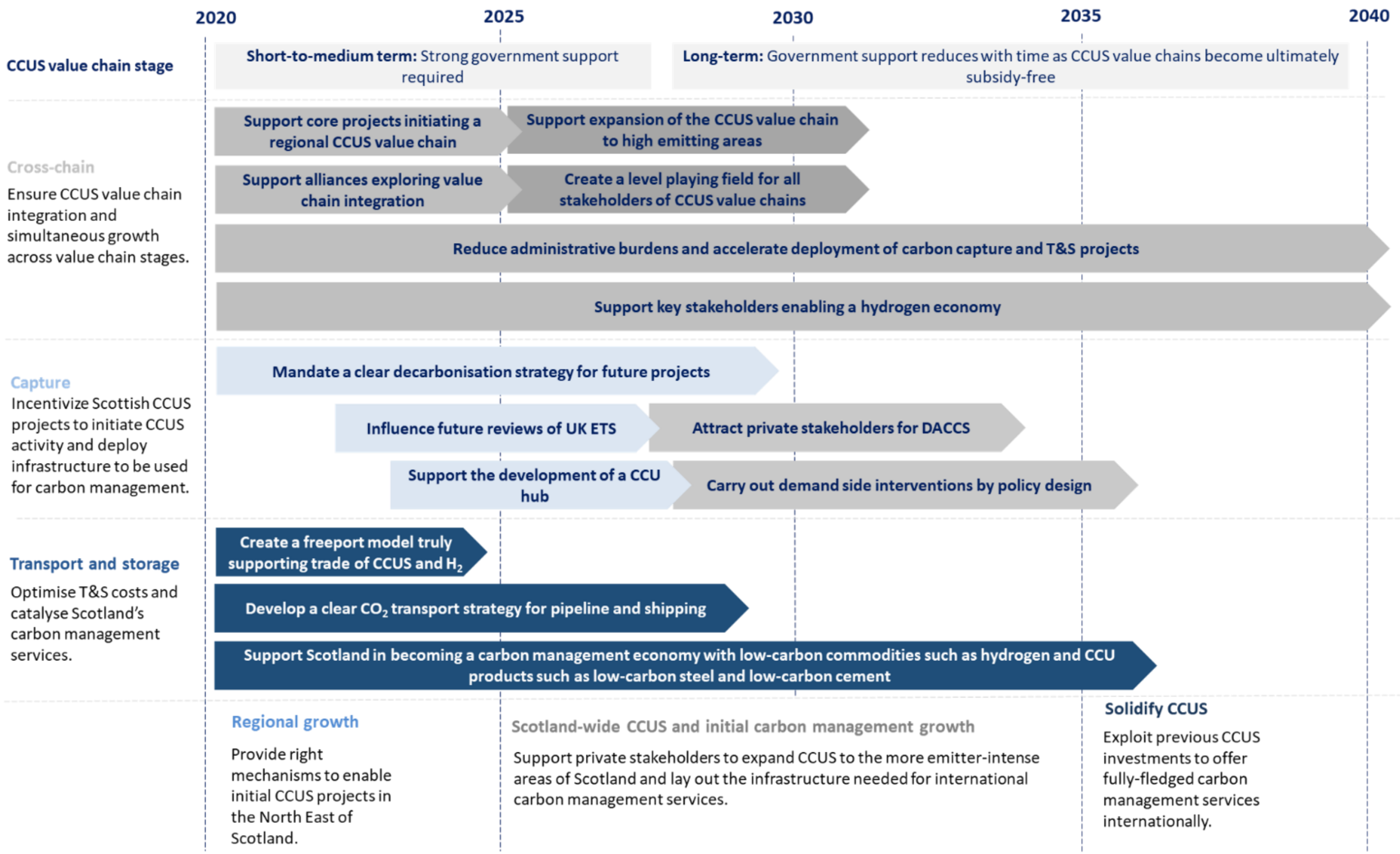
Support for CCUS growth will require the development of a wide range of policies



Acronyms and abbreviations

ABEX	Abandonment Expenditure
ATR	Autothermal Reformer
bpd	Barrels per day
BCA	Border Carbon Adjustment
BECCS	Bioenergy with CCS
BEIS	UK Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CfD	Contract-for-Difference
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CCU	Carbon Capture and Utilisation
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalents
DACCS	Direct Air Capture with CCS
EINA	Energy Investment Needs Assessment
EPCm	Engineering, Procurement and Construction Management
ETI	Energy Technologies Institute
ETS	Emissions Trading Scheme
FES	Future Energy Scenarios
FID	Final Investment Decision
FOAK	First-of-a-kind
GDP	Gross Domestic Product
GGR	Greenhouse Gas Removal
GTAP	Global Trade Analysis Project
GVA	Gross Value Added
H_2	Hydrogen
IEA	International Energy Agency
IRR	Internal rate of return
MER	Maximise Economic Return
MMV	Measurement, Monitoring and Verification
MoU	Memorandum of Understanding
Mt	Mega tonne
NECCUS	North East Carbon Capture Utilisation and Storage Alliance
NETs	Negative Emissions Technologies
NOAK	Nth-of-a-kind
NTS	National Transmission System
OPEX	Operational Expenditure
O&G	Oil and Gas
PPS	Peterhead Power Station
(pre)-FEED	(pre)-Front-End Engineering Design
RAB	Regulated Asset Based
RD&D	Research, Development & Demonstration
SME	Small and medium enterprise
SMR	Steam Methane Reformer
SNZR	Scotland's Net Zero Roadmap
SOAK	Second-of-a-kind
SPRI	Scottish Pollutant Release Inventory
TRI	CO_2 Transport and Storage Regulatory Investment Model
TRL	Technology Readiness Level
TWh	Terawatt hour
T&S	Transport and Storage
UKCS	UK Continental Shelf
ViEW	Vivid Economy-Wide
WWF	World Wide Fund for Nature

Note on terminology

Whilst Carbon Capture, Utilisation, and Storage (CCUS) and Carbon Capture and Storage (CCS) are used almost interchangeably in the literature, for consistency purposes, this report uses CCUS, with an exception when CCS is used directly in the cited sources or when utilisation is explicitly excluded.

Potential blending of hydrogen into the NTS and injection of CO_2 into offshore network is expected to be done in St Fergus Gas Terminal, but St Fergus is used throughout the report for simplicity. All hydrogen blending figures refer to a volume basis (v/v%).

'**Blue hydrogen**' refers to hydrogen produced from a feedstock of natural gas by steam methane reforming (SMR) or autothermal reforming (ATR) coupled with CCUS of the resulting carbon dioxide emissions. '**Green hydrogen**' refers to hydrogen produced through water electrolysis using renewable electricity.

Contents

1 Introduction

1.1 Context

Scotland has ambitious plans to reach Net Zero emissions. In 2019, the Committee on Climate Change (CCC) published 'Net Zero: The UK's contribution to stopping global warming'. The report advised the UK to commit to achieving Net Zero greenhouse gas emissions by 2050 and Scotland by 2045. Following this advice, the Scottish Government imposed its own ambitious target to become carbon neutral by 2045. In 2020, the publication of the Sixth Carbon Budget, which Element Energy supported, states that CCUS will play a key role in contributing to UK's Net Zero targets. Scotland is already taking action to materialise the benefits of CCUS, aiming to have in place the necessary infrastructure to enable the deployment of CCUS by 2032, as part of a Just Transition for Scotland's industry[6].

CCUS could play a major role in Scotland's just energy transition, including protecting key existing industries. Many industrial sites have independently deployed financially viable decarbonisation technologies, such as energy efficiency options. However, meeting Scotland's Net Zero target requires long-term deep decarbonisation of all sectors of the Scottish economy and would involve large-scale deployment of growing technologies, such as CCUS and hydrogen. The North Sea provides a unique asset with extensive potential for renewable energy generation and the presence of major subsurface CO_2 storage sites that offers the opportunity to develop a Scottish economy where renewables, hydrogen and CCUS coexist and complement each other.

CCUS deployment could bring benefits beyond achieving decarbonisation targets. There are significant opportunities for unlocking socioeconomic value in Scotland by building on the existing energy industry to deploy further CCUS, carbon management, hydrogen, and related renewable energy sectors. This includes protecting jobs in energy intensive industries (e.g., chemicals and petrochemicals), transitioning the skills and capabilities of the O&G workforce and unlocking value through providing skills and services in CCUS value chains[7].

Scotland has established a leading position in the CCUS sector in the UK and can be a key contributor to the UK's ambition to store 10 $MtCO_2$/year of CO_2 by 2030. Scotland has a range of existing skills and potential infrastructure and perhaps the most developed project through the Acorn consortium. Scotland's North Sea is home to over 50,000 $MtCO_2$ of potential storage capacity in aquifers and depleted hydrocarbon fields (P50 theoretical storage capacity), which makes it an attractive point to gather and store CO_2 for the UK and internationally via CO_2 shipping. CO_2 shipping can connect Scottish ports with potential early movers, such as Norway and Netherlands, and other key industrial hubs with limited offshore CO_2 storage potential.

1.2 Objectives and scope of the work

The objective of this study is to explore and provide evidence on the nature and extent of the economic opportunity presented by CCUS in Scotland. This includes assessing the implications of CCUS scenarios differing in level, focus, geography, and timing of CCUS deployment, including the potential for development of a carbon management sector. The key objectives are:

- Develop robust scenarios for deployment of CCUS in Scotland across industry, power and hydrogen, aligning with the NECCUS' Scotland's Net Zero Roadmap (SNZR) scenarios. These will vary in scope, scale, focus and ambition.

[6] Scottish Government, 2018-2032 Update to the Climate Change Plan, 2020
[7] Through the North Sea Transition Deal, the oil and gas sector and government will work together to use the sector's expertise to execute offshore infrastructure projects needed for CCUS growth and meet the UK's Net Zero goals. This collaboration can help deliver up to 40,000 supply chain jobs in CCUS, hydrogen and decarbonising UKCS production.

- Quantify and describe the economic impacts of CCUS deployment in nature and scale, differentiating domestic CCUS from international carbon management.
- Analyse the potential for Scotland to develop a carbon management sector, including the competitive advantages and the economic impacts/value.
- Assess the policy mechanisms and interventions required to deploy CCUS in the short and longer term, including discussion of the differing needs of the CCUS sectors.

It is crucial for the project, as well as national decision making, to be supported by robust and unbiased analysis on the costs, benefits and impacts of decarbonisation pathways.

1.3 Report structure

The remainder of this report is structured into 8 chapters as follows.

Chapter 2 provides a high-level assessment of the potential CO_2 sources and their geographical distribution, and also reviews the emerging development that could enable system-wide decarbonisation in Scotland.

Chapter 3 quantifies the CO_2 volumes that could be captured from the different sectors of the economy and sets out four scenarios for the evolution of the Scottish carbon economy differing in scale, scope, timeline, and relative relevance of the CO_2 shipping and pipeline transport routes.

Chapter 4 assesses the infrastructure requirements within each scenario for each of the pipeline transport, shipping, and storage parts of the value chain, and estimates the corresponding investment needs.

Chapter 5 reviews the sector-specific challenges hindering CCUS uptake and summarises the options available to policy makers to foster deployment.

Chapter 6 provides an assessment of the skills, supply chain and capabilities required to support the development of the Scottish carbon economy.

Chapter 7 presents the investment required for achieving these deployment scenarios and the macroeconomic benefits of successful deployment.

Chapter 8 summarises the key findings and provides recommendations.

This report is also accompanied by an appendix detailing key figures of the scenarios and assumptions.

2 Understanding the potential for CCUS in Scotland

2.1 Mapping of CO_2 emissions and clustering

In 2018, **Scotland emitted a total of 41.6 $MtCO_2e$**[8], of which 11.9 $MtCO_2$ originated from emitters above 10,000 tCO_2/year, according to the Scottish Pollutant Release Inventory (SPRI)[9]. **The largest emitters are located in the Central Belt of Scotland and East Coast areas**, with 80% of Scotland's industrial emissions originating in this area[10]. The most promising CO_2 sinks are located in the North Sea, North East of St Fergus. Pipeline transport will thus be required to connect the main emitters to the storage sites in the North Sea. Ongoing work on the Scotland's Net Zero Roadmap has grouped Scottish CO_2 emitters in various **geographical groups**[11], with the potential of each cluster to share common decarbonisation infrastructure, such as a **CO_2 transport pipelines crossing Scotland from the Central Belt to St Fergus**. The cluster regions' relative distance form this pipeline helps understand how CCUS value chains may evolve and grow in Scotland.

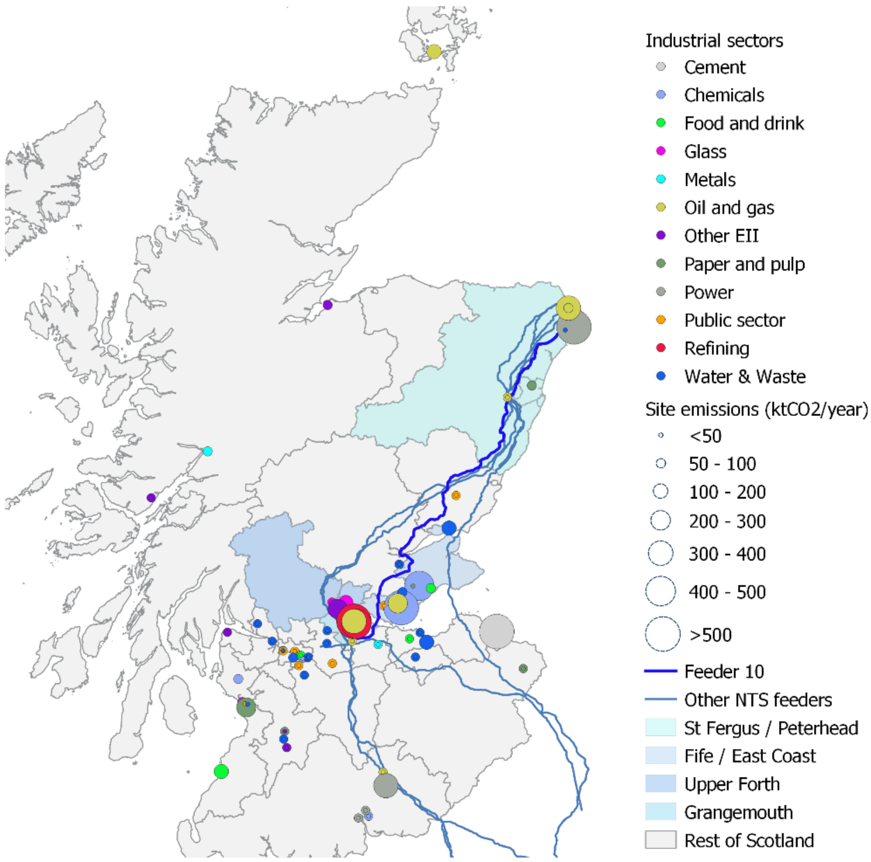


Figure 2-1: Main emitters and key infrastructure in Scotland

The timeframes for CCUS deployment in the industrial heart of Scotland will be **principally enabled by the commissioning of a CO_2 feeder pipeline.** This will enable industrial decarbonisation but also carbon capture from other areas such as **power, capture of biogenic CO_2 or DACCS**. CCUS infrastructure can also support other decarbonisation pathways, such as **fuel switching to blue hydrogen for heating** of residential and commercial buildings, as well as use in the transport sector. This would be enabled around Scotland once infrastructure growth from the initial regional clusters expands to reach other Scottish areas. There are several options for CO_2 abatement for Scotland's economic sectors, including:

- **CCUS**, which consists in the capture of the CO_2 emitted in the process of producing industrial goods or when combusting fuels. In CCUS, this captured CO_2 can be used in downstream processes

[8] Scottish Government, Greenhouse gas emissions 2018: estimates (2020).
[9] SCCS for SNZR: ISCF Decarbonisation of Industrial Clusters: Scotland's Net Zero Roadmap – Work Package 1. Scotland's Industrial CO_2 emissions - 2018 baseline data and proposed industrial and geographic scope for phase 2 (2020)
[10] NECCUS: The Project – Scotland's Net Zero Roadmap (2020)
[11] SNZR has recently received ISCF Phase 2: Roadmap funding from the UK Government to elaborate a roadmap towards decarbonisation of Scotland's industrial sector.

(utilisation route) or be permanently sequestered (storage route). Both routes aim to mitigate the climate change effect of CO_2 emissions.

- **Fuel switching**, which consist of replacing the use of an incumbent fuel by another one with less negative climate impacts. This fuel switching is preferably done to fuels such as clean hydrogen (including blue hydrogen), renewable electricity or other fuels such as biomass.
- **Energy efficiency,** whereby emissions reductions are attained by optimising the use (and minimising waste) of energy and fuel use for a given level of activity.
- **Resource efficiency**, which includes a range of approaches to reducing the amounts of materials used to produce a product and hence the processing requirements.
- **Reduction in demand** for products, with the consequent decrease in energy and resource requirements.
- **DACCS,** which is an emerging technology consisting of the engineered removal of CO_2 from the atmosphere, followed by the conventional CO_2 utilisation or CO_2 sequestration routes.

As Scotland transitions to Net Zero it will require a number of different solutions to minimise CO_2 emissions. This is likely to result in the creation of new economic activities helping Scotland further reduce through, and potentially benefit from, carbon management services. Some of these components are DACCS and importing CO_2 from other regions, which are predicted to play important roles in the future.

2.2 Enabling system-wide decarbonisation: The Acorn projects

The Acorn projects, namely Acorn CCS and Acorn Hydrogen, are two sister projects bringing several partners together and led by Pale Blue Dot Energy, aiming to deploy low-carbon infrastructure at large scale in Scotland[12]. The projects are expected to be initially developed and collocated around the St Fergus Gas Terminal, a key injection point to the UK's natural gas grid. As the first of their kind projects in Scotland, Acorn CCS and Acorn Hydrogen will act as the anchor projects helping Scotland meet its Net Zero goals. Both projects are scalable and with the development of the appropriate infrastructure can expand a CCUS network south and help decarbonise regions beyond Scotland's North East coast, as shown in Figure 2-2 and Figure 2-3. In addition to their role in capturing direct emissions in Scotland, Acorn is also investigating the opportunities for Scotland to supply hydrogen and CCUS services to the wider UK and internationally, enabling fuel switching to hydrogen and decarbonisation of a wider geographic scope.

The location chosen for these projects is advantageous, as much of the infrastructure required is already present, both onshore and offshore in the UK Continental Shelf (UKCS). This could lead to cost savings and help the Acorn projects become some of the earliest enablers for large-scale use hydrogen and CCUS in the UK. Moreover, the Acorn projects could bring long-term benefits by leveraging O&G skills and infrastructure and sustaining the local communities.

The Scottish Cluster project that incorporates the Acorn CCS and the CO_2 SAPLING projects are aiming to provide the infrastructure required to kick-start a CCUS value chain in Scotland by capturing CO_2 from St Fergus Gas Terminal and safely and permanently sequestering the CO_2 in the Acorn CO_2 store. The project is divided in two phases of growth:

- Phase 1 would capture 0.3 $MtCO_2$/year CO_2 from mid-2020s from gas processing in the St Fergus Gas Terminal. Importantly, this phase will lay the groundwork for additional CO_2 volumes to arrive at St Fergus in Phase 2 once onshore infrastructure allows for CO_2 to be captured and transported from other regions of Scotland.

[12] More information on these projects can be found here.

- Phase 2 would therefore help Scotland decarbonise some of its more emission intensive areas, such as the Central Belt of Scotland or Peterhead. This phase also aims to develop a major hydrogen production and international CO_2 storage hub in Scotland.

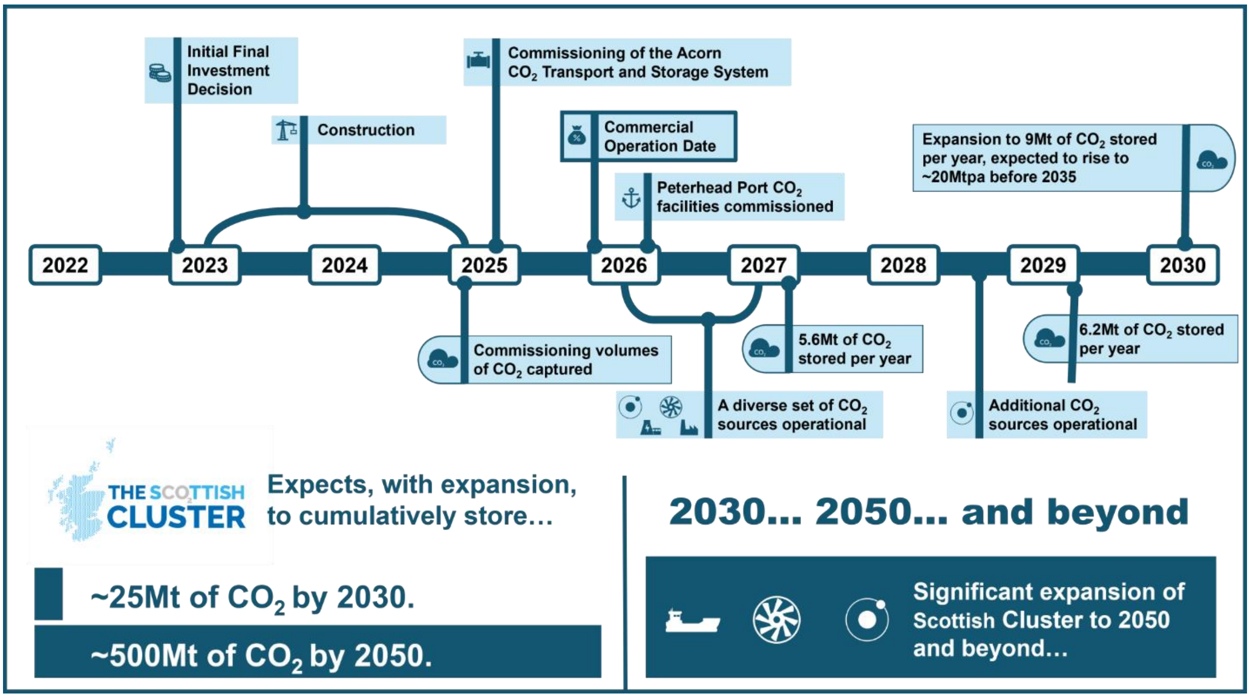


Figure 2-2: Timeframe for the two phases of the Acorn CCS / Scottish Cluster project (as of 2020)[13]

Acorn CCS is currently completing its Front-End Engineering Design (FEED) studies, with a date for Final Investment Decision (FID) in 2022 for a mid-2020s start[14]. On 19 October 2021, UK Government announced that the Scottish Cluster would be treated as a "reserve cluster" for track 1 of the BEIS Cluster Sequencing Competition.[15] In the long term, the project is aiming to repurpose the Goldeneye, Atlantic and Miller Gas System pipelines for CO_2 transport as well as depleted fields for CO_2 storage (Acorn CO_2 and East Mey). Despite the exit of the UK from the EU, the project is listed as a Project of Common Interest and has received funding from the European Commission via the Connecting Europe Facility programme.

[13] https://theacornproject.uk/2021/07/21/scottish-cluster-expected-to-deliver-31000-jobs-in-the-next-decade/
[14] Dates consulted in stakeholder engagement activities and assumes no delays are caused by COVID-19, revised from the originally publicised information in Accelerating CCS Technologies: Acorn Project: D20 Final Report, ACT Acorn Project (2019).
[15] UK Parliament, Climate Change Update – Statement made on 19 October 2021 (Statement UIN HCWS325). Accessible at Written statements - Written questions, answers and statements - UK Parliament

Acorn Hydrogen is aiming to produce blue hydrogen from natural gas arriving at St Fergus Gas Terminal and utilise Acorn CCS infrastructure to transport the CO_2 for storage[16]. Initial uses being considered for the produced hydrogen include blending it into the National Transmission System (NTS) and supplying Aberdeen via its gas distribution network, as part of Aberdeen Vision. Acorn Hydrogen's strategic location also implies that the project could grow with time. For example, a recent study conducted by Element Energy identified additional end uses for Acorn Hydrogen and other similar blue hydrogen projects, such as industry (7 TWh/year by mid-2030s) or exports (48 TWh/year by 2050)[17]. Production could start in 2025 through the construction of a 200 MW facility, allowing for a blend of 2% into the NTS[18], which could then be expanded on a modular basis.

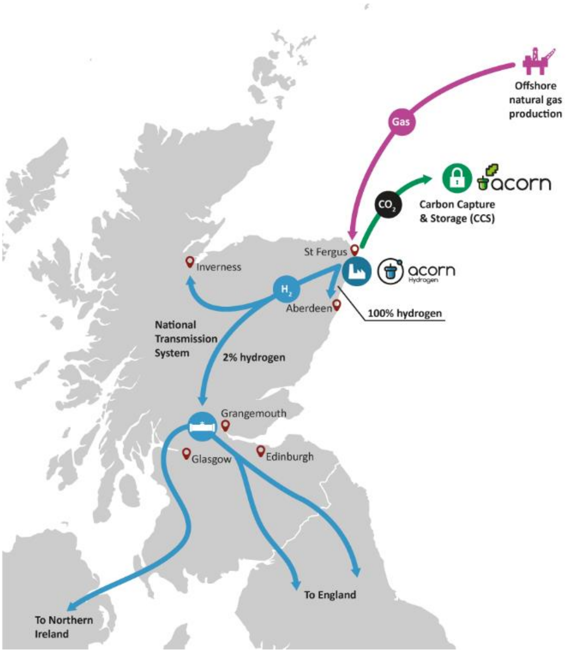


Figure 2-3: Overview of the Acorn Hydrogen concept

The analysis presented in this report considers the role of the Acorn project, recognising its potential to drive CCUS and hydrogen deployment across Scotland. As the most advanced Scottish project in terms of project development, Acorn CCS assumptions on project timeline and initial plans represent an anchor point in CCUS deployment and shape the CCUS scenarios developed as part of this study. Similarly, for the case of hydrogen use in Scotland, this study also uses the information available on Acorn Hydrogen, particularly around timeline and potential growth opportunities. Infrastructure is a key component of both Acorn projects, and their ambition for infrastructure use is used as the foundation and starting point for the infrastructure growth and sequencing assumptions described in this study.

The following chapter presents four scenarios that examine the applicability of CCUS across a range of emitting sectors as well as uncertainties in the development of transport and storage (T&S) infrastructure. These scenarios explore multiple degrees of CCUS uptake by investigating the role of different parameters such as infrastructure deployment, timeframes, among others.

[16] Figure provided by Pale Blue Dot Energy for the project "Element Energy for Pale Blue Dot Energy, Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero (2020)".
[17] Element Energy for Pale Blue Dot Energy, Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero (2020)
[18] Pale Blue Dot Energy, Acorn Hydrogen: Project Summary (2019)

3 Potential for CCUS uptake in Scotland

The capture, transport and permanent storage of CO_2 in CCUS value chains can **enable deep decarbonisation of important economic sectors**. CCUS can reduce process and fuel emissions directly in a facility with carbon capture technology, or indirectly via allowing for hydrogen fuel switching to reduce fuel emissions. Additionally, **CCUS underpins negative emissions technologies** - which have been identified as key technologies to help the UK meet its Net Zero targets – via DACCS and BECCS[19].

The development of CCUS projects often faces a "chicken-and-egg" coordination problem, where the deployment of carbon capture at emitter sites would not start before the availability of T&S infrastructure, and T&S infrastructure developers would not roll-out appropriate carbon management assets until a commitment with emitters is reached. Furthermore, it is recognised that the **timeframes of T&S infrastructure deployment** are key in driving the timeframes when emitters deploy carbon capture.

Carbon capture and storage (CCS) deployment in the UK is regarded as a necessity, not an option, and the **important role which CCUS may play in Scotland to help reach Net Zero** has been highlighted and evidenced in multiple reports[20]. In addition, CCS deployment is deemed to be needed as part of any balanced scenario aiming to reduce overall Net Zero costs[21]. Scotland has multiple economically important power and industrial players, such as refining and chemical facilities. As a deep decarbonisation technology, CCUS can help industries maintain their competitiveness in a Net Zero world. This study explores a series of scenarios focused on the role of CCUS in reducing Scottish emissions from existing sectors and its role in emerging markets, including import of CO_2 and exports of hydrogen.

Uses and drivers for CCUS value chains in Scotland

Different areas of economic activity could deploy CCUS in a wide range of applications: industry, power, bio-CCS, DACCS, CO_2 imports and blue hydrogen production. The potential for CCUS use varies across different sectors and technologies, each with its own CCUS value chain drivers which will determine the extent of CCUS uptake within each of these options, as discussed in this chapter.

CO_2 transport is needed to manage flows of CO_2 and connect point emitters with storage sites. When it comes to CO_2 transport, Scotland could rely on either a mix of pipeline infrastructure and/or CO_2 shipping.

- **CO_2 transport by pipeline** is mature and has been demonstrated worldwide for over 50 years, with over 8,000 km pipeline deployed globally[22]. Whilst many CO_2 projects rely on the development of new pipelines, Scotland has several onshore pipelines (called "Feeders") forming part of the NTS, which are expected to see a decline in use and could be repurposed for CO_2 transport. Three Feeders (Feeders 10, 13 and 24) have similar technical and operational characteristics. These are potential candidates for conversion to CO_2 transport, with Feeder 10 having received most attention in conversion studies[23]. This could provide a cost-effective way of transporting CO_2 emissions from large emitters, mainly located in the Central Belt to St Fergus.
- **Shipping** represents a less mature option for CO_2 transport consisting of liquefying CO_2 at an origin port, loading it onto a ship, transporting it to a destination port, where the CO_2 is conditioned (or converted back to a gaseous form), and then transported by pipe to the storage site. Small-scale CO_2 shipping is deployed today in the food industry, but several CCUS projects - particularly those in areas with limited T&S storage infrastructure - are investigating its potential.

[19] Scottish Government has released an update to the Climate Change Plan 2018 – 2032, dedicating a chapter to negative emissions technologies. This update explains the role for negative emissions technologies in the vision to 2045, detailing and discussing actions and ambitions for the contribution of negative emissions technologies to 2032.
[20] Committee on Climate Change, Net Zero - The UK's contribution to stopping global warming (2019)
[21] The Sixth Carbon Budget: The UK's path to Net Zero, Committee on Climate Change (2020).
[22] Wood Mackenzie for The Oil & Gas Technology Centre: Closing the Gap, Technology for a Net Zero North Sea (2020)
[23] Finding from stakeholder engagement activities.

The role of the two transport alternatives is investigated in this study.

Hydrogen infrastructure will also play a key role in determining the timeframes and scale of hydrogen use in Scotland, and thus the potential for hydrogen production from natural gas with CCUS. Whilst several options for a Scotland-wide hydrogen network exist, wide-engagement suggests that early hydrogen adoption will occur around existing projects, including Acorn Hydrogen as the anchor blue hydrogen project. Outwards expansion would be expected, first around large clusters of demand, such as industrial sites and mobility hubs, before a full-scale conversion of the gas grid to hydrogen, supplying hydrogen to domestic and commercial users, as well as smaller industrial sites. Alternatively, deployment of hydrogen infrastructure could be limited to specific regions, where producers and consumers such as industrial sites are adjacent to one another, allowing for direct pipeline connections.

Offshore CO_2 T&S infrastructure in the UKCS is needed in all four scenarios, where St Fergus is considered as the primary node connecting CO_2 onshore transport with the offshore pipelines and storage. As previously mentioned, each scenario examines the use of existing pipeline infrastructure for offshore CO_2 transport (Goldeneye, Atlantic and Miller Gas System pipelines), and the Acorn CO_2 and East May storage sites as per Acorn CCS project plans.

A vision for growth and sequencing of CCUS projects in Scotland

This study examined opportunities and scenarios for CCUS development in Scotland considering both short term opportunities as well as the potential for consolidation and expansion.

Early opportunities for CCUS are represented by capturing emissions from emitters in the close proximity of the Acorn anchor projects or those using CO_2 shipping as a means for CO_2 transport.

- In the short-term, the CCUS value chain is envisaged to start at a regional level around St Fergus, with the commissioning of the Acorn CCS and Acorn Hydrogen facilities in mid-2020s, respectively. These two projects are deemed to catalyse the initial demand for CO_2 storage and help the CO_2 injection facilities in St Fergus gather experience on CO_2 T&S.
- In the late 2020s, transport of CO_2 from early carbon capture projects in industry in the Central Belt to St Fergus would be enabled by the development of port infrastructure for CO_2 shipping from Firth of Forth Ports to Peterhead Port[24]. This port infrastructure also enables the start of CO_2 imports to Peterhead.
- Peterhead becomes a CO_2 hub, also allowing for the decarbonisation of Peterhead Power Station (PPS). By the late 2020s, Acorn CCS is assumed to have a fully developed Phase 2, capable of accommodating these CO_2 volumes and prepared for additional scale-up in the expansion stage.

The expansion phase would be very infrastructure dependent and would commence with the repurposing of one of the Feeders for CO_2 transport from the Central Belt to St Fergus, enabling decarbonisation of large emitters from the industrial heart of Scotland. The higher onshore CO_2 throughput would, in turn, require expansion of the offshore T&S capacity.

- The date of repurposing is explored across the scenarios, but CO_2 pipeline availability allows for i) the connection of a wider range of emitters and ii) the development of a fully-fledged CCUS supply chain for cross-Scotland carbon management which spreads to the more CO_2 intensive regions of Scotland. CO_2 pipeline collection networks branch out from the main CO_2 pipeline to reach the location of certain emitters in the Central Belt.
- The expansion phase would also enable blue hydrogen production around Grangemouth. Capture of relatively pure CO_2 stream from hydrogen production will allow fuel switching in industry and beyond.

[24] Firth of Forth ports include a variety of ports such as the Grangemouth port or Fife ports. We use the generic "Firth of Forth ports" term to represent any possible combination of port(s) which may deploy CCS infrastructure for shipping. Albeit it is possible that those with liquefaction facilities or current experience of offloading of gases may be better-placed candidates.

- CO_2 imports will continue to arrive to Scotland from the uptake of CCUS in the UK and internationally.

The consolidation phase will come after the initial and expansion stages, and is focussed on the capture of CO_2 predominantly from large emitters in Scotland. This would allow Scotland to build expertise and operational resources to become a provider of carbon management services for other regions in the longer term. This could lead to commissioning of further storage infrastructure. During this phase:

- There will be further opportunities for capture from blue hydrogen catalysed by the geographic expansion of the converted distribution gas network allowing decarbonisation of residential and commercial heat, as well as fuel switching at smaller industrial sites connected to the gas grid.
- Connection of industrial emitters and hydrogen production sharing common T&S infrastructure will lead to economies of scale. This would allow the capture in smaller-scale emitters such as biogenic CO_2 emitters. Capturing biogenic carbon will generate 'negative emissions', which could be used to offset remaining Scottish emissions, setting Scotland on its path to Net Zero.
- Direct Air Capture would represent another source of negative emissions, taking advantage of Scotland's abundance in vast geological storage sites and availability of cheap renewable electricity.
- Scotland is expected to continue help to decarbonise other regions in the long term, both in terms of handling and storing shipped CO_2 but also with the potential to provide negative emissions credits.

To further explore this vision, several scenarios are considered in this study, as discussed below.

Four scenarios for CCUS and hydrogen, varying in scale and geographic scope

This chapter and the next discuss the potential for CCUS deployment across Scotland through four scenarios.

		Scenario			
Category	**Driver**	**Core**	**Soft Start**	**Ambition**	**Carbon Management**
	Industrial emissions sources with CCUS	Process emissions and internal fuel use at largest sites	As Core	As Core and CHP/boilers at refinery, petrochemicals and largest glass plant and bio-CCS	As Core
	Power sites that deploy CCUS	Peterhead Power Station	As Core, but delayed timeframes	Use of H2 at PPS and new natural gas CCS power plant in Grangemouth	As Core
	Direct air capture deployments	Equivalent to 40% of UK DACCS requirement	Limited to the initial PBDE/Carbon Engineering MOU	Equivalent to 60% of UK DACCS requirement	Equivalent to 80% of UK DACCS requirement
H_2	H2 for large industry	35%	As Core, but delayed timeframes	65%	As Core
	H2 for small industry and commercial sector	None	As Core	65%	As Core
	H2 demand from other sectors	Regional Acorn ambitions: NTS blending, Aberdeen heat and transport	As Core, but delayed timeframes and higher mix of green H2	As Core and H2 for heat and transport across Scotland	As Core
	Share of green versus blue H2	High blue share due to use of H2 around Aberdeen and in industry	Higher % of green H2 than in Core due to short-term green H2 adoption	Alignment with Acorn Hydrogen/ARUP Hydrogen Assessment	Scottish demand as Core, but higher long-term green penetration for exports
	Blue H2 production locations	Acorn and Grangemouth	As Core	Across Scotland, as required	As Core
	Availability of T&S infrastructure	Pipeline and some shipping from Scotland, UK and imports	Delayed pipeline and additional shipping from Scotland. UK and imports as Core	Pipeline and reduced shipping from Scotland, UK and imports	Extensive domestic and international shipping; H2 exports

Figure 3-1: Overview of the scenarios and main drivers for CCUS deployment[25]

[25] Percentages in "H2 for large industry" row refer to percentage of energy demand not already addressed with CCUS.

These scenarios consider the factors listed above as well as emitter specific aspects (e.g. source of emissions, CO2 concentration in flue gases etc) and the availability of appropriate T&S infrastructure, both for onshore and offshore pipelines and for CO_2 maritime shipping.

- **Scenario 1 – Core:** This scenario considers the uptake of CCUS in key industrial applications, in particular at large industrial sites in high-emitting areas of Scotland, in the power sector and for regional blue hydrogen production. Hydrogen is used extensively around the St Fergus/Peterhead region and in industrial sites around the Central Belt: Grangemouth, Fife/East Coast and Upper Forth. Most of the captured CO_2 is transported via onshore pipeline and intra-Scotland shipping plays a limited role but provides resilience. Some CO_2 is shipped to Scotland from UK clusters and internationally.
- **Scenario 2 – Soft Start:** This scenario is similar to Core, with carbon capture technology being adopted with the same geographic scope and scale in large industrial sites and in the power sector. However, this scenario sees a **delayed roll-out of key onshore pipeline CO_2 infrastructure**. This delay in availability results in a faster penetration of green hydrogen around the Central Belt of Scotland, higher intra-Scotland CO_2 shipping volumes and delayed growth of CO_2 imports by shipping.
- **Scenario 3 – Ambition:** This scenario increases the geographical outreach of the Core scenario and sees the uptake of CCUS in a wider range of industrial applications throughout Scotland, such as bio-CCS and smaller industrial sites. The increased ambition allows for an accelerated repurposing of onshore pipeline infrastructure. Similarly, this scenario sees a major role for hydrogen throughout Scotland, with the residential sector converting to run on hydrogen. This also allows for hydrogen fuel switching in smaller industrial sites around Scotland. As a result, the production of blue and green hydrogen is geographically distributed across Scotland.
- **Scenario 4 – Carbon Management:** The scenario sees the same level of deployment of CCUS and hydrogen as in the Core scenario. However, in this scenario Scotland leverages its CCUS value chain to help other regions of the UK and Europe decarbonise. In addition, Scotland leverages its abundant renewable energy resources to support an ambitious deployment of DACCS and to grow a market for hydrogen exports, mostly green. Shipping plays a key role to support imports of CO_2, and the lack of onshore pipeline infrastructure in Scotland means that increased shipping is also used to move CO_2 from the Central Belt of Scotland to the North East.

3.1 Industry

Emissions from the Scottish industrial sector amounted to 11.5 $MtCO_2e$ in 2018, equivalent to 28% of all Scottish emissions in the same year[26]. Industrial emitters are geographically concentrated around the Central Belt of Scotland and specifically in the Grangemouth and Fife area: out of the top 10 largest emitters, only the Dunbar cement plant and the St Fergus Gas Terminal are located outside of this region. Such clustering of industrial emitters should be considered when prioritising the development of new infrastructure supporting CCUS and hydrogen pipelines. It is also noteworthy that just six sites contributed to 42% of all emissions from Scottish industries in 2018 (4.2 $MtCO_2e$), and five of these belong to the refining and petrochemicals sector[27]. Since these large-emitting sites and sectors are also some of the largest employers in the region, it is critical to consider the socio-economic impacts of CCUS – and of CCUS-supported pathways making use of blue hydrogen – on these sites and on the wider Scottish industrial sector.

[26] The 11.5 $MtCO_2e$ figure refers to emissions from sources classified within the Scottish GHG inventory with the Climate Change Plan mapping 'industry', which includes two source sectors: "Business and Industrial Process", and "Energy Supply". Overall Scottish emissions are discussed in Section 2.1.
[27] Olefins are by far the most common type of petrochemical product manufactured in Scotland. The term olefins and petrochemicals are therefore use interchangeably in this report.

It is useful to categorise industrial emission sources according to the applicability of alternative decarbonisation pathways (i.e. CCUS and hydrogen fuel switching), since this has an impact on the carbon economy. Four high-level categories are considered in this study:

1. **Emission sources that are suitable for carbon capture**. Criteria for establishing suitability are discussed below.
2. **Sites within clusters with a potentially large demand for hydrogen**. These sites are assumed to constitute the most likely early adopters for hydrogen, since investment in the hydrogen supply chain could be de-risked by pooling demand from these sites.
3. **Emission sources that cannot be decarbonised via carbon capture or fuel switching**. This includes "process emissions" at remote sites away from supporting infrastructure as well as most flaring-related emissions.
4. Smaller industrial sites that would likely only **fuel switch when hydrogen becomes available on the local gas grid**.

Site-level emissions data relating to the first three categories was obtained from the SPRI dataset. This includes information on all sites emitting at least 10 ktCO_2e per year, which were collectively responsible for nearly two thirds of all Scottish industrial emissions in 2018 (7.4 MtCO_2e)[28].

This analysis uses the **2019 emissions levels to set a baseline** for assessing the potential for CO_2 capture and hydrogen use across the relevant sites. It should be noted that this study does not attempt to forecast the future output from the industries considered. Instead, **it is assumed that industrial output remains steady** throughout the timeline of interest.

The Grangemouth refinery – the largest industrial emitter in Scotland and operated by Petroineos – was treated separately to reflect the likely impact of the recent announcement by Petroineos that refining capacity will be cut. This is discussed in Box 1.

Box 1 – Grangemouth refinery: current emissions and future decarbonisation

In November 2020, Petroineos announced that they will be mothballing their 65,000-bpd crude distillation unit 1 and the 25,000-bpd fluidised catalytic cracker unit, which will reduce refining capacity to about 150,000 bpd[29]. This is estimated to result in a permanent reduction in emissions of around 500 ktCO_2e, or 30% of its 2018 level. To more accurately estimate the possible contribution of carbon capture and hydrogen fuel switching to decarbonize the Grangemouth refinery, the projected level of future emissions (i.e., 1.1 MtCO_2e/year) is used instead of historical data.

As noted above, this study considers two options for abating refining emissions, i.e., CCUS and hydrogen fuel switching, the relative contribution of which will be influenced by technical constraints to the applicability of either decarbonisation approaches to individual emissions sources. Following engagement with relevant industry stakeholders, it was determined that **about half of the projected future emissions from the Grangemouth refinery could be tackled via carbon capture**. Hydrogen fuel switching is instead considered to be the preferential decarbonisation option for other emissions sources within the refinery[30].

Recent policy announcements on the phase out of new petrol and diesel cars by 2032 suggest there may be a subsequent gradual decline in demand for fossil fuels in the decades ahead. One potential outcome is a shift in business model from producing fossil fuels to, for instance, producing hydrogen. For this reason, the **Ambition scenario** – characterised by significant growth in the demand for hydrogen – **assumes that the refinery stops operating as a fossil fuel producer and transforms into a blue hydrogen producer**.

[28] Reporting threshold for inclusion within the SPRI dataset.
[29] Reuters article: Petroineos looks to mothball nearly half of Grangemouth oil refinery (2020)
[30] Emissions sources for which hydrogen fuel switching is considered viable include furnaces where carbon capture is not deployed, but exclude flaring.

The transformation is assumed to occur in the late 2020s or early 2030s, by which time it is envisioned that the CO_2 T&S infrastructure could become available. This implies that, within the Ambition scenario, the refinery does not implement carbon capture or fuel switching within the existing emissions sources within the “industry” sector. Instead, the converted site would be assumed to operate and emit CO_2 under the “blue hydrogen” sector.

Industrial decarbonisation options

CCUS and hydrogen fuel switching heavily influence the carbon economy and, together with electrification, they are key decarbonisation options for industry. They are therefore the focus of the present analysis[31].

A previous Element Energy study for the Scottish Government found electrification and hydrogen fuel switching to be theoretically viable from a technical standpoint for the majority of industrial processes in Scotland. To determine the optimal decarbonisation route, detailed consideration of practical constraints such as infrastructure availability and the relative disruption and impact of alternative routes on the production process and on product quality would be therefore required[32].

In some cases, CCUS could also be considered as an alternative to fuel switching. It is therefore likely that different sites will opt for alternative decarbonisation pathways and that a ‘hybrid’ pathway that includes multiple decarbonisation routes will emerge across Scottish industries. These insights underpin the assumptions employed in this study on the relative uptake of hydrogen fuel within different scenarios, discussed below.

Finally, energy efficiency could be a way for industry to minimise the additional fuel use and costs of all fuel-switching pathways, assuming low-carbon hydrogen and electricity remain more expensive than fossil fuels, by reducing fuel demand for a given amount of output. The same study however showed that, while energy efficiency has an important role to play in reducing emissions cost-effectively, there is only limited opportunity remaining to further increase efficiency in most of Scotland’s energy-intensive industries.

Carbon capture

It was noted earlier that carbon capture is considered as a viable decarbonisation route for a limited set of emission sources. The main criteria employed to screen the relevant sources are**:**

- **Overall amount of emissions to be captured from a site**, which can significantly influence the economics of CCUS projects**.** Sites that emitted less than 50 $ktCO_{2e}$ in 2019 were thus excluded.
- **Possibility of clustering** with neighbouring emitters to achieve economies of scale and hence de-risk and justify the development of costly new or repurposed infrastructure[33]. If clustering is not possible, site-level emissions must be significantly greater than the threshold indicated above to enable sufficient economies of scale in CO_2 transport logistics[34].
- **Availability of alternative decarbonisation options**. As discussed in Box 2 CCUS could be the only viable option to abate “process emissions” as well as emissions from the combustion of “internal fuels”.

Nine industrial sites were deemed eligible for carbon capture after applying the above criteria. Cumulative baseline emissions from these sites, listed in Appendix 9.1, were estimated at around 4.7 $MtCO_2e$.

The first carbon capture deployment is assumed to occur in mid-2020s at the St Fergus Terminal, in line with Acorn CCS plans. Next, carbon capture is assumed to be deployed in 2028 at high-purity emission sources (Grangemouth refinery’s SMR, and the Kinneil Terminal’s CO_2 separation step), followed in the early

[31] It should be further noted that hydrogen fuel switching only affects the carbon economy only insofar as blue hydrogen is used.
[32] Element Energy report for the Scottish Government, Deep decarbonisation pathways for Scottish industries (2020).
[33] These neighbouring emitters would also need to feature large-enough emission sources. Clusters can involve emitters from sectors other than industry.
[34] Indeed, the Dunbar cement plant it the only remote site assumed to deploy carbon capture.

2030s by larger emission sources in the vicinity of the Feeder pipeline (the olefins plants and other refinery emissions sources). Sites further away from the Feeder pipeline are assumed to deploy carbon capture only later on, by which time the CO_2 supply chain is assumed to have matured sufficiently.

Carbon capture was assumed to be deployed on a different selection of emissions sources in the scenarios (note that the same carbon capture related assumptions are employed in the Core, Soft Start, and Carbon Management scenarios):

- No carbon capture is envisioned for the Grangemouth refinery in the Ambition scenario (for the reasons discussed in Box 1).
- The steam and electricity supplied to the Grangemouth and Fife/East Coast sites via combined heat and power (CHP) units, boilers, and the Grangemouth power station are assumed to be decarbonised via carbon capture only in the Ambition scenario[35]. In the other scenarios (Core, Carbon Management, Soft Start), the corresponding energy demands are instead met through a mix of hydrogen fuel switching and electrification[36].
- Due to its smaller size, the Alloa glass plant is only assumed to deploy carbon capture in the Ambition scenario. Fuel switching instead occurs in the other scenarios.

As shown in Figure 3-2, these assumptions result in a stepwise increase in the volumes of captured CO_2 that plateaus at just over 2 $MtCO_2$/year in the Core scenario and reaches nearly 3 $MtCO_2$/year in the Ambition scenario, with the difference between the two fully explained by the different uptake assumptions summarised in Appendix 9.2. The 2032 CO_2 captured volumes across these scenarios from Figure 3-2 represent 13-20% of the industry emissions reduction pathway to 2032, shown in the Update to the Climate Change Plan from Scottish Government.

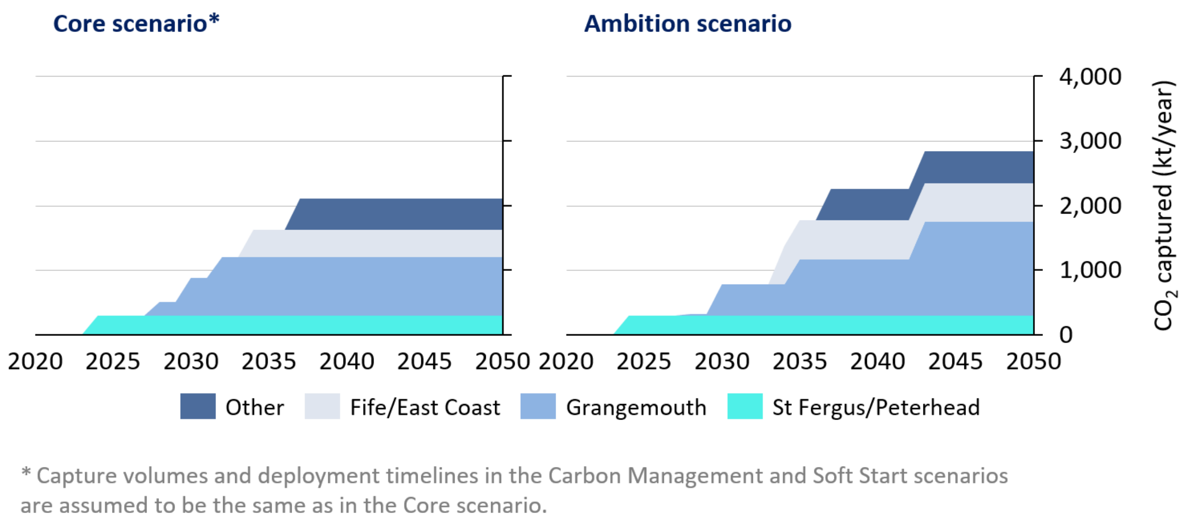


Figure 3-2: Deployment of carbon capture technology in industry in the different geographical groups

[35] This also explains the higher amounts of CO_2 captured at the Grangemouth olefins plant and the Fife ethylene plant in the Ambition scenario.
[36] Specifically, 35% of the energy (steam and/or electricity) supplied by these plants is assumed to be generated with hydrogen, whereas the remaining demand is assumed to be met either via direct connection to the grid or via a private-cable connection to renewable energy sources, possibly coupled with energy storage.

Box 2 – Process emissions and internal fuels

Two types of industrial emission could be best avoided with CCUS, i.e., "process emissions" and emissions arising from the combustion of "internal fuels". Since neither types of sources can be mitigated via energy efficiency improvements or fuel switching, the only alternative to carbon capture would entail process and/or product changes, which may in turn require a radical re-design of the factories.

The term "process emissions" refers to GHG emissions directly arising from chemical reactions involved in certain industrial processes (rather than arising from energy use). **The main sources of process emissions within Scottish industries** and the estimates for the corresponding 2018 emissions are, on an annual basis:

- The calcination reaction occurring within the cement kiln (ca. 385 ktCO_2e).
- SMR at the Grangemouth refinery (ca. 190 ktCO_2e).
- Carbon anode degradation in the aluminium electrolysis process (ca. 65 ktCO_2e).
- Raw material degradation during glass melting (ca. 50 ktCO_2e across 4 sites).
- The CO_2 separation step and purging of the flare heads within the gas terminals[37].

Internal fuels are industry by-products that cannot be sold or serve any other purpose and are therefore generally burned on-site. Specifically, the internal fuels relevant to Scottish industries are, on an annual basis:

- Fuel 'off-gases' co-produced within the petrochemical industries (ca. 1,050 ktCO_2e across two sites)[38].
- Fuel 'off-gases' from the refining process and gas terminals (ca. 700 ktCO_2e).
- Petroleum coke (or 'pet-coke') produced and consumed within the refinery's fluid catalytic cracker (ca. 200 ktCO_2e today, but due to be mothballed as discussed in Box 1).

Hydrogen fuel switching

It was noted earlier that hydrogen fuel switching and electrification are theoretically viable from a technical standpoint for the majority of industrial processes in Scotland. In addition to the relative economics, multiple factors will influence the technology choices made by industrial sites looking to decarbonise, for instance whether product quality would be impacted, the availability of enabling infrastructure or the reliability of the local supply chains. The uptake of hydrogen fuel switching is aligned with the UK-consensus as modelled by Element Energy as part of the Climate Change Committee's Sixth Carbon[39].

The specific hydrogen uptake assumptions vary by scenario and by site type as summarised in Appendix 9.2. The main difference between the scenarios considered is that, of the energy demand suitable for fuel switching, a higher portion is assumed to be met with hydrogen in the Ambition scenario (65%) compared to the Core, Soft Start and Carbon Management scenarios (35%). This also implies that alternative decarbonisation routes like electrification are pursued more commonly in the latter scenarios, in alignment with the findings of previous work for the CCC. It should also be noted that no hydrogen is assumed to be used for processes where carbon capture is deployed.

[37] The Kinneil Terminal is the only site for which emissions from these sources could be estimated (as ca. 50ktCO_2e).
[38] These fuels are largely, though not exclusively, combusted within the olefins steam cracking process.
[39] Element Energy report for the CCC: Deep Decarbonisation Pathways for UK Industry (2020)

Box 3 – Hard-to-abate emissions: flaring and process emissions from small sites

Carbon capture and fuel switching are considered to be important components of any pathway to deeply decarbonise Scottish industries. However, they will not be sufficient to fully eliminate emissions from all sources. It is especially hard – if not economically prohibitive – to decarbonise two types of emission sources via these methods, i.e., flaring and process emissions from smaller sites.

The term "flaring" refers to the combustion of hydrocarbon feedstock gases for operational reasons, and do not supply energy to a process. For this reason, fuel switching is not a relevant option. Flaring may be carried out at the refinery, petrochemical plants, or gas terminals to prevent the potentially explosive build-up of gases. Flaring could also occur to avoid venting methane-rich gases to the atmosphere, which has a higher global warming potential than CO_2.

Carbon capture is not likely to be a technology that is deployable to abate flaring emissions. First and foremost, the backpressure applied by the capture equipment onto emergency flaring equipment could pose a safety risk. Secondly, significant logistical challenges would need to be overcome to capture the CO_2 from the flue gas stream[40] . Finally, it would likely not be cost-effective to install expensive equipment that is rarely used (due to the infrequent and intermittent nature of flaring). Hence, while there may be cases where carbon capture can help, it cannot be relied upon to fully eliminate flaring emissions. Likewise, other ways that have been put forward to reduce emissions from flaring are not expected to remove the problem[41].

As for the process emissions from smaller sites (e.g., those within the glass and O&G industries), which are often far from other large potential users of the future CO_2 infrastructure, it is possible that carbon capture will become sufficiently affordable in the future also for smaller emission sources. However, even in this case it is possible that the transport costs for relatively small volumes of CO_2 over long distances may prove uneconomical.

Considering that some flaring is likely to continue to be required, it appears that policy may need to encourage sites responsible for these hard-to-abate emissions to consider alternative options such as the purchase negative-emission offsets to reach net zero emissions across industry. This could include paying for, e.g., direct air capture combined with CO_2 storage, as discussed in Section 3.5.

The Ambition scenario is also the only scenario where the gas grid is assumed to be progressively converted to hydrogen, which enables smaller sites to fuel switch to hydrogen. In all other scenarios, it is assumed that only large sites that can be grouped within sufficiently large clusters can fuel switch to hydrogen. The full set of uptake assumptions is provided in the appendix. The uptake of hydrogen fuel switching in industry is assumed to be strongly linked to the geographical availability of hydrogen, discussed in Section CCUS 3.3. Accordingly, Figure 3-3 shows how different geographies contribute to the significantly different levels of long-term industrial hydrogen uptake projected under the different scenarios: over 13,000 GWh/year of hydrogen would be demanded from industry by 2050 in the Ambition scenario, compared to just over 6,000 GWh/year in other scenarios.

[40] In the case of the refinery, flue gases are released at a height of 150 meters.
[41] Element Energy report for the CCC: Assessment of Options to Reduce Emissions from Fossil Fuel Production and Fugitive Emissions (2019).

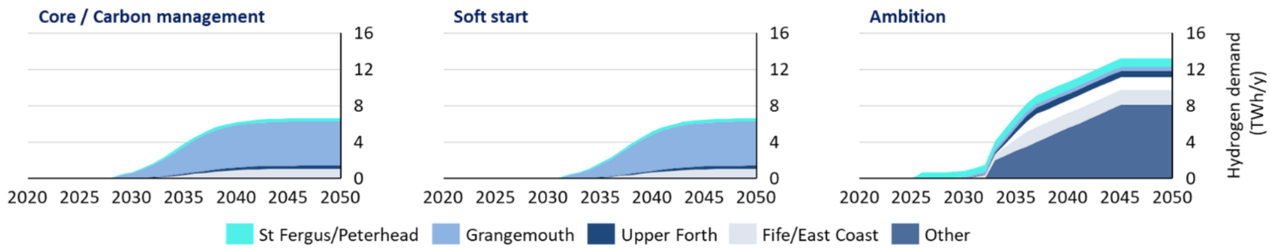


Figure 3-3: Hydrogen uptake in industry by scenario and geography

3.2 Power

Scotland uses a wide range of electricity generation technologies, combining conventional thermal gas-fired generation with nuclear and an increasing share of renewables, such as offshore wind. A mix of generation assets are key to the electricity grid, especially in a high decarbonisation scenario, as conventional sources complement renewables at times of low renewable generation. **CCUS would thus play a key role in decarbonising conventional power whilst contributing towards the grid stability**.

PPS is owned and operated by SSE Thermal. It is the only large-scale natural gas-fired power plant in Scotland, with a nameplate capacity of 1.15 GW. The power station is one of the largest emitters in Scotland, with 1.58 $MtCO_2$ (reported in 2019)[42,43].

Two main options for long-term power decarbonisation rely on CCUS deployment and include: i) natural gas power generation with post-combustion capture, and ii) turbine replacement for hydrogen fuel switching[44]. These technologies require a considerable upfront investment and are therefore best suited for new, highly efficient facilities with a lifetime long enough to enable investment recovery. In this study, it is therefore assumed that these technologies would require a new PPS facility, which would be built in the late 2020s.

During the completion of this study, SSE Thermal **announced plans to develop and operate a new low carbon combined cycle gas turbine with a carbon capture plant at Peterhead,** in alignment with Scottish Government's ambition to reduce the average carbon emissions from the power sector[45].

The Core, Soft Start and Carbon Management scenarios assume that the new PPS facility would be deployed in 2027 (2030 for Soft Start) and would **run on natural gas with post-combustion carbon capture**[46]. Conversely, to reflect possible alternative means to decarbonise, the Ambition scenario sees the new PPS

[42] Scottish Environmental Protection Agency, 2019 SPRI
[43] This is equivalent to a natural gas demand of 8.8 TWh/year. Natural gas demand is estimated based on a load factor of 56% and an average turbine efficiency of 57%, as presented in previous EE work as part of the Hy-Impact Study 3, Element Energy for Equinor, 2019.
[44] Additional long-term decarbonisation options exist for PPS which have not been considered, such as BECCS. The decarbonisation options selected in these scenarios are candidates being considered by SSE Thermal. The selection of options should not be treated as a concrete proposal and are intended to show potential scenarios which could be developed.
[45] As per recent publications, the proposed power plant would have a nameplate capacity of up to 910MW and would be expected for operation in 2026.
[46] It has been assumed that the new PPS facility would be of similar characteristics as the existing plant. In the scenario where CCS is adopted it is assumed that the new PPS facility has a nameplate capacity of 1GW, a load factor of 56%, an average turbine efficiency of 57% and an availability of 95%. In the scenario where hydrogen is adopted, the energy requirements correspond to those used from natural gas in PPS in 2019. The change in approach to new hydrogen PPS capacity is due to uncertainty around the 100%-hydrogen ready turbine efficiencies achievable in 2030.

facility **running on hydrogen using 100% hydrogen-ready turbines**. In the Ambition scenario, CO_2 emissions would be produced at the point of blue hydrogen production and not in the PPS facility.

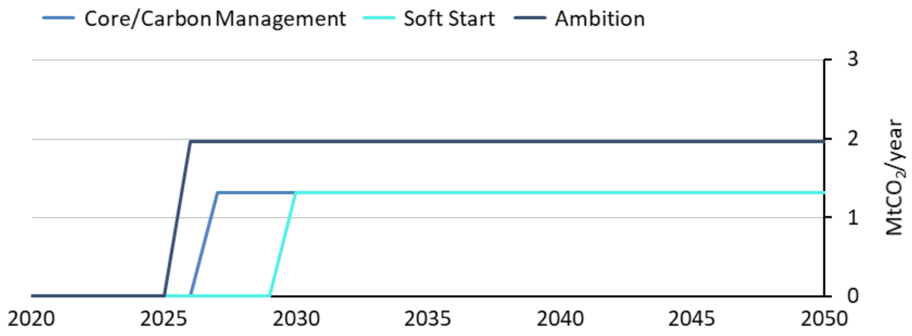


Figure 3-4: Total CO_2 profile for power related CO_2 emissions. In the Ambition scenario, CO_2 is sourced from the future Grangemouth power plant.

CCUS could also play an important role for the existing PPS facility, as blue hydrogen generated nearby by the Acorn project would be mixed with natural gas and blended up to 10% by volume in the existing three turbines. This option would become available once regional hydrogen transport infrastructure in the North East of Scotland is commissioned in the mid-2020s and is assumed to continue until 2030, a year in which the existing PPS is assumed to be decommissioned and operations fully replaced by the newly built PPS[47].

The Ambition Scenario assumes an additional natural gas fired power station with CCUS in Grangemouth, a high energy demand area. This development is intended to reflect the early ambition for deep decarbonisation of both power and industry within the Grangemouth industrial cluster, in alignment with the decarbonisation opportunities which may originate from possible government support through funds and competitions for the Grangemouth industrial cluster[48,49]. We assume the deployment of a 1.5 GW power station in the mid-2020s, leading to an estimated 2 $MtCO_2$/year[50] captured annually.

3.3 CCUS as an enabler for hydrogen production

Overview

In its Hydrogen Policy Statement, Scottish Government has confirmed its support for the strategic growth of a hydrogen economy in Scotland[51]. In parallel to CCUS, **low-carbon hydrogen is another energy vector** which can provide long-term deep decarbonisation in Scotland, as hydrogen can find applications in many sectors using CO_2 emitting fuels such as power or heating. New uses for hydrogen will be possible if projects such as Acorn Hydrogen come to fruition to enable the large-scale use of hydrogen around Scotland. Hydrogen from Scotland can also be exported to other regions for which demand in these sectors cannot be met locally.

In all scenarios, **Acorn Hydrogen (expected to start operations in 2025) is expected to represent an early opportunity to help grow the use of hydrogen in Scotland** and catalyse an initial and regional hydrogen demand in the St Fergus/Peterhead regional group. Acorn Hydrogen is expected to supply hydrogen for blending into the NTS at St Fergus. In addition, the project is assumed to start blending hydrogen in the

[47] This transitional period reflects the expected minimum lifetime of the current turbines in PPS based on their year of installation, which are assumed to have a lifetime of 30 years.
[48] The £1bn CCS Infrastructure Fund, announced by the UK Government in the Prime Minister's Ten Point Plan, intends to facilitate the deployment of CCUS in two industrial clusters by the mid-2020s, and a further two clusters by 2030. Grangemouth is one of the eligible clusters in the UK.
[49] The Grangemouth industrial cluster has submitted decarbonisation plans for the cluster as part of Phase II of the Industrial Decarbonisation Challenge Fund (see Scotland's Net Zero Infrastructure).
[50] This nameplate capacity has been selected based on previous announcements on possible abated power generation projects in the Grangemouth area, such as the Caledonia Clean Energy Project and the GBTron Power Ltd proposal.
[51] Scottish Government Hydrogen Policy Statement (2020)

distribution grid of Aberdeen (as part of Aberdeen Vision) and Aberdeenshire in 2026 to supply hydrogen to the residential and commercial sectors for heating. Local hydrogen availability in this region would also allow for hydrogen use in the transport sector, and proximity of Acorn Hydrogen to Peterhead could facilitate small hydrogen trials in at the Peterhead Power Station in the mid-late 2020s.

In all scenarios and in parallel to Acorn Hydrogen, **hydrogen production around Grangemouth** is expected as a result of the drive for fuel switch large industrial sites in Grangemouth, Fife/East Coast and Upper Forth, and would enabled by the availability of a CO_2 transport pipeline connecting the Central Belt with St Fergus.

Infrastructure requirements for hydrogen distribution

Use of hydrogen for residential and commercial heating could represent a large demand and could allow early opportunities for proliferation of CCUS and blue hydrogen.

- All scenarios consider blending at small ratios in the mid-2020s, in line with the Acorn Hydrogen ambition. The blending ratio will continue to raise but will eventually cease in the mid-2030s, aligned with the start of the gas grid transition to support Net Zero, and hydrogen production previously used for blending will be shifted towards meeting demand in the heating sector.
- In the Ambition scenario, full conversion of the distribution grids of the different regional groups would be **phased and follow a sectorised approach, starting in the early 2030s in Aberdeen** and in regions where blue hydrogen production is located, and expanding outwards by 2045 with the more remote parts of the distribution network[52]. To meet hydrogen demand at the distribution level, the transmission network could either repurpose transmission assets currently used for natural gas or could alternatively build a parallel hydrogen transmission network connecting to the distribution grids[53].
- Specifically, hydrogen would be available throughout Scotland as shown in the diagram below. The Core, Soft Start and Carbon Management scenarios therefore **envisage the regional use of blue hydrogen in Scotland** to be limited to the regional groups of i) St Fergus/Peterhead (supplied by Acorn Hydrogen) and ii) Central Belt (where production sites would be built to meet large-scale industrial hydrogen demand)[54]. In addition, the Carbon Management scenario would see hydrogen being exported to other regions of the UK and internationally.
- The Ambition scenario differs from the Core, Soft Start and Carbon Management scenarios regarding the scale of geographic expansion of hydrogen infrastructure/The Ambition scenario envisages the evolution of hydrogen use **from the localised hydrogen hubs around St Fergus/Peterhead and Central Belt to a Scotland-wide hydrogen economy**, primarily enabled by a full-scale conversion of the gas grid to run on hydrogen. This conversion would enable the residential and commercial heating demand in other regions to be met by hydrogen and facilitate hydrogen fuel switching in industrial sites which did not previously have a direct connection to a hydrogen supplier. This geographically broader supply of hydrogen would also allow for a larger hydrogen use in the transport sector, with an annual demand of up to 10.2 TWh by 2045.

[52] It is assumed that the early date for Aberdeen Vision to start blending hydrogen in Aberdeen City prior to full conversion will help Scotland acquire experience in the process of converting gas distribution grids to run on hydrogen. Therefore, it is assumed that conversion of subsequent distribution networks around Scotland will be directly to 100% hydrogen use.
[53] Additional information on the phased transition of the distribution network as well as the options for transport of hydrogen in transmission pipelines in Scotland can be found in Section 2.1 of Element Energy for Pale Blue Dot, Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero (2020).
[54] This statement refers to large-scale use of hydrogen (of the TWh/year scale). Various regional projects, either already deployed or in the pipeline (mostly green hydrogen projects), located in regions away from large areas of hydrogen demand will also support use of hydrogen, such as the Surf 'N' Turf project.

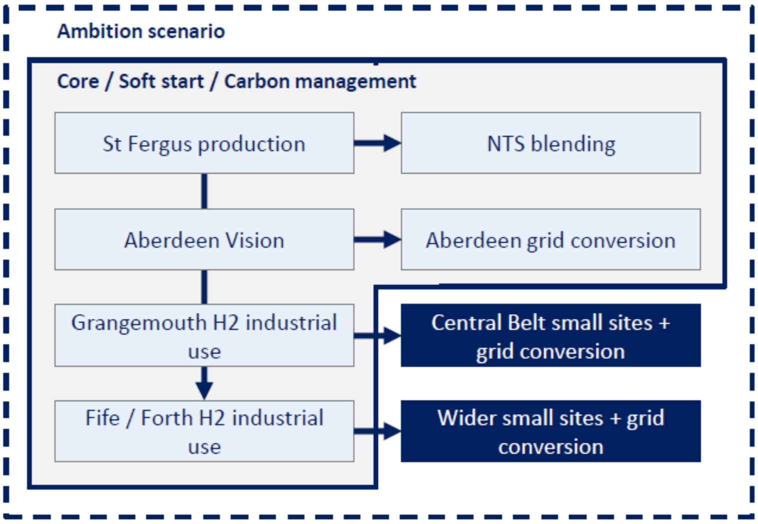


Figure 3-5: Growth of hydrogen uses facilitated by the geographic expansion of infrastructure

Figure 3-6 below summarises the hydrogen demand by sector for the various scenarios. By 2050, the total hydrogen demand in the Core and Soft Start scenarios would be of around **9 TWh/year**. In the Carbon Management scenario, total hydrogen demand would be of **36 TWh/year**, as a result of the scale of hydrogen exports (27 TWh/year)[55]. In the Ambition scenario, Scotland-wide conversion of the gas grid results in a higher hydrogen demand, amounting to **61 TWh/year**. Detailed information on the timeline for regional hydrogen availability can be found in Appendix 9.3.

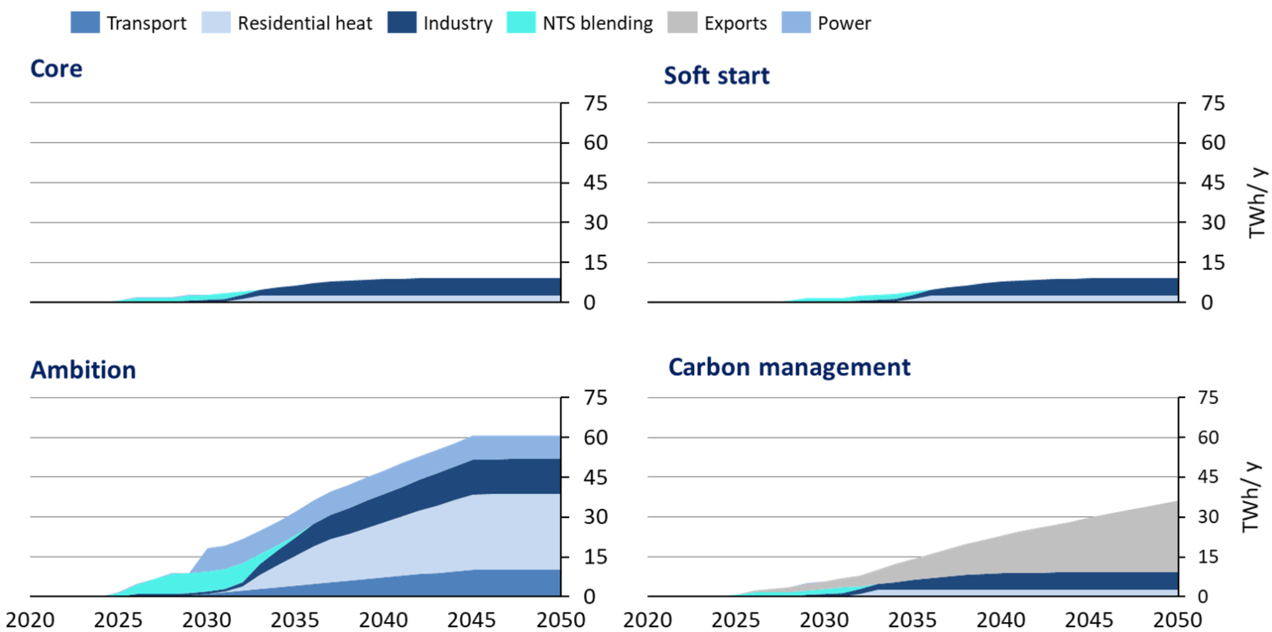


Figure 3-6: Summary of annual hydrogen demand by sector for the four scenarios.

[55] Figure for hydrogen exports corresponds to those reported in the study from Arup and E4Tech for Scottish Government: "Scottish Hydrogen Assessment (2020)" for the Hydrogen Economy scenario in 2045. Figures extrapolated to 2050.

CCUS and blue hydrogen production would enable green hydrogen in the longer term

Blue hydrogen production is presently more economically competitive than green hydrogen production. However, cost projections suggest that the two production methods are expected to reach cost parity in the future, which is **an opportunity for blue and green to complement each other in the path to net zero**. Long-term green hydrogen production would have the opportunity to exploit critical infrastructure for hydrogen transport, storage and use, which is expected to be deployed to support earlier blue hydrogen production in the short and medium-term.

Scotland has an advantageous position to **produce both blue and green hydrogen at large scale, and both hydrogen archetypes are envisaged to be used in Scotland up to 2050**[56]. However, the evolution of new blue and green hydrogen production in Scotland will vary according to the scenario, depending on the timing of CCUS infrastructure availability and envisaged end-use of hydrogen. For example, green hydrogen is better suited for use in transport due to the high purity requirements of fuel cells and the possibility to be produced in decentralised locations such as hydrogen refuelling stations.

The breakdown of blue and green hydrogen production to 2050 is calculated on a **regional basis** i.e., we differentiate between expected production in St Fergus versus production in other areas such as Grangemouth, and it is also based on **existing hydrogen production projects in the pipeline** (see Appendix for a more detailed breakdown of the blue/green split of new hydrogen production capacity)[57]:

For hydrogen production in St Fergus:

- All scenarios consider **early blue hydrogen production** by Acorn Hydrogen, supplying hydrogen for NTS blending, Aberdeen Vision (heat and transport), and to PPS (small blending in Core and Carbon Management until 2030 and dedicated hydrogen use PPS new build in Ambition). As a result of this project, **most of the long-term production in the St Fergus/Peterhead region is expected to be blue hydrogen.**

For hydrogen production in other areas of Scotland:

- For use of hydrogen in other areas (e.g. Central Belt industry and Scotland-wide gas grid in Ambition), the **blue and green hydrogen ratio is based on the penetration of green hydrogen deployment as new hydrogen production capacity**, as shown in Table 13. In the short to medium term, the penetration of green hydrogen is low due to its higher costs and lower technological maturity relative to blue hydrogen. In the longer term (e.g., beyond 2040), all new build capacity is assumed to be green hydrogen, once the economics of both production methods reach parity.

[56] Refer to the "Note on terminology" section to see the definitions of blue and green hydrogen.
[57] The Dolphyn project is aiming to deploy offshore hydrogen production using wind turbines coupled to electrolysers. Once fully developed, the project will aim to have a green hydrogen production of 12 TWh/year by 2037.

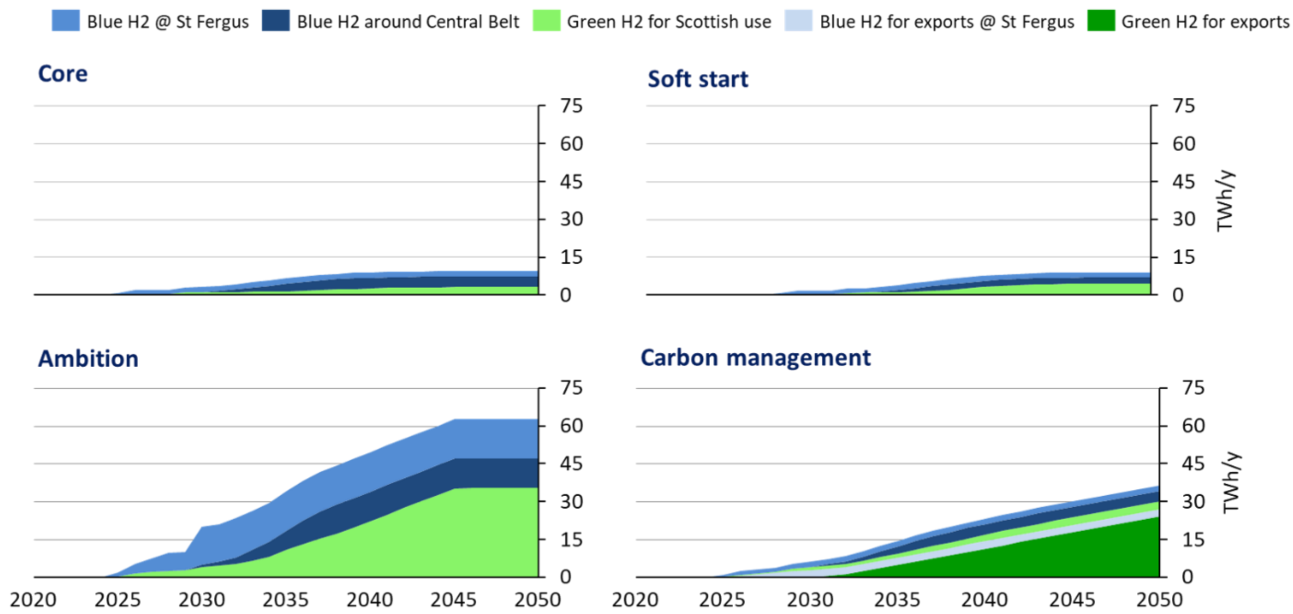


Figure 3-7: Breakdown hydrogen demand being met by blue and green hydrogen production

In addition to economic drivers, uptake of green hydrogen would also depend on the expected **timeframes for hydrogen demand** and other factors enabling blue hydrogen production, such as **early availability of T&S infrastructure**. Variations in these factors are explored across scenarios. Compared to the Core scenario:

- The Soft Start scenario sees a higher penetration of green hydrogen production in the Central Belt before 2030. This is because the Feeder pipeline would not become available until 2032, which is assumed to be required to transport CO_2. However, once the pipeline becomes available, the **first large blue hydrogen projects are commissioned in the Central Belt**.
- The Ambition scenario sees a higher uptake of green hydrogen by 2035 to keep up with the high demand resulting from the full grid conversion to hydrogen, and to also **account for regional projects,** which are expected to mostly produce green hydrogen.
- The Carbon Management scenario sees **green hydrogen production increasing more steeply to meet demand for hydrogen exports,** and for such end-use, green hydrogen is expected to dominate the mix. The role of blue hydrogen exports is limited to installed capacity before 2030 and would most likely be dedicated to UK use rather than EU[58].

The timeframes and breakdown of for blue and green hydrogen, particularly the ones for the Ambition scenario, are aligned with the Scottish Hydrogen Assessment conducted by Arup for the Scottish Government[59]. We estimate that between 1.1 $MtCO_2$/year (Soft Start scenario) and 6.8 $MtCO_2$/year (Ambition scenario) could be generated from blue hydrogen production in 2050.

[58] Whilst the potential for blue hydrogen exports in Scotland is considerable. Recent work commissioned by Scottish Government suggests that green hydrogen exports will constitute the majority of hydrogen exports in the long-term.
[59] Arup and E4Tech for Scottish Government: Scottish Hydrogen Assessment (2020)

3.4 Capture of biogenic CO_2 (Bio-CCS)

Bio-CCS can be defined as the **capture and storage of CO_2 which originates from biomass**[60] use in producing energy, such as in a combined heat and power facility; biological processes producing CO_2, such as fermentation; or biomass decomposition in landfill sites[61].

Over 3.5 Mt of biogenic CO_2 were available in Scotland in 2018, coming from various sources: from biomass or other combustion sources (for heat or CHP), anaerobic digestion processes, and fermentation processes to produce alcohol[62]. However, in many cases, the CO_2 from these sources is **generated at small scale or in remote locations** (e.g., distilleries in the Highlands), where the **potential for capture, T&S is limited or uneconomic[63]**. Some application for biogenic CO_2 from more remote emitters could be represented by utilisation in the production of new products, as illustrated in the case study on Section 3.7.

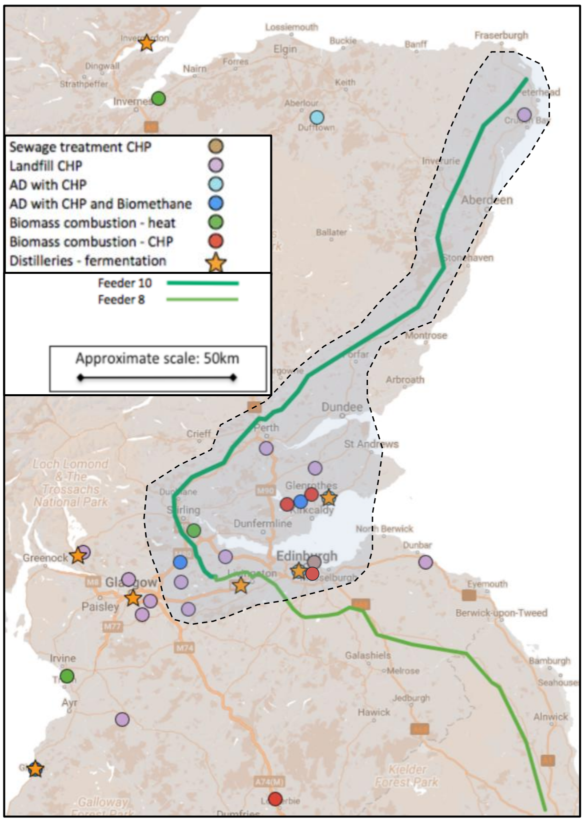


Figure 3-8: Location of the biogenic CO_2 emission sources meeting the criteria for CCUS adoption. Selected sites represented within shaded area.

Capture and storage of biogenic CO_2 is more likely to be adopted in sites with a **sizeable amount of biogenic CO_2 emissions** (>10,000 tCO_2 year) and which are **in proximity to CO_2 transport infrastructure** (CO_2 pipelines deployed for other projects). The sites at which carbon capture would be adopted can be seen in Figure 3-8 [64]. The earliest date for bio-CCS deployment around the Central Belt is **expected to be in the late 2020s**, once transport infrastructure has been commissioned. Several sites are located in Fife/East Coast regional group, in which case connection to main pipeline would be dependent on additional pipework, expected to be deployed as part of the large CCUS projects in the area.

Given the dispersed location of the sites and the generally small scale of emissions, the **adoption of bio-CCS will be limited to the Ambition scenario**, where the total biogenic CO_2 emissions captured will be close to 1 $MtCO_2$/year (ca. 29% of all Scottish biogenic emissions)[65]. In total, **16 sites could adopt bio-CCS**

[60] European Biofuels Technology Platform, Biomass with CO_2 Capture and Storage (Bio-CCS), (2012).
[61] In this study, bio-CCS is differentiated from bioenergy with CCS (BECCS) in the sense that bio-CCS economics are not driven by sales of power. Bio-CCS consists in the adoption of CCS in at sites discussed in this section, which are distinct from power BECCS, which we define as using biomass for electricity production and negative emissions, in a power station, such as Drax.
[62] Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions, Scottish Carbon Capture and Storage (2018). In the source, calculation of the total number of biogenic emissions required using some assumptions, as data availability was limited and biogenic emissions not always adequately reported in inventories.
[63] Road or rail transport are options when pipeline transport is not available. Use of these options would require CO_2 liquefaction, which is an expensive addition to transport costs for remote emitters. Element Energy determined in a study for BEIS that truck transport tends to be the least cost-competitive option, and rail evaluating rail infrastructure connections with the required T&S infrastructure requires in-depth analysis.
[64] Original map is from "SCCS: Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions (2018). Modified to include shaded area to represent geographic scope, and latest project developments, such as Edinburgh's Millerhil Recycling and Energy Recovery Centre.
[65] It must be noted that the assumed volumes of biogenic emissions in the Ambition scenario, as well as those captured via DACCS may show some discrepancy with the recent publication of the Climate Change Plan update (CCPu) envelope by the Scottish Government. The scenarios were not implicitly designed to capture the system-wide requirements for negative emissions, but were designed to

technology. Most of the biogenic CO_2 emissions captured could come from CHP or heat processes burning biomass, however around 20% of all captured biogenic emissions are expected to come from landfill gas and sewage (16%, "other CHP" in chart); fermentation (7%) and biomethane (1%)[66].

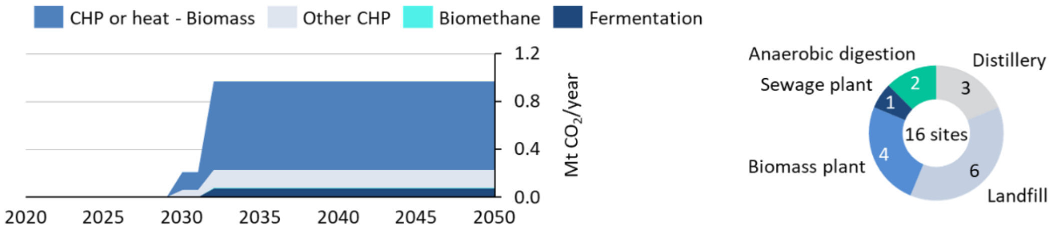


Figure 3-9: CO_2 profile from bio-CCS processes in sites adopting bio-CCS in the Ambition scenario [67]

3.5 DACCS

Storing carbon dioxide from DACCS is a form of engineered greenhouse gas removal (GGR) which can be used to extract CO_2 out of the atmosphere. As in the case of bio-CCS, this generates "negative emissions". However, the technology is at the early stage of market penetration, with around fifteen pilot scale and demonstration projects currently operating. The technology could play an important role in helping nations meet their decarbonisation targets, by using negative emission credits to offset hard to abate emissions from certain sectors such as aviation or agriculture. The UK Government's Net Zero Review: Interim Report concludes that **DACCS is the GGR technology with the largest deployment potential in the UK by 2050**.

There is uncertainty around the cost projections for DACCS to 2050, as the economics are heavily influenced by the cost of energy needed and because the technology is yet to be demonstrated at large scale, with current prototypes using a large amount of energy. However, **cost reductions for DACCS are expected to commence by 2025 to 2030**[68]. DACCS energy demand is typically significantly higher than capture from other sources. As of today, manufacturers of the technology have identified the lack of policy support as the main barrier to deployment. Additionally, profitability of the technology largely depends on the costs of emitting CO_2.

DACCS facilities could be placed strategically close to CO_2 T&S infrastructure, and they do not have to be placed close to the emitters providing the funds. However, it is desirable that these facilities are powered with renewable energy sources. Colocation with large industrial sites could enable DACCS plants to use the industrial waste heat, reducing costs associated with heat and electricity consumption (data on heat and electricity requirements for DACCS across scenarios available in Appendix 9.4).

Scotland is advantageously suited to deploy DACCS in the future, especially around the North East coast of Scotland, around St Fergus and/or along CO_2 pipelines. The technology could leverage the proximity to renewable energy generation capacity, CO_2 storage facilities and land area availability and help Scotland become a major player within the UK on DACCS deployment. In fact, Pale Blue Dot Energy and Carbon Engineering have signed a Memorandum of Understanding (MoU) to deploy a commercial DACCS facility close to Acorn CCS, aiming to remove 1 $MtCO_2$/year[69]. This could be the first DACCS plant in the UK and it could start operations as early as in 2026.

amplify potential for hydrogen deployment and CO2 shipping. The authors recognise that additional work will need to be conducted in this space.

[66] Capture rates of biogenic CO_2 will vary depending on the process and feedstock: landfill CHP (60%), biomass combustion (90%), biomethane production (90%), fermentation (50%).

[67] In these charts, biomethane production occurs in anaerobic digestion facilities.

[68] European Commission Joint Research Centre, Direct air capture, Facts Behind the Debate (2019)

[69] Pale Blue Dot Energy: Pale Blue Dot Energy and Carbon Engineering create partnership to deploy Direct Air Capture in the UK (2020)

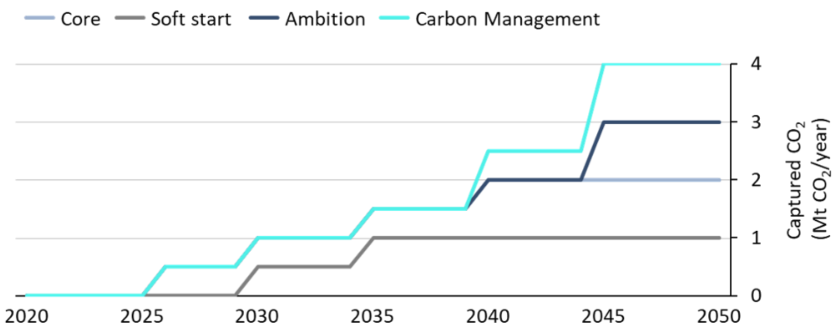


Figure 3-10: Total CO_2 captured by DACCS in the four scenarios

In its recent publication on the Sixth Carbon Budget, the CCC has estimated that **up to 5 $MtCO_2$/year of DACCS installed capacity could be reached in the UK by 2050** under the Balanced Pathway scenario[70]. Scotland could contribute significantly to these targets. In our Soft Start scenario, we assume that DACCS deployment is limited to the initial 1 $MtCO_2$/year project from the MoU. The Core and Ambition scenarios see subsequent increases, whereas the Carbon Management scenario assumes that 80% of UK's DACCS deployment will be located in Scotland, helping Scotland and UK achieve Net Zero targets. At such levels of DACCS deployment, the total energy requirements could be of up to 2TWh/year and 7TWh/year of electricity and heat, respectively (see Appendix for annual breakdown). Nevertheless, this is based on current estimates. and the energy requirements in 2050 would likely decrease once the technology's commercialisation reaches maturity[71].

3.6 Imports of CO_2

The extensive CO_2 storage resources available in the UK's Central North Sea are an opportunity for Scotland to provide safe storage for CO_2 sources located beyond Scotland, such as the wider UK and Europe. **A CO_2 import hub could be developed at Peterhead Port**, which is a deep-water port close to St Fergus capable of accommodating large scale vessels[72]. However, the **port infrastructure required for CO_2 offloading would need to be developed**.

Project timeline for Acorn CCS suggests that imports of CO_2 to Peterhead Port could begin in 2026 and it is expected that imports of CO_2 could come from various sources around the UK and EU. Early imports of CO_2 are expected to come predominantly from other UK clusters, such as the South Wales or Southampton clusters - where there is a lack of available resources for CO_2 storage - or from industrial sites away from clusters. Conversely, imports from Europe are envisaged to be a more predominant long-term source of CO_2.

In the European context, four key European industrial clusters near the UK have emissions of over 80 $MtCO_2$/year: Rotterdam, Antwerp, Ruhr and Le Havre[73]. There are local storage options available, and even though not all these CO_2 levels can be assumed to be captured, **the relatively early start date for CO_2 imports suggests that Scotland is likely to capture a fraction of the international shipping requirements**. Additionally, the scale of CO_2 imports estimated would allow Scotland to provide back-up storage for other CO_2 shipping projects when needed - such as the Northern Lights project - and vice-versa

[70] The Sixth Carbon Budget: The UK's path to Net Zero, Committee on Climate Change (2020). DACCS assumption belongs to the Balanced Pathway scenario.
[71] Heat and electricity requirements have been included to provide an estimate of the required supporting utilities infrastructure. Potential reductions in these due to technology improvements have not been reflected due to underlying uncertainties. Associated electricity and heat requirements have been provided as an average for various technologies (solid and liquid), extracted from IEA figures, but averages of 0.15 Mtoe/$MtCO_2$ for heat and 0.04 Mtoe/$MtCO_2$ for electricity have been used in the figures.
[72] The UK, alongside the Netherlands and Norway, successfully passed at the International Maritime Organization in 2019 a provisional amendment to the London Protocol to allow for cross-border transportation and storage of CO_2.
[73] Element Energy for BEIS, CO_2 Shipping Study (2018)

(see box below). However, there is still uncertainty about the precise location of CO_2 import sources, due to the lack of existing CO_2 shipping contracts as well as defined shipping routes.

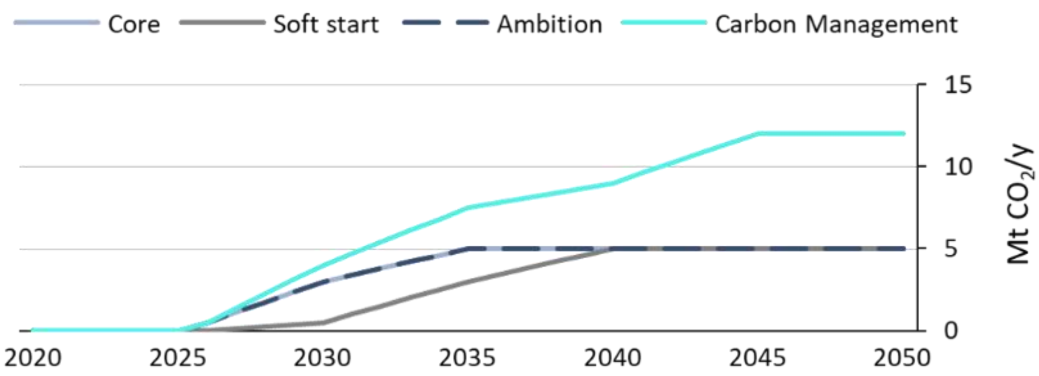


Figure 3-11: Total amount of CO_2 imports in each scenario

To meet these shipping requirements **a downstream pipeline connecting Peterhead Port with St Fergus would have to be build**, as there is no existing transportation asset which can accommodate the expected annual CO_2 throughput from Peterhead Port. A full description of the infrastructure constraints for CO_2 shipping and the variation of CO_2 volumes across scenarios is provided in Section 4.2.

Box 4 – Northern Lights, a pioneer project in carbon management services

The Northern Lights project is an initiative of Equinor, Total and Shell, aiming to deploy T&S infrastructure in the North Sea, as shown in Figure 3-13[74]. This development will represent the **core project to enable a full-scale CCS project in Norway**, covering the various stages of the value chain, including:

- CO_2 capture in the Oslo-fjord region from industrial sources, such as cement and waste to energy plants.
- Shipping of liquid CO_2 form these industrial capture sites to an onshore terminal on the Norwegian west coast for intermediate storage.
- Transport of the liquid CO_2 to an offshore storage site.

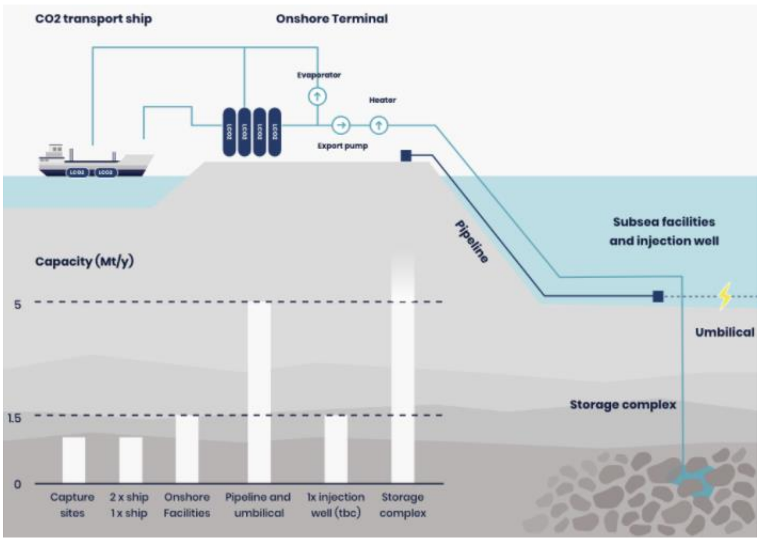


Figure 3-12: Illustration of the Northern Lights project

Northern Lights reached the final investment decision in 2020 and is expected to commence operations in 2024. The project is to be structured in two phases:

Phase 1 will be capable of transporting, injecting and storing up to 1.5 $MtCO_2$/year. Almost 50% of the storage annual throughput is expected to come from imports.

Phase 2 would increase total capacity to 5 $MtCO_2$/year. Progress to the second phase is contingent to additional market demand for CO_2 storage being established.

[74] Figure and information extracted from Northern Lights website.

To account for growth opportunities, Phase 1 will be scaled up for the basic functionality requirements of the receiving terminal, offshore pipeline and the umbilical of the offshore template to be able to reach the 5 $MtCO_2$/year.

There are over 80$MtCO_2$ being emitted in main industrial clusters around Europe every year, representing an attractive opportunity for CO_2 shipping projects which may come after Northern Lights to also ensure contracts for CO_2 storage. In addition, Acorn CCS could act as a back-up storage site for Northern Lights in case of downtime or other issues[75]. However, this is likely to be relatively low. For example, a 5% downtime would lead to 0.075 to 0.25 $MtCO_2$/year of back-up storage.

3.7 Carbon Capture and Use

Carbon Capture and Use (CCU) can be defined as the **process of capturing CO_2 and using the CO_2 either directly in a process, or as a feedstock to produce materials and commodities which can be sold** at a market value. Some of the commodities which can be produced via CCU include materials (concrete, aggregates), polymers (polyols, polyurethane), chemicals (light olefins, methanol, formic acid) and fuels (synthetic methane, ethanol and middle distillate hydrocarbons). These commodities can be produced via a wide range of processes, some of which have a relatively low technology readiness level (TRL) compared to their counterfactuals, such as conventional formic acid production using natural gas as a carbon source[76].

Whilst CCU consist of sequestration of carbon dioxide into products, the climate benefits of CCU are still to be fully understood, considering a lifecycle analysis of associated emissions. Nevertheless, CCU climate benefits are maximised when electricity and other feedstock used in the CCU process (such as hydrogen) are produced sustainably. CCU can use CO_2 from any source, but the **process' environmental footprint is most improved if the CO_2 is sourced from DACCS or biogenic emissions,** as these can deliver negative emissions.

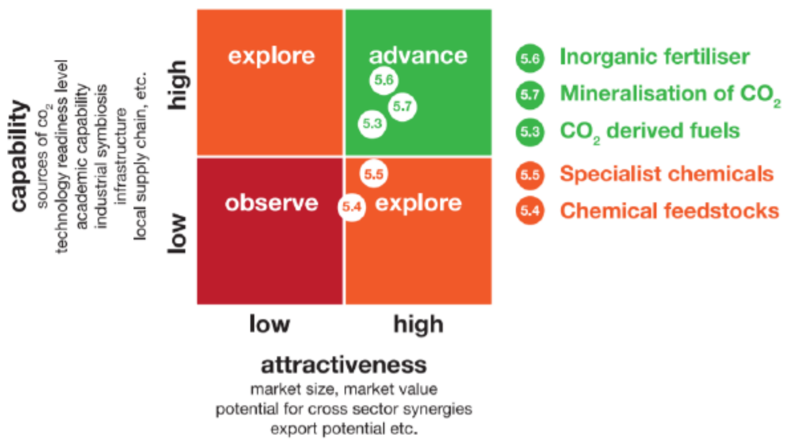


Figure 3-13: Matrix evaluating the potential for adoption of CCU options in Scotland[77]

Our analysis points out that the potential for use of CCU processes in the Scottish context could be divided into two categories:

- Case 1: **Large scale production of clean commodities, such as synthetic fuels, methanol and building aggregates.** This could be realised by capturing emissions form large scale industrial emitters located around the Central Belt of Scotland. Whilst the potential of those utilisation routes is high, the

[75] The UK and Norwegian Governments signed an MoU in 2018 to on the cooperation in the field of CCUS.
[76] International Energy Agency: Putting CO_2 to use (2019)
[77] Wilson, G., et al. "Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland." (2017).

associated technology has a lower TRL and the commodities produced would require market mechanisms to be competitive against counterfactual petrochemicals.

- Case 2: **Smaller-scale applications, such as production of inorganic fertiliser and algae cultivation using biogenic CO_2 from Scotland's distilling sector**[78]. Distilleries are more geographically dispersed and generally emits less CO_2 per site than industrial candidates in the group above but could deploy these technologies earlier due to higher TRL and the products could be used locally.

Case 1: Production of synthetic fuels, methanol and aggregates by large-scale industries. Scotland has a variety of industrial sites which could produce such commodities via engineered CCU pathways. The potential for such pathways is exemplified by estimating the benefits which result from using 0.1 $MtCO_2$/year per CCU process to produce the listed commodities.

Table 1 below summarises the amount of hydrogen and electricity required to produce a certain output of synthetic fuels, methanol and aggregates as well as the CAPEX and OPEX investment needed[79]. These products are **expected to be new commodities for the industrial sites which implement the CCU technology** and would result in a product with added value due to its enhanced sustainability which can replace less climate friendly options.

Table 1: Techno-economic requirements and market potential for certain CCU pathways

CCU Process	TRL	H_2 used	Electricity used	Commodity output	CAPEX	OPEX[80]	Market potential
[-]	[1-9]	[tH_2/y]	[GWh/y]	[tonnes]	[m$]	[m$/y]	[-]
Synthetic fuels	5-7	14,000	N/A	25,600	63.0	28.4	To replace fossil fuels: aviation, maritime
Methanol	8	14,000	101	68,000	46.2	39.2	Existing market: green methanol with added value
Aggregates[81]	8	-	9.5[82]	57,000	14.2	4.1	Novel ways to make building materials

The use of CCU technologies is not limited to the industrial sites with on-site capture of CO_2. Once captured, the CO_2 could be transported to neighbouring industries which produce market commodities under the same category as those listed above e.g., chemicals, refineries or non-metallic minerals. The high density of industrial sites in the Central Belt of Scotland suggests that CO_2 trade between producers and consumers is possible, where the CO_2 could be used by existing industries.

Case 2: Production of inorganic fertiliser and algae cultivation by the distilling sector. Scottish distilleries are important producers of biogenic emissions from fermentation (0.47 $MtCO_2$/year in 2016)[83]. However, many of such distilleries are in remote locations away from the large-scale potential industrial users mentioned above. Nevertheless, there is still an opportunity for distilleries to use CCU, as CO_2 from fermentation streams is generally of high purity.

There are 50 malt distilleries in the Speyside region, many of which are close to one another. These **Speyside distilleries emit 0.17 $MtCO_2$/year from fermentation**, of which 50% can be collected when CO_2 is purest and

[78] In May 2021, BEIS announced the project winners for the Green Distilleries Competition: Phase 1 feasibility reports. Over half of all competition winners are focused in Scotland.
[79] CAPEX assumed First-of-a-kind (FOAK), OPEX does not include cost of hydrogen, CO_2 and electricity.
[80] OPEX costs for methanol and synthetic fuels include the costs of hydrogen, and electricity for 2030.
[81] The analysis for aggregates assumes a CO_2 uptake in the product of 25% i.e., 25,000tCO_2.
[82] The energy consumption reported is for the extraction and precipitation steps.
[83] SCCS: Negative Emission Technology in Scotland: carbon capture and storage for biogenic CO_2 emissions (2018)

at a rate deemed economical for CO_2 collection (0.085 $MtCO_2$/year)[84,85]. The CO_2 is compressed and ready for transport after a purification stage which involves a series of washing stages to remove the water and impurities from the fermentation process[86].

The captured CO_2 can then be used as feedstock to produce inorganic fertiliser, by combining the CO_2 with other material inputs such as a cellulosic material (such as draff from distilleries), ammonia and phosphate[87]. If the 0.085 $MtCO_2$/year produced by Speyside distilleries were to be used for inorganic fertiliser production, **up to 270,000 tonnes of inorganic fertiliser could be produced**[88]. This is equivalent to 36% of all inorganic fertiliser used in Scotland in 2018[89]. At an average spot price of £250/tonne of inorganic fertiliser, the total value of this production could be of £68mn[90].

To materialise this CCU opportunity for distilleries, the captured CO_2 from Speyside distilleries would have to be transported over short distances to an inorganic fertilizer production hub located in proximity to the regional distilleries. In this facility, the CO_2 would be mixed with the other reactants (some of which could be sourced locally too). **The final inorganic fertiliser product could be used by the local agriculture sector**. Besides the economic benefits stated above, this would be an example of circular economy for the Scottish distillery and agriculture sector.

Alternative options for the use of fermentation derived CO_2 includes the cultivation of algae. Algae strips the CO_2 from the fermentation stream in a bioreactor, turning it into protein and oils which can be used as animal feed. The technology also uses distillery wastewater streams to capture chemicals[91].

3.8 Summary of CO_2 captured volumes in the scenarios

Figure 3-14 summarises the CO_2 profiles for the four scenarios until 2050. Uptake of CCUS varies considerably among the scenarios considered, with the Soft Start and the Carbon Management scenarios reaching a **maximum CO_2 annual storage requirement of 10.5 and 22 $MtCO_2$/year, respectively**.

In all scenarios, CO_2 imports represent an important fraction of the total annual CO_2 volumes. Most noticeably, in the Carbon Management scenario, the combined volumes of CO_2 imports and DACCS add up to 16 $MtCO_2$/year. This figure suggests that **up to three quarters of all CO_2 volumes arriving at St Fergus could come from carbon management services** being provided by Scotland to sources from external locations.

Figure 3-14 also highlights the close interplay between a hydrogen economy relying partially on blue hydrogen and CCUS value chains in Scotland. In the Ambition scenario, **blue hydrogen related CO_2 would account for a third of all volumes in 2050**, as is more clearly illustrated in Figure 3-15, which provides an overview of the flows of CO_2 across Scotland (see appendix 9.4 for equivalent illustrations for other scenarios). This relative contribution would be even higher in the 2030s, a period where demand for hydrogen continues to be met predominantly by blue hydrogen.

[84] This number is calculated based on the pure alcohol production figures for the Speyside region (226,150,000 litres per annum in 2016) and the calculated emissions intensity of biogenic CO_2 form fermentation (0.754 $kgCO_2$ per litre, calculated for reported figures from the Glenfiddich Distillery biogenic CO_2 form fermentation and annual output).
[85] Russell, Inge, Charles Bamforth, and Graham Stewart. Whisky: technology, production and marketing. Elsevier, 2014.
[86] SCCS: Carbon capture in the heart of the city (2018)
[87] CCm Technologies are a UK small-and-medium enterprise (SME) which has developed a process to produce inorganic fertiliser by attaching the CO_2 to a cellulosic material (grass, waste, woodchip etc.) coated with a nitrogenous material. The CO_2 is then stabilised on the cellulose surface, making it into a carbonate material. Additional materials which can be used as nutrients are added so that the final output can be used as a fertiliser.
[88] Figures are based on the material balances provided by CCm Technologies for their inorganic fertilizer manufacturing technology, as described in Wilson, G., et al. "Actions required to develop a roadmap towards a Carbon Dioxide Utilisation Strategy for Scotland." (2017).
[89] Total of 750,000 tonnes of inorganic fertiliser used in Scotland is calculated from The British Survey of Fertiliser Practice: Fertiliser Use on Farm Crops for Crop Year 2019, Department for Environment, Food and Rural Affairs (2019.
[90] Price data from Agriculture and Horticulture Development Board, GB Fertiliser Prices (2020)
[91] This technology has only been trialled once in Scotland, in the Glenturret distillery, capturing 38 tonnes of CO_2/year.

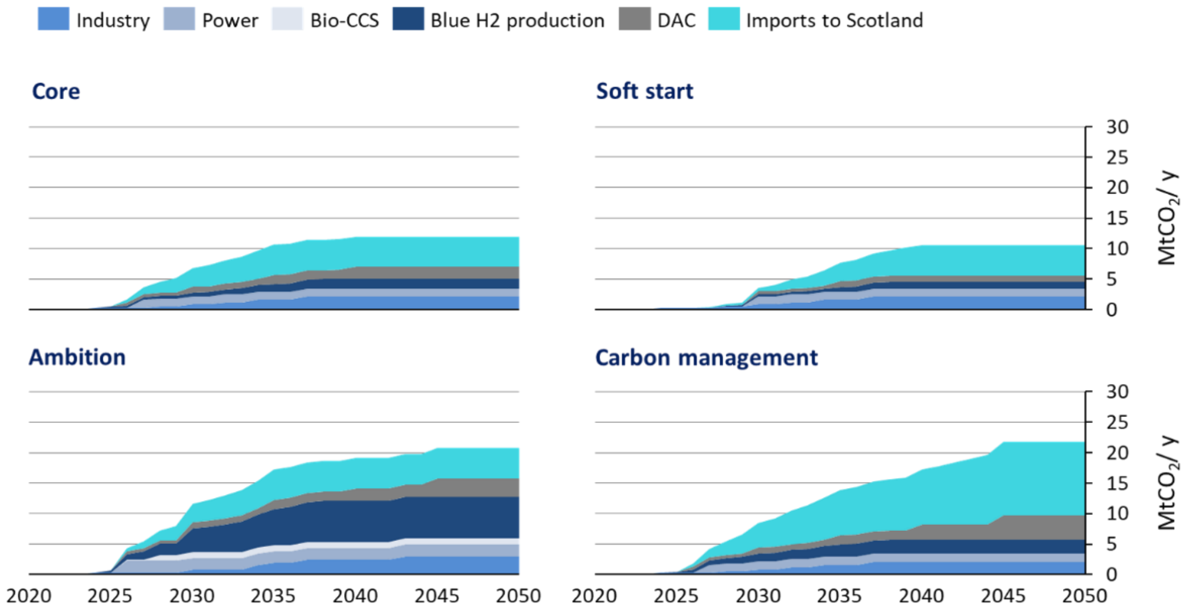
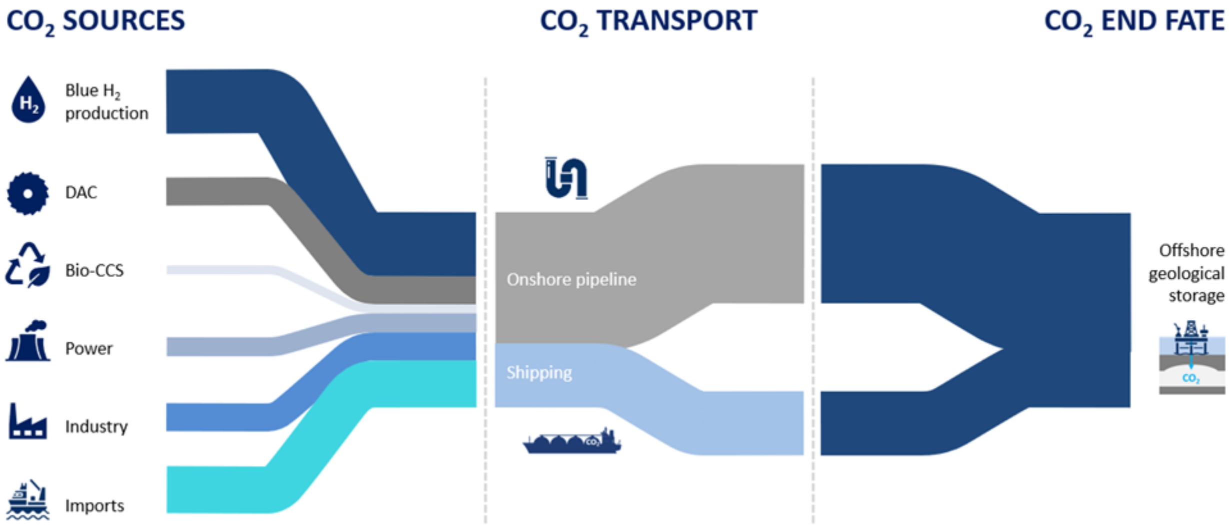


Figure 3-14: Summary of the CO_2 profiles from various CO_2 sources



The thickness of the lines originating from the six emitting sectors are scaled to represent the relative volume of CO_2 captured in 2050 under the Ambition scenario. Likewise, the thickness of the lines associated with the CO_2 transport options match the relative volume of CO_2 passing through onshore pipeline (either in the local network in St Fergus or via the Feeder 10 pipeline) or imported to the Peterhead Port via ship.

Figure 3-15: Breakdown of the CO_2 flows from the six emitting sectors and across different transport modes for the Ambition scenario in 2050

4 Infrastructure requirements for managing carbon across Scotland

4.1 Overview

CCUS value chains consist of three major stages: capture, T&S. The capture of CO_2 from various sources and sectors was discussed in the previous section, whilst this chapter examines the implications on the T&S stages of the potential Scottish CCUS value chain.

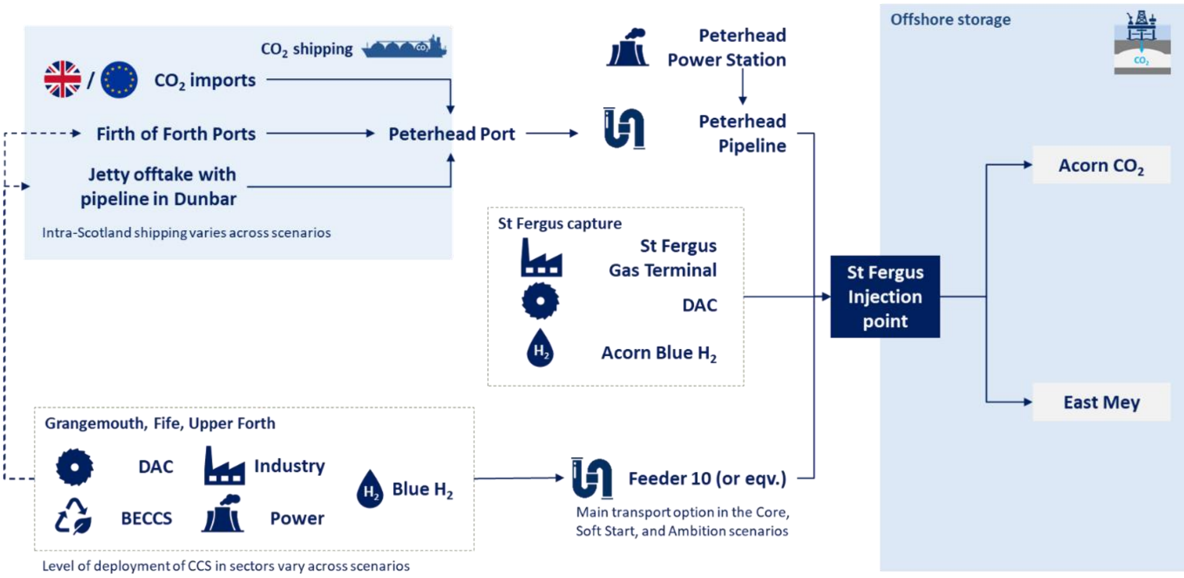


Figure 4-1: Illustration of the CO_2 value chain in Scotland for capture, T&S

Pipeline transport and CO_2 shipping represent key options for transporting the CO_2 from various sources, such as industry, power, blue hydrogen production, bio-CCS, DACCS and imports, to offshore storage sites. Research shows that CO_2 from the Central Belt of Scotland could be transported to St Fergus via either onshore pipeline or shipping. In St Fergus, the CO_2 would be conditioned and prepared for injection into the final storage facilities. Having two options for the transport of CO_2 is expected to provide system resilience to the CCUS value chains and also allow for remote emitters to adopt CO_2 capture technology.

Our scenarios explore a mix of CO_2 transport pathways:

- In the Core, Soft Start and Ambition scenarios, transport of CO_2 via an onshore pipeline is the primary method to connect emitters in the Central Belt of Scotland with St Fergus facilities. In these three scenarios, **intra-Scotland shipping of CO_2 to Peterhead Port will also be available, albeit this transport method is expected to play a more limited role**. In these scenarios, CO_2 shipping plays an important role in allowing CO_2 imports, expected as early as in 2026.
- Conversely, **intra-Scotland transport of CO_2 to St Fergus in the Carbon Management scenario is considered to take place exclusively via CO_2 shipping.** This scenario intends to reflect the underlying uncertainty around the future of existing assets that could be repurposed and account for any issues in securing funding or overcoming technical barriers. As a result, the CO_2 shipping industry could grow at a faster rate than in the other scenarios, not only acting as a transport pathway from the Central Belt of Scotland to St Fergus but also bringing a larger volume of CO_2 from other clusters to Scotland.

4.2 CO_2 transport

Onshore pipeline transport

As envisaged in the Acorn CCS project concept, **Scotland has the opportunity to reuse some of its existing natural gas transmission assets to connect emitters in the Central Belt to Acorn CCS facilities in St Fergus**. In particular, three feeders have been identified as having the largest potential for repurposing to transport CO2: Feeder 10, Feeder 13, and Feeder 24. These feeders are part of the NTS and are fully operational assets owned by National Grid crossing Scotland from St Fergus to Grangemouth, and then continuing into England as shown in Figure 2.1.

The similar design of these pipelines suggests that each could achieve similar CO_2 annual throughputs. However, **Feeder 10 reconversion has received most attention in the past**, with previous studies having covered both technical and economic aspects of reconversion[92]. In addition, the reconversion of one of these feeders is also being **considered to transport hydrogen**. The selection of pipeline reconversion for hydrogen or CO_2 transport and their operating strategy requires additional work to be completed.

In the Core, Soft Start and Ambition scenarios, it is assumed that one of these feeders will act as the core transmission asset integrating the entire onshore CCUS supply chain. Once a feeder is commissioned, CO2 emitters in the different geographical groups shown in the map in Figure 2.1 will start connecting to this asset via CO2 pipeline collection networks, which can connect in Grangemouth or through various intermediate points. The assumed timeline for pipeline commissioning and subsequent connections with the geographical groups is shown in Figure 4-3[93].

Figure 4-2: Map of existing transport infrastructure in Scotland

In the Core scenario, the feeder pipeline would become available for transport in **2029**. A three year delay to **2032** is included in the Soft Start scenario[94]. Relative to Core, this delay in Soft Start results in additional

[92] Scottish Power CCS Consortium: UK Carbon Capture and Storage Demonstration Competition: FEED Close Out Report (2011) and Pale Blue Dot Energy Ltd: Onshore Transportation Feasibility Report Caledonia Clean Energy Project (2016)

[93] Whilst the sequencing of adoption of carbon capture in the different geographical groups follows a growth approach from closer groups for more distant ones, the expected date of Feeder 10 commissioning has been determined following stakeholder engagement activities.

[94] Reconversion works for Feeder 10 are assumed to begin two years prior to full repurposing of the pipeline. The final date of repurposing could vary, and the date is expected to be heavily influenced by both technical and commercial factors: sufficient safety cases, engineering work being performed on the pipeline, appropriate government signalling and available funding mechanisms. The latter two are deemed to be critical to accelerate Feeder 10 repurposing (or equivalent existing asset).

carbon capture projects in the Central Belt **to ship their CO_2 as well as a higher green hydrogen deployment** rate to meet the growing industrial demand for hydrogen in Grangemouth.

In the Ambition scenario, the pipeline would become available for CO_2 transport in **2026**, aligned with an increased ambition for decarbonisation of the Grangemouth industrial cluster[95]. The early date of pipeline commissioning is assumed to be driven by i) the **commissioning of the generic power station using natural gas with CCUS** acting as the early CO_2 pipeline user and by ii) an aggressive and ambitious decarbonisation policy[96]. The early commissioning date would reduce the need for early CO_2 shipping from Firth of Forth, however shipping could still play a redundancy role in the long term.

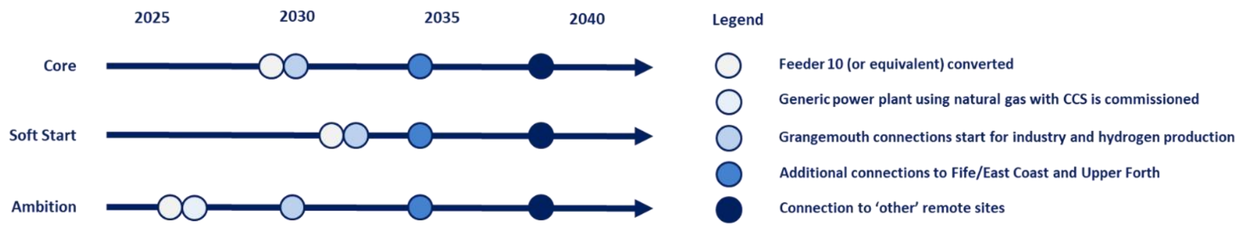


Figure 4-3: Timeline for initial CCUS infrastructure availability and subsequent growth

The annual Feeder CO_2 throughput for the Core, Soft Start and Ambition scenarios are shown in Figure 4-4. By 2050, pipeline flows in the Core scenario could amount to **2.1 $MtCO_2$/year**, with the CO_2 coming from industry and blue hydrogen production. In Soft Start, the bigger role in the Central Belt for CO_2 shipping and higher green hydrogen penetration reduce the CO_2 profile to **1.3 $MtCO_2$/year**. In the Ambition scenario, up to **8.0 $MtCO_2$/year** are transported by 2050. The figure below also shows that blue hydrogen production is the dominant source of CO_2, as Ambition sees large hydrogen production facilities being used to supply hydrogen to the heating sector.

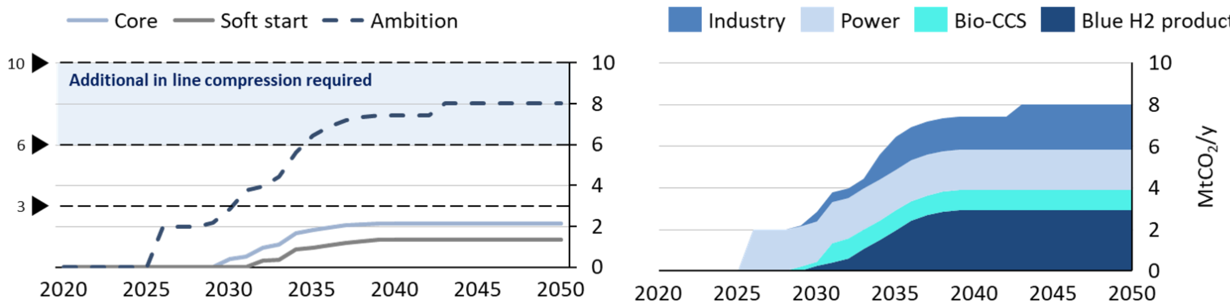


Figure 4-4: CO_2 throughput through feeder pipeline (left) and breakdown of CO_2 sources flowing through the pipeline in the Ambition scenario (right)

Previous studies have estimated Feeder 10's optimal and maximum annual CO_2 throughput[97,98,99]. These studies showed that, under its current configuration, the pipeline can transport up to **6 $MtCO_2$/year**, and

[95] The Grangemouth industrial cluster has successfully submitted an application as part of the ISCF Deployment Phase 2, which is aiming to provide funds to industrial cluster decarbonisation projects, aiming to start kickstart their initial deep-decarbonisation before 2030.
[96] Some projects have already shown interest in developing decarbonized baseload power generation in Grangemouth - such as the Caledonia Clean Energy Project and the GBTron Power Ltd proposal.
[97] Brownsort, Peter A., Vivian Scott, and R. Stuart Haszeldine. Reducing costs of CCS by shared reuse of existing pipeline - case study of a CO_2 capture cluster for industry and power in Scotland. Edinburgh: University of Edinburgh. (2016)
[98] CO2DeepStore. (2012). Proposal for the DECC 2012 CCS Commercialisation Programme.
[99] Accelerating CCS Technologies: Acorn Project: D17: Feeder 10 study, ACT Acorn Project (2017).

additional in line compression can increase this throughput to **10 $MtCO_2$/year**[100]. Therefore, use of this pipeline (or equivalent) in the Ambition scenario would **most likely require installation of additional compressors** to meet the expected CO_2 profiles.

Conversely, Feeder 10 also has a lower annual throughput limit below which it becomes **less cost-effective to invest in repurposing the pipeline** to transport CO_2 due to underutilisation. This limit has been roughly estimated to be of **3 $MtCO_2$/year**[101]. The Core and Soft Start scenarios currently exhibit **annual CO_2 throughput below this limit**[102]. Options to meet the minimum flow requirements include locating future users of CO_2 transport infrastructure - such as future DACCS facilities or blue hydrogen production sites - around pipeline entry points. This strategy would also allow for a **faster ramp up in the pipeline's CO_2 profiles** for the Core and Soft Start scenarios, further supporting transport economics. The economies of scale associated with different flow rates through Feeder 10 pipeline is shown in the box below.

Box 5 – The economics of CO_2 transport by onshore pipeline

Repurposing Feeder 10 (or an equivalent asset) is required to connect emitters in the Central Belt of Scotland with the CO_2 injection point in St Fergus in the Core, Soft Start and Ambition scenarios. However, repurposing a fully operational transmission pipeline will require a series of investments[103]:

- Prior to operation, cost of transfer of an NTS asset for CO_2 use from National Grid Gas to another equivalent entity managing CO_2 transport, as well as the engineering and construction work.
- During operation, costs associated with the pipeline and compression, as well as any overheads and potential fees to Ofgem.

Additionally, **use of the pipeline at flowrates above 6 $MtCO_2$/year will require additional compression**. This is the case for the Ambition scenario, estimated to have a maximum annual throughput of 8 $MtCO_2$/year.

Figure 4-5 shows the CO_2 transport (£/tCO_2) for Feeder 10. The transport fee is calculated as an average over the asset life and assumes a full scenario roll-out[104]. As seen in the figure, an over threefold increase in the transport fee is observed between the Soft Start **(£16.5/tCO_2)** and Ambition scenarios **(£4.6/tCO_2)**, each transporting 1.3 and 8.0 $MtCO_2$/year in 2045,

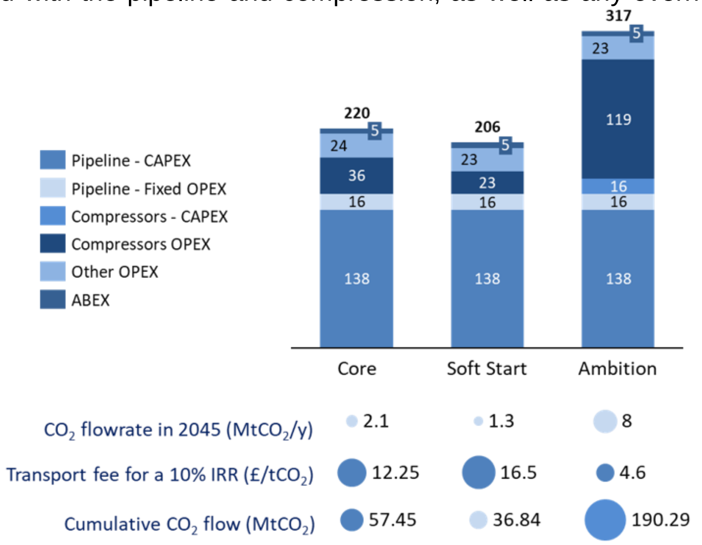


Figure 4-5: Economic assessment for the use of Feeder 10 for CO_2 transport[1]. Total investment in m£.

[100] Stakeholder engagement activities suggest that further engineering and simulation work is required to conclude that the maximum throughput capacity of Feeder 10 is 10 $MtCO_2$/year.
[101] Minimum annual throughput value sourced from stakeholder engagement activities.
[102] The gap in annual CO_2 throughput could further increase if the refinery continues to reduce its activity, on top of already announced activity reduction. This risk could have a considerable impact to the total estimated onshore pipeline throughput of the Core and Soft Start scenarios.
[103] Accelerating CCS Technologies: Acorn Project: D17: Feeder 10 study, ACT Acorn Project (2017). The costs used in this analysis correspond to Feeder 10, which is the transmission pipeline which has received most attention for reconversion in literature.
[104] It must be noted that earlier emitters connecting may pay a higher fee due to a lower total CO_2 flowrate at the time of connection before full economies of scale are achieved or if a different asset life is used in the calculation.

respectively[105,106]. In the Soft Start, the capacity utilisation rate of the pipeline is only 20%, leading to the high fees. Previous similar work on the economics of CO_2 transport in Feeder 10, considering a different annual throughput and asset lifetime assumptions, concluded that a fee of £5.5/tCO_2 was required to reach an internal rate of return (IRR) of 10%[107].

The low-cost transport is partially achieved due to the repurposing of an existing pipeline, which leads to cost reductions relative to a new build. For example, for the Ambition scenario, the **CAPEX of a new equivalent pipeline would be twice as large**[108].

The transport fee decreases with an increasing annual CO_2 throughput, suggesting that **the pipeline can benefit from economies of scale**. In the Ambition scenario, higher pipeline utilisation leads to a transport fee 70% lower than that of the Soft Start scenario, even when the costs from additional in line compression are accounted for.

Industrial emitters in the Central Belt are not necessarily located next to the Feeder's potential CO_2 injection point(s) and **connections to deliver the CO_2 are therefore likely to be required**. These CO_2 collection networks would add to the total transport fee to be paid by emitters. However, the distances and capacity of such collection pipelines would be considerably smaller than those of the Feeder, suggesting that the fraction of the transport fee associated with delivering the CO_2 to the Feeder injection point would be marginal. Planning for future connection requirements would bring an opportunity to minimise CO_2 delivery costs by optimising the network arrangement and reducing total pipeline mileage.

CO_2 shipping

Shipping of CO_2 will be required to either connect Sottish emitters or CO_2 imports shipments with CO_2 injection facilities in St Fergus. However, **much of the infrastructure required to service these shipments is not currently present in the origin and destination ports**. The figure illustrates the equipment required to ship CO_2 in Scottish ports.

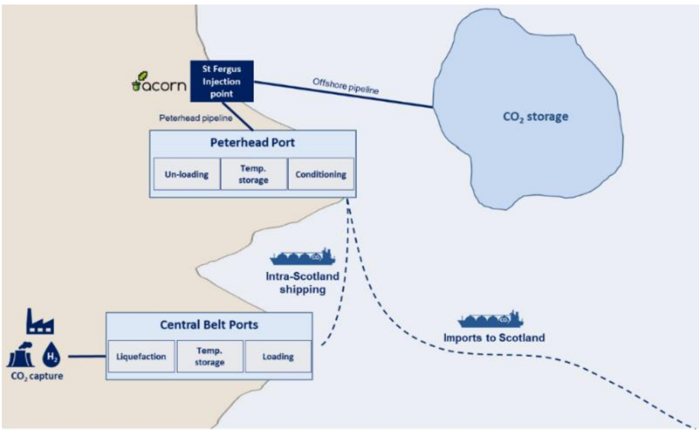


Figure 4-6: Simplified map of the CCUS value chain requirements in order to support a CO_2 shipping industry in Scotland

The main infrastructure needed in origin ports includes:

i) **CO_2 liquefaction equipment** to condition the gaseous CO_2 coming from pipeline collection networks into the ports into liquid form.
ii) **CO_2 temporary storage** to store the liquefied CO_2 while loading is not possible or not required.
iii) **Loading of the CO_2 into the vessel**. Loading arms used for loading LPG or LNG can be used for this purpose and so this piece of infrastructure may already be present in some of the origin ports.

[105] Previous work as part of the Accelerating CCS Technologies: Acorn Project: D17: Feeder 10 study, ACT Acorn Project (2017), concluded that a transportation fee of £5.5/tCO_2 would be needed to reach an IRR of 10%, for a transport of 4.6 MtCO_2/year.
[106] The transport fees presented here are high-level and shown for illustrative purposes. These should not be used to inform future pipeline transport fees. Additional in-depth work is required to reduce the cost uncertainty and to better understand the technical implications associated with the reconversion of Feeder 10.
[107] Accelerating CCS Technologies: Acorn Project: D17: Feeder 10 study, ACT Acorn Project (2017). Note that differences in the Feeder 10 costs come from i) differences in the annual throughput, of 2.13 versus 4.6 MtCO_2/year, and from ii) differences in the asset life, of 30 versus 20 years.
[108] Calculated using Element Energy for BEIS: CCS deployment at dispersed industrial sites (2020)

Origin ports are assumed to be i) Central Belt ports such as Firth of Forth Ports and ii) a potential offtake point with a ship loading jetty/quay in Dunbar, in proximity to the cement plant. Dunbar Port, used mostly for fishing activities, may not be able to accommodate CO_2 shipping infrastructure.

The infrastructure needed in the destination port (Peterhead Port), or in adjacent areas, includes:

- **Unloading from the vessel** to the CO_2 temporary storage facility. This uses the same infrastructure as for loading.
- **CO_2 temporary storage** to regulate the flow of CO_2 to the conditioning facilities, a step needed before subsequent pipeline transport.
- **Conditioning or gasification of the CO_2** before its downstream pipeline transport to St Fergus injection facilities. This step changes the temperature and pressure conditions needed for liquid CO_2 pipeline transport (conditioning) and is the expected form of post-shipping CO_2 transport. Alternatively, the liquid CO_2 is converted to gaseous form (gasification).

There are various options regarding the cargo size of the CO_2 vessels, which primarily depends on the design liquefaction pressure at which the CO_2 is shipped: low, medium, or high pressure. Currently, CO_2 shipping is used in the food and beverage industry at a much smaller scale required in a CO_2 import industry, and transport is performed at medium pressure. Due to its unusual physical properties, low pressure CO_2 shipping allows for larger CO_2 vessel capacities[109]. As CO_2 shipping flows increase resulting from the uptake of carbon capture technology, it is likely that dedicated, new low-pressure vessels will become available in the medium term, with several options being under design currently.

The role of CO_2 shipping in the Scottish context

Shipping of CO_2 within Scotland is expected to commence in the mid-2020s, with earliest flows coming from the Central Belt to Peterhead Port. The expected start date means that shipping of CO_2 in Scotland will be one of the earliest projects relative to other CO_2 shipping international projects. Consequently, it is expected that initial intra-Scotland shipping of CO_2 will be performed at medium pressure using vessels with a CO_2 capacity of around 20,000 tCO_2[110]. The early date for CO_2 shipping suggests that repurposing part of the existing semi-refrigerated LNG vessel fleet could help Scotland meet the short-term shipping targets[111].

Roll-out of CO_2 shipping infrastructure in Scotland would provide robustness to Scotland and the wider UK's CCUS supply chains, as CO_2 shipping routes can be flexible. This means that CO_2 ships could operate in dedicated routes between Central Belt to Peterhead Port. Alternatively, ships coming from the rest of the UK as well as internationally could stop in Firth of Forth Ports to fill in their remaining CO_2 capacity before arriving at Peterhead Port.

The role of CO_2 shipping will vary across scenarios and will depend on the availability of alternative CO_2 transport infrastructure (i.e., Feeder 10 or equivalent) and the timeframes of carbon capture at large emitter sites:

- **Full-scale shipping**, as an alternative onshore pipeline transport is considered in the Carbon Management scenario: all CO_2 captured in Scotland in the Central Belt is shipped, totalling 2.5 $MtCO_2$/year.
- **Shipping from key sites**: Across all other scenarios, shipping from the Dunbar Cement plant (0.5 $MtCO_2$/year) is considered due to the isolated location of the industrial site, away from any on-shore CO_2 transport pipeline.

[109] Once liquefied, low pressure CO_2 has a density of 1,119 kg/m^3 (-41 C and 9.8 bar), whereas medium pressure CO_2 has a density of 1,029 kg/m^3 (-19.5 C and 20 bar).
[110] This figure has been reached following stakeholder engagement discussions and translated to ships with a deadweight tonnage of 50,000t. Ships used for importing CO_2 from other UK clusters or internationally could vary in their CO_2 capacity, although capacity constraints in Peterhead Port described in Section 3.6 need to be accounted for.
[111] Some companies already have dual-purpose CO_2/LNG vessels.

- **Shipping from early-movers**: the Core and Soft Start scenarios also consider early deployment of carbon capture, before the Feeder pipeline becomes available, such as a pilot project (0.2 $MtCO_2$/year) in the Core scenario. The Soft Start scenario assumes a higher uptake of CO_2 shipping, due to a delay in commissioning of onshore pipeline transport, with early demonstration projects accounting for 0.6 $MtCO_2$/year being shipped from Central Belt ports (excl. Dunbar).

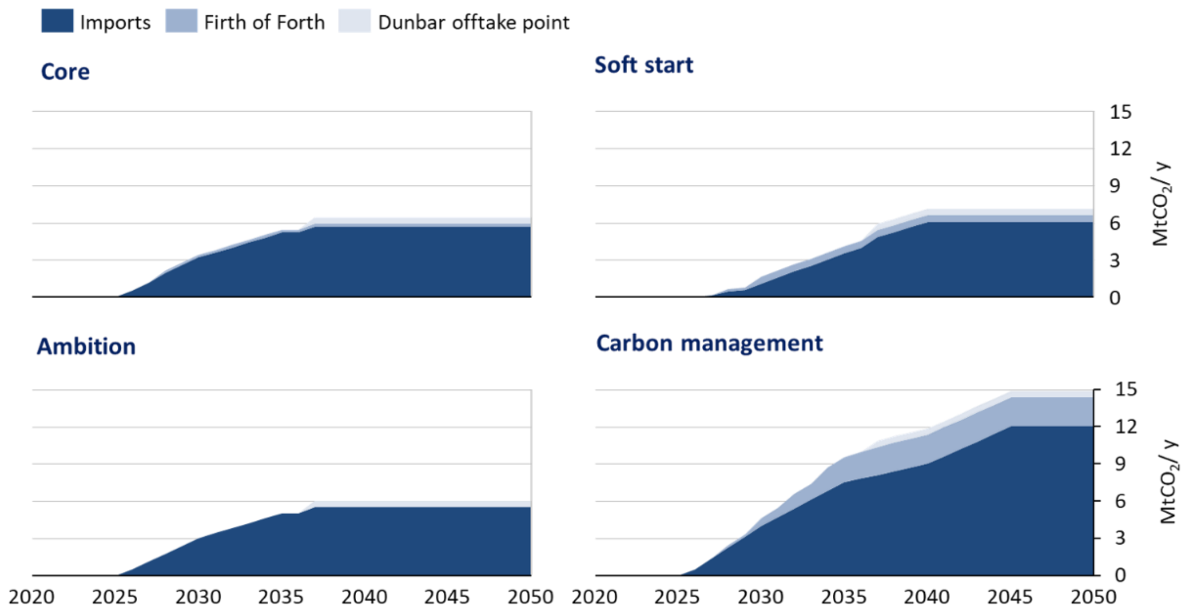


Figure 4-7: Breakdown of the CO_2 sources for shipping

The total CO_2 profiles for shipping in the scenarios are shown in Figure 4-7, and the volumes of CO_2 shipping have been summarised in Table 2. All scenarios include CO_2 being shipped within and to Scotland from the UK and internationally, with Carbon Management reaching 12 $MtCO_2$/year by 2050.

Imports of CO_2 to Scotland could commence in 2026, once Peterhead Port facilities becomes operational. Welcoming imports to Scotland in the mid-2020s could position Scotland as a leader in storing CO_2, alongside other European projects in the North Sea offering Storage as a Service, such as Porthos (in the Netherlands) and the Northern Lights (Norway)[112]. Section 4.4 provides an overview of the potential competitiveness of Scotland in Carbon Management compared to other regions.

Table 2: CO_2 intra-Scotland and import volumes for the scenarios

Scenario	Scottish sites	Imports (UK clusters and international)
Core	• Pilot project deployment at Firth of Forth (0.21 $MtCO_2$/year), starting in 2028 and continuing to 2050[113]. • Shipping from Dunbar (0.56 $MtCO_2$/year), starting in 2037 and continuing to 2050.	• Imports start in 2026, going up to 5 $MtCO_2$/year by 2050[114]. Imports could come from other UK clusters e.g., South Wales and Southampton and back-up options from the Northern Lights[115].

[112] The Porthos and Northern Lights projects aim to store CO_2 in offshore geological reservoirs.
[113] This assumes that the Kinneil Terminal and Refinery SMR do CO_2 shipping due to date of deployment of carbon capture. Carbon capture at the Kinneil Terminal is only assumed to be deployed at the CO_2 separation step.
[114] Start year set as per revised plans for Acorn CCS, which is expected to start CO_2 imports to Peterhead Port in 2026.
[115] These clusters could represent around 7 $MtCO_2$/tear, although it is assumed that not all emissions from South Wales would likely be shipped to Scotland, as the cluster is already in discussion with the HyNet cluster. However, the volumes may vary depending on the future of industrial activity in those clusters and improvements due to efficiencies.

Soft Start	• Delayed onshore pipeline leads to more CO_2 shipping from Firth of Forth (0.56 $MtCO_2$/year), starting in 2028 and continuing to 2050[116]. • Shipping from Dunbar (0.56 $MtCO_2$/year), starting in 2037 and continuing to 2050.	• Scale of imports is as Core, but delayed start due to later date for availability of infrastructure.
Ambition	• Early commissioning of pipeline negates need for shipping from Firth of Forth. • Shipping from Dunbar (0.56 $MtCO_2$/year), starting in 2037, continuing to 2050.	• Scale of imports is as Core.
Carbon Management	• No onshore pipeline, so all sites use shipping to Peterhead port via Firth of Forth and Dunbar. Up to 2.5 $MtCO_2$/year shipped in 2050.	• Up to 12 $MtCO_2$/year by 2050 including both UK and international sources, as concluded from stakeholder engagement.

Peterhead Port

Whilst Scotland benefits from wide CO_2 storage capacity, imports could be constrained at different points in the CCUS value chain, based on previous studies investigating the maximum annual port capacity to import CO_2[117]. The total volume of CO_2 which can be imported is heavily influenced by the vessel size and the tanker jetty design. Taking these considerations into account, vessels carrying up to 21,000 tCO_2 could be docked[118].

Only one tanker jetty is currently available, which would allow for a maximum throughput of close to 9 $MtCO_2$/year[119]. However, the annual capacity of the port could be expanded to 12 $MtCO_2$/year to a maximum of 16 $MtCO_2$/year if the tanker jetty capacity were expanded to accommodate for a higher Scottish ambition for CO_2 imports (the case of Carbon Management scenario). Nevertheless, more work would need to be conducted to understand the exact turnaround times, and how frequently the port could be utilised for CO_2 offloading relative to all other uses, such as seafood exports.

Just as for CO_2 imports, Peterhead Port will be the sole destination port for intra-Scotland CO_2 shipping. Figure 4-8 shows the total shipping CO_2 profiles in Scotland. This figure is similar to Figure 4-7, but adds the intra-Scotland CO_2 shipping flows on top of the expected CO_2 import profiles, described in Section 3.6:

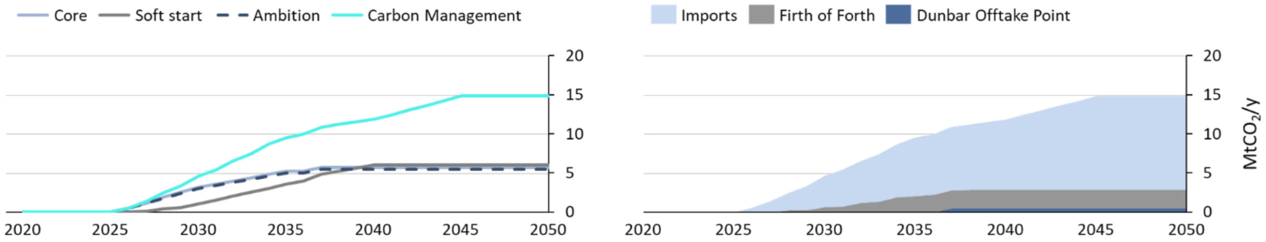


Figure 4-8: Total CO_2 flows through Peterhead Port in each scenario (left) and distribution of CO_2 by source in Carbon Management (right)

[116] This assumed that the Grangemouth Olefins plant's steam cracking facility does CO_2 shipping due to date of deployment of carbon capture.
[117] Accelerating CCS Technologies: Acorn Project: D18 Expansion Options, ACT Acorn Project (2018). The study concluded that the maximum capacity of Peterhead Port for CO_2 imports would be of around 12-16 $MtCO_2$/year.
[118] As per stakeholder engagement, 21,000tCO_2 seems to be the maximum size which Peterhead Port can currently accommodate for.
[119] Internal calculations. Note that this is the maximum practical throughput possible for the maximum vessel cargo capacity (21,000tCO_2). No consideration of the interplay of CO_2 imports with other existing port activities. Assumption of total port availability of 90% and total turnround time of 19h for a vessel come from Accelerating CCS Technologies: Acorn Project: D18 Expansion Options, ACT Acorn Project (2018)

An alternative to port expansion would be direct offshore offloading of the CO_2, however this is not considered as a short-term option in this study[120]. Offshore offloading technologies are currently being used in the O&G sector, however offshore offloading of CO_2 remains unproven. Some challenges for CO_2 offshore offloading include incapacitated offloading infrastructure due to harsh weather conditions, increased costs due to the off-grid nature of the operations and difficulties to meet the offloading energy demands with renewable energy[121]. Due to these short-term challenges, offshore offloading is seen as a potential long-term and complementary solution to help Scotland provide additional carbon management services by relaxing the capacity constraints in Peterhead Port.

Peterhead pipeline

Besides Feeder pipeline, the Peterhead CO_2 pipeline would constitute the other major onshore pipeline asset in all scenarios, regardless of Scottish CO_2 arriving via onshore pipeline or via shipping through Peterhead Port. This pipeline would connect Peterhead Port with PPS (a short distance, ~2km South) and then continue onwards to the CO_2 injection facilities at St Fergus (approx. 20 km from PPS).

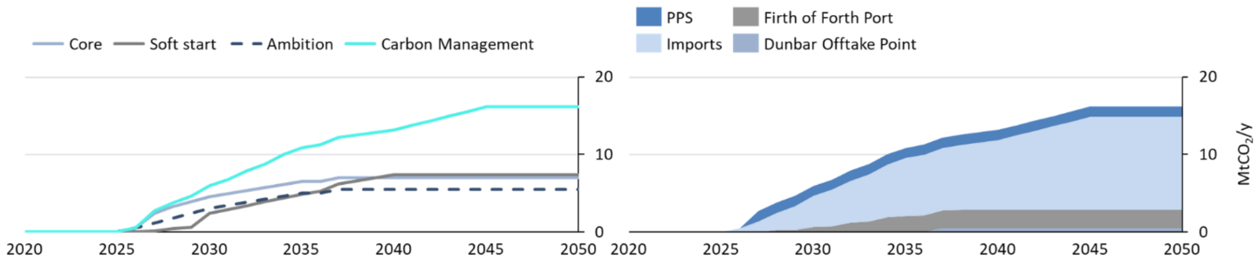


Figure 4-9: Total annual CO_2 flows through the Peterhead pipeline per scenario (left) and breakdown of CO_2 flows by source for Carbon Management (right)

A previous study found that the capacity of existing low pressure pipeline network from Peterhead to St Fergus would only allow the throughput capacity to be of 1.2-1.5 $MtCO_2$/year[122]. As exhibited in Figure 4-9, this capacity would not be sufficient to meet the throughputs of this study's scenarios, and so commissioning of a new pipeline system would be required. Such pipeline system could be comprised of one major pipeline capable of accommodating all throughput and be oversized to cater for eventual increases in CO_2 transport. Alternatively, various smaller pipelines could be built in parallel over time to meet the growing CO_2 transport demand. A more detailed evaluation of the benefits of economies of scale of the first option would have to be weighed against the additional upfront cost and cross-chain risks due to increased transport demand uncertainty. This pipeline system would have to be commissioned in by 2026 to meet the first CO_2 imports from the UK.

Annual CO_2 flow through the Peterhead pipeline is similar for the Core, Soft Start and Ambition scenarios, with around 5-7 $MtCO_2$/year coming from CO_2 shipping, both imports and intra-shipping. In Core and Soft Start, the newly built power plant adds 1.3 $MtCO_2$/year to the Peterhead pipeline. In the Carbon Management scenario, additional CO_2 imports and no cross-Scotland pipeline (Feeder 10 or equivalent) raise annual flows in Peterhead pipeline to 16.1 $MtCO_2$/year. The Carbon Management scenario is shown as the example in the figure above, but CO_2 imports dominate the flow of CO_2 through the Peterhead pipeline in all scenarios.

[120] Offshore offloading is a port-to-storage shipping option where the CO_2 can either i) be directly injected from the vessel to the store or ii) passed through an offshore platform with temporary storage, where the CO_2 is treated prior to injection. On its latest update to the T&S business model, BEIS acknowledges that direct offshore offloading may become a feature of CCUS clusters in the future, and that the prevalent business model will have to be revisited when this practice emerges.
[121] Element Energy for IEAGHG, The Status and Challenges of CO_2 Shipping Infrastructures (2020)
[122] Giles, C. (2012). Peterhead CO_2 Importation Feasibility Study. Petrofac Engineering Ltd

Box 6 – The economics of connecting the Central Belt to St Fergus

The main options for the transport of CO_2 include shipping and pipeline. Previous work by Element Energy discussed that the more cost-effective option depends on the CO_2 annual transport volume, generally concluding that shipping becomes more economical as transport distances increase[123]. Whilst the transport costs could favour one of the options, having a redundant CCUS value chain with both transport options can have a variety of advantages: it encourages CCUS uptake amongst most risk averse companies, it provides system resiliency, minimises overall system downtime and reduces likelihood of system saturation were Scotland to receive more external CO_2 than predicted. The analysis below provides a comparison of the costs of having both transport options for the Scotland CCUS value chain.

CO_2 shipping could provide system resilience but would require increased policy support.

Figure 4-9 shows the intra-Scotland CO_2 shipping fees for using the port infrastructure and ships deployed across Scotland (e.g., at Firth of Forth and Peterhead ports), and accounting for the optimisation of the ship[124]. The figure shows that the CO_2 shipping fee varies according to the intra-Scotland CO_2 shipping opportunity and the CO_2 volumes shipped annually[125]:

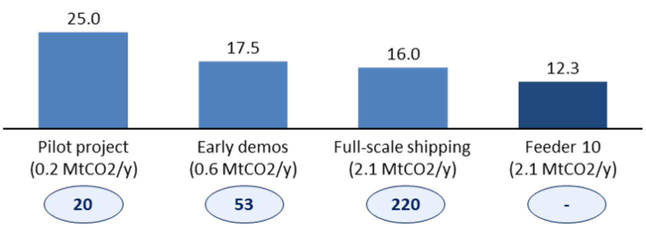


Figure 4-10: CO_2 shipping fee required to reach same internal rate of return as for CO_2 pipeline transport and total number of roundtrips required. Units in £/tCO_2.

- **Pilot projects in the Core scenario:** Early carbon capture projects requiring CO_2 transport before a pipeline is available will have to use shipping, however the shipping fee is expected to be relatively high.
- **Early demonstration in the Soft Start scenario:** Delayed commissioning of pipeline results in additional early carbon capture projects requiring CO_2 shipping, hence the reduction in the shipping fee.
- **Full-scale shipping in the Carbon Management scenario:** Economies of scale benefits are fully materialised, as all carbon capture projects in the Central Belt transport the CO_2 via shipping, and the lowest shipping fee of £16/tCO_2 is achieved.

Due to the difference in transport fees, the commissioning of a Feeder pipeline would create long-term competition with small-scale shipping. However, it is important to consider the value of system resiliency brought in by CO_2 shipping, as utilising the shipping infrastructure initially deployed for early projects could provide a secondary transport option during pipeline downtimes for any other carbon capture project. This would minimise the investment needed for temporary CO_2 storage (or otherwise the CO_2 would have to be leaked during pipeline downtime).

[123] Element Energy for BEIS, CO_2 shipping model (2018).
[124] Transport fees required to reach IRR of 10%. Undiscounted investment over 30 years' asset life. Note that the Peterhead pipeline, connecting the Peterhead Port and St Fergus is not included, this would add additional costs to the Carbon Management scenario.
[125] The shipping fee analysis presented in this section assumed a vessel cargo capacity of 21,000 tCO_2. CO_2 temporary storage infrastructure, required in origin ports, needs to be sized to meet the requirements of the cargo size e.g., storage for 21,000 tCO_2. For the Pilot project and Early demonstration cases, this leads to storage equipment underutilisation. Vessels with smaller cargo capacity could be used and this would lead to lower unit costs for ships and temporary storage and hence lower reduced fee. However, use of smaller vessels could become economically detrimental in the long term. This is because less CO_2 would be imported in such smaller vessels, relative to the import capacity achievable with the assumed cargo capacity of 21,000 tCO_2 (which is the cargo size that maximises the CO_2 import opportunity in Peterhead port). Additional work in this area investigating optimal cargo sizes, effect of national and international shipping routes on economics, and port infrastructure implications would allow for the further optimisation of CO_2 shipping economics.

Operation of CO_2 shipping could continue for small-scale pilot and early demonstration carbon capture projects after pipeline deployment. However, policy support would be needed to protect emitters from the potentially higher CO_2 transport fees to be incurred in CO_2 shipping. This is because operators of CO_2 shipping infrastructure will need reassurance of long-term viability and operability of the shipping value chain. This support could come in the form of operational subsidies to narrow the CO_2 transport fee gap between pipeline and shipping.

CO_2 shipping at full-scale would be more expensive than transport via Feeder pipeline

Scaling of infrastructure for CO_2 shipping leads to economies of scale, due to saving lower investment costs incurred by incremental increases in port infrastructure capacity, with a 15% cost reduction when scaling from 0.2 $MtCO_2$/year to 2.1 $MtCO_2$/year.

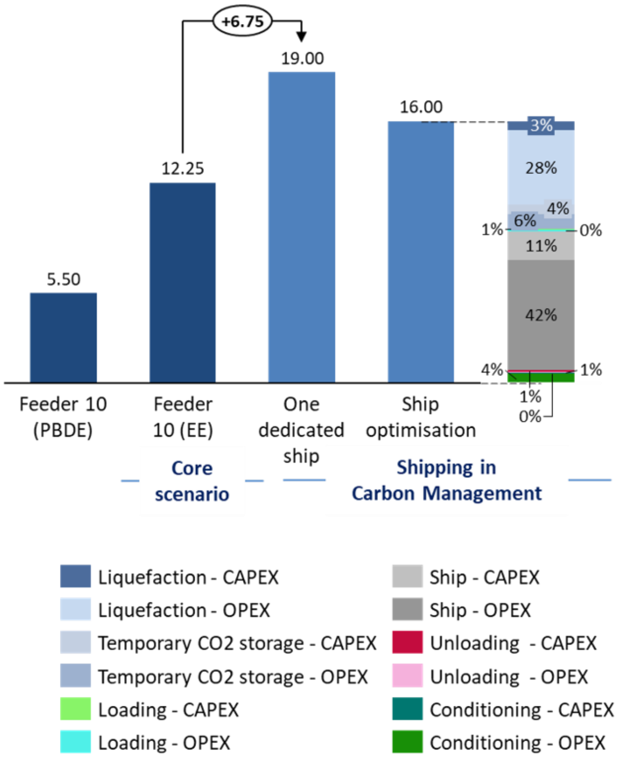


Figure 4-11: Comparison of the pipeline and shipping transport fees for intra-Scotland uses only, versus an optimised use. Breakdown of total infrastructure investment for the optimised shipping case.

Figure 4-10 shows the fee for transporting the same amount of CO_2 from emitters in the Central Belt to CO_2 injection facilities in St Fergus via pipeline transport (Core) and CO_2 shipping (Carbon Management)[126,127]. For shipping, two cases were considered[128]:

- **One dedicated ship:** The use of a dedicated 21,000 tCO_2 capacity ship used exclusively for Firth of Forth – Peterhead trips, at an estimated utilisation of 71%, leading to a cost of £19/tCO_2[129].
- **Ship optimisation:** Optimised shipping utilisation, where the ship is used for trips from other non-Scottish ports when not transporting CO_2 from Firth of Forth (for instance, shipping CO_2 from Wales). As mentioned, this increase in efficiency of use reduces the transport fee by 15%.

As it can be seen in the figure, the transport fee in the ship optimisation case is roughly a third more expensive than in the pipeline case. The main drivers in the cost differences arise from the cost savings from repurposing an existing pipeline as well as from the high energy and fuel costs of liquefaction and ships. Once the CO_2 is unloaded from a vessel at Peterhead Port, the CO_2 needs to be transported onwards via pipeline to the injection facilities in St Fergus via the Peterhead pipeline[130].

[126] To ensure consistency, emissions from Dunbar Cement plant are not considered in any case, as Dunbar would not feasibly connect to Feeder 10 and would have its own shipping infrastructure.
[127] The transport fees are calculated for a 10% IRR over a 30-year asset life. Undiscounted investment.
[128] Assumptions for shipping analysis: Total trip time is 2.18 days, with a port turnround time of 19 hours per port. Distance covered in one trip is 200 km. Possible investment requirements for a tanker jetty extension is not accounted for in the analysis.
[129] This is consistent with previous estimates of cost of shipping of around £ 9.2-11.5/tCO_2 as per "Element Energy for BEIS, CO_2 shipping model (2018)" and work for IEAGHG.
[130] Use of this would require an additional transport fee which is not included in the figure above, although it is expected to be relatively low due to the short distance connecting Peterhead Port with St Fergus.

From an infrastructure perspective, imports of CO_2 require a lower investment compared to intra-Scotland shipping.

Figure 4-11 shows the CAPEX investment in CO_2 shipping infrastructure in the Carbon Management scenario. The figure suggests that infrastructure associated with receiving CO_2 at the port of destination (CO_2 conditioning and unloading), is significantly cheaper than infrastructure associated with exporting CO_2 (liquefaction equipment) deployed at origin ports. This suggests that Scotland would be able to store more CO_2 at a lower cost by focussing investment on CO_2 imports rather than intra-Scottish shipments. However, additional work would need to be conducted to understand potential operational synergies, especially with hydrogen exports, that could further reduce the costs of intra-Scotland shipping[131].

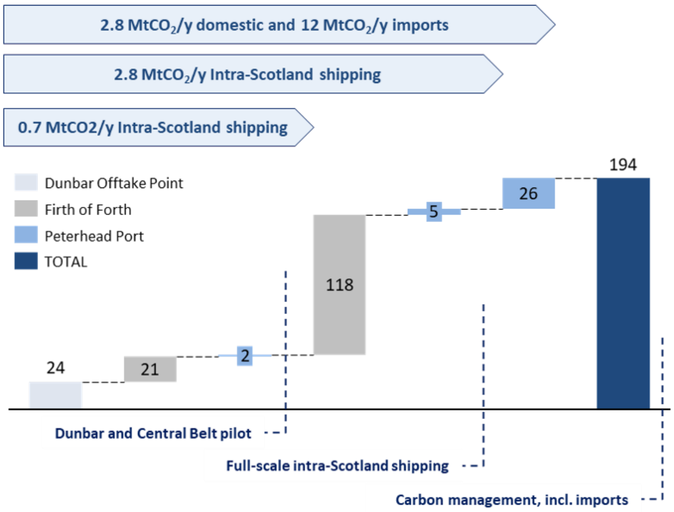


Figure 4-12: Baseline CAPEX investment in port infrastructure across scenarios (excluding ship costs) and additional investment required to accommodate increasing CO_2 shipping flows.

CO_2 injection facilities at St Fergus

As described in the sections above, **all CO_2 captured is expected to arrive at St Fergus facilities** prior to compressing to 120 bar and injecting the CO_2 into offshore stores for its permanent storage, as per Acorn CCS plans. In the four scenarios, the CO_2 captured will arrive from a variety of locations:

- CO_2 from Grangemouth: To arrive either via the repurposed **onshore pipeline and/or Firth of Forth ports**.
- CO_2 from Peterhead Port and Peterhead Power Station via a **newly built Peterhead pipeline**.
- CO_2 from local sources: Includes CO_2 from the St Fergus Gas Terminal (**Acorn CCS**), blue hydrogen production (**Acorn Hydrogen**) and **DACCS projects** deployed in proximity to Acorn CCS.

[131] In its Hydrogen Policy Statement, Scottish Government envisages the possibility to also export hydrogen via a pipeline connecting Scotland to Europe.

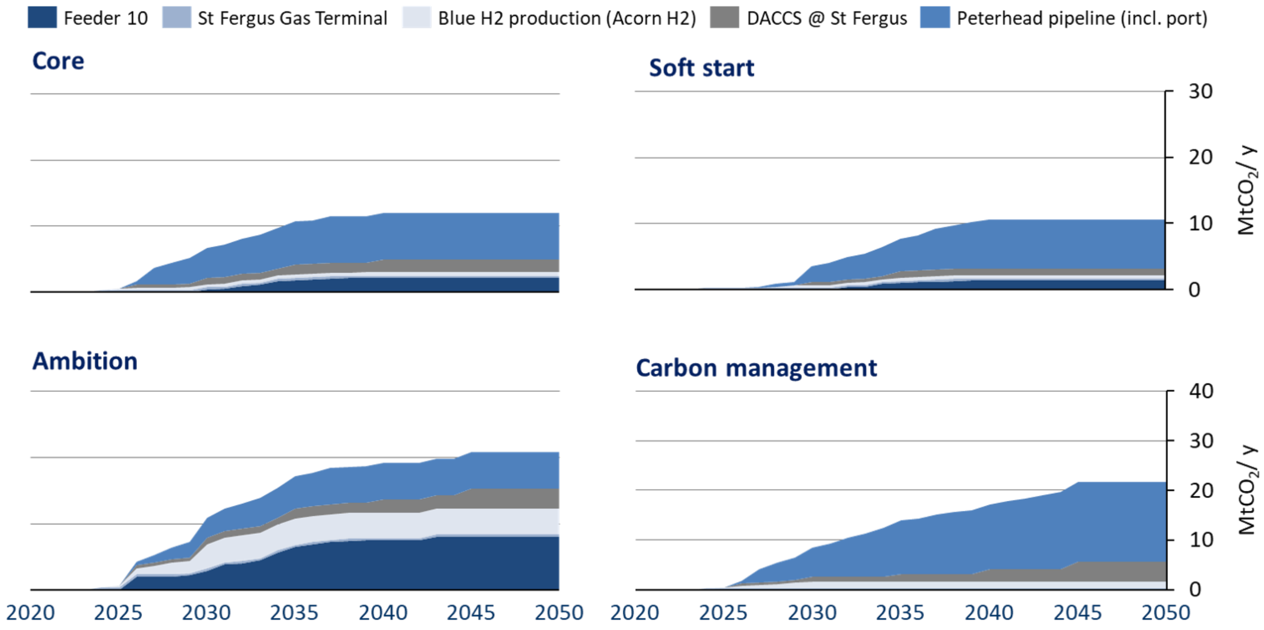


Figure 4-13: Breakdown of the location points for incoming CO_2 at St Fergus

Annual profiles of CO_2 arriving at St Fergus from the various Scottish locations are included in Figure 4-13. These profiles vary from **12 $MtCO_2$/year for Core and Soft Start to up to 22 $MtCO_2$/year for Carbon Management**. In Core and Soft Start, the CO_2 plateau roughly at the start of 2040, whereas imports and additional DACCS deployment in Ambition and Carbon Management lead to growing CO_2 annual profiles up to 2045. The scale of annual CO_2 throughput the varying rates of growth have important implications on the development of offshore infrastructure (described in the next section).

4.3 Offshore pipeline transport and storage

Scotland has a legacy of O&G infrastructure resulting from the region's history of extraction of offshore fossil resources. The **repurposing of some of this infrastructure to support CCUS supply chains** provides an opportunity for Scotland to re-invigorate some of the assets which would otherwise be subject to an expensive decommissioning process and reduce costs, as repurposing ageing pipelines could cost 75% less than building new ones[132]. More specifically, Acorn CCS is considering the repurposing of three legacy pipelines: the Goldeneye, Atlantic and Miller Gas System O&G pipelines for the offshore transport of CO_2. The project is also aiming to repurpose the Acorn CO_2 (also known as Captain Sandstone) and East Mey depleted fields for the safe and permanent storage of CO_2. As shown in Figure 4-14, the Goldeneye and Atlantic pipelines are connected to the Acorn CO_2 store, whereas the Miller Gas System connects to the East Mey store. Repurposing of the pipelines is subject to integrity inspection and repair of any previously unknown physical damage to the pipelines. However, required asset integrity and rectifying possible offshore pipeline corrosion could increase the overall capex up to four-fold[133].

Reuse of the existing three offshore pipelines will require additional engineering work to be completed to evaluate the integrity and exact CO_2 throughput which could be available for each pipeline. Nevertheless, previous Acorn CCS studies suggest that the pipelines' repurposing is technically feasible and that the

[132] Accelerating CCS Technologies: Acorn Project: D11 Infrastructure Re-use, ACT Acorn Project (2018)
[133] CO_2 Infrastructure development and potential reuse, Stuart Haszeldine, European's Cement Research Academy's online conference on CO_2 Infrastructures, held 3rd-4th of February 2021.

estimated capacity of the Goldeneye, Atlantic and Miller Gas System could be of 5 $MtCO_2$/year, 4 $MtCO_2$/year and 10 $MtCO_2$/year, respectively, **adding up to a total throughput capacity close to 20 $MtCO_2$/year** [134].

Regarding the storage of CO_2, **Acorn CCS has plans to initially use the Acorn CO_2 storage site**, which can store up to 152 $MtCO_2$[135]. This represents over 15 years of storage potential for Scottish emissions. Once an appropriate signal for sequencing arises (such as earmarking of Acorn CO_2 capacity via storage contracts), the **East Mey store could get commissioned for storage[136].** This second storage site has a storage capacity of approximately 500 $MtCO_2$[137]. Even though these two sites combined provide sufficient capacity for the levels of CO_2 which need to be stored to 2050 in the scenarios, additional offshore fields could be repurposed if needed[138].

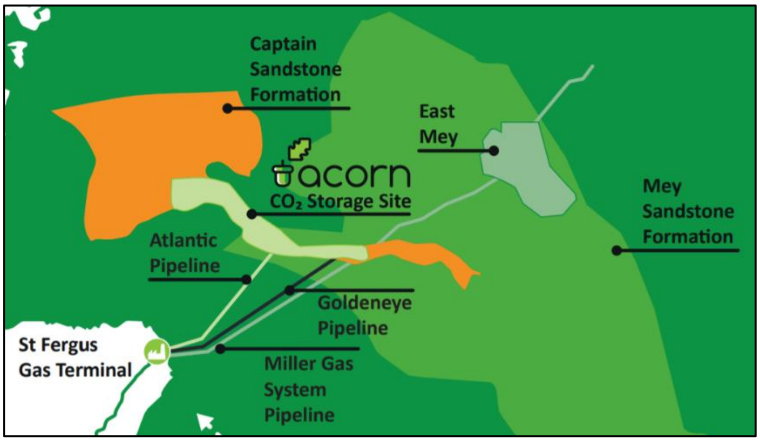


Figure 4-14: Illustration of the planned infrastructure reuse as part of Acorn CCS project.

Figure 4-15 shows the sequencing plan for offshore infrastructure i.e., how the pipelines are commissioned to accommodate for the growing CO_2 throughput and how these connect to the two CO_2 storage sites[139]. The approach selected attempts to **remove possible infrastructure constraints in the achievable annual CO_2 transport by commissioning additional pipelines as needed**. When sequencing transport infrastructure, priority is given to existing pipelines i.e., the Atlantic pipeline is commissioned once the Goldeneye pipeline reaches maximum transport capacity. Nonetheless, all scenarios require the roll-out of new pipeline(s) to Acorn CO_2 besides those existing ones[140].

In addition, the figure shows that **all scenarios require the use of the second store option**, East Mey, to meet demand for CO_2 storage. New pipeline(s) are also needed once the Miller Gas System pipeline reaches its maximum capacity. The date at which East Mey becomes available for storage varies among scenarios: Ambition is the earliest scenario (2038) and Soft Start the latest (2047). In all scenarios, it is assumed that East Mey would be ready for commission by the time Acorn CO_2 reaches its full capacity. At such point in time. Acorn CO_2 is sealed and its pipelines and injection wells are decommissioned prior to the post-closure monitoring.

It is thus the case that **the potential for CO_2 storage is not limited by the storage site capacity in the short and medium term**. Several other storage sites in the North Sea have been identified and appraised, providing a vast storage potential in the long term. This suggests that the limiting factors in the deployment of CCUS across Scotland consist in:

- **The lead timeframes for development of carbon management infrastructure**, in the form of pipelines or shipping infrastructure connecting the clusters of emitters to St Fergus.

[134] Accelerating CCS Technologies: Acorn Project: D11 Infrastructure Re-use, ACT Acorn Project (2018)
[135] Accelerating CCS Technologies: Acorn Project: D20 Final Report, ACT Acorn Project (2019).
[136] Alternatively, East Mey could be commissioned prior to the Goldeneye and Atlantic pipelines reaching their maximum throughput.
[137] Both the Acorn CO_2 and East Mey stores will require additional engineering work and simulations to further characterise the injection and monitoring operation as well as optimal well placement, among other activities. East Mey capacity extracted from Accelerating CCS Technologies: Acorn Project: D20 Final Report, ACT Acorn Project (2019).
[138] Extensive appraisal work was performed by the Energy Technologies Institute to characterise the suitability of North Sea aquifers and depleted oil and gas fields. Information available on: ETI, A Summary of Results from the Strategic UK CO_2 Storage Appraisal Project (2016). ETI has appraised 12 potential CO_2 storage sites in Scotland, with a CO_2 storage capacity of around 3,000 Mt CO_2.
[139] Accelerating CCS Technologies: Acorn Project: D20 Final Report, ACT Acorn Project (2019).
[140] It is assumed that new offshore pipelines would require transport capacities of 5-10 $MtCO_2$/year, in alignment with the throughput of the existing offshore pipelines to the two stores.

- The **economic case of deployment of carbon capture at large emitters** and provision of suitable business models and policies enabling this and reducing uncertainty and cross-chain risks.
- **Supply chain constraints**.

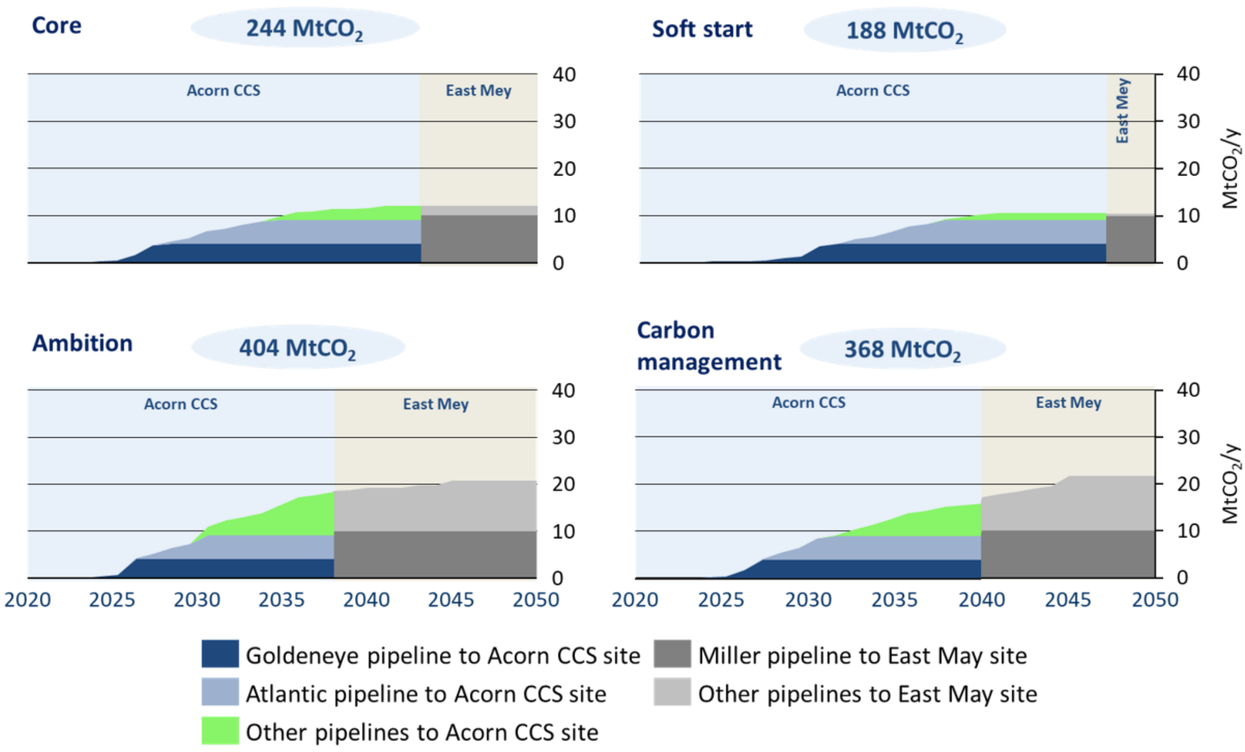


Figure 4-15: Timeline for utilisation of repurposed and new CO_2 offshore T&S infrastructure for each scenario

4.4 Emerging conclusions

Storing the CO_2 arriving at St Fergus will require the development of T&S infrastructure to connect the injection facilities at St Fergus with the Acorn CO_2 and East Mey stores. Part of this infrastructure is already present and can be repurposed, such as the Goldeneye, Atlantic and Miller Gas pipelines. However, additional infrastructure is required. This infrastructure can be broadly categorised as:

- **CO_2 injection facilities:** A compressor station is required at St Fergus to increase the pressure of the incoming CO_2 to the design pressure of the offshore pipelines.
- **Offshore transport:** Once compressed and dried, the CO_2 will arrive at the store location via offshore pipelines, which can be either repurposed or new build.
- **Offshore storage:** The CO_2 offshore pipelines arriving at each storage site are assumed to connect to a manifold. The manifold distributes the CO_2 to the various injection wells via in-field pipelines. Operation of offshore equipment is monitored and controlled from the onshore injection facilities through an umbilical connection to shore.

As annual CO_2 storage requirements increase, so will the need for additional offshore pipelines, compressors, and injection wells. As a result, the total amount of additional infrastructure and its sequencing will differ in each scenario. However, all scenarios are expected to store CO_2 in East Mey before 2050 - once the storage capacity of Acorn CO_2 is reached.

Improved economies of scale are achieved in scenarios with high CO_2 volumes

Scenario analysis suggests potential fees for the Acorn CO_2 site in the range of £11-12/tCO_2, with potential reductions of around 30% for the East Mey site (£8.2-9.5/tCO_2), with average fees across the two sites varying between £9.9-12/tCO_2, as shown in the figure below, when considering a 10% pre-tax IRR over the asset useful life[141].

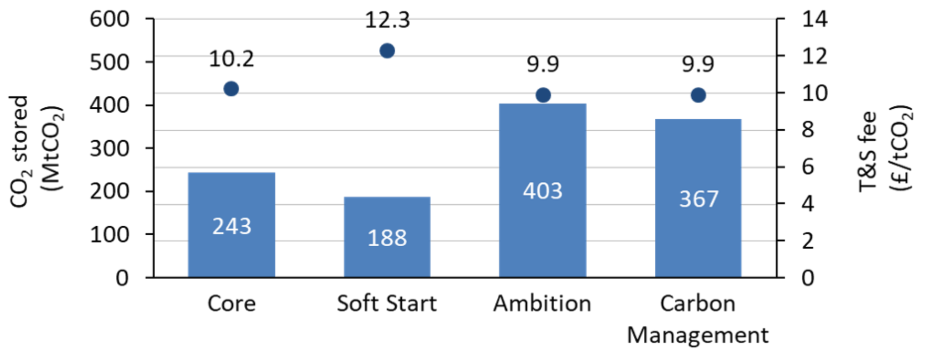


Figure 4-16: Average offshore T&S fees for Acorn CO_2 and East Mey (bubbles, right y-axis) in relation to each scenario's overall CO_2 storage volumes (columns, left y-axis)

Observed cost reductions can be attributed to the following drivers:

- **Scale of emissions stored:** the faster the growth in annual CO_2 storage requirements, the earlier additional offshore infrastructure is to be commissioned and the earlier East Mey would be deployed for CO_2 storage.
- **Storage capacity and project lifetime**: the average useful life for Acorn CO_2 offshore assets, such as pipelines and injection wells, is shorter than for East Mey. This is because East Mey's capacity is more than three times that of Acorn CO_2, and sufficiently large to take over 20 years to reach full capacity in the Carbon Management scenario. On average, East Mey useful life is 16 years longer than that of Acorn CO_2.
- **Synergies between the two projects**: a part of the investment needed to start storing CO_2 in East Mey is avoided, such as compressors from the common injection point at St Fergus.

This analysis considered the economies of subsequent commissioning of the two storage sites. However, similar economies of scale have been reported during the early commissioning of Acorn CO_2 and subsequent growth phases[142]. For example, an initial project phase consisting of an injectivity of 0.2 MtCO_2/year would have a unit cost of CO_2 storage of £155/tCO_2, whereas scaling up injection to a peak injection rate of 4.5MtCO_2/year brings cost reductions of 90%, to £14/tCO_2, similar to the £11-12/tCO_2 estimated for Acorn CO_2. This behaviour is repeatedly exhibited by other CO_2 storage projects around Europe, and the key to shortening the initially higher storage costs is by accelerating the rate at which additional CO_2 storage contracts are gained.

Efficient utilisation of infrastructure would be crucial for reducing the costs associated with offshore T&S. For example, clear monitoring and forecasting of CO_2 volumes should be used in guiding investment decisions. Whilst our analysis considered subsequent commissioning of East Mey following the filling of Acorn CO_2, East Mey could be commissioned once Acorn CO_2 has achieved a high filling rate. This would ensure that investment in infrastructure to increase injectivity (such as pipelines and wells) could focus on the developing

[141] Asset lifetime is based on the time it takes to fill up the storage site, based on a constant CO_2 annual flowrate past 2050. However, the amounts stored for East Mey shown in the figure represent the CO_2 storage requirements up to 2050, therefore assuming that the T&S fee required is maintained constant throughout the CO_2 store asset lifetime.
[142] Accelerating CCS Technologies: Acorn Project: D15 Economic Model and Documentation, ACT Acorn Project (2018). Costs reported in real terms for 2018. These are the cost requirements required to reach a Net Present Value of 0% and an IRR of 5.4%.

East Mey, instead on increasing the injectivity at the Acorn CO_2 site, which would be approaching the end of life. Although this approach would help reduce T&S fee of Acorn CO_2, long-term certainty for CO_2 storage contracts would be required to justify earlier investment in East Mey, a site significantly larger than Acorn CO_2. This contracting certainty would likely facilitate earlier approval by from Crown Estate Scotland for the licence for CO_2 storage in East Mey.

Scotland's competitive potential: price differential among storage sites

Similar studies have been conducted to estimate the T&S fees for potential offshore CO_2 storage sites in Europe. These studies, shown in Figure 4-17, can vary in terms of the cost accuracy of the estimates depending on the project stage e.g., FEED versus concept studies[143]. Nevertheless, these studies can be used to contextualise the cost-competitiveness of offshore CO_2 storage in Scotland relative to other similar projects in the North Sea:

- **UKCS:** The Energy Technologies Institute (ETI) conducted an appraisal study on the economics for CO_2 pipeline T&S on five sites in the UKCS[144]. T&S costs vary between the selected sites: Bunter 36 (£5.7/tCO_2), Viking A (£9.2/tCO_2), Forties 5 Site (£9.9/tCO_2) and Captain X (£13.4/tCO_2). The study also compared the cost data with previous FEED studies: Endurance (£4.3/tCO_2), Hewett (£9.3/tCO_2) and Goldeneye (£21/tCO_2).
    - Emerging project focus on the storage of CO2 from Humber and Teesside clusters in the Northern Endurance site (large saline aquifer). The development timeframes are similar to that of Scotland, however limited information is available on the plans for CO2 imports and the proposed T&S fees.
- **Netherlands Continental Shelf:** The Netherlands O&G Exploration and Production Association conducted a study for the storage of CO_2 transported from Rotterdam and Ijmuiden[145] back in 2009. The project aimed to store 30 Mt CO_2/year in the long term via pipeline transport. Long-term T&S costs have been estimated to be around £6.7/tCO_2 for a total storage of 900 MtCO_2. The costs calculated in the study were scoped for use of the same reservoir being considered by the Porthos project (a different project but one which is aiming to commence operations in 2024, aiming to store 2.5 MtCO_2/year in its early years).
- **Norwegian North Sea:** The Norwegian Full-Scale CCS Demonstration Project aims to capture CO_2 from two sites and use T&S infrastructure from the Northern Lights project to store the CO_2. T&S costs for this early project stage have been estimated at £42/tCO_2. However, it is expected that capacity utilisation increase, optimisation and learnings will lead to costs to reduce to £11/tCO_2 in the long term[146].

Many of the T&S costs required to reach breakeven for the storage sites presented above are similar to the costs presented in this analysis, which concluded that breakeven costs for Acorn CO_2 would vary between £6.8/tCO_2 and £9.0/tCO_2, depending on the scenario.

[143] It is noteworthy mentioning that the projects in Figure 4-17 are subject to different levels of proven storage capacity, mostly due to different levels of store appraisal. Cost data based on published literature. Costs for commissioned projects may vary depending on scale, timeframes, injection rate, and returns to T&S infrastructure operator. Costs for Acorn CO_2 and East Mey correspond to Core Scenario.

[144] ETI, Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: A Summary of Results from the Strategic UK CO_2 Storage Appraisal Project (2016). Information on other sites can also be found in Strategic UK CCS Storage Appraisal Project, funded by DECC - ETI Open Licence for Materials (2016). Costs reported for 2015 and T&S fee estimated to reach breakeven. All these fields are depleted gas fields or saline aquifers. Costs for these fields are deemed to be comparable on a like for like basis due to similar methodologies being used.

[145] DHV, Potential for CO_2 storage in depleted gas fields at the Dutch Continental Shelf: Phase 2: Costs of transport and storage, (2009). Storage in depleted offshore gas reservoirs. Costs reported for 2009 and T&S fee estimated to reach breakeven.

[146] DNV GL, The Norwegian Full-Scale CCS Demonstration Project: Potential for reduced costs for carbon capture, transport and storage value chains (2020). Costs reported are for the investor's perspective case. Costs reported for 2018 and T&S fee estimated to reach breakeven. Storage would be in the Aurora saline formation.

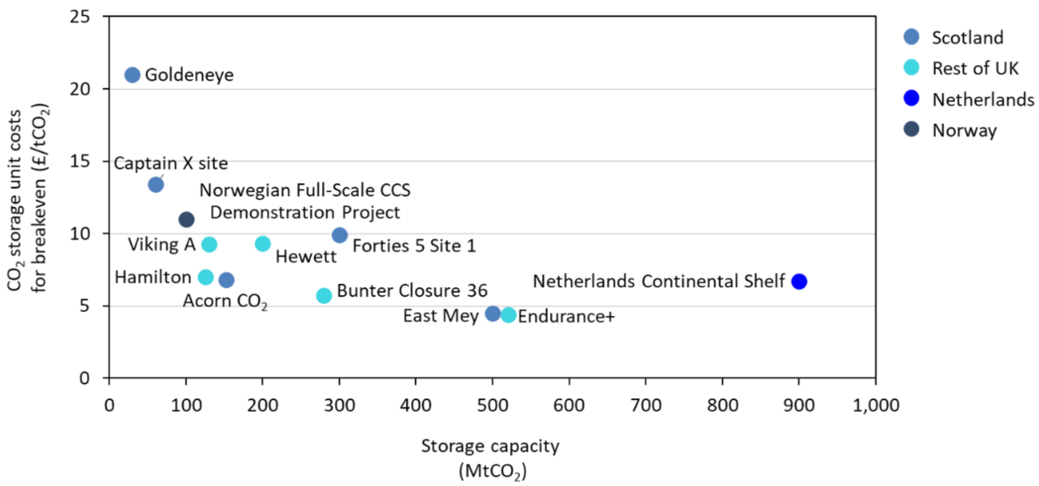


Figure 4-17: Comparison of T&S fee needed for breakeven for various CO_2 stores, including the price of pipelines. Costs for Acorn CO_2 and East Mey correspond to Core scenario.

A deeper look into Europe's most developed CO_2 storage projects: optionality in storage

Europe's most developed offshore CO_2 storage projects are Norway's Northern Lights, the Netherland's Porthos and Scotland's Acorn CCS (Acorn CO_2 hereby reported in Table 3). The three projects plan to start operations of their initial catalyst phase in 2024, where the projects will demonstrate T&S operations. Initial CO_2 storage is expected to be used to abate CO_2 from regional industrial sites, and successive growth could allow the three projects to use CO_2 shipping to help other regions decarbonise.

Table 3: Comparison of the key characteristics of three CO_2 T&S projects[147]. *Initial phase maximum growth is based on the maximum initial pipeline sizing. Acorn CCS reported here includes range of possible onshore transport fees on top of the offshore T&S fee shown in Section 4.4.

		Acorn CCS -	**Northern Lights -**	**Porthos -**
Project description	Expected start of operations	2024	2024	2024
	Completion of FID and expected date	○ - 2022	●	○ - 2022
	Domestic CO_2 transport mode	Pipeline Onshore pipeline connects to offshore pipeline in St Fergus	Shipping and pipeline Collection via ship and injected to offshore pipeline	Pipeline Backbone pipeline in port connects to offshore pipeline
	Name & capacity of initial store ($MtCO_2$)	Acorn CO_2 - 152	Aurora - 100	P18 field - 37
	Initial volume ($MtCO_2$/y)	0.2	1.5	2.5
	Initial phase maximum growth* ($MtCO_2$/y)	4	5	10
Key cost drivers	Considering shipping for CO_2 imports	●	●	●
	Access to additional storage capacity	●	●	●
	Initial repurposing of infrastructure	●	○	○
	CO_2 storage contracts signed	◔	●	◕
	Concentration of emitters	◕	◑	●
	Total distance of initial T&S value chain	◕	◔	●
	Estimated T&S by 2030 (£/tCO_2)	**15-29**	**25-47**	**38**

[147] Expected T&S estimates for the Northern Lights and Porthos projects were obtained in the European's Cement Research Academy's online conference on CO_2 Infrastructures, held 3rd-4th of February 2021. It is noteworthy noting that the costs for Porthos and Northern Lights have been based on external analyses featuring varying degrees of certainty, assurance and financial assumptions, reflecting the different stages of maturity each project is at. Please note that the comparison is sensitive to GBP-EUR exchange rates.

The estimated fees correspond to estimated values by 2030, although it is acknowledged that these could be offered at an earlier date due to accelerated CO_2 storage contracting. The T&S fee range provided for Acorn CCS corresponds to the lower (Ambition scenario) and upper (Soft Start scenario) range of fees estimated in this study. The Acorn CCS focus of Table 3 is Scotland specific, where the overall T&S fee results from the added fees for Feeder pipeline and offshore T&S.

The lower T&S fee expected for Acorn CCS relative to the other projects is partly due to the repurposing of existing offshore and onshore pipeline infrastructure, which could lead to up to 75% lower capital expenditure costs[148]. This presents Acorn CCS' true competitive advantage against other CO_2 T&S projects relying almost entirely on new infrastructure being built. Whilst the expected date for operation is very similar for the three projects, Porthos and Northern Lights have clearer contracting visibility (and thus lower perceived risks), with both Porthos and Northern Lights having signed either confirmed or preliminary contracts for storage.

The complexity and cost-effectiveness of T&S value chains is partially determined by i) the concentration of carbon capture sites, to maximise infrastructure sharing and the ii) total distance between the capture stage and the final CO_2 storage stage, to minimise total pipeline mileage and CO_2 shipping distances. Against these two factors and relative to Porthos and Northern Lights, Acorn CCS offers a good compromise, relying on Grangemouth's industrial cluster as its largest contributor of regional CO_2 sources. This requires a T&S chain leads of around 400km of onshore and offshore pipelines.

A commonality between these T&S projects - and other exemplars outside Europe such as Alberta's Carbon Trunk line - is the oversizing of initial transport infrastructure to account for future growth opportunities. The case for additional upfront capital investment is justified by i) the economies of scale inherent to pipeline CO_2 transport and by ii) the growing interest of potential future customers. The effect of initial underutilisation of oversized CO_2 pipelines on compression operations can be accounted for by reducing the flow of CO_2 to avoid phase change, enabling initial CO_2 volumes to be up to ten times lower than maximum throughput. Consequently, the Northern Lights, Porthos and Acorn CCS are using this scale-up strategy in order to reduce costs.

Box 7 – Accelerating project timeframes for carbon capture projects

Carbon capture is a mature technology, but successful development of carbon capture retrofit projects have been limited up to date, with just over 20 facilities currently operating worldwide[149]. As with any other engineering project, a typical carbon capture project must undergo a series of distinct project development stages which increase the level of project definition. Figure 4-18 shows the project schedule for a generic post-combustion carbon capture project in a large-scale industrial site. The first year is represented as the start for the pre-FEED stage, although prior project stages, such as concept and feasibility, are usually needed. Most carbon capture projects in the UK are either in the pre-FEED stage or earlier.

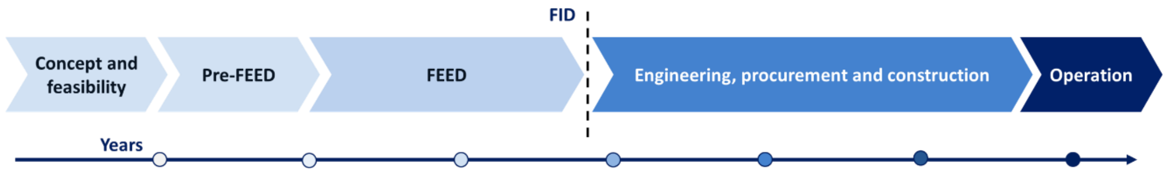


Figure 4-18: Illustrative (conservative) duration and phases for a large-scale industrial carbon capture project

[148] See Footnote 132.
[149] IEA: carbon capture, utilisation and storage.

As it can be seen from the chart, large-scale carbon capture projects can take up to 6 years to advance from pre-FEED to project operation. The complexity and size of this projects usually leads to multiple teams, contractors, and subcontractors being involved. The longest stage is the engineering, procurement and construction, as major equipment lead times drive the schedule. Permitting and consenting activities, whose awarding success is a requirement prior to FID, may increase the duration of the overall project schedule.

Duration of the overall project schedule shown above suggests that earlier carbon capture projects are advised to enter the initial project schedule stages within the short-term. This is especially true in the Ambition scenario, where the earlier commissioning of the pipeline for CO_2 transport could help carbon capture projects be commissioned as early as 2026.

The majority of the carbon projects within the power, industry and bio-CCS sectors are envisaged to reach operations by mid-2030s, and the smaller scale of some of these projects may lead to lower project timelines. Nevertheless, early carbon capture projects are considered to be essential to kickstart roll-out of CCUS infrastructure, and so a delay in these could lead to a domino effect to projects further down the timeline.

It is possible to accelerate some of these stages with increased ambition and resources. In addition to this, overall project timelines may be reduced once the Scottish CCUS supply chain acquires experience and leverages experience and knowledge sharing.

4.5 CCUS value chain investment requirements

The development of the CCUS scenarios will require investments in infrastructure for the capture, T&S of CO_2. The investment is broken down into capital (CAPEX), operational (OPEX), and abandonment investment (ABEX). In all scenarios, first capital investments into the CCUS supply chain are expected to begin several years before commissioning of the first projects in 2025 and continue until all the required supporting infrastructure is rolled out. As it can be seen from Figure 4-19, cumulative CAPEX investment plateaus between 2040 and 2045 for all scenarios, with all infrastructure in place ahead of the Net Zero target date[150]. The total CAPEX investment for CCUS infrastructure could vary between the £3.6bn to £7.8bn. In all scenarios, CAPEX investment in offshore CO_2 transport infrastructure is a very important component, even considering the cost savings resulting from the repurposing of existing infrastructure.

- In the Core scenario, the costs for capture in the different Scottish sectors and new markets (industry, power, blue hydrogen production and DACCS) are similar in magnitude and total £2.2bn (half of all the value chain CAPEX).
- Relative to the Core scenario, Carbon Management requires an increased investment of £0.7bn to transport offshore the additional CO_2 from DACCS and imports. Even if no cross-Scotland pipeline, such as Feeder 10, is repurposed, additional CAPEX investment is also needed in shipping and onshore transport infrastructure to connect Peterhead Port with St Fergus, and hydrogen production CAPEX increases to meet hydrogen exports.
- Investment into blue hydrogen production is an important component - especially in the Ambition scenario – where it represents a third of the total CAPEX investment. The Soft Start scenario has a similar CAPEX investment as Core. Most noticeably, the delay in deployment of infrastructure to support blue hydrogen production in the Central Belt leads decreases the blue hydrogen related investment of £0.3bn.

[150] Assuming a useful lifetime of carbon capture hardware of 30 years, a second wave of ABEX and CAPEX investment would be expected in 2050s for the earlier carbon capture projects deploying the technology in 2020s. This would also apply to offshore T&S infrastructure.

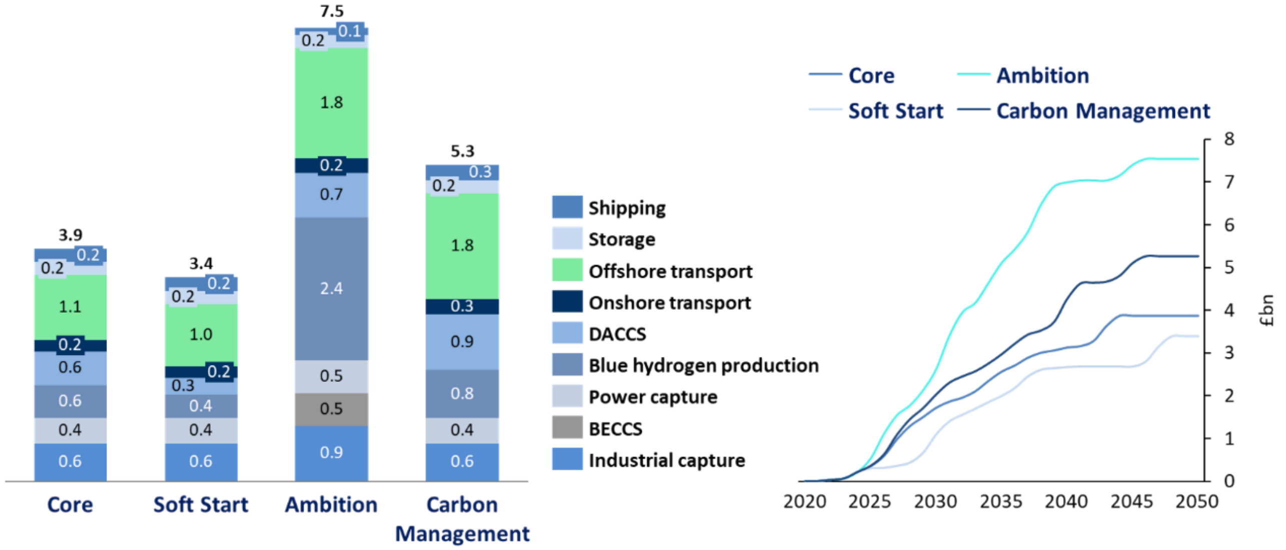


Figure 4-19: Capital expenditure breakdown up to 2050 per sector (left) and cumulative (right), both in £bn

When it comes to the capture stage of the CCUS value chain, most expenditure is dominated by the OPEX related to blue hydrogen production and DACCS, even if the latter exhibits some costs reductions as the technology matures[151]. All scenarios exhibit an early peak in investment before 2030 coming from the power sector for the newly built power plant: carbon capture equipment of the natural gas facility in the Core, Soft Start and Carbon Management scenarios; and blue hydrogen production equipment to supply the facility. After 2030, total investment in capture infrastructure remains relatively constant for the scenarios.

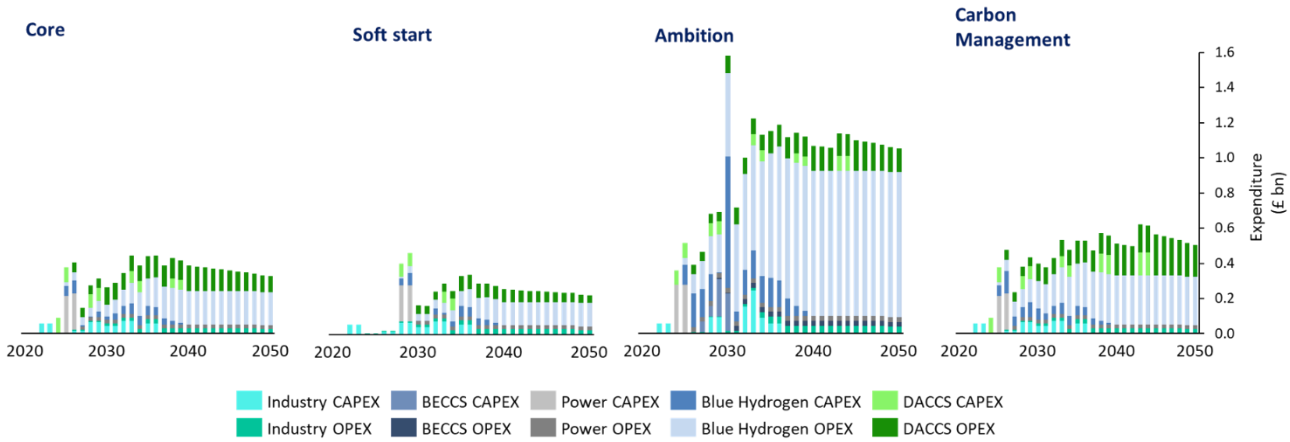


Figure 4-20: Total investment costs in each sector to deploy and operate carbon capture technology

This investment analysis accounts for potential cost reductions in carbon capture equipment resulting from technological progression. This analysis assumed that in the 2020s, all industrial carbon capture technology deployed will be FOAK. In this decade, carbon capture is expected to be deployed at scale both within the UK and internationally, leading to increased technology learning and expertise. In early 2030s, projects have been assumed to be second-of-a-kind (SOAK). In late 2030s, a time when the last industrial carbon capture projects occur, the technology is assumed to be nth-of-a-kind (NOAK).

[151] The costs of blue hydrogen production, especially the natural gas feedstock costs, have been assumed to remain constant. However, some literature suggests that natural gas prices may experience a slight increase in wholesale prices to 2050.

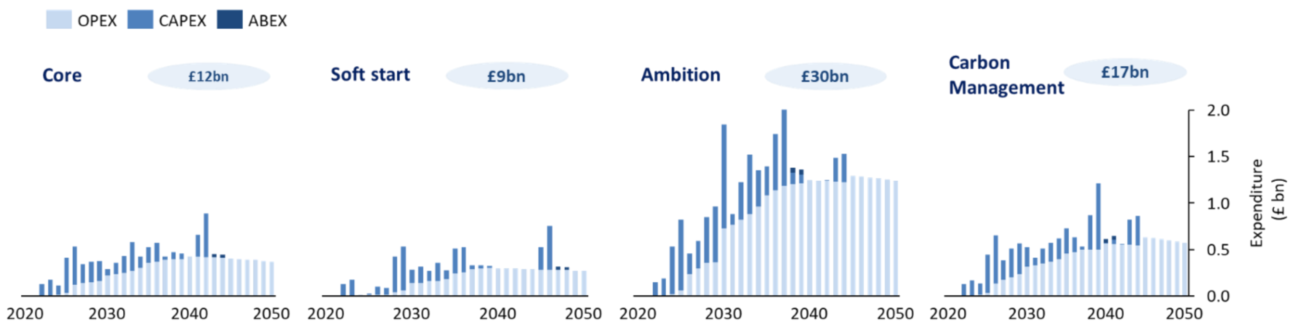


Figure 4-21: Annual expenditure in CCUS value chains per scenario (chart), and total cumulative expenditure to 2050 (bubble)

Figure 4-21 shows the CAPEX and OPEX annual investment for the CCUS value chain. A general trend among the scenarios is that operational investment of the CCUS value chain is the more important component, majorly due to blue hydrogen production OPEX associated with natural gas and electricity as well as due to the operation of DACCS. The latter peak in transport CAPEX and storage CAPEX (incurred in the late 2030s and early 2040s for all scenarios) comes from the investment required in the commissioning of East Mey, repurposing of the Miller Gas System pipeline and an additional pipeline to accommodate all for the large annual flows (especially coming from CO_2 imports as discussed earlier).

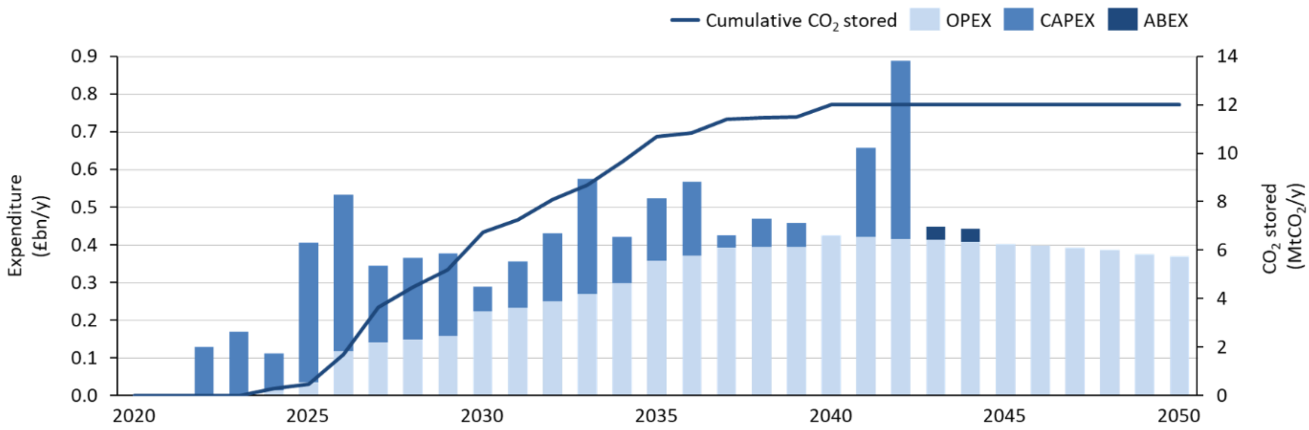


Figure 4-22: Annual investment in the CCUS value chain required in the Core scenatio (left y-axis) against the annual CO_2 volume being stored (right y-axis). Equivalent graphs for other scenarios in Appendix 9.4

Figure 4-22 shows the investment required in the CCUS value chain for the Core scenario against the annual CO_2 being captured. The figure suggests that the unit cost expenditure per tonne of CO_2 stored in the short- and medium-term is higher than in the long term, where annual CO_2 volumes are at its maximum. The trend is similar for the other scenarios too. This is because essential capital investments will be required to roll-out initial CCUS infrastructure, such as repurposing of pipelines, opening a CO_2 store and adopting less mature FOAK carbon capture technology. Latter investments in T&S are generally marginal in nature and are needed to accommodate higher annual volumes, such as additional compression, as discussed in Section 4.4.

This implies that the initial carbon capture projects could potentially be subject to higher transport fees, where transport fees would only reduce once more carbon capture projects tap into existing T&S infrastructure. This is exemplified in the Scotland pipeline transport fees reported in, which showed the average fee needed for financial viability of the reconversion project (however, this fee is an average over the asset lifetime and at scale, not reflecting the annual price of early CO_2 transport). Initial carbon capture projects may therefore require financial government support to remove some of the economic burden which may deter some projects otherwise.

5 Policies and interventions in support of CCUS

At present, CCUS technologies are not yet investable in the UK, although current work being carried out by UK Department for Business, Energy and Industrial Strategy (BEIS) on CCUS business models will bring financially viable business cases. **Development of such business models and other policy interventions** will act as crucial enablers to make CCUS an investable proposition in Scotland, where reliable revenue streams needed for investment can be taken forward. Policy interventions can help allocate risks and costs, and can ensure that initial CCUS projects can be progressively expanded to include all emitters that need CCUS.

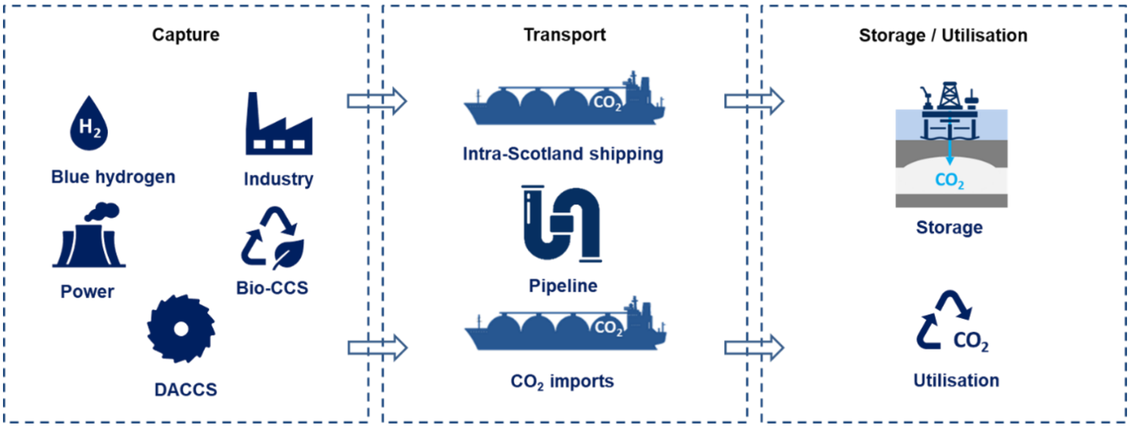


Figure 5-1: Illustrative representation of the various stages in CCUS value chains

This chapter will outline the different phases of the CCUS innovation chain and their effect on policy design. The chapter will then describe forms of policy/support available for CCUS. The chapter is then closed with a description of the main challenges within future CCUS segments which policy should address. This will be complemented with a synthesis of the likely future CCUS support mechanisms currently under development.

5.1 CCUS deployment phases

Government support for CCUS will evolve as the market pull for CCUS technologies grows over time. We can differentiate between two main phases that exhibit progressively reduced levels of risk and which could thus benefit from different policy interventions[152]:

- **Scale-up.** Characterised by a project-by-project approach, where public sector support is needed to reduce private sector exposure to risks and to prove technological viability and deliverability. The high-level of support provided is to be commensurate with a thorough understanding of project costs.
- **Roll-out.** Acceleration of CCUS deployment should be supported by robust business models, which include both financial support and risk sharing arrangements between the public and private sector. Support is intended to incentivise operational efficiency and reduce costs. During this phase, costs are gradually passed on to consumers and dependence on government support is reduced. Evolving commercial frameworks/business models and increasing carbon prices would help CCUS value chains slowly move towards independent market mechanisms. At such point of commercialisation, economies of scale would be fully realised and risks adequately distributed between stakeholders for long-term operation.

[152] Element Energy for IEAGHG: Enabling the Deployment of Industrial CCS Clusters. IEAGHG Technical Report (2018)

Box 8 – Existing and future UK-wide CCUS funds and competitions

An important support mechanism for the scale-up phase is through the provision of funds, normally granted either through UK-wide or Scotland specific competitions. These funds are generally provided for research and development/innovation and for early deployment.

Research and development. This form of funding aims to advance the technological understanding of capture technologies, provide innovative designs, and minimise the challenges needed for CCUS progression. In this category, recent funds have been granted i) to establish an Industrial Decarbonisation Research and Innovation Centre (£20mn) and ii) to develop DACCS and other GGRs through an ongoing competition (£100mn).

Early deployment. Funds for early deployment usually aim to commercialise CCUS by bringing funds to post-concept project phases (feasibility, demonstration and establishment of early CCUS infrastructure). We can differentiate between i) funds focused around CCUS, such as the CCUS Infrastructure Fund (£1bn) and Industrial Strategy Challenge Fund: Roadmap and Deployment (£170mn); ii) and funds for which CCUS is an eligible technology, such as the Energy Innovation Programme (£1bn), or the Industrial Energy Transformation Fund (£315mn).

Some examples of Scottish funding competitions and funds available to support CCUS (either currently open or in development) include:

- Energy Investment Fund (£20mn – closed), although CCUS is not a main focus.
- Low Carbon Infrastructure Transition Programme (>£60mn - closed)
- Green Investment Portfolio (£3bn)
- Scottish National Investment Bank (£2bn)
- Emerging Energy Technologies Fund (£180mn)
- Carbon Capture and Utilisation Challenge Fund (£5mn)
- Scottish Industrial Energy Transformation Fund (£34mn)
- Low Carbon Manufacturing Challenge Fund (£26mn)
- Energy Transition Fund (£62mn - closed)

5.2 CCUS policy design can take many forms

Policies available to support growth of CCUS can target all stages of its value chain. Some of these policies can be complementary and implemented in parallel. A summary of the policy options is included below (further details in the following sections):

- **Direct capital support:** Public bodies can provide grant funding support for projects which support advances in RD&D or which support the deployment of strategic CCUS projects. This policy can be used in combination with the majority of other options and is seen as a key form of capital support by industry to take projects past the FID stage. See box above for Scottish specific programmes.
- **Regulations and mandatory standards:** These include mandates to meet decarbonisation requirements, which can simultaneously influence multiple value chain stages. For instance, these can legislate the installation of carbon abatement measures, establish preconditions for regulatory approval for new facilities or determine the fee which is paid to T&S operators. Mandatory standards on producers and consumers can ensure that products bought or sold comply with carbon intensity requirements.
- **Direct operational subsidies:** This encompasses any policy providing long-term support, aiming to reduce the financial uncertainty which conventionally surrounds many CCUS projects, and help companies achieve their established hurdle rates needed for project approval. Operational subsidies include important business models such as Contract for Difference (see below) or Cost Plus Open

Book (where the government compensates the emitter via agreed-upon grants for the incurred operational costs and capital investment of a carbon capture project).

- **The UK Government and Devolved Administrations are currently working to establish initial support for CCUS value chains.** For example, in 2019 the UK Government carried out a consultation to CCUS stakeholders on potential business models for CCUS use in industry, power, T&S and other sectors such as low carbon hydrogen[153]. Further details on the structure and mechanisms of the business models will occur in 2021, and the completed business models should be in place in 2022, as set out in the Ten Point Plan[154,155].
- **Tax incentives:** These are tax credits (on a £/tCO_2 basis) which reduce the tax liability of emitters for fulfilling specific criteria aimed at decarbonisation. These can complement carbon pricing policies, and credits should be tradeable to fully realise their decarbonisation incentive value, albeit a government buyback may compensate if not possible.

- **Market mechanisms:** Initially introduced through regulation, market mechanisms demand companies to meet certain requirements/criteria, or alternatively allow them to pay others, for compliance purposes:
    - **Standards/benchmarks with obligations:** Performance standards can also reward environmental performance by imposing a penalty on emitters producing goods with a carbon intensity above a benchmark. A Tradeable CCS certificate + obligation, for instance, would require companies with no carbon capture deployment to buy CCS certificates from emitters with carbon capture.
    - **Carbon pricing:** Carbon pricing can come in the form of a cap-and-trade system or as a carbon tax. Whereas in the former a market allows companies to buy or sell emissions allowances based on their environmental performance, the latter is simply a financial penalty paid by emitters, based on their emissions. To protect industry against lower international carbon prices, a border carbon adjustment mechanism can be used.
- **Demand-side measures:** These policies are aimed at growing and promoting the market for CCUS-related infrastructure or products and have the potential to increase the market price for cleaner products by promoting the "added value". For example, procurement mechanisms can be used to ensure that a share of the materials used in construction projects come from processes implementing CCS or CCU. Use of these products can also be promoted by differentiation through certifications and labelling.

5.3 Key challenges and support mechanisms for CCUS segments within the value chain

Carbon capture: industry

Decarbonising Scotland's industrial sector would require addressing the risk of carbon leakage. Carbon leakage refers to the relocation of industrial activity to jurisdictions with less stringent environmental regulations (in this case a lower carbon price). This risk has been previously discussed for the case of Scotland in earlier work[156].

The price which businesses have to pay in order to emit CO_2 is a carbon price. In the UK, this carbon price is expected to be determined through an emissions trading scheme. If the UK carbon price is set higher than international carbon prices, it may impact businesses' ability to compete in an international market (particularly

[153] Department for Business, Energy and Industrial Strategy, Carbon Capture, Usage and Storage: A Government Response on potential business models for Carbon Capture, Usage and Storage (August 2020).
[154] Department for Business, Energy and Industrial Strategy, Carbon Capture, Usage and Storage: An update on business models for Carbon Capture, Usage and Storage (December 2020).
[155] HM Government, Energy White Paper (December 2020)
[156] Element Energy report for the CCC: Deep Decarbonisation Pathways for UK Industry. (2020)

for highly traded products). Carbon leakage is an undesired effect since it does not lead to CO_2 emissions reductions but solely to their relocation. Carbon leakage adversely affects local industrial economic activity and can lead to job losses.

Link between the expected future carbon price and support for CCUS

The UK Government and Devolved Administrations are working towards establishing a **UK Emissions Trading Scheme (ETS) this year to replace the UK's participation in the EU ETS.** This could be one of the more important UK carbon policy levers to drive decarbonisation. Whilst carbon pricing policy can affect sectors other than industry, this section focuses on the link between carbon price and industry.

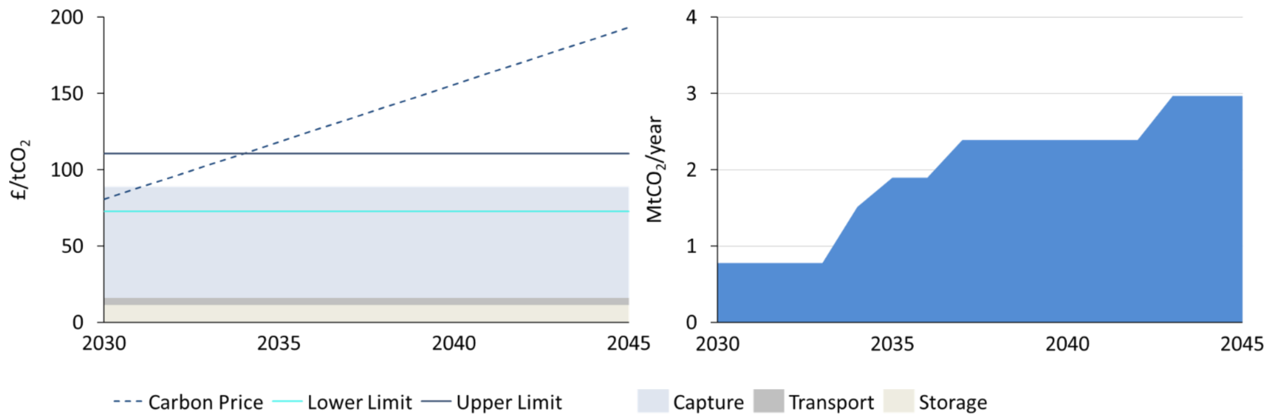


Figure 5-2: Left: Comparison of the full-chain costs for industrial CCUS in Scotland against the projections for the UK carbon price[157]. Right: Profile of industrial CO_2 capture[158].

Figure 5-2 compares the full-chain costs to capture, transport and store a tonne of CO_2 (on a £/tCO_2 basis) against BEIS predicted evolution of the carbon price. The figure focuses on long-term full-chain cost estimates, jumping over the shorter-term period (2020s) in which initial heavy capital investment would likely lead to higher full-chain costs.

According to the figure, price parity between average carbon price and full-chain costs would be reached in early 2030s. This study envisages that **up to a third of Scotland's industrial carbon capture capacity is deployed before such date**. This implies that CCUS deployment in the short to medium term (up to 2030s) **will require a strong supporting policy: direct subsidies, business models and other policy options** described in the sections below. Sufficient support would ensure that the combined effect of high carbon capture project costs but a relatively low carbon price does not deter the early development of CCUS[159]. This level of support would be expected to vary per sector, as suggested by the lower and upper limits exhibited in Figure 5-2.

As discussed above, policy available to drive industrial decarbonisation is not limited to use of a carbon price. This is because **even though a carbon price can lead to emissions reduction, additional policies may be needed to address the issue of carbon leakage**.

[157] UK Government: Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal (2020). Carbon price for the traded scenario.
[158] Graph assumptions: Costs depicted as an average of the costs of capture for Scotland's industrial sector for the Ambition scenario. The generic site is located in the Central Belt, uses onshore pipeline transport and stores CO_2 in Acorn CO_2 store. Financing assumptions for T&S fees as described in Chapter 4.
[159] The description provided does not consider the possible effect and interplay which the cumulative deployment of the carbon capture may have in the evolution of carbon price. Whilst influential to some extent, the carbon price projection is determined as an economy-wide guidance to value emissions. In addition, carbon price projections could differ based on standalone/linking UK ETS system with other ETSs. Due to timing of the project, this report has not given consideration to the potential size of the UK ETS, and the inherent differences it may have with the EU ETS in terms of volatility and liquidity due to the smaller nature of the UK market.

Preventing carbon leakage

Figure 5-3 shows the marginal CO_2 capture cost curve for different industrial sectors in Scotland. The economic impact of carbon capture on industrial process is not equally distributed across sectors because i) the cost of capturing a tonne of CO_2 depends on the carbon capture application, ii) products and commodities have different market values and production costs, and iii) the carbon intensity - which relates product output to the amount of CO_2 captured - of each industrial product varies (see Figure 5-4).

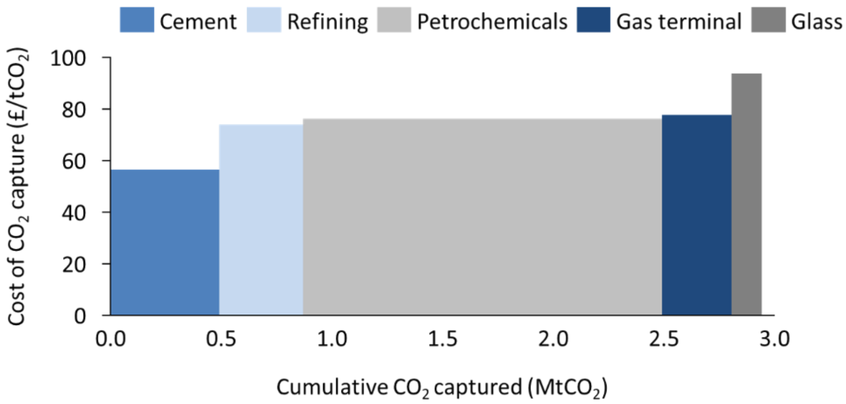


Figure 5-3: Marginal CO_2 capture cost curve for different Scottish industrial sectors[160].

Whilst Figure 5-3 is an important indicator of the impact of CO_2 economics on different Scottish industrial sectors, it is not the only driver of carbon leakage. This is because an industrial subsector is considered to be at risk of carbon leakage if **its carbon capture costs are high relative to current production costs** and if the sector **is highly competitive and internationally traded and/or has high price sensitivity of demand for output**. Figure 5-4, and Figure 5-5 investigate separately the implications which the curve shown in Figure 5-3 has on these variables.

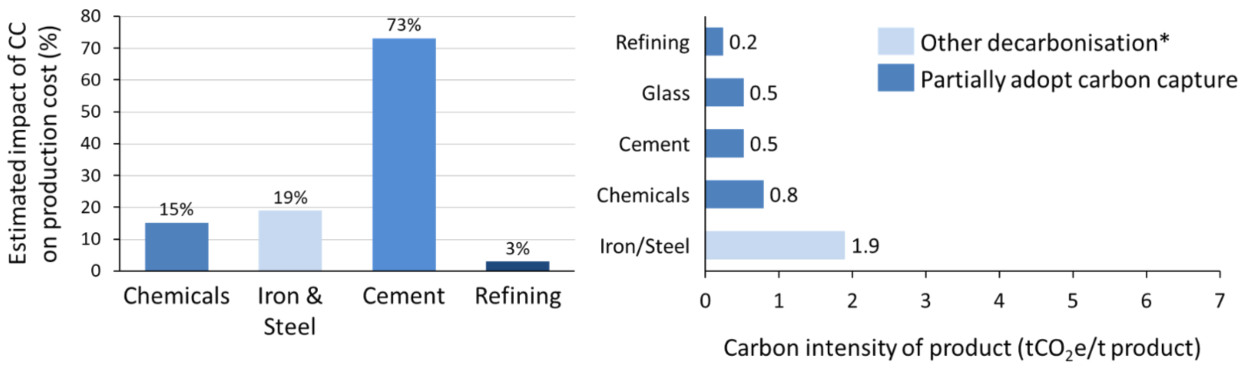


Figure 5-4: Left: Estimated impact of implementing carbon capture on production costs[161]. Right: Carbon intensities of different industrial products[162]. *Other decarbonisation includes fuel switching (to biomass, hydrogen, electrification), energy efficiency etc.

Figure 5-4 shows the estimated impact of implementing carbon capture on production costs for various industries. Based on this metric, the figure suggests that adoption of carbon capture would lead to the cement

[160] Chart shows carbon capture deployment for the Ambition scenario. Carbon capture technology used is advanced amines (or blends). Figure includes CAPEX, OPEX, fuel costs and costs of financing and excludes T&S costs. Petrochemicals include olefins. Based on expected year of deployment, CAPEX and OPEX costs vary per sector depending on FOAK/SOAK/NOAK progression e.g., cement project in 2037 deploys NOAK carbon capture.
[161] Analysis from Element Energy for BEIS, Industrial Carbon Capture Business Models (2018). The figure does not include T&S costs.
[162] From Element Energy for BEIS, Industrial Carbon Capture Business Models (2018) and Vivid Economics for DECC, Case Studies (2014).

sector experiencing the largest disruption to current production costs. An important reason for this is due to the relatively low market price per tonne output. Price changes resulting from carbon capture adoption in the other sectors are less disruptive relative to manufacturing costs.

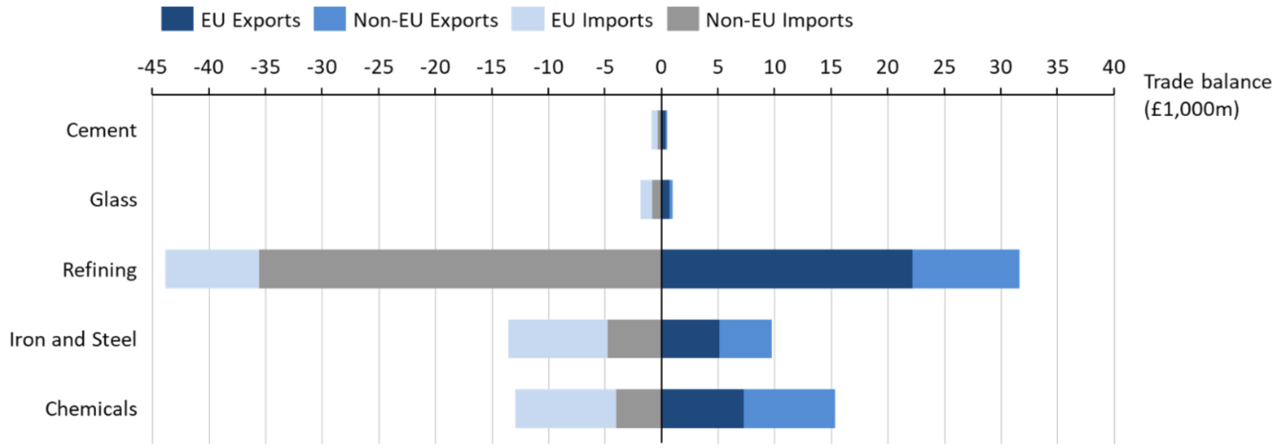


Figure 5-5: Breakdown of the international trade balance of imports and exports for the UK for key sectors likely to adopt carbon capture, and total value of UK exports for the specific sector[163].

However, the risk of carbon leakage is also influenced by exposure to international trading. Figure 5-5 shows the contribution of imports and exports to UK's trade balance. The figure suggests that all sectors within scope are at present substantially **exposed to international trade** - with the trade balance shifted towards import of commodities in many instances. As a result, the intensity of imports suggests that locally produced commodities could readily be replaced by imported equivalents if industrial competitiveness were reduced. The resulting possible loss in export economic value for the UK is also shown in Figure 5-5.

Based on the discussion presented, it can be concluded that **all Scottish industries deploying carbon capture would be expected to require support mechanisms**. To preserve Scottish industrial competitiveness in international markets, **an adequate support mechanism would ensure that the cost of production for a plant with carbon capture is equal to cost of production without carbon capture (which may include a carbon price).** In the short term, this can be achieved with an appropriate business model, such as a Contract for Difference (as described below).

To mitigate the impact of a potential carbon pricing divergence, a border carbon adjustment (BCA) could be linked and integrated with the UK ETS as the latter tightens over time. A BCA is a carbon policy which imposes an equivalent domestic carbon price - reflecting the true carbon content of a product - levied on Scotland imports that are produced in countries with lower carbon prices. Similarly, a BCA can account for the higher local carbon prices when it comes to exports too, as the mechanism can provide rebates or tax/regulatory reliefs to Scottish exporters to ensure these remain competitive in international markets[164].

Albeit potentially effective in protecting UK industries, BCAs may come with significant administrative complexities (cross-referenced)[164]. It can be challenging to establish the carbon content of products manufactured in foreign regions. Additionally, a BCA would also require regular adjustments and reviews in order to reflect changes to other regions' carbon pricing policies, such as varying international carbon prices. Other important Scottish trading partners, such as the EU, are considering imposing a BCA[165]. If applied in

[163] UK Trade Info: Overseas trade data tables for specific sectors in the UK with EU and non-EU regions for 2020. Sectors are generic and may include sub-products which are not produced in Scotland.
[164] Catapult Energy Systems: Industrial Decarbonisation: Net Zero Carbon Policies to Mitigate Carbon Leakage and Competitiveness Impacts (2020).
[165] European Commission: Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions. The European Green Deal (2019)

both jurisdictions, it remains unclear whether the BCAs would exclude regions with analogous carbon pricing mechanisms.

Whilst costs for a generic industrial project have been reported in the figure above, each subsector will realistically exhibit different costs. **Different levels of support would be needed per sector**, as sector-specific characteristics come into play, such as different techno-economics, role within the wider CCUS value chains and variations in risk and financial viability. These are discussed for each sector below.

Business models and supporting mechanisms for industry and power

Industry and power sectors would require significant policy support and clear business models to ensure viability of carbon capture projects, as stakeholders in these sectors generally operate under low profit margins.

- The **Contract for Difference (CfD) business model** is an operational subsidy which provides carbon capture project developers direct protection from market prices, in this case fluctuating carbon prices. A CfD strike price covers, for an agreed period of time, the price differential between the cost of implementing carbon capture and the cost recovered through carbon price avoidance. CfDs agreed-upon strike price may vary on a contract basis, but earlier projects would likely require higher strike prices due greater uncertainty and higher financial risk. CfD is the main business model option being considered in the UK for industry, with slight sector variations in its use.
    - In industry, it is likely that the strike price will be based on the prevailing CO_2 allowance price and agreed based on a per tonne of CO_2 abated. Besides providing capital funding for initial FOAK CCUS projects, the latest update for CCUS business models by BEIS proposes to use an **Industrial Carbon Capture Contract** and is specifically targeted for those sites for which have no other deep decarbonisation option**.** The model aims to cover operational expenses as well as T&S fees and rate of return on capital expenditure.
    - In the power sector, the latest update for CCUS business models by BEIS proposes to use a **Dispatchable Power Agreement**, which would replicate key provisions from the standard CfD business model. This business model is designed to incentivise dispatchable operation of CCUS power plants, in order to avoid displacing renewable electricity generation.
    - **Advantages.** CfDs are proven models offering a well-balanced compromise of benefits and acceptability to both industry and the government. With regards to industrial benefits, the model makes carbon capture more investable, as the long-term nature of CfDs brings clear revenue visibility. For the government, CfDs are familiar mechanisms which reduce the cost to government through their link to a market (carbon) price.
    - **Disadvantages.** CfDs come at some cost to the taxpayer, although the costs of this business model are lower than other options. Agreeing on a CfD strike price can be challenging, as the capture costs among industry vary widely and their capture cost estimations come with an uncertainty. In addition, CfDs need to ensure that the subsidy to an emitter does not incentivise more CO_2 production so as to receive additional payments.
- Additional policy options to support power and industry include market mechanisms **such as CCS obligations and tradable certificates** for both power and industry, **mandatory standards** for industrial products or **demand-side measures** such as labelling, certification or procurement.

Carbon capture: blue hydrogen production

Blue hydrogen is expected to be an important energy vector in Scotland, with the potential to contribute with up to 7 $MtCO_2$/year in Scotland, in the Ambition scenario. The risks and uncertainties associated with earlier blue hydrogen production sites are perceived as high by investors. This is because blue hydrogen is currently more expensive than the fossil fuels it replaces, and early projects would therefore require supply contracts to hydrogen consumers in order to progress. The small initial hydrogen demand but large demand growth projections could lead to the first projects being oversized, with added capital costs and initially low load-factors resulting in larger subsidy requirements in earlier project phases.

Mechanisms are not yet widely available to support low-carbon hydrogen production:

- Detailed assessment of potential business models for low-carbon hydrogen production at scale are being carried out by BEIS this year. The Department will take a disaggregated approach to business model design, differentiating by project scale as well as value chain stage, with commercial frameworks developing over time.
    - Various low-carbon hydrogen business models are being considered by BEIS after the publication of the report on possible business model options[166]. However, out of the recommended options, there is a preference for a business model offering **contractual payments to producers**, such as premium payment models or CfDs**.**
- Additional policy options can come through market-creation mechanisms encouraging low-carbon hydrogen demand via **incentivising fuel switching** to hydrogen and/or **low carbon fuel standards**.

Carbon capture: DACCS and BECCS

DACCS and BECCS are GGR technologies. There is currently a **lack of dedicated regulation to support CO_2 removal technologies, with little defined direction of GGR policy having yet been established nor integrated into emissions accounting frameworks**[167]. Support mechanisms for both technologies could consist of policies implemented cohesively:

- **Increased funding for RD&D[168]:** Increasing TRLs of GGRs is vital. Grant support is required to advance concerted RD&D efforts and demonstration projects, especially if a head start in technology deployment is desired[169]. Support for DACCS may also be combined with support for CCU projects, as it may aid initial market creation.
- **Operational subsidies and obligations**: Direct financial support of GGRs is likely to be needed, albeit it is important that the technologies advance to a market-based mechanism as soon as possible.
    - For BECCS, the UK Government is currently considering the form of policy support for BECCS use in the power sector, informed by a study from Vivid Economics[170]. Some options include:
        - Implementing an evolutionary pathway through a **CfD linked to the electricity price**. This model could be topped up with a negative emissions payment. This form of operational support is likely to be required until cost reductions are materialised.
        - **Implementing GGR obligations schemes**, where companies are required to secure negative emission certificates to meet their obligations. However, short-term

[166] Frontier Economics for BEIS: Business Models for Low-Carbon Hydrogen Production (2020)
[167] The UK Government has launched a call for evidence on GGRs, aimed at strengthening the government's base on GGRs, with an emphasis on GGR viability in the UK, role for the government and supporting policies.
[168] There have already been some examples of funding competitions for GGRs, such as the Direct Air Capture and other Greenhouse Has Removal technologies competition from BEIS (closed in February 2021).
[169] The UK Government has launched the Direct Air Capture and other Greenhouse Gas Removal technologies competition. The competition will be comprised of two phases. Phase 1, which was open for submissions until February 2021, will provide up to £250,000 in funding for design studies. Phase 2 will take forward the most promising designs from Phase 1 to pilot or for further development of the design.
[170] Vivid Economics for BEIS, Greenhouse Gas Removal policy options – Final Report (2019)

uncertainty around market prices suggests that these schemes would be best suited for the long-term.

- DACCS deployment requires market creation for tradable negative emissions certificates, with a value tailored to the technology in order to account for the emission reduction potential. A **policy-supported Negative Emissions Technologies (NETs) obligations framework** could ensure that sufficient negative emissions credits are purchased by emitters to secure demand volumes for CO_2 capture. This is particularly important in earlier DACCS projects to avoid underutilisation and balance supply and demand for CO_2 capture, where uptake of DACCS capacity could be higher than demand from emitters. International offsetting policy will also determine the suitability of DACCS use to abate emission from regions outside of the UK by trading certificates.

Carbon capture: CCU

CCU face barriers as **CCU technologies are generally not mature, and products manufactured via CCU pathways tend to be more expensive** than counterfactuals. In addition, not all CCU pathways are equally effective at sequestering CO_2 and so policies incentivising CCU need to consider long-term climate goals. Altogether, supporting CCU may require policy interventions in the whole CCU value chain, from capture of CO_2 to use of low-carbon products as well as incentivising the development and demonstration of new utilisation technologies. A series of options exist to incentivise CCU adoption:

- **Financial support:** direct capital support and operational subsidies (via contractual payments to producers), and **tax credits** are all suitable choices to promote CCU pathways, particularly in early stages of development.
- **Demand-side measures and regulation** can be effective policy interventions to promote CCU product adoption via mechanisms such as **mandatory or performance standards**, **certifications or labelling, and procurement**. For instance, specifying a percentage of the product or commodity to come from low carbon sources could be one action to promote CCU processes such as production of synthetic fuels or CCU aggregates.
- **Regulation to support CCU** needs to ensure that CO_2 is accounted correctly, without double counting. Full lifecycle analysis is important to rigorously assess the carbon benefits of a CCU option.

Transport and storage: pipeline and storage infrastructure

CO_2 T&S infrastructure is key to develop CCUS value chains, the successful deployment of which needs to consider various challenges:

- **The deployment needs to be a coordinated with carbon capture projects** to minimise demand uncertainties. It is unlikely that a company will own both the capture and T&S stages of CCUS value chains and so strong cooperation is needed between stakeholders. This can increase the financial funding clarity and reduce uncertainty around the total investment required to catalyse a CCUS value chain.
- **It is possible that, initially, only one CO_2 transport and one storage companies are operational in Scotland.** This could result in a regional monopoly. The regulated approach for the future **CO_2 T&S infrastructure** business model (see below) needs to ensure that the T&S fees are set at a price which removes monopolistic advantages.
- **Responsibility for leakage costs would remain with the T&S operator until the liability is transferred to the government.** T&S operators would be expected to use private insurance to mitigate risk exposure to leakage. However, private insurance may not always be available long term

and the government may have to provide last resort insurance. In addition, a commercial insurance market for leakage does not yet exist, and economic quantification of risks would need to develop.

- **The certification mechanism to allow for the storage of CO_2 emissions coming from EU emitters in the UK remains uncertain**. Ensuring compatibility of the UK and EU legal frameworks and potential agreements for coordinated monitoring and verification is vital to facilitate transboundary CCUS value chains.

Both the initial and ongoing investments into T&S infrastructure projects can be partially recovered through an appropriate business model:

- The **Regulated Asset Based (RAB) business model** has been proposed as the main support mechanism for T&S in the UK. The RAB mechanisms allows T&S operators to charge a regulated and agreed-upon fee based on T&S project costs. A RAB model helps project developers estimate a projected return on investment. The fee charged to users can fluctuate with time to reflect uncertainty of costs over the operational period of projects, thus helping to spread certain risks between T&S operators and users. Recent update from BEIS on CCUS business models suggests that the T&S business model to be implemented is likely to be referred to as **CO_2 Transport and Storage Regulatory Investment Model (TRI)**, and the fee is expected to have two components: a volumetric fee and a capacity fee**.**
    - **Advantages.** The RAB model is acceptable to both industry and government. The model allows for full investment recovery, bringing revenue certainty. The model, which has a strong policy track record in the energy industry. The T&S fee is agreed with an independent regulator, whose involvement and decision-making power encourage the selection of more cost-effective projects.
    - **Disadvantages.** Under a RAB model, it can be challenging to determine the ownership structure (whether public or private) and roles of system operator as well as the level of government support required. Finally, the RAB model can be administratively complex and T&S fee negotiations with independent regulators cap project returns, changing the investor profile.

Transport and storage: CO_2 shipping and CO_2 imports

Importing CO_2 can create jobs and bring economic benefits to Scotland by levying a storage fee per tCO_2 imported. However, there is a series of challenges which need to be addressed:

- CO_2 shipping value chains could be formed by numerous stakeholders, such as vessel owners and operators, port owners and infrastructure operators. Incorporating all players into future CO_2 shipping models could be a complex task, where careful design would be required to avoid double subsidies.
- CO_2 shipping is likely to be operated by private companies. However, as shown in this study it is likely that an intra-Scotland CO_2 shipping option proves less cost effective than pipeline transport. Whilst investment in intra-Scotland CO_2 shipping infrastructure would require higher expenditure, this initial investment could still prove beneficial in the medium to long-term as CO_2 imports activities would be facilitated by, and supported on, previous investments.
- An additional complexity is possible differences in subsidy architectures implemented throughout Europe, as operational support through business models is expected to come from Member States. This can lead to certain countries with higher subsidies to dominate international CO_2 shipping industries and reduce opportunities for intra-Scotland CO_2 shipping.

Business models being investigated for CO_2 transport do not presently include CO_2 shipping in their scope, albeit it is acknowledged that this is an area for future expansion and further work in this topic is required[171].

- **Expanding the RAB model for CO_2 shipping** could promote competition by granting a license for operation to those companies offering the lowest CO_2 transport fees. This expansion could result in the envisaged transport pipeline-shipping fee gap narrowing (if intra-Scotland CO_2 shipping were to eventually become a reality, see Chapter on recommendations)[172].

Criteria	Key drivers and projects in scope
Risk of carbon leakage: Maintain industrial competitiveness	For industries most exposed to carbon leakage (risk measured via **higher product price disruption** or **more international exposure to trade)** which have no deep decarbonisation solution other than CCUS.
Accessibility to T&S: Minimise construction of new pipelines	Projects closer to core infrastructure such as Feeder pipeline in **Grangemouth cluster** and CO_2 injection points in **St Fergus** would reduce investment in supporting infrastructure such as CO_2 collection networks.
Cost-competitiveness: Reward cost-effectiveness	If comparable on a like-for-like basis (e.g. carbon capture projects within the same industry), **projects with higher cost competitiveness** would increase funding availability for additional projects.
Scale of captured CO_2: Evaluate project decarbonisation potential	Projects aiming **for higher annual CO_2 capture** would help Scotland accelerate its 2030 decarbonisation goals and reduce cross-chain costs by ramping-up the T&S asset utilisation rate.
Co-benefits with blue hydrogen: Exploit project synergies	Projects which **include a complementary decarbonisation strategy** via hydrogen fuel switching or projects including **expansion for blue hydrogen production** would kick-start hydrogen supply and remove barriers for hydrogen deployment.
First-mover advantage: Maximise additionality of projects	Projects which capture market opportunities whose **additionality value is reduced** if competitor projects are deployed elsewhere. Examples of first-mover advantage would be **hydrogen export** and **carbon management** opportunities.

Figure 5-6: Usable criteria to evaluate potential areas for project support prioritisation

[171] Department for Business, Energy and Industrial Strategy, Carbon Capture, Usage and Storage: An update on business models for Carbon Capture, Usage and Storage (December 2020).
[172] On their latest update to the TRI business model, BEIS have acknowledged the future need to develop the licence conditions and business model arrangements so that shipping can be accommodated by the TRI model. More will be published on the topic during 2021.

6 Skills, supply chain and capability requirements

This section of the report presents the results of an analysis to understand the skills gaps in the Scottish industrial supply chain, for the deployment of CCUS and hydrogen. This is an important consideration in the Scottish Government's CCUS policy toolkit, since skills gaps in the supply chain are likely to impact on the overall effectiveness of CCUS policy and therefore also the approach to the 2045 Net Zero target.

6.1 Summary

The EIC SupplyMap supply chain database (details in Box 1) and the Energy Innovation Needs Assessment (EINAs) CCUS report were used to quantify the potential gap between the Scottish O&G and CCUS industries in 2045. By comparing the potential revenue able to be captured in the CCUS supply chain (goods and services) in 2045 based on the EINAs CCUS report, with the potential revenue able to be captured in the O&G supply chain (goods and services) in 2045, if CCUS equipment were to be installed at O&G facilities – for which we used the ViEW modelling conducted for Task 1.4 in conjunction with the EIC SupplyMap database – we were able to understand the potential gap. This was done across the entire CCUS supply chain, encompassing capture and pollution control; conversion and generation; T&S; MMV and EPCm.

Stakeholder interviews were conducted to further substantiate the quantitative gap analysis and understand potential policy solutions. By comparing and contrasting with findings from the Climate Emergency Skills Action Plan by Skills Development Scotland and the Scottish Just Transition Commission's green recovery report, we were able to triangulate across the evidence base.

Our analysis finds that the total gap seems manageable relative to the size of the Scottish CCUS supply chain in 2045, but significant when we zoom into individual supply chain categories (capture and pollution control, conversion and generation, T&S, MMV and EPCm)**.** Specifically, we find that:

- **There is a gap in two out of five of the CCUS supply chain categories.** These are capture equipment and EPCm. The total gap is ~£125mn[173].
- **There is a gap of ~£110mn in potential revenue able to be captured by Scottish companies, in capture equipment between the 2045 Scottish O&G sector and the 2045 Scottish CCUS sector**. This gap is ~10% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 (~£1bn) or ~6% of total revenue able to be captured across the entire Scottish O&G industry today (~£1.8bn). However, since there are gaps in only two out of the five CCUS categories, it is important to note that the gap in capture equipment represents ~90% of the total gap of £125mn.
- **There is a gap of ~£15mn in potential revenue able to be captured by Scottish companies, in EPCm between the 2045 Scottish O&G sector and the 2045 Scottish CCUS sector**. This gap is ~2% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 (~£1bn) or less than ~1% of total revenue able to be captured across the entire Scottish O&G industry today (~£1.8bn). However, since there are gaps in only two out of the five CCUS categories, it is important to note that the gap in EPCm represents just ~10% of the total gap of £125mn.

[173] These numbers have a high degree of uncertainty associated with them, including underlying assumptions on the size of the market (quantity of CCUS able to be deployed and costs), the potential market share which could be captured in the UK and the translation of that potential market share to Scotland. Additionally, there are uncertainties in the policy mechanisms which may enable deployment of CCUS and the evolution of its cost curves. Because of the significant uncertainty in forecasting the energy system and demand for CCUS technology in the future, it is not possible to quantify the level of uncertainty, so we do not provide error bars. However, all numbers from the analysis should be read cautiously and not seen as definitive. Any use of these numbers should appropriately include these caveats for the avoidance of doubt, particularly in public dissemination.

- **The 2045 Scottish CCUS supply chain is smaller than the 2045 Scottish O&G supply chain in conversion goods and services, storage and transport goods and services and MMV goods and services**, meaning that there is no gap in these CCUS supply chain categories.

Our stakeholder interviews confirm the findings from our top-down analysis - many of the leading trade bodies recognise that the skills needed to enable Scotland to participate in the Net Zero transition exist. The key findings are:

- **Scotland has many strengths which can be translated to the CCUS industry.** There are no major technical skills gaps. The requisite skills, expertise and capability to build a CCUS supply chain in Scotland already largely exist and the Industrial Strategy Challenge Fund should help some companies get off the ground.
- **But there are barriers which will need to be overcome**. These include the lack of a formal regulatory environment for CCUS; the potential to be outcompeted on scale as most of the CCUS clusters in the UK are not in Scotland; limited availability of high quality public datasets for companies to start evaluating potential CCUS storage sites; limited availability of high quality public datasets for companies to start evaluating potential CCUS storage sites; limited understanding of how plugging and abandonment of CO_2 wells will work and limited government investment in CCUS relative to what might be possible given State Aid provisions after Brexit.
- **The key gap in skills is in specialist technical skills such as subsurface geological modelling**. Additional investment in the UK's Centres for Doctoral Training was mentioned during stakeholder engagement and it is clear that these are seen as an effective means to start to bridge the gap between academic R&D and solving technical challenges in industry.[174]

There are a number of potential policy interventions which government could make to help overcome these barriers. These include making finance available for companies to invest in developing new capabilities; joint governmental procurement of CCUS equipment for Scottish CCUS projects, establishment of a CCUS regulator; publication of a policy statement and action plan for CCUS by the Scottish Government; increasing local content requirements and increased investment in line with Subsidy Control provisions.

6.2 Outline

This section begins by outlining the current state of the Scottish industrial supply chain, including how the supply chain has been pivoting away from O&G in the past few years. It then quantifies where there are gaps in the end-to-end supply chain for CCUS in Scotland in 2045, based on a comparison with the potential size of the 2045 Scottish O&G sector. The EIC SupplyMap (see Box 9) and the Energy Innovation Needs Assessment CCUS reports are used for this analysis. Finally, evidence from stakeholder interviews on the gaps in the supply chain and skills is discussed, including potential policies to plug these gaps and evidence of their effectiveness from the literature.

[174] Centre for Education and Policy Analysis: The DTC Effect: ESRC Doctoral Training Centres and the UK Social Science Doctoral Training Landscape (2018)

Box 9 – EIC SupplyMap

EIC SupplyMap is a software tool developed from 2018 onwards by the Energy Industries Council. It provides an up-to-date and verified map of more than 3,500 UK energy sector supply chain companies. Key features of EIC SupplyMap were identified in selecting it for the supply chain gap analysis. These are:

- **Highest granularity:** Includes all companies with revenue >£1m, since these are most likely to be focussed on export market.
- **Widest sectoral coverage:** Broad categories, such as auxiliary equipment and ancillary equipment are included.
- **Constantly updated:** EIC constantly update and revise the data, including addition of new firms. They plan on covering Hydrogen and potentially other emerging low carbon technologies in the coming months.
- **User friendly:** Data can be filtered and cut/analysed in multiple ways through a slick interface requiring minimal training/support.
- **Industry standard:** Captures the entire supply chain at the granularity needed and has had extensive input across the entire supply chain.

6.3 History of Scottish industrial supply chain

The Scottish industrial supply chain has historically been built around the O&G industry. The supply chain has grown organically in two phases. In the first phase, engineering fabrication facilities were started to supply parts and equipment for the Industrial Revolution. Part of this was to provide facilities for the Scottish ship building sector growing up around ports such as Glasgow. The decline of an industry for building commercial ships, led to a gradual decrease in the number of such companies. Those that remained up to the Second World War, provided engineering fabrication and construction for industrial facilities in other parts of the UK. At this time, engineering consultancy services – such as Wood Group – started to appear and grow. In the second phase, when the Montrose oil field was discovered 135 miles east of Aberdeen, in December 1969, a much larger number of engineering fabrication facilities started to emerge, as the Scottish industrial supply chain started to evolve to support complex FOAK engineering projects.[175]

6.4 Recent changes in the Scottish industrial supply chain

In recent years, the Scottish O&G sector has undergone structural changes due to changes to asset ownership and economic incentives. Importantly, the decline in O&G production has come despite increases in O&G exploration and production, incentivised by a regulator which is seeking to maximise economic return (MER) in the North Sea.[176]

Three key trends have driven these structural changes in the Scottish O&G sector. First, new investors have entered the North Sea, as companies with legacy fields and offshore production platforms, have exited the market – as part of portfolio optimisation strategies - and sold to private equity companies such as Harbour Energy.[177] Based on a model where such private equity companies invest in assets before making an exit a few years later (rather than holding on to assets in the long term), such deals have started to result in increased

[175] Julian Turner for Power Technology: A clean start: could Aberdeen become a destination for renewables? (2020)
[176] UK Oil & Gas Authority: Maximising economic recovery of UK petroleum: the MER UK strategy. OGA publication (2016)
[177] Wood Mackenzie: UK North Sea M&A gains pace with NEO, Waldorf deals. (2021)

investment in technology to extend the life of maturing O&G assets.[178] This has combined with the second key trend: increased economic incentives for enhanced O&G production have resulted in changes to the petroleum taxation regimes, including the setting of the Petroleum Revenue Tax permanently to 0% (from 50% in 2013) and the decrease in the Supplementary Charge to 10% (from 32% in 2013).[179] Combined, these two trends have started to result in a slight uptick in O&G production from the North Sea. A third trend has then acted to prevent the abandoning of mature offshore O&G infrastructure. This is the increase in deployment of offshore wind off the coast of Scotland – owing in part to the UK Government's strong policy commitment to the technology and the success of the CfD scheme - which utilises O&G infrastructure such as platforms.[180] Indeed, there is now talk of electrifying offshore O&G platforms by provision of energy through offshore wind farms to these platforms, helping to tackle the 10% of the UK total energy supply emissions currently attributed to such platforms.[181]

The Scottish industrial supply chain has also been changing, due to more varied and diverse offerings to both the O&G sector and the emerging offshore wind sector. For example, the change in ownership of O&G assets in the North Sea, has resulted in an increase in orders for equipment and materials for existing platforms and new infrastructure being built to facilitate the maximisation of economic revenue.[182] This has led to increases in orders for equipment and engineering consultancy services to modify platforms, pipelines and equipment, as well as designing, constructing, commissioning and operating new infrastructure.

6.5 Future impact of climate policy on Scottish industrial supply chain

The Scottish Government's climate policies – including the 2045 Net Zero target – add new pressures and provide new opportunities for the Scottish industrial supply chain. Two aspects were assessed:

- the potential gap in the size of the 2045 Scottish CCUS industrial supply chain
- the view of industry stakeholders on strengths, barriers and potential policy interventions, to enable participation of the Scottish industrial supply chain in CCUS and hydrogen.

6.5.1 Potential gap in the size of the 2045 Scottish CCUS industrial supply chain

There are similarities between the O&G and CCUS supply chains. These include in the design, engineering and fabrication of materials and equipment such as pumps, compressors, turbines, valves and pipework, as well as in the provision of services such as EPCm services, finance, insurances and legal services. It is important to recognise that although CCUS is a nascent industry, it is essentially still a heavy engineering industry and therefore can utilise skills and expertise from the O&G supply chain. Stakeholder interviews summarised later in this section confirm this. Box 2 explains the key aspects of the CCUS supply chain. Key differences between the O&G and CCUS supply chain concern the role of the sector as either primarily one which creates high value commodities from raw materials (O&G), or primarily removes a waste product but also transforms some of the waste product into a useable but relatively low-value commodity in the form of CO_2 (CCUS).

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[178] Allen & Overy: Private equity's upstream journey. Will investment in the world's ageing oil and gas basins ultimately pay off?. Report in association with Petroleum Economist (2020)
[179] UK Oil & Gas Authority: Exploration & production taxation. Overview
[180] Martin Whitmarsh for Offshore Wind Industry Council: The UK Offshore Wind Industry: Supply Chain Review (2019)
[181] Dentons: Oil and gas and renewables in the UK: synergies on the way to Net Zero. Article (2020)
[182] UK Oil & Gas Authority: Maximising economic recovery of UK petroleum: the MER UK strategy. OGA publication (2016)

Box 10 – Categories in the CCUS supply chain[183]

Carbon capture and air pollution control equipment: Relevant for power and industry. It is the part of the supply chain concerned with capturing CO_2 from flue streams, concentrating it for compression and compressing it for storage. Components include air pollution controls such as specialty solvents, flue gas desulphurisation, and air separation and compression equipment.

Generation equipment: Relevant for power only. Components include gas, coal, or biomass combined cycle turbines and specialty oxyfuel turbines.

T&S components: Relevant for power and industry. It is the part of the supply chain concerned with moving the compressed CO_2 to storage sites. Components include both the associated capital equipment, such as pipelines and injection equipment, and the potential opportunity to store CO_2 as a service for other countries.

Measuring Monitoring and Verification: Relevant for power and industry. It is the part of the supply chain concerned with ensuring that the CO_2 is captured, transported and stored safely without leaks. Components include instruments related to measuring, monitoring, and verification of CO_2 capture, transport, and storage.

Engineering, procurement, and construction management services: Relevant for power and industry. It is the part of the supply chain concerned with designing, building and installing CCUS plant and equipment. Includes engineering, procurement, and construction management services for CCUS projects.

In order to understand the potential gap in the size of the 2045 Scottish CCUS industrial supply chain, a gap analysis was conducted. Specifically, the following steps were undertaken (detailed methodology available in Appendix 9.6):

- The revenue which the Scottish O&G supply chain captures today was calculated from the EIC SupplyMap supply chain database.
- This value was then translated to a 2045 potential revenue for the Scottish O&G supply chain, by applying a percentage change in the size of the Scottish O&G sector from today to 2045, from ViEW modelling conducted for Task 1.4 of this report.[184] The Ambition scenario was used, as this has the highest level of CCUS deployment in the Scottish O&G industry and therefore represents the largest change in the size of the Scottish O&G sector relative to today. Using the percentage change from this scenario enables a direct comparison.
- The potential revenue which the Scottish CCUS supply chain could capture in 2045 was calculated from the EINAs CCUS report[185].
- The difference in potential revenue between the 2045 Scottish O&G and CCUS industries was calculated as the potential gap in the size of the 2045 Scottish CCUS industrial supply chain.

Figure 6-1 summarises the approach.

[183] Modified from Vivid Economics for BEIS: Energy Innovation Needs Assessment for CCUS (2019)
[184] Approximately 25% increase in GVA of fossil fuel production sector in Ambition scenario in 2045 relative to Baseline (where fossil fuel GVA ~0) (2019£M)
[185] Vivid Economics for BEIS: Energy Innovation Needs Assessment for CCUS (2019)

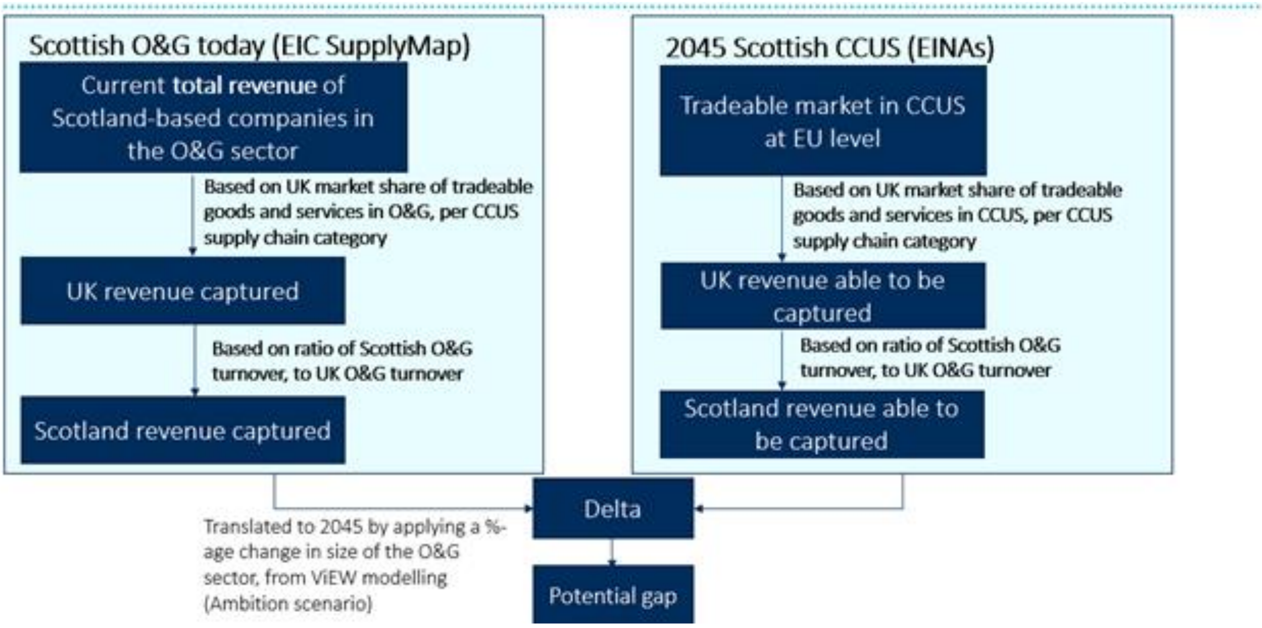


Figure 6-1: The potential 2045 Scottish O&G supply chain revenue was compared with the potential 2045 Scottish CCUS supply chain revenue to determine the potential gap[186,187]

Key findings

The analysis indicates that there are potential gaps in two out of five categories of the CCUS supply chain. The gaps exist mainly in capture equipment and EPCm, whilst there are no gaps in conversion goods and services, storage and transport goods and services and MMV goods and services. Figure 6-2 summarises these findings.

There is a gap of ~£110mn in capture equipment between the 2045 Scottish O&G sector and the 2045 Scottish CCUS sector (Figure 6-2). This is equivalent to ~10% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 or ~6% of total revenue able to be captured across the entire Scottish O&G industry today. There is therefore a potential investment gap in the design and manufacture of capture and compression equipment, which the Scottish Government could work with private finance to close. The fundamental skills in designing and manufacturing the capture equipment are likely to be the same as currently for O&G, but the skills may be applied differently, e.g., in now being familiar with engineering design standards pertaining to high pressure supercritical fluids (CO_2) where before an engineer or technician may only have had to be familiar with engineering design standards pertaining to low or medium pressure fluids.

There is a gap of £15mn in EPCm between the 2045 Scottish O&G sector and the 2045 Scottish CCUS sector. This is equivalent to ~2% of total revenue able to be captured across the entire Scottish CCUS industry supply chain in 2045 or less than ~1% of total revenue able to be captured across the entire Scottish O&G industry today. The gap in EPCm may require a different approach to closing the gap than for capture equipment, as EPCm requires intangible capital such as engineering and project management skills and experience, rather than physical capital such as plant and machinery. The skills and training needs are different and are discussed later in this section.

[186] The CCUS categories are (i) capture and pollution control, (ii) conversion and generation, (iii) transport and storage, (iv) MMV and (v) EPCm; EINAs 2050 values linearly scaled to 2045.
[187] Vivid Economics, EIC SupplyMap, [BEIS Energy Innovation Needs Assessment for CCUS](2019)

The 2045 Scottish CCUS supply chain is smaller than the 2045 Scottish O&G supply chain in conversion goods and services, storage and transport goods and services and MMV goods and services, meaning that there are no gaps in these CCUS categories. Stakeholder interviews conducted during the EINAs work on CCUS indicated that Scotland (and the UK more widely) has lower competitive advantage in these goods and services than in CCUS capture equipment and EPCm, due to large established companies with experience in building such goods and providing such services in Europe. Indeed, the market shares for conversion, storage and transport and MMV goods and services in the EINAs CCUS work indicates this quite clearly, with UK market shares which are lower than for capture equipment. Box 11 summarises the key findings from the EINAs industry workshop.

Box 11 –Summary of industry workshop regarding business opportunities in the EINAs CCUS work[188]

- The UK's comparative advantage is in engineering, designing, and assembling CCUS projects, while the UK is less competitive in the manufacture of CCUS components.
- First-mover advantage is crucial for international competitiveness in the sector. If the UK can successfully deploy several large-scale CCUS projects, it is more likely to successfully compete for EPCm contracts.
- The equipment to deploy CCUS is ready. The main challenge is the economics of the project given the price of carbon today.
- There is an opportunity for UK firms to lead in CO_2 T&S. In order to store the quantities of CO_2 IEA CCUS deployment projections[189] entail, a 30 to 50 times increase in project scale is required.
- The UK can offer complementary services for CCUS projects, such as financing, insurance, legal, regulatory, and educational services and the licensing of intellectual property.

It may be possible for Scotland to itself have a larger market share within the UK. However, as the current ratio of Scottish O&G sector turnover to UK O&G sector turnover was used to apportion revenues to the Scottish CCUS supply chain and given that this number is already very high (78% in 2018), it is not clear whether additional market share might be possible. The use of the O&G turnover ratio (78%) already reflects the fact that the Scottish O&G industry is a disproportionate size of total UK O&G turnover and that being so well established, we would expect it to continue to capture a disproportionate size of UK CCUS turnover in the future.

[188] Reproduced directly from Vivid Economics for BEIS: Energy Innovation Needs Assessment for CCUS (2019), Box 8
[189] IEA: CCUS in Clean Energy Transitions. Flagship report (2020)

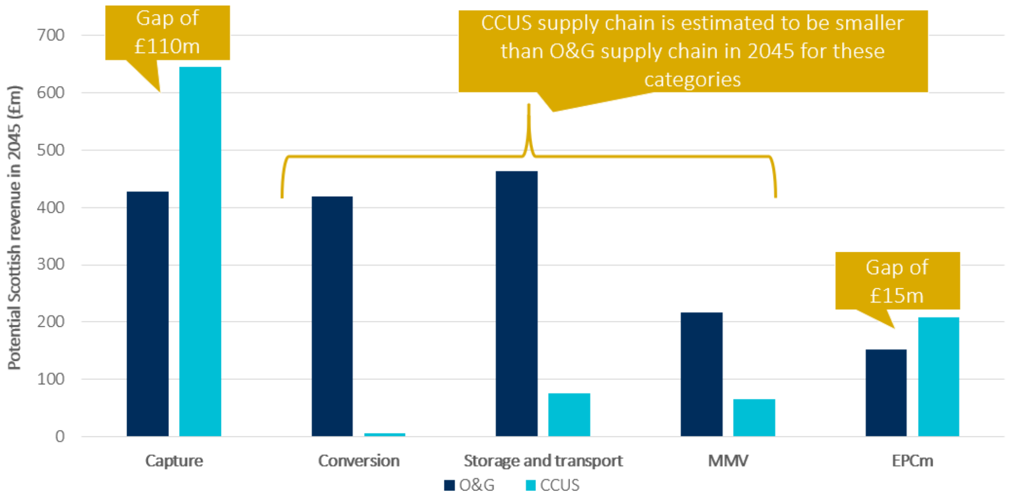


Figure 6-2: There is a gap of ~£110mn in potential Scottish revenue in capture equipment and ~£15mn in EPCm services between the O&G and CCUS sectors in 2045[190]

6.5.2 View of industry stakeholders on strengths, barriers and potential policy interventions

To better understand the potential of the Scottish industrial supply chain to participate in the net zero transition, Vivid Economics and Element Energy conducted interviews with leaders in key trade bodies. Trade bodies were selected on the basis of their role in either the O&G sector, CCUS or hydrogen sectors, or both. For example, Oil and Gas UK has relevance both for understanding the impact of climate policy on the transition of the O&G sector to CCUS and Hydrogen. Four key interview questions were developed. These were:

1. What are the main **technical, regulatory, skills and finance/risk gaps** you see in the Scottish (and wider UK) CCUS supply chain between now and 2045?
2. What are the main **public and private sector interventions** which you believe could help fill these gaps?
3. Of the interventions you have identified, can you indicate when you believe these would be most critical to helping achieve Scotland's 2045 net zero target according to the following timeframe?
    - **Immediate/medium term** (~to 2030), including post-COVID recovery.
    - **Long-term** (~2031 onwards), including accounting for Just Transition and realigning the Scottish economy to net zero.
4. What do you believe might happen in the Scottish CCUS supply chain **if sufficient government or private sector interventions are not made** according to the timelines above?

The stakeholder interviews suggest that the Scottish O&G sector is ready and able to participate in the development of a CCUS industry. The key findings are:

- **Scotland has many strengths which can be translated to the CCUS industry.** There are no major technical skills gaps. The requisite skills, expertise and capability to build a CCUS supply chain in Scotland already largely exist and the Industrial Strategy Challenge Fund should help some companies get off the ground.
- **But there are substantial barriers which will need to be overcome**. These include the lack of a formal regulatory environment for CCUS; the potential to be outcompeted on scale as most of the

[190] Vivid Economics, EIC SupplyMap, BEIS Energy Innovation Needs Assessment for CCUS

CCUS clusters in the UK are not in Scotland; limited availability of high quality public datasets for companies to start evaluating potential CCUS storage sites; limited availability of high quality public datasets for companies to start evaluating potential CCUS storage sites; limited understanding of how plugging and abandonment of CO_2 wells will work and limited government investment in CCUS relative to what might be possible given State Aid provisions after Brexit.

- **The key gap in skills is in specialist technical skills such as subsurface geological modelling**. Additional investment in the UK's Centres for Doctoral Training was mentioned during the interview with OGA and it is clear that these are seen as an effective means to start to bridge the gap between academic R&D and solving technical challenges in industry.[191]
- **There are a number of potential policy interventions which government could make to help overcome these barriers**. These include making finance available for companies to invest in developing new capabilities; joint governmental procurement of CCUS equipment for Scottish CCUS projects, establishment of a CCUS regulator; publication of a policy statement and action plan for CCUS by the Scottish Government; increasing local content requirements and increased investment in line with Subsidy Control provisions.

Table 4 summarises the responses to the interviews, broken into four key factors which are likely to impact on the ability of the Scottish CCUS industry to thrive: technical skills and technology availability, regulation/policy, finance and export potential.

Table 4: Summary of responses to interviews on strengths, barriers and potential policy interventions in the Scottish industrial supply chain, detailed by factors impacting on the Scottish industrial supply chain for CCUS

Factor impacting on the Scottish industrial supply chain for CCUS	Strengths in the Scottish industrial supply chain	Barriers in the Scottish industrial supply chain to deployment of CCUS	Potential policy interventions recommended by interviewer	Evidence of effectiveness of interventions from the literature
Technical skills and technology availability	• **No real technical skills gaps** • **Lots of subsurface** storage space • Scottish companies can **utilise existing approaches to O&G**, in CCUS • **The know-how to participate in challenging projects exists**, e.g., in the Offshore Wind Sector Deal, where an industry was created virtually from scratch	• **UK no longer a powerhouse in manufacturing certain equipment** such as pipes and compressors • Most of the CCUS consortia not in Scotland, so **could be outcompeted due to scale of opportunity elsewhere in the UK** • There is a **skills gap in specific technical** subsurface geological modelling skills • **There is a volume gap for certain equipment** such as geophysical seismic survey equipment		

[191] Centre for Education and Policy Analysis: The DTC Effect: ESRC Doctoral Training Centres and the UK Social Science Doctoral Training Landscape (2018)

Factor impacting on the Scottish industrial supply chain for CCUS	Strengths in the Scottish industrial supply chain	Barriers in the Scottish industrial supply chain to deployment of CCUS	Potential policy interventions recommended by interviewer	Evidence of effectiveness of interventions from the literature
Regulation/policy	• **Industrial Strategy Challenge Fund** in place will help get the industry off the ground	• **Limited regulation for CCUS**, e.g., the national planning framework is still only for fossil fuels and does not adequately cover Hydrogen or CCUS. Additionally, it is not clear if the National Gas Act 1986 covers CO_2	• **Clarify scope for CCUS within existing regulations** • **Jointly procure CCUS equipment** for Scottish CCUS projects • **Establish an economic regulator for CO_2 transport**, which could take a strategic approach to skills and certifications • **Release a Scottish Government policy statement and action plan for CCUS**	• **Clarity on regulations and policy has been shown to assist in companies making decisions**. For example, a survey of companies found that the benefit of removing a key policy for energy efficiency, would 'negatively impact demand for energy efficient products by removing a key incentive'.[192] • **Centralised procurement has been shown to** offer benefits such as economies of process, information, and compliance, even if it may not always be associated with lower costs[193] • **A centralised approach to skills setting has been shown to increase mobility**. A Norwegian study found that certification of already acquired skills has some value in itself.[194] Additionally, adult apprenticeships have more positive effects on future earnings, as they involve greater individual skills development
Finance	• **Funding for Centres for Doctoral Training provide a good point** from which to build a training base for additional skills	• **Limited availability of high quality public datasets** for companies to start evaluating potential CCUS storage sites • **Limited understanding of how plugging and**	• **Fund new data acquisition**, particularly using new higher resolution imaging technology. Begin now, since the process of collecting and validating data can take 3-4 years	• Data has been considered the new oil and **there is** evidence **to suggest that government should play a leading role in its acquisition**, along with industry and

[192] Traverse for Department for Business, Energy & Industrial Strategy: The Energy Technology List: beyond the Enhanced Capital Allowance scheme. Engagement report (2019)
[193] Ole Helby Petersen et al: The effect of procurement centralization on government purchasing prices: evidence from a field experiment. International Public Management Journal (2019)
[194] Bernt Bratsberg et al: Economic returns to adult vocational qualifications. Journal of Education and Work (2020)

Factor impacting on the Scottish industrial supply chain for CCUS	Strengths in the Scottish industrial supply chain	Barriers in the Scottish industrial supply chain to deployment of CCUS	Potential policy interventions recommended by interviewer	Evidence of effectiveness of interventions from the literature
		abandonment of CO_2 wells will work	• **Give full grants for the 5-10 CCUS wells** needed to go from pilot to commercial scale • **Consider establishing a carbon shipment price** through a contract for difference • **Make finance available** for companies to invest in developing new capabilities • **Reduce barriers in letting companies form joint ventures** in bidding for CCUS cluster work	academic stakeholders[195] • **The UK's contract for difference for new renewables plants has led successfully to a substantial decline in the cost of deploying these new technologies**. A recent study has shown that by holding regular auctions investors' uncertainty and costs can be lowered.[196] • **Joint ventures are useful** to help reduce the risk of investing in new capabilities (such as bidding for participation in an industrial technology cluster),[197] but it is not clear that procurement rules which BEIS has set in the ongoing CCUS cluster sequencing work, has such barriers
Export potential	• **Strong capabilities** in capture, facilities management, transport, hardware	• **Export potential for Scotland-based companies is not clear**, particularly where the projects are being exported to countries which might have local content requirements of their own • **The UK does not appear to be near the level of Subsidy Control support for industry as Europe** – there is therefore potential for the UK Government to do	• **Increase local content requirements** when providing funding support for CCUS • **Increase spending on support for CCUS**, as Subsidy Control rules will change post-Brexit, to reflect limits on state intervention[198]	• **The** Offshore Wind Sector Deal **has sought to encourage the increase in UK local content requirements to 60%**.[199] There is evidence to suggest that this has been beneficial in incentivising a greater level of investment in the UK offshore wind industry and had created jobs and economic growth[200] • Figure 23 of the EU's State Aid Scorecard

[195] Murray et al: Data challenges and opportunities for environmental management of North Sea oil and gas decommissioning in an era of blue growth. Marine Policy, Volume 97 (2018)
[196] Marijke Welisch and Rahmatallah Poudineh: Auctions for allocation of offshore wind contracts for difference in the UK. Renewable Energy Volume 147, Part 1 (2020)
[197] Global CCS Institute (2016). Global Status of CCS: Understanding Industrial CCS Hubs and Clusters. Special Report (2016)
[198] UK Government, Subsidy Control Bill, 2021
[199] Department for Business, Energy & Industrial Strategy: Offshore wind: Sector Deal. Policy Paper (2020)
[200] Martin Whitmarsh for Offshore Wind Industry Council: The UK Offshore Wind Industry: Supply Chain Review (2019)

Factor impacting on the Scottish industrial supply chain for CCUS	Strengths in the Scottish industrial supply chain	Barriers in the Scottish industrial supply chain to deployment of CCUS	Potential policy interventions recommended by interviewer	Evidence of effectiveness of interventions from the literature
		more to support nascent technologies and industries without falling foul of EU State Aid rules		2019 shows **that although the UK was amongst the top 5 spenders of State Aid in 2018, it spent less than Germany and France on environmental measures**,[201] implying the scope to invest in CCUS without falling foul of State Aid rules. More importantly, State Aid rules no longer apply to the UK, following the UK's departure from the EU[202]

6.6 Skills gaps for CCUS

Many of the leading trade bodies recognise that the skills needed to enable Scotland to participate in the net zero transition exist. In submissions to the Just Transition Commission Scotland, bodies such as OGUK, UNITE, RMT and SCCS made the following statements regarding the ability of the Scottish O&G industry to support jobs in CCUS:[203]

- **The O&G industry has the skills, capabilities and expertise** to play a role in the development of CCUS technology at scale.
- **Many of the skills and expertise acquired within the industry are readily transferable** to other energy sectors such as offshore renewables and CCUS.
- **The existing O&G workforce will need to be upskilled – particularly in technology** – in order to ensure that they can participate in the energy transition (including CCUS).
- **Developing common standards and practices across energy sectors to allow for ease of transfer of skills will be key**.
- To support the transition away from O&G jobs, **existing policy support mechanisms such as the Scottish Government's £12mn Transition Training Fund, will need to be scaled up** substantially (although limited data means that the exact amount cannot be estimated).
- **The Scottish Government can leverage better work standards including pay, pensions, conditions, and union recognition in workplaces**, in order to prevent Scottish O&G supply chain jobs being undercut by cheaper labour (with associated poorer work conditions) from overseas.

The boxes summarise policy implications relevant to the skills and supply chain considerations of the Scottish Government's CCUS policies.

[201] European Commission DG Competition: State aid Scoreboard 2019.
[202] European Commission DG Competition: Withdrawal of The United Kingdom and EU Rules in the Field of State Aid. Notice to Stakeholders (2021)
[203] Just Transition Commission Scotland: Advising on a net-zero economy that is fair for all. Paper 4/2 Industry session (2019)

Box 12 – Policy implications of the Scottish Just Transition Commission's green recovery report

The Scottish Just Transition Commission released an interim report outlining policy recommendations for a green recovery from COVID-19.[204] The key recommendations and their implications – in the context of the Scottish industrial supply chain for CCUS and Hydrogen – are discussed below.

- **Boost investment in warmer homes.** Specifically, the report calls for a doubling of budgets for homes in select local authority area-based energy efficiency and fuel poverty alleviation schemes and the launching of a non-domestic boiler scrappage scheme to support manufacturing opportunities for zero-emission heat solutions. The latter in particular, will act to create demand for Hydrogen, which in turn, can support the CCUS infrastructure needed to decarbonise Scotland's hard-to-abate industrial emissions.

- **Maintain and create new jobs for O&G workers**. Specifically, the report calls for a large scale decommissioning program with capital support, to drive activity in the North Sea; the acceleration of Scotland's industrial decarbonisation cluster, including Acorn; the speeding up of new initiatives such as the Shetland Energy Hub and public investment in facilitating infrastructure such as ports and harbours. Most interestingly, the report also recommends "direct investment in manufacturing facilities to build competitiveness in specific off-shore wind components and net-zero enabling technology". Indeed, this is in line with comments made during the stakeholder interviews documented above. Local content requirements and a clear government commitment are necessary to ensure that CCUS projects are able to deliver successfully. It is worth noting however, that according to the OGA's analysis, the ability to recycle existing infrastructure from the O&G sector in order to lower the CAPEX and OPEX costs of new offshore platforms for wind and CCUS, might be limited to 30-40% of the new CAPEX. This means that there may be an upper limit to the extent to which such a program of decommissioning through capital support, can be supportive.

- **Align skills development – for young and old – with the Net Zero transition.** Here, the report specifically recommends that "retraining initiatives direct sufficient resources towards opportunities in the net-zero economy by giving strong direction to delivery agencies such as Skills Development Scotland and Scottish Enterprise". Crucially, it also recommends that the Scottish Government's "young person's jobs guarantee promotes opportunities such as apprenticeships that are aligned with the transition to net-zero".

Box 13 – Assessing the Climate Emergency Skills Action Plan by Skills Development Scotland

Skills Development Scotland have created a Climate Emergency Skills Action Plan which provides specific guidance on how the Scottish economy can create the jobs needed to meet the demands of a net zero Scotland https://www.skillsdevelopmentscotland.co.uk/media/47336/climate-emergency-skills-action-plan-2020-2025.pdf.[205] Specifically, the strategy identifies six priority areas, of which the most relevant to the context of CCUS and hydrogen, are:

1. Supporting a green labour market recovery from COVID-19.
2. Building better understanding and evidence of future skills needs to support Scotland's transition to Net Zero.
3. Developing the future workforce for the transition to Net Zero.
4. Ensuring fairness and inclusion in the skills system as part of a just transition to Net Zero.
5. Taking a collaborative approach to ensure a skills system responsive to changing demands.

[204] Just Transition Commission for the Scottish Government: advice on a green recovery. Report (2020)
[205] Skills Development Scotland for Scottish Government: Climate Emergency Skills Action Plan 2020-2025. Key Issues And Priority Actions.

Although a detailed analysis of the specific recommendations underlying these priority areas and how they relate to CCUS/Hydrogen is beyond the scope of the present work, three key themes – and how they relate to CCUS policy in Scotland - are highlighted here:

- The call for a **Green Jobs Skills Hub** "to provide leadership, influence and guidance in developing the required knowledge, skills, standards, behaviours, attitudes and education to support the transition to net zero", is useful because this and similar interventions should help to **fill the gap in the current data on green jobs**. Indeed, Oil and Gas UK forecasts a decline in jobs in the O&G sector from ~270,000 in 2019, to 155,000 in 2025.[206] Just as importantly, the idea of a Skills Wallet, is in line with how CCUS clusters in other parts of the UK – such as Zero Carbon Humber, are envisaging filling the skills gap, whilst simultaneously **tackling the job losses and reduced delivery of apprenticeships, caused by COVID-19**.[207]
- **The creation of specific skills academies to maximize the benefits from the energy transition**, including the Michelin Skills Innovation Park Advanced Skills Academy and plans to develop an online Skills Academy, will be **necessary to ensure the coordination of skills development for a net zero Scotland, between industry and government**. Furthermore, given the issues associated with the existing Apprenticeship scheme, models of enhanced apprenticeships will need to be offered.
- **Working with Trade Unions in developing solutions for the Just Transition**, will be crucial in the context of declining global demand for Scottish O&G for example, even as CCUS enables production to continue production. Indeed, the challenge of ensuring a Just Transition for the O&G sector, was a comment specifically raised during the stakeholder interview with OGUK.
- **Building a 'Toolkit' to help small/micro businesses develop the skills and knowledge they need to adapt** to the demands of the transition to net zero, is particularly relevant to enable the thousands of SMEs which play a role in the Scottish industrial supply chain.

6.7 Conclusions

This section of the report presented the results of an analysis to understand the skills gaps in the Scottish industrial supply chain, for the deployment of CCUS and hydrogen. The EIC SupplyMap supply chain database and the Energy Innovation Needs Assessment CCUS report were used to quantify the potential gap between the Scottish O&G and CCUS industries in 2045. Stakeholder interviews were conducted to further substantiate the quantitative gap analysis and understand potential policy solutions.

Overall, we find that there is large overlap between O&G and CCUS skills as both make us of similar fundamental skills. However, there are some applied skills gaps, such as tech. to adopt fundamental skills to CCUS and learn new applied skills, more training support is needed, such as the Scottish Government's Transition Training Fund.[208] Table 5 **summarises the key findings from the quantitative and qualitative analysis**.

[206] OGUK: Workforce Report (2019)
[207] Drax: Jobs, skills, zero emissions – the economic need for carbon capture (2020)
[208] UK Government: National Transition Training fund. My World of Work Website

Table 5: Key findings from the quantitative and qualitative analysis[209]. N/A=Scottish CCUS sector is smaller than O&G sector in 2045.

Supply chain category	Potential gap between Scottish O&G and CCUS industries in 2045	Key gaps in Scottish CCUS supply chain based on stakeholder interviews	Potential policy solutions
Capture and pollution control	~£110mn	• UK not a manufacturing powerhouse • Export potential unclear	• Increase finance for CCUS • Increase local content • Increase State Aid support
Conversion and generation	N/A	• UK not a manufacturing powerhouse • Export potential unclear	• Increase finance for CCUS • Increase local content • Increase State Aid support
T&S	N/A	• Volume gap for equipment • Limited high-quality data • Limited regulation for CCUS	• Fund data acquisition • Full grants for 5-10 wells • Carbon shipment price
MMV	N/A	• Export potential unclear	• Increase local content • Increase State Aid support
EPCm	~£15mn	• Export potential driven by large multinational UK-based companies such as Wood and Petrofac but could be limited by local content requirements in export markets	• Increase local content • Increase State Aid support

7 Economic impact assessment of the CCUS scenarios

7.1 Key findings

- **In this study, the potential impact of CCS uptake was measured relative to a hypothetical baseline which assumes no CCS deployment in 2045, and therefore greater electrification and green hydrogen use as the production of blue hydrogen is reliant on CCS.** This allows the model to contrast the four scenarios to a baseline with no CCS deployment and hence quantify the economic impact of CCS fully, but is otherwise not considered credible according to CCC modelling.[210]. A scenario without CCUS is not considered credible because:
    - The CCC 6th Carbon Budget assumes that some CCUS is already deployed in the UK in 2030 and the Prime Minister's Ten Point Plan commits to at least 2 CCUS clusters being online by the mid-2020s.
    - Specifically for Scotland, the CCC's 6th Carbon Budget points out that "*Scotland's 75% target for 2030 will be extremely challenging to meet, even if Scotland gets on track for Net Zero by 2045. Our Balanced Net Zero Pathway for the UK would not meet Scotland's 2030 target – reaching a 64% reduction by 2030 – while our most stretching Tailwinds scenario reaches a 69% reduction*"
- **Under the scenarios assessed in this study, the CCS uptake has a positive impact on the Scottish economy.** In 2045, Scottish GDP can be 1.3-2.3% (£3.8bn - £6.7bn) higher than a hypothetical baseline which meets net zero but does not have access to CCS. This baseline is used purely for comparison purposes and is not considered as a credible pathway for Scotland. Relative a more credible baseline that has a modest CCS uptake, the GDP increase in 2045 can reach up to 1%

[209] Vivid Economics, EIC SupplyMap, BEIS Energy Innovation Needs Assessment for CCUS
[210] CCC 6th Carbon Budget, 2020.

(£2.9bn) depending on the scenario. These are significant additional increases in GDP, but relatively small compared to the 70% increase in the Scottish baseline GDP from under £170bn to £290bn over 2019 – 2045.

- The increase in Scottish GDP relative to the 2045 baseline is driven by three reasons:
    1. Access to CCS and blue hydrogen as alternative technologies **lowers the cost of reaching the net zero target for the Scottish economy** and its sectors. ViEW, the CGE model used in this analysis, estimates that CCS can decrease the carbon price, in other words the cost of emitting CO_2, in 2045 up to 90% relative to the baseline without access to CCS. A lower carbon price and hence energy costs benefit **energy intensive industries such as chemicals, non-metallic minerals, paper, and iron & steel.**
    2. The increase in economic activity and demand for blue hydrogen supports a managed and Just Transition as GVA and employment are supported **in fossil fuel production, i.e., O&G extraction, oil refining and gas processing.**
    3. The higher economic activity in energy intensive industry and fossil fuel production reverberates through the economy, boosting the demand further for these sectors and other sectors that are not emissions intensive, such as **services**.
- **Food production and manufacturing** do not benefit from the lower carbon price, and high investment needs of CCS infrastructure, along with competition with energy intensive industry and services, could increase its capital and labour costs. It could gain from CCS if savings from the lower energy and abatement costs exceed the increase in capital and labour costs, or in fact it could lose if the latter counters the former.
- **At the sector level, higher GVA growth does not necessarily translate to higher job creation.** Energy intensive and lower emissions industries become more capital intensive over time and decrease their labour intensity, leading to job losses despite GVA gains. This is evidenced by real world trends. For example, in developed economies, industries increasingly invest to automate their production processes and hence decrease their labour costs and intensity.[211] At the national level, driven by the calibration of the CGE model, employment losses in shrinking sectors, such as electricity counterbalances employment gains in fossil fuel production and services.[212]
- **The impact of carbon management and direct air capture (DAC) on GVA and employment is positive but negligible in size** when compared to the impact of energy intensive industries and fossil fuel production. The CCS and DACCS infrastructures have low GVA and labour intensity. In other words, the CCS and DACCS infrastructures add low value and whilst creating employment opportunities requires relatively few workers per tonne CO_2 stored.

7.2 Objective and Approach

The objective of this analysis is to estimate the economic impacts for Scotland of CCUS deployment under different scenarios. The outputs of the task include national GDP, sectoral gross value added (GVA), and sectoral employment presented at annual resolution from 2020 to 2050. It is important to note that the results presented in this section intend to illustrate potential scale and direction of differences between the CCUS uptake scenarios and the Baseline rather than exact numbers.

[211] Breguel, The impact of industrial robots on EU employment and wages: A local labour market approach, 2018.
[212] This result is a feature of the modelling setup. As a CGE model, ViEW assumes full employment, and following a shock the economy works its way always back to natural employment. There also are no labour market frictions and hence costs when reallocating jobs between the sectors. As a result, if one sector gains employment, other sectors need to lose employment, keeping the total employment at the same level.

To deliver this objective, the study adopts a top-down approach centred around Vivid Economy-Wide (ViEW) model. Figure 1 presents a summary of the approach. ViEW is a CGE model of economic activity, energy production, and CO2 emissions specifically designed to analyse the socioeconomic impact of climate policies. The model is well-suited for this exercise as it includes a detailed representation of economic sectors, including resource extraction, and interactions between these. It accounts for feedback loops and interactions between economic agents, such as firms, households, governments, and the rest of the world. In doing so, it can provide a more accurate and comprehensive estimate of impacts across different sectors and agents of the economy. The key advantage of ViEW compared to the widely used input-output methodology is that it is designed for a whole-economy analysis. ViEW also allows for flexible prices, and the economic sectors can change the inputs they use. These features make ViEW suitable for short- and long-term analysis of the economic impacts. Appendix 9.5 provides more detail about ViEW and it features.

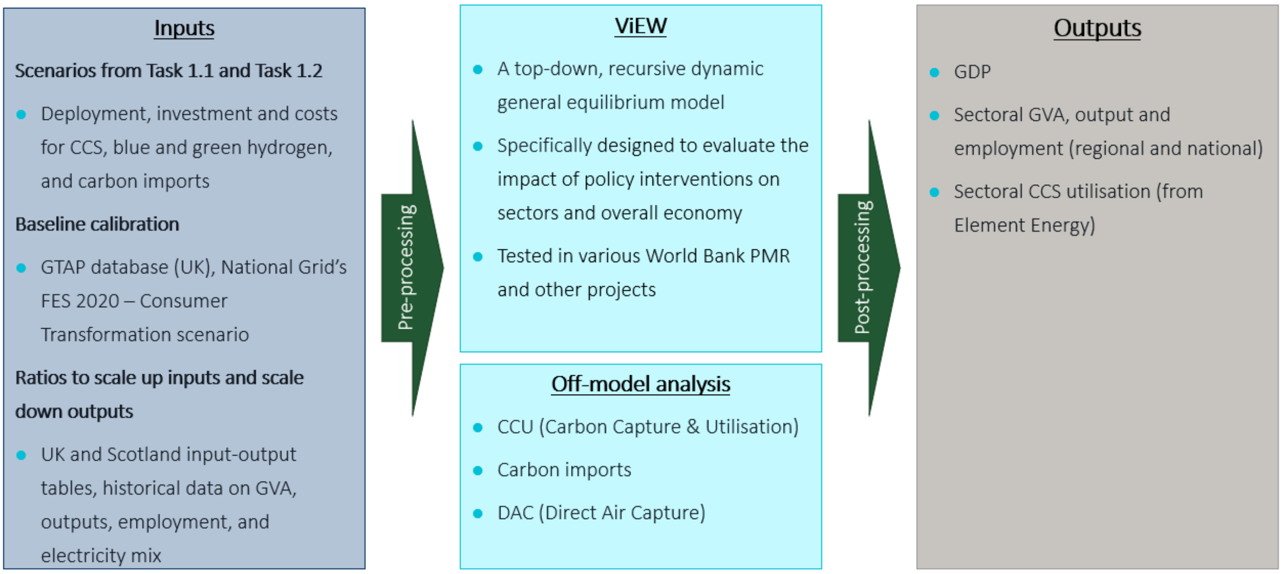


Figure 7-1: Approach to quantifying the potential economic impacts of CCUS deployment[213]

For this project, the ViEW model was extended to include the CCS, blue hydrogen, and green hydrogen technologies across the Scottish economic sectors. Based on the sectoral CCS, blue hydrogen, and green hydrogen deployment in the four scenarios outlined above, the economic sectors in ViEW are provided access to these technologies, as shown in Figure 7-2

- Electricity generation, chemicals, and non-metallic minerals can access to all three technologies.
- Oil refining, gas extraction and processing, iron & steel and blue hydrogen production can deploy CCS only.
- Paper, food processing, services, road transport, and households can use blue hydrogen and green hydrogen as an energy input but cannot deploy CCS.
- ViEW is complemented with off-model analysis to account for CCU, DAC, and carbon imports, as these are not considered in ViEW. However, since the analysis uses logic related to supply/demand, pricing and the market, which is used in the CGE model, as well as jobs multipliers from reputed studies, the results are directly comparable and consistent with the CGE analysis.
- The details are documented in Section 9.5.6.
    - In summary, for CCU, the off-model calculation of direct GVA consists of using the difference between total revenue and input costs and the off-model calculation of direct jobs consists of

[213] GTAP: Global Trade Analysis Project, https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx, FES 2020: Future Energy Scenarios 2020, https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents, GVA: gross value added; GDP: gross domestic product

using multipliers from the Scottish Annual Business Survey. For the off-model calculations for indirect GVA and jobs, we focus on GVA and jobs supported by electricity generation and hydrogen production, with the same approach as for direct jobs.

- Off-model calculations for carbon imports consists of multiplying the price differentials for carbon shipping and storage between the EU and Scotland, with projected carbon imports in the CCUS uptake scenarios to calculate the supported GVA. There is no job impact originating from the cost differential.
- Finally, for DACCS, we take the difference of the UK carbon price from the Green Book[214] in each year and the total levelized costs of DACCS shared by Element Energy and then multiply this difference with the total CO_2 captured by DACCS. To calculate the job impact of DACCS, we refer to the job multipliers of Rhodium Group. As an energy intensive process, DACCS relies on chemicals reactions to remove CO_2 from the atmosphere and consumes large amounts of electricity during this process. That's why, the analysis considers chemicals and electricity consumed by DACCS to quantify the indirect impacts. For chemicals, the job multiplier comes from Rhodium Group, whereas the GVA multiplier is compiled from Scottish Annual Business Survey 2018. For electricity, ViEW provides the GVA multiplier, while the job multiplier is calculated using Scottish Annual Business Survey 2018.

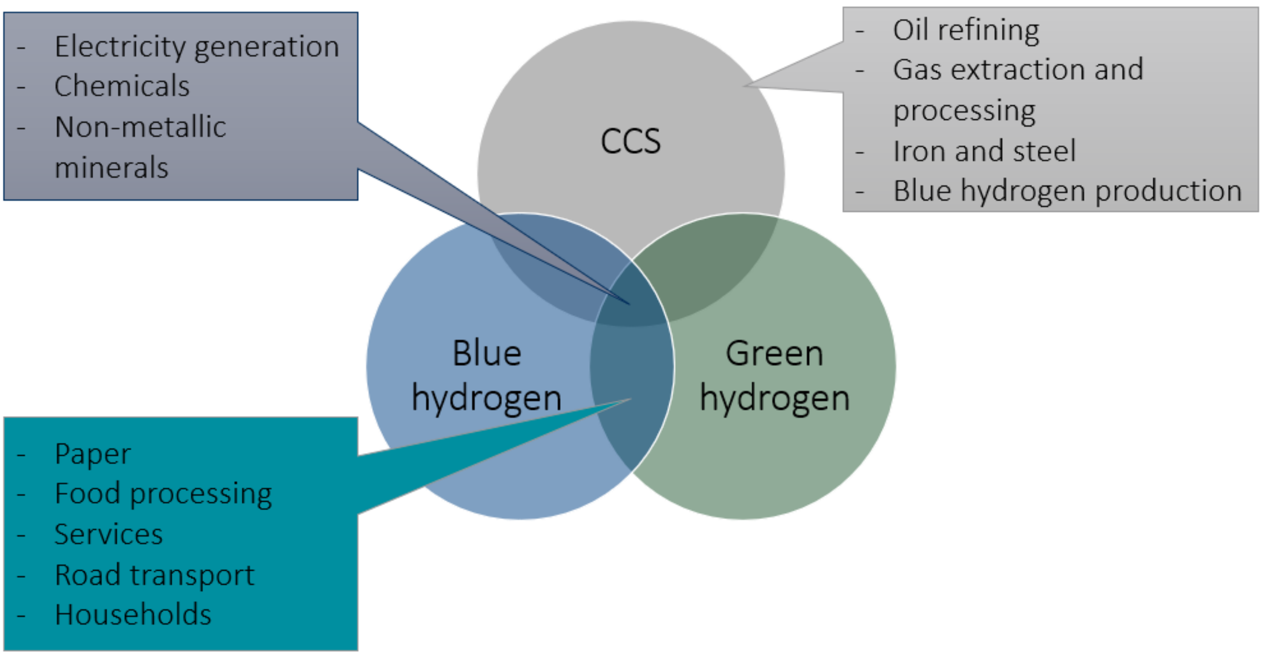


Figure 7-2: ViEW is extended to include CCS, blue hydrogen, and green hydrogen technologies across the Scottish economic sectors

ViEW applies a top-down approach and runs at the UK level, while pre-processing inputs and post-processing outputs at the Scotland level. The top-down approach is preferable because the UK and Scottish economies are strongly linked. Running ViEW at the UK level accounts for UK policies and hence avoids large leakages of economic activity from Scotland to the rest of the UK that may result from policy differences. Potential leakages could distort the modelling results and conclusion derived from these. The top-down approach follows five steps:

1. Calibrate the ViEW baseline at the UK level;

[214] Traded central scenario in Table 3 from Green Book supplementary guidance. Available at https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

2. Scale up the CCS and hydrogen deployment targets from the CCUS uptake scenarios from the Scotland level to the UK level using the sectoral GVA ratios of the two levels, also called pre-processing;
3. Dial in the scaled-up CCS and hydrogen deployment targets into ViEW;
4. Scale down the ViEW outputs from the UK level to the Scotland level using sectoral GVA and GDP ratios of the two levels, also called post-processing; and
5. Compare the results from the CCUS uptake scenarios to the results from the baseline.

As a CGE model, ViEW requires a wide range of data for the calibration of its baseline. The main data input for ViEW is the Global Trade Analysis Project (GTAP) 10 database. The GTAP 10 database's primary purpose is to provide expansive and granular data on economic sector activity, input-output relationships between economic sectors, and trade between national economies. The detailed data on input-output relationships allows ViEW to estimate the elasticities that characterise the consumption and production functions that underpin the model. The database also includes CO2 emissions by fuel, user, and region from the International Energy Agency (IEA). Additional data needed for the calibration of the ViEW baseline include forecasts for GDP, fuel prices, and electricity generation by fuel. Section 1.3.1 provides more detail about the ViEW baseline.

The model offers a robust representation of the differential impacts of the CCUS uptake on a range of key economic indicators at an aggregate and sectoral level, but the results must be interpreted with caution. The model delivers economic outcomes at an aggregate and sectoral level across a range of the CCUS uptake scenarios. These outcomes are not offered as forecasts: the analysis focuses on the differences in economic outcomes between a scenario of the future of the UK economy with and without the CCUS uptake to evaluate the impacts of CCUS. The results intend to illustrate potential scale and direction of differences between scenarios rather than exact numbers.

7.3 Scenarios

To calculate the impact of the CCS deployment on the Scottish economy and its economic sectors, four scenarios are run through ViEW and then compared against the ViEW baseline. The four scenarios are Soft Start, Core, Ambition, and Carbon Management. All scenarios including the baseline assumption that the Scottish economy will reach net zero in 2045 as legislated in the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019.[215]

The section presents the baseline in more detail and explains how the CCUS uptake scenarios are fed into ViEW.

7.3.1 Baseline

To allow comparison to an alternative decarbonised future, the Baseline model assumes no CCS deployment in 2045, and therefore greater electrification and green hydrogen use as the production of blue hydrogen is reliant on CCS. This allows the model to contrast the four scenarios to a baseline with no CCS deployment and hence quantify the economic impact of CCS fully. As far as known to us, BEIS, the CCC and other government institutions has not modelled a net zero scenario for the UK that does not contain CCS, due to it not being specifically feasible. Indeed, a route with no CCS deployment and green hydrogen and electricity only, is not considered credible according to CCC modelling and which specifically states that "*Scotland's 75% target for 2030 will be extremely challenging to meet, even if Scotland gets on track for Net Zero by 2045. Our Balanced Net Zero Pathway for the UK would not meet Scotland's 2030 target – reaching a 64% reduction by 2030 – while our most stretching Tailwinds scenario reaches a 69% reduction".* Therefore, this baseline is considered for comparison purposes only.

[215] https://www.legislation.gov.uk/asp/2019/15/contents/enacted

However, despite the deep economy-wide decarbonisation without CCS is not credible and due to the necessity of a comparator for CCS, we create our bespoke baseline using Consumer Transformation Scenario from National Grid's Future Energy Scenarios (FES) 2020 as the starting point. At the UK level, the scenario assumes high electrification across the economic sectors and has the lowest level of CCS deployment among the available alternative scenarios. The scenario is further altered to replace BECCS and blue hydrogen with green hydrogen and electricity generation with renewables, to achieve a baseline with no CCS deployment. Figure 3 compares the final energy demand under Baseline in 2019 and 2045. The share of fossil fuels in the UK final energy mix decreases from around 90% in 2019 to less than a quarter in 2045 as green hydrogen and electricity from renewables replace fossil fuels.

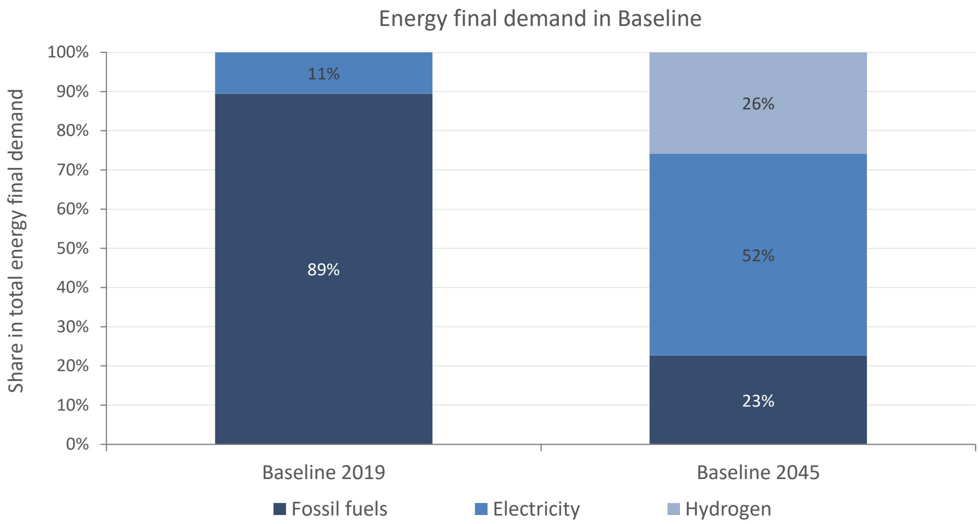


Figure 7-3: Fossil fuels replacement by hydrogen and electricity in the Baseline scenario

7.3.2 CCUS uptake scenarios

The top-down modelling with ViEW and the bottom-up CCUS uptake scenarios introduced in Chapter 3 complement each other and allow for a complete whole-economy analysis. ViEW is well suited to assess whole-economy impacts of CCS as it models the interactions between the economic sectors and agents and accounts for feedback loops between these. However, ViEW's disaggregation of the economic sectors lacks granularity, and it represents each sector as one firm only, missing within-sector nuances. Conversely, the four bottom-up CCUS scenarios account for sectoral and within-sector nuances in great detail, however they miss the whole-economy impacts and intertemporal optimisation considered by ViEW. Hence, the combination of the two approaches leverages their strengths and addresses their individual shortcomings.

However, aligning ViEW and the CCUS uptake scenarios is not straightforward. The two approaches assess the economic impacts and project CCS and hydrogen deployment from two opposite angles. They have different underlying modelling dynamics and assumptions, making it difficult for ViEW to hit all CCS and hydrogen deployment targets. Ideally, ViEW and the uptake scenarios have to be iterated multiple times to achieve a full alignment. However, the timeline and scope of this project allowed for a one-way approach instead. The scenarios are fed into ViEW, but the ViEW outputs are not fed back to further iterate the uptake scenarios.

ViEW meets most of the CCS, blue hydrogen, and green hydrogen deployment targets from the uptake scenarios. The model prioritises CCS deployment targets over hydrogen deployment targets as the primary focus of the project is on CCS. This results in lower GVA and jobs from hydrogen deployment than initially envisaged by the CCUS uptake scenarios. Only in two economic sectors ViEW cannot meet the CCS uptake targets:

- Under Soft Start, Core and Carbon Management in 2045, ViEW meets around 60% of the CCS deployment target for fuel processing because ViEW estimates a lower natural gas demand than the uptake scenarios.
- Under all CCS scenarios in 2045, ViEW does not deploy blue hydrogen in chemicals. In chemicals, natural gas combined with CCS and blue hydrogen are competing technologies. As ViEW is an optimisation model, it cannot deploy two competing technologies at the same time and prefers natural gas combined with CCS over blue hydrogen.

Appendix 9.5 presents the tables that show the share of the CCUS and hydrogen deployment targets hit by ViEW by technology and scenario in 2045.

7.4 Channels of the economic impact

CCS deployment can drive the economic growth through three channels, as shown in Figure 7-4:

- **Direct:** The deployment of CCS and blue hydrogen decreases the energy input and abatement costs of an economic sector. Assuming everything else is constant, the lower energy input and abatement costs results in a higher sectoral GVA and hence a higher GDP.
- **Indirect:** A higher sectoral GVA increases attractiveness of an economic sector for investment as its return to capital increases. Higher investment boosts productive activity, i.e., output, in the economic sector and along its supply chain, leading a higher GDP.
- **Induced:** A higher sectoral GVA translates to higher wages and increases household income. Households spend and save more. Higher household spending increases the demand and fuels economic activity across the economic sectors, boosting the GDP. Higher household savings increase capital in the economy and leads to higher investment in the economic sectors, supporting the indirect channel further.

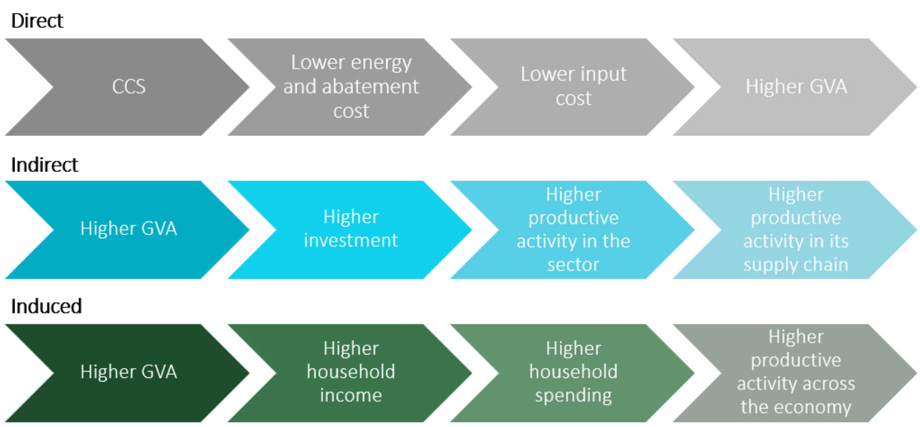


Figure 7-4: The CCS deployment can drive the economic growth through three channels

7.5 Modelling results

The section presents the macroeconomic modelling results and explains what drives them. The results discussed here include (i) GDP impacts, (ii) carbon price, (iii) sectoral GVA, (iv) sectoral employment, and (v) findings from the hydrogen sector.

7.5.1 GDP impacts

In Baseline, the Scottish economy grows by 70% from around £170bn in 2019 to £290bn in 2045. It is important to note that the Scottish economy experiences significant growth in the presence as well as absence of the CCS and blue hydrogen technologies. This is driven by the calibration of the baseline and is in line with macroeconomic forecasts of BEIS.[216]

The CCS scenarios bring an additional growth on top of Baseline. As shown in Figure 7-5, the additional year-on-year growth supported by CCS and blue hydrogen in 2045 is relatively small compared to the economic growth in Baseline from 2019 to 2045. Relative to Baseline, in 2045, Ambition and Carbon Management add £6.7bn (2.3%) and £4.8bn (1.7%) to the economy, respectively, while Core and Soft Start each increase the GDP by £3.8bn (1.3%).

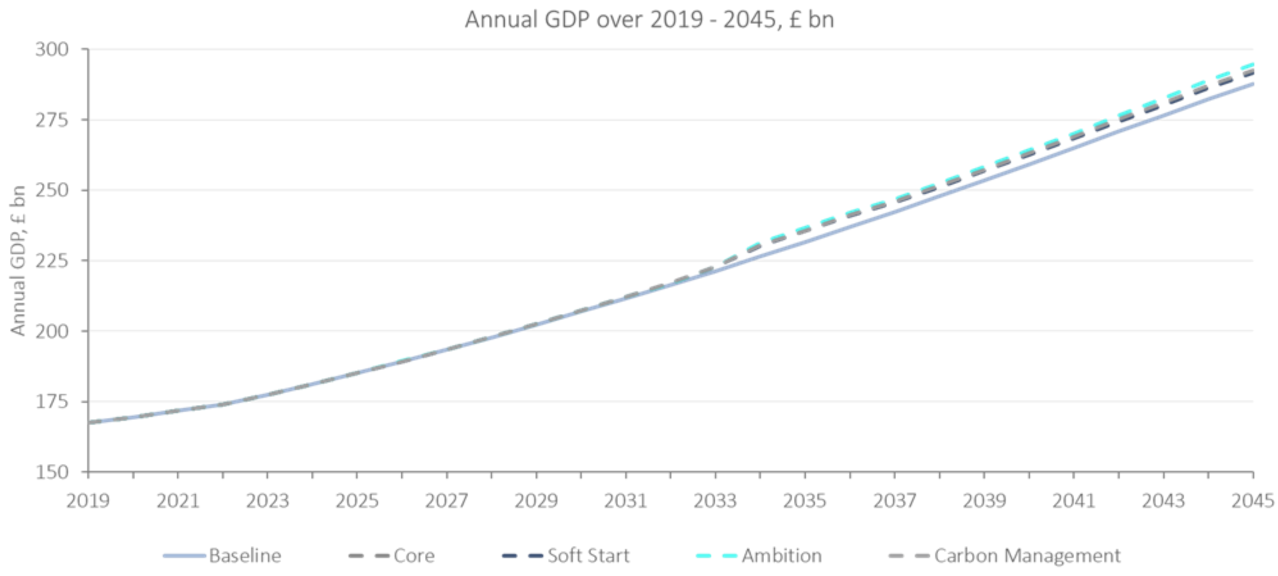


Figure 7-5: Over 2019 – 2045, the Scottish baseline GDP increases from under £170bn to £290bn, an increase of 70%, while the CCS scenarios brings additional growth

Alternative baselines can be used to assess the impact of CCS on the Scottish economy. To benchmark the GVA and employment impacts of the CCUS scenarios, we use Baseline as the reference scenario throughout the study. This allows for a comparison of the CCS scenarios to a world with no CCS and blue hydrogen, amplifying the modelling results. As an alternative, Soft Start can be used as the reference scenario to compare the CCS scenarios to a world with a modest CCS uptake, leading to smaller modelling impacts.

Relative to Soft Start, Ambition increases GDP by 1%, consistent with the findings of the Committee on Climate Change[217] and Energy Technologies Institute[218], which conclude that the presence of CCS can halve the cost of achieving net zero in the UK by 2050. The impact of Core relative to Soft Start is negligible as both scenarios have similar sectoral CCS and hydrogen uptake targets and differ only slightly regarding their timing. The GDP comparisons relative to Soft Start are shown on the right hand side of Figure 7-6.

[216] BEIS, updated energy and emissions projections: 2019.
[217] Committee on Climate Change (2016). A strategic approach to Carbon Capture and Storage. Available at https://www.theccc.org.uk/wp-content/uploads/2016/07/Letter-to-Rt-Hon-Amber-Rudd-CCS.pdf
[218] Energy Technologies Institute (2014). Carbon Capture and Storage: Potential for CCS in the UK. Available at https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2014/03/ETI_CCS_Insights_Report.pdf

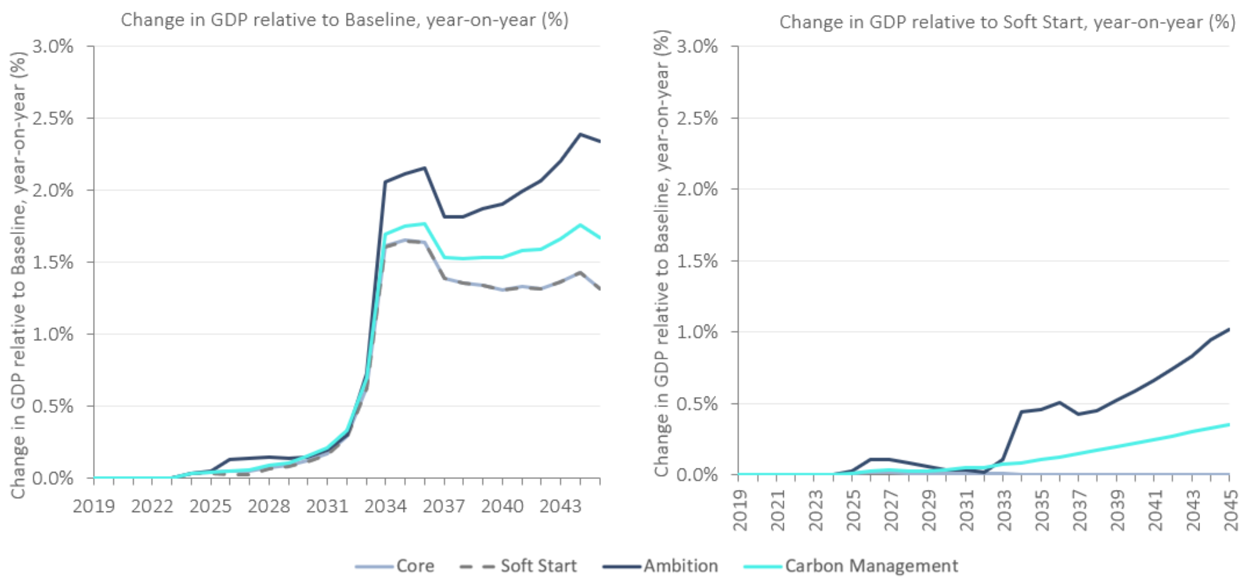


Figure 7-6: In 2045, the impact of CCS and hydrogen on the Scottish economy is around 1% in Ambition relative to Soft Start

The positive GDP impact of the CCS scenarios mainly driven by the significant decrease in the carbon price, to which we will turn next.

7.5.2 Carbon price

Access to CCS can decrease the cost of decarbonisation for the Scottish economy significantly. Figure 7-7 shows how the carbon price in each CCS scenario evolves from 2020 to 2045 relative to Baseline. Under Soft Start and Core, access to CCS and blue hydrogen can decrease the carbon price by 35% in 2045. The decrease in the carbon price reaches 83% under Ambition as the scenario has higher targets for the CCS and hydrogen uptake than Soft Start and Core.

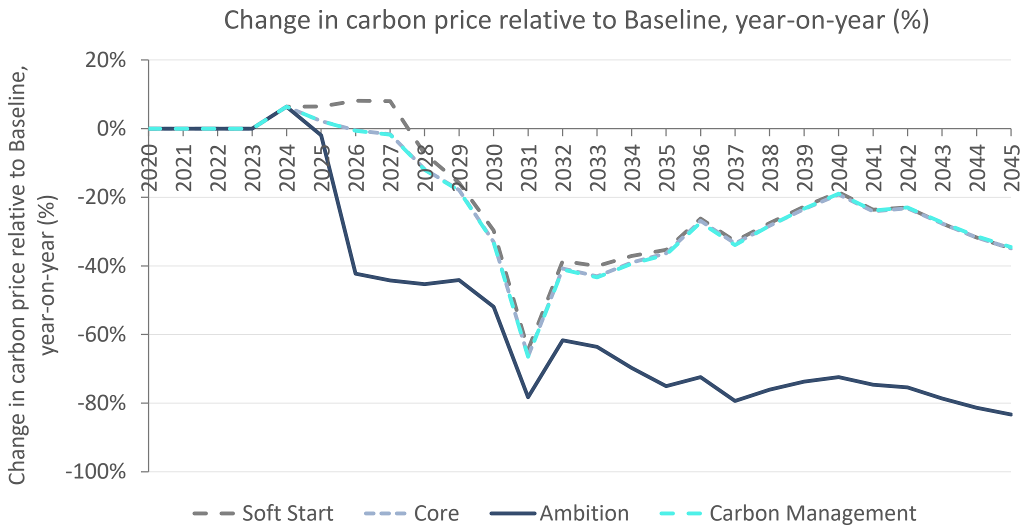
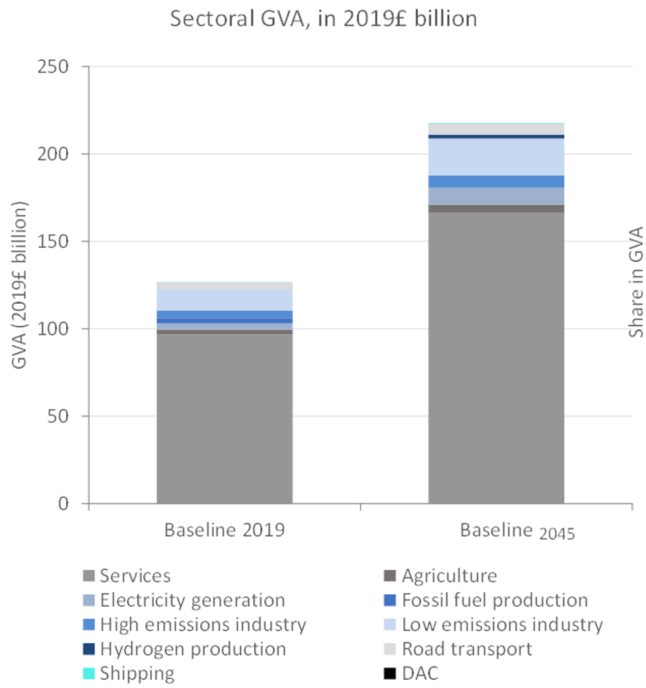


Figure 7-7: Access to CCS and hydrogen technologies decreases the cost of decarbonisation for the Scottish economy significantly

7.5.3 Sectoral GVA

In line with GDP growth, the cumulative GVA of the selected economic sectors grows significantly from £127bn to £218bn over 2019 – 2045. Figure 7-8 shows GVA of the economic sectors in Baseline in 2019 and 2045. The presented economic sectors are fossil fuel production (i.e., O&G extraction, oil refining, and gas processing), energy intensive industry (i.e., chemicals, pulp and paper, non-metallic minerals, and iron and steel), lower emissions industry (i.e., food and beverage processing, motor vehicles, and other manufacturing), electricity generation, shipping for carbon management, hydrogen production, road transports, DACCS, services, and agriculture.[219]



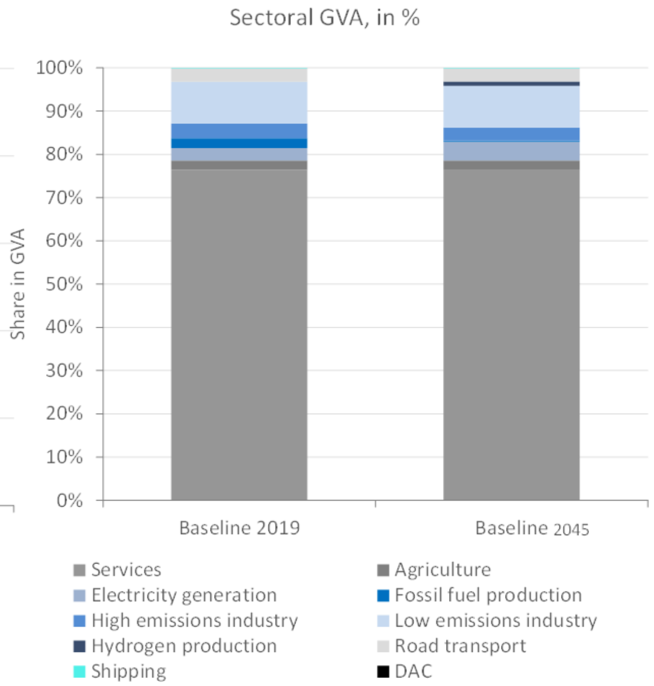


Figure 7-8: Over 2019 – 2045, the GVA of the selected sectors almost doubles from £125bn to £220bn[220]

The comparison of Baseline in 2019 and 2045, shows that:

- **Fossil fuel production** phases out almost completely and sees its share in the GVA diminishing from 2.3% to 0.2% over 2019 – 2045 as the Scottish reaches net zero emissions in 2045.
- Similarly, the share of **energy intensive industry** declines from 3.4% to 3.1%. There are two drivers: (i) the carbon price increases input cost of these sectors; and (ii) these are hard-to-abate sectors and end up adopting expensive abatement options to eliminate their emissions so the Scottish economy can reach net zero in 2045.
- The **electricity sector** increases its share in the GVA from 2.8% to 4.4% as fossil fuels phase out and industry, buildings and transport electrify.

[219] ViEW can model the GVA impacts on 65 distinct economic sectors. We have grouped these into nine sectors for ease of presentation.
[220] GVA includes production factors labour, land, capital, natural resources, and technology specific factor. Fossil fuel production includes oil and gas extraction, oil refining, and gas processing. Energy intensive industry includes chemicals, pulp and paper, non-metallic minerals and iron and steel. Lower emissions industry includes food and beverage processing, motor vehicles and other manufacturing. Shipping stands for carbon management and includes sea transport, T&S of CO_2, and value add due to price differential between Scotland and Northern Lights.

- **Hydrogen production** accounts for around 1% of the GVA in 2045 as the economy switches from fossil fuels to hydrogen to decarbonise.
- As the largest economic sector, **services** dominate the Scottish economy and account for around three quarters of the total sectoral GVA. As the economy grows, Services maintain its share in the total sectoral GVA from 2019 to 2045. Similarly, the GVA share of **lower emissions industries, road transport and agriculture** remain the same. These sectors have lower emissions intensity and are relatively less affected from reaching net zero.
- **DACCS** is not shown in the figures as Baseline has no CCS deployment and hence no DACCS.

The comparison of the CCUS scenarios to the Baseline for 2045 shows that there are stark differences between the GVA performance of individual economic sectors

- **Access to CCS and blue hydrogen will support a managed and Just Transition of emissions intensive sectors, such as fossil fuel production and energy intensive industry**. The Scottish net zero target means that without CCS, these sectors would shrink substantially. In fossil fuel production, the demand for blue hydrogen and increase in economic activity drive the demand for oil and natural gas, boosting the GVA in these sectors (£0.4bn – £0.6bn). In energy intensive industry, access to alternative technologies lowers the carbon price and hence energy costs for these sectors, while the increase in economic activity provides an additional boost to these sectors (£0.7bn – £1.3bn).[221, 222]
- **Lower emissions industry** could gain or lose from the CCS uptake, depending on the scenario (-£0.1 – £0.1bn). Having low energy consumption, it does not benefit from the lower carbon price much. High investment needs of CCS infrastructure and competition with energy intensive industry and services increase capital and labour costs, countering gains from the lower energy cost and abatement cost.
- **Electricity sector** has a lower GVA in the CCUS uptake scenarios in 2045(-£0.4bn – -£2.0bn) because, compared to the 2045 Baseline, less renewables are used to generate electricity, which have a higher GVA than other electricity generation technologies, such as using natural gas combined with CCS and BECCS.[223] This impact is driven by the calibration of the CGE model and the CCUS uptake scenarios used in the analysis. The scenarios force the electricity sector to uptake CCS, decreasing the share of renewables in the electricity mix. In the CGE model, renewables have higher GVA intensity than natural gas with CCS, resulting in a net decrease in GVA.
- **Carbon imports** add limited value to the economy, around £0.1bn across the CCS scenarios. It includes GVA from shipping of CO_2, transport of CO_2 from port to storage facility, storage of CO_2, and the value add from the price differential between Scotland and Northern Lights.[224] The value add from the price differential accounts for around half of the GVA gain, followed by T&S of CO_2 (around 40%).
- **DACCS** emerges as a new sector in the economy**.** Although the sector's share in total economy activity is modest, its contribution to the change in GVA relative to Baseline ranks third after fossil fuel

[221] Note that the size of fossil fuel production in 2045 under all CCUS uptake scenarios is smaller than its size in the 2019 Baseline.
[222] All CCS uptake scenarios and Baseline reach net zero emissions in 2045. An increase in economic activity in fossil fuel production and energy intensive industry does not relax the 2045 net zero emissions target. Additional emissions from these industries will be captured by CCS or offset by NETs, such as reforestation and soil carbon sequestration. Vivid Economics studied Scotland's NETs potential in WWF (2019). Delivering on net zero: next steps for Scotland. Available at https://www.wwf.org.uk/sites/ default/files/2019-10/WWF_Report_VIVID_Climate_2019_web.pdf
[223] Note that the generation and GVA of the electricity sector in 2045 are higher than in 2019 in Baseline and all CCUS uptake scenarios.
[224] We assume that it is a seller market. In other words, Scotland can price carbon management services at the price of its closest competitor and pocket the profit.

production and energy intensive industry. This is largely driven by the high carbon price in 2045 and rapid decrease in the levelized cost of DACCS over the modelling window.[225,226]

- **Services and agriculture** gain from CCS and blue hydrogen too although they have lower emissions intensity (£2.7bn – £5.6bn and £0.3bn, respectively). This is because CCS brings additional growth to the economy. The sectors benefiting from CCS, such as fossil fuel production and energy intensive industry, and households demand more services and agricultural products, benefiting these sectors.

7.5.4 Sectoral employment

Despite the GDP growth, total employment in the Scottish economy remains constant over 2019 – 2045. This results in significant labour productivity increases across all economic sectors considered in the model. As a CGE model, ViEW assumes full employment, and following a shock, the economy works its way always back to natural employment.[227] There also are no labour market frictions and hence costs when reallocating the workforce between the sectors. As a result, if one sector gains employment, other sectors need to lose employment, keeping the total employment at the same level.

But the distribution of labour across the economic sectors changes significantly over 2019 – 2045 as the economy decarbonises. Figure 7-9 shows how the labour composition of the economy changes from 2019 to 2045 in the Baseline, whereas the impact of the CCUS uptake scenarios relative to the Baseline in 2045 is discussed in the accompanying text. The sectoral disaggregation in replicates the one shown above for GVA.

The comparison of Baseline in 2019 and 2045 shows that:

- As the largest economic sector, **services** account for 83% of the total employment in 2019 and 2045. Its share in the total employment is higher than its share in the total GVA presented above because Services are labour intensive compared to industries, electricity generation, and fossil fuel production. Figure 7-9 does not present Services due to presentational reasons.
- As **fossil fuel production** phases out almost completely over 2019 – 2045, its share in employment decreases from 2.5% in 2019 to 0.5% in 2045. Similarly, the share of **energy intensive industry** declines slightly and remains around 0.9%.
- The **electricity sector** increases its share in the total employment from 1.7% to 3.3%. The sector gains because industry, buildings and transport electrify to reach net zero in 2045.
- **Hydrogen production** emerges as a new sector as the economy deploys green hydrogen to decarbonise. Its share in the total employment in 2045 in 0.2% only because of low employment intensity of hydrogen production.
- The employment share of **lower emissions industries, road transport and agriculture** remain broadly the same. Given their lower emissions intensities, these sectors are relatively less affected from reaching net zero.
- **DACCS** is not shown in the figures as Baseline has no CCS deployment and hence no DACCS.

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[225] The GVA impact of DACCS is calculated off-model as DACCS is not represented as a sector in ViEW. The calculations assume that the carbon price will reach 193 £/tCO_2 in 2045 and the levelized cost of DACCS will decrease from 164 £/tCO_2 in 2020 to 102 £/tCO_2 in 2045. DACCS requires subsidies until 2036 as its GVA impact is negative over 2020 – 2035 due to the relatively high levelized cost and low carbon price. Appendix 9.6 provides more detail on the approach and sources.
[226] DACCS consumes electricity and chemicals as intermediate inputs. The indirect GVA supported by electricity and chemicals are considered under electricity generation and energy intensive industry, respectively.
[227] Based on Scottish Annual Business Statistics 2018 and the Scottish Parliament's industry overview, the study assumed the total employment in Scotland at 2.5mn in 2016 and over the modelling period. National Records of Scotland estimates that the Scottish population will increase from 5.44mn in 2018 to 5.57mn in 2043. We assume the aging population will counterbalance the slight population increase, keeping the total employment at the same level over the modelling period.

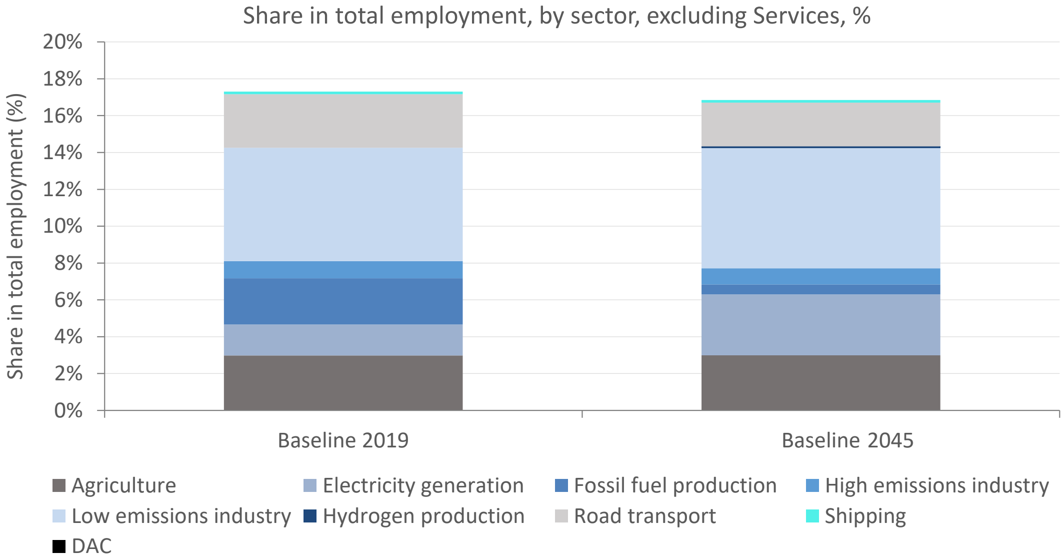

Figure 7-9: In Baseline, over 2019 – 2045, the distribution of the employment across the sectors changes as the economy decarbonises[228]

The comparison of the CCS scenarios in 2045 to Baseline in 2045 shows that gains in sectoral GVA does not translate directly to gains in sectoral employment (see Figure 7-9):

- **Fossil fuel production** increases its 2045 employment by 1,500 – 3,300 workers across the CCS uptake scenarios because it benefits from CCS. [229] However, it is important to note that the employment of fossil fuel production in 2045 under all CCUS uptake scenarios is smaller than its employment in the 2019 Baseline.
- **Energy intensive industry** suffers a decrease in employment in Soft Start, Core and Carbon Management by around 900 workers although it gains from the CCS and hydrogen uptake. The CCS and hydrogen uptake leads to investment in capital and technology while decreasing the sector's labour intensity. In Ambition, the employment increases by 3300 workers because the scenario channels hydrogen and CCS to sectors with higher labour intensity, such as paper and non-metallic minerals for the former and non-metallic minerals for the latter.
- Similarly, **lower emission industry** registers a decrease in employment, ranging from 1,200 to 4,700 employees across the scenarios, as it increases capital intensity at the cost of labour intensity.
- The **electricity sector** loses the most from the deployment of CCS and hydrogen relative to a baseline scenario of high electrification, 3,800 – 17,700 employees. The main driver for the employment losses is the replacement of renewable electricity with natural gas combined with CCS and BECCS because

[228] Fossil fuel production includes oil and gas extraction, oil refining, and gas processing. Energy intensive industry includes chemicals, pulp and paper, non-metallic minerals and iron and steel. Lower emissions industry includes food and beverage processing, motor vehicles and other manufacturing. Shipping stands for carbon management and includes sea transport and T&S of carbon emissions. Services are excluded from the figure for ease of presentation. It accounts for around 83% of the total employment. The modelling approach assumes that the total employment in Scotland will remain the same over the modelling period at 2.5mn.

[229] All CCS uptake scenarios and Baseline reach net zero emissions in 2045. An increase in economic activity in fossil fuel production and energy intensive industry does not relax the 2045 net zero emissions target. Additional emissions from these industries will be captured by CCS or offset by NETs, such as reforestation and soil carbon sequestration. Vivid Economics studied Scotland's NETs potential in WWF (2019). Delivering on net zero: next steps for Scotland. Available at https://www.wwf.org.uk/sites/ default/files/2019-10/WWF_Report_VIVID_Climate_2019_web.pdf

the latter's labour intensity is lower than the former's. This is due to the calibration of the CGE model as discussed in the Appendix.

- **Carbon imports** add limited employment, around 200 – 500 workers across the CCS scenarios. This includes employment from shipping of CO_2, transport of CO_2 from port to storage facility, and storage of CO_2. All these components of the value chain have low labour intensity.
- **DACCS** emerges as a new sector and supports around 400 – 1,700 employment across the CCS uptake scenarios.[230]
- **Services** increases its 2045 employment across the CCS uptake scenarios by around 4,700 – 18,000 workers. As the economy grows more compared to Baseline thanks to the CCS and hydrogen uptake, demand for services ramps up too, increasing the labour-intensive sector's total employment. The increase in labour demand pushes wages higher. As a result, the energy intensive industry and lower emissions industry invest in capital and decrease labour intensity to decrease their overall costs.

7.5.5 Hydrogen sector

The hydrogen value chain can add significant value to the Scottish economy.[231] The figure below shows that GVA supported by the hydrogen value chain can range from £0.06bn in Soft Start to £1bn in Ambition in 2045. Soft Start and Core have similar GVA impacts as their hydrogen production and deployment levels are similar. The GVA impact of hydrogen production in the Carbon Management scenario relative to the volume of hydrogen production, is disproportionate compared to the GVA impact of hydrogen production in the Ambition scenario relative to hydrogen production in the scenario. Total hydrogen production in the Carbon Management scenario is more than half of the production of hydrogen in the Ambition scenario. However, the GVA impact of hydrogen production in the Carbon Management scenario, is less than half of that in the Ambition scenario. This is because all hydrogen in Ambition is deployed in Scotland, whereas around 80% of hydrogen in Carbon Management is exported, which is adds no value in downstream.

[230] This includes jobs from operation and maintenance of the DACCS facilities as well as jobs from plant investment. The latter is uniformly distributed over the lifetime of the DACCS facilities. The indirect jobs supported by electricity and chemicals, which are the two main inputs of DAC, are considered in electricity generation and energy intensive industry, respectively.

[231] The numbers presented in this section reflects largely the OPEX phase, i.e., operation of the infrastructure, as ViEW distributes the GVA and jobs impacts of the CAPEX phase, i.e. construction of the infrastructure, over the lifetime of the assets. The GVA and job impacts of the CAPEX phase could be considerably higher, but these will be one off impacts coming before 2045.

The GVA impact of the hydrogen value chain is unevenly distributed among its components. The hydrogen value chain includes (i) upstream sectors, i.e., the sectors that provide inputs for green and blue hydrogen production, such as electricity, natural gas, manufacturing, and services; (ii) green and blue hydrogen production; and (iii) downstream sectors that use green and blue hydrogen as inputs, such as chemicals. A value chain component's GVA impact is inversely proportional to its input intensity. For example, in Ambition in 2045, as shown below the upstream sectors, i.e., renewable electricity and gas, account for around half of the GVA impact of the hydrogen value chain due to their low input intensity, whereas the hydrogen production supports around a fifth of the GVA impact only because it is a highly input intensive process.

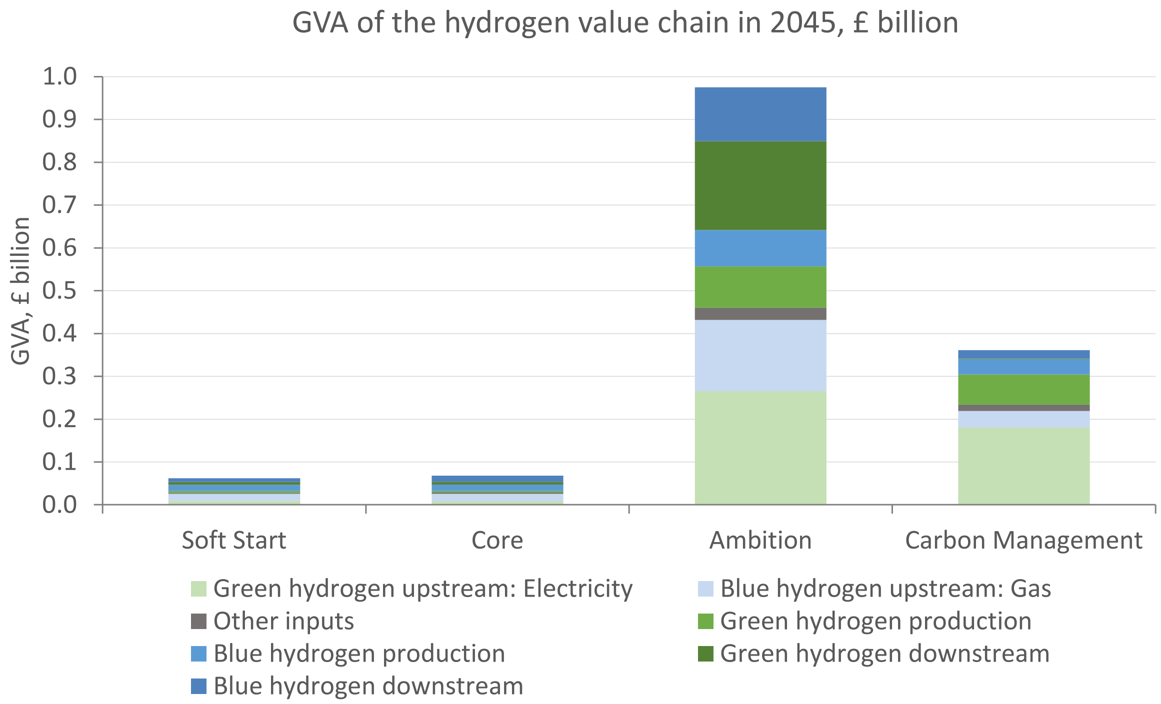

Figure 7-10: The hydrogen value chain can support up to £1bn GVA in 2045[232]

The aggregate job impacts of the hydrogen value chain mimic its GVA impacts. The hydrogen value chain can support from 600 jobs in Soft Start to 10,500 jobs in Ambition by 2045, as shown in the figure below. The distribution of the job impacts across the hydrogen value chain is skewed towards hydrogen production. For example, in Ambition in 2045, hydrogen production accounts for a third of the job impacts, while the downstream and upstream sectors support around 40% and a quarter of the job impacts, respectively.

[232] The hydrogen value chain includes (i) upstream sectors, i.e., the sectors that provide the inputs for green and blue hydrogen production, such as electricity, natural gas, manufacturing, and services; (ii) green and blue hydrogen production; and (iii) downstream sectors that use green and blue hydrogen as inputs, such as chemicals, non-metallic minerals, and pulp & paper. In the downstream sectors, the GVA attributable to hydrogen is equal to GVA in that sector multiplied by the share of hydrogen in all intermediate inputs in that sector.

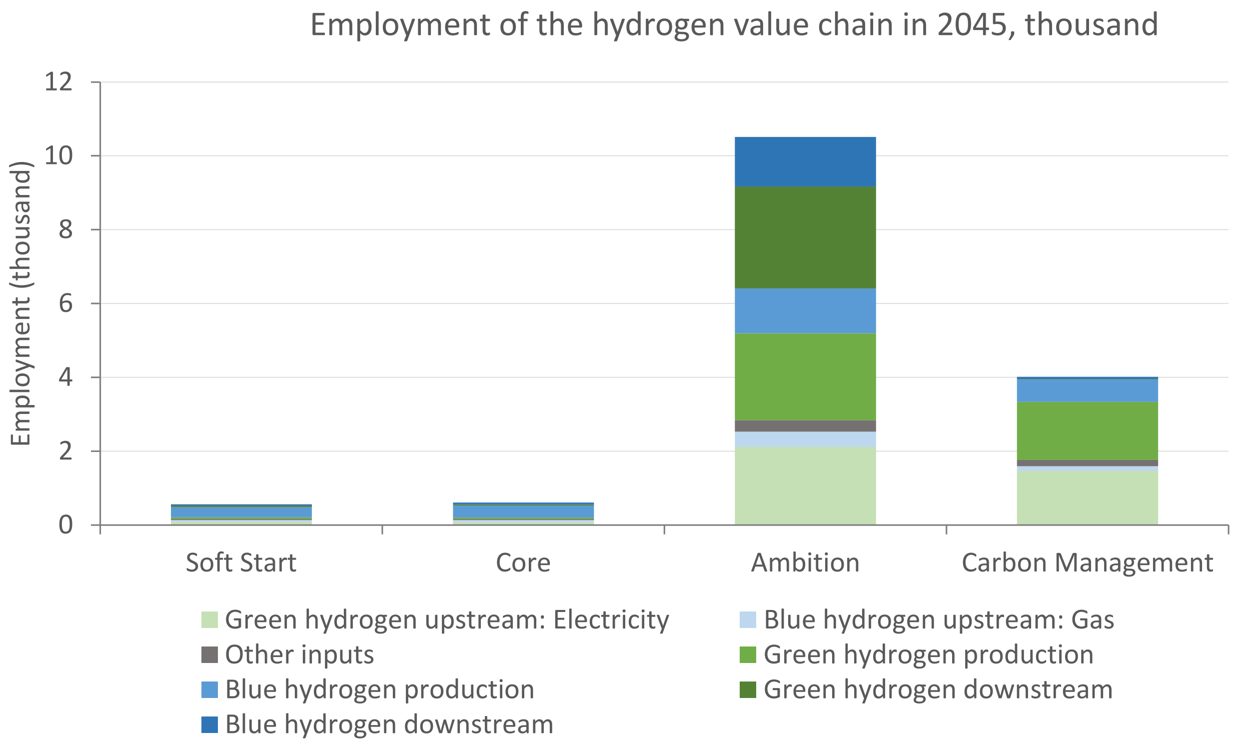

Figure 7-11: The hydrogen value chain can support up to 10,500 jobs in 2045233

7.5.6 CCU

An off-model analysis quantified the direct and indirect GVA and job impacts of 0.1 $MtCO_2$/year CCU deployment in FOAK plants to produce synthetic fuels, methanol and aggregates in 2030. The table below summarises the findings of the analysis.

- In 2030, a FOAK plant deploying CCU to produce **synthetic fuels** can be economically viable without relying on any support. According to the analysis, a FOAK plant deploying 0.1 $MtCO_2$/year CCU can support £22.3mn direct GVA and 1,315 direct jobs. The indirect impacts arising from hydrogen consumption can be significant too: around £10.1mn and 63 jobs.
- A FOAK plant deploying CCU to produce **methanol** may be close to breakeven, requiring little support. Its direct GVA impact can be negative because cost of inputs can exceed revenues from outputs, while the plant can support 940 jobs. Methanol production's high energy intensity can support £15.3mn indirect GVA and 105 indirect jobs.
- A FOAK plant deploying CCU to produce **aggregates** may need significant support as its direct GVA can be significantly negative, around -£0.6mn, because revenues from outputs fall far short of covering input costs. The direct jobs supported by the plant might be negligible, as a proportion of existing employment in plants producing aggregates without CCS, due to the negative direct GVA.[234]

[233] The hydrogen value chain includes (i) upstream sectors, i.e., the sectors that provide the inputs for green and blue hydrogen production, such as electricity, natural gas, manufacturing, and services; (ii) green and blue hydrogen production; and (iii) downstream sectors that use green and blue hydrogen as inputs, such as chemicals, non-metallic minerals, and pulp & paper. In the upstream and downstream sectors, the jobs attributable to hydrogen is equal to jobs in that sector multiplied by the share of payments to labour factor that is linked to hydrogen in total payments to labour factor in that sector.

[234] The indirect impacts originating from a FOAK plant deploying CCU to produce aggregates are not calculated due to lack of data.

Table 6: In 2030, FOAK plants deploying CCU to produce synthetic fuels may be economically viable, whereas FOAK plants deploying CCU to produce methanol and aggregates are likely to need financial support.

Commodity	Direct impacts for a plant utilising 0.1 $MtCO_2$/year		Indirect impacts for a plant utilising 0.1 $MtCO_2$/year	
	GVA (thousand £/year)	Jobs	GVA (thousand £/year)	Jobs (thousands)
Synthetic fuels	22,320	1,315	10,169	63
Methanol	-60	940	15,271	105
Aggregates*	-603	12	N/A	N/A

Notes: Indirect impacts consider electricity generation and hydrogen productions as these two are main inputs of the three commodities considered in this analysis. *Energy consumption for aggregates production is expected to be negligible. This analysis is based on the energy consumption and costs shown in Table 1.

7.5.7 Discrepancies between our analysis and previous studies

A comparison of our results with previous studies have shown discrepancies. It is important to note that the results intend to illustrate potential scale and direction of differences between the CCUS uptake scenarios and the Baseline rather than exact numbers. Our study takes a different approach compared to previous studies that quantify the economic impacts of CCS and hydrogen. Deploying a CGE model, our study considers the whole system impact of the CCS and hydrogen uptake rather than just the gross impacts produced by multiplier-based input-output models. Models deploying the two approaches produce a wide range of results. Results from CGE models tend to sit at the lower end, whereas results from the multiplier-based input-output models are at the higher end of this range. The results of this CGE based study are therefore more conservative and because of the economy-wide interactions captured, are likely to be more robust from the perspective of capturing the wider impact of the introduction of CCS and hydrogen.

The discrepancy between the results of CGE and by multiplier-based input-output models can be explained by

- **Scarcity:** a key reason is that in CGE models sectors compete for primary factors. In other words, the available primary factors are limited in amount, and every activity in a CGE model has an opportunity cost. That is, primary factors used to produce certain quantities of CCS and hydrogen inputs are redirected from other sectors in the economy, decreasing economic activity in the latter, resulting a low GVA. In multiplier-based input-output models, there is no competition for primary factors. The approach assumes that these are abundant and additional, without considering that these must be diverted from another productive activity. In other words, adjustments in other sectors are not required to accommodate output from new technologies, leading to a high GVA.
- **Attribution:** in CGE models, if CCS and hydrogen would not be available, most of the economic activity supported by them would still materialise as sectors would replace these technologies and inputs with others available in the market. So, not all economic activity supported by CCS and hydrogen is attributed to them, resulting in low GVA. In multiplier-based input-output models, all economic activity supported by CCS and hydrogen is attributed to them. Assuming the economic activity is fully additional results in high GVA.

8 Conclusions and recommendations

This study has identified multiple actions required to enable the roll-out of CCUS in Scotland. Those are shown in detail in the Figure 8-1 below and described on the next pages. **Key actions** include:

- Support core projects initiating a regional CCUS value chain, in the short-term, such as the Acorn projects emerging around the North East of Scotland (short-term).
- Support the expansion of the CCUS value chain to high emitting areas of Scotland, by supporting anchor projects and enabling connection of the Central Belt to St Fergus (short-term).
- Ensure connections between supply and demand, both for CCUS and hydrogen, to enhance supply chain integration by creation of a level-playing field for stakeholders (short and medium term).
- Mandate future industrial projects to have a decarbonisation strategy in their planning proposals aligned with the industrial decarbonisation goals of Scottish Government (short and medium-term).
- Create a freeport model which truly supports carbon management activities in order to attract investment into trade of CCUS and hydrogen (short-term).
- Develop a clear CO_2 transport strategy for pipeline and shipping, where an increased understanding of value of CO_2 transport infrastructure resiliency helps determine use of CO_2 shipping (short /medium-term)
- Support key stakeholders enabling a future hydrogen economy, particularly around the areas of grid network conversion and incentivising hydrogen fuel switching (short, medium and long-term).
- Influence future reviews of UK ETS to include DACCS to ensure that offsets are included in a timely manner, aligned with Scotland's early ambitions to deploy this technology (short-term).
- Incentivise the CCU route by carrying out demand side interventions and by supporting demonstration of technology projects (medium and long-term)
- Support Scotland becoming a carbon management economy to support growth of CO_2 imports, hydrogen exports and deployment of DACCS (medium and long term).

To ensure the scenarios are on the critical path, short term recommendations should be prioritised.

8.1 Detailed recommendations

Support core projects initiating a regional CCUS value chain (short-term)[235,236]:

The first Scottish project to enable the start of a regional CCUS value chain would be Acorn CCS, aiming to capture CO_2 from St Fergus Gas Terminal. With the expectation that funds will also be provided by private companies, public-private partnerships could develop whereupon Scottish Government could provide:

- **Direct capital support for Acorn CCS is vital,** as Acorn CCS would serve as the core project, the successful completion of which would see the development of a scalable CCUS value chain in the North East of Scotland. On top of the funds provided for FEED completion, Acorn CCS site preparation will most likely require additional support for a successful FID.

- **Direct capital support for other regional projects facilitated by, and supporting Acorn CCS, such as Acorn Hydrogen**, would help stack-up regional demand for CO_2 storage in the short term and support the transfer of regional skills from the O&G sector into low-carbon technologies such as hydrogen and CCUS. It would also help Scotland become a UK pioneer of hydrogen injection into transmission pipelines.

- Clawback mechanisms could help Scottish Government recover some of the capital support provided by claiming a fraction of the revenues expected to come from the T&S fees imposed through the TRI business model.

[235] Short-term: 2021 to 2024; Medium-term: up to 2030: Long-term: beyond 2030.
[236] Scotland can design their own decentralised state aid schemes, although these need to be signed off by the Department of Business, Energy & Industrial Strategy

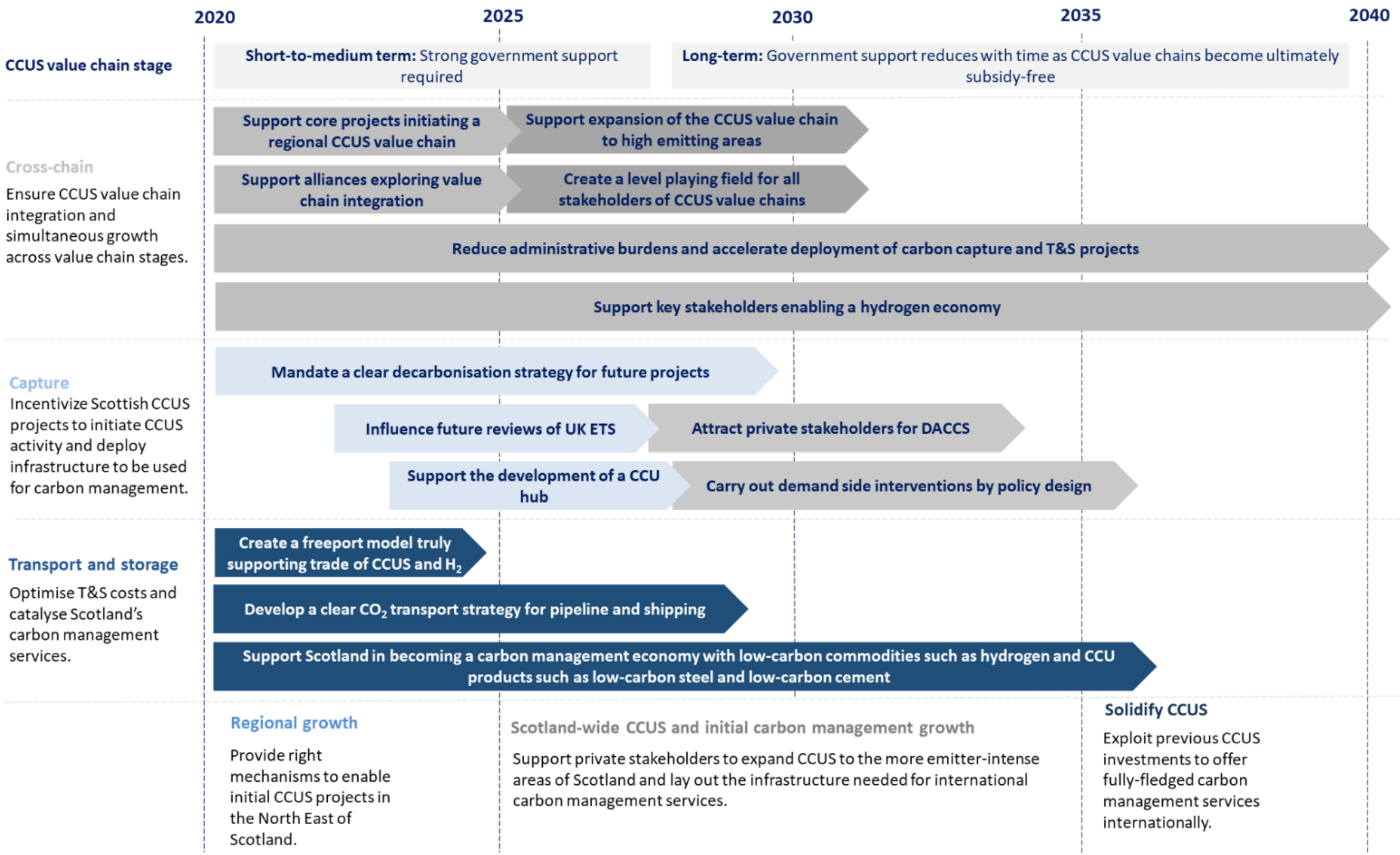

Figure 8-1: Summary for the timeline and sequencing of recommendations to support CCUS

Support the expansion of the CCUS value chain to high emitting areas of Scotland (short-term)

A ‘clustered emitters’ approach to CCUS value chains can reduce total T&S fees, as shown in Figure 8-2, due to increased sharing and utilisation of infrastructure. For Acorn CCS, achieving this would require the CCUS value chain to move from St Fergus into high-emitting areas where industry concentrates, such as Grangemouth industrial cluster. Financial support, would need to target early ‘low-hanging fruit’ projects in the Central Belt which could kick-start the development of an integrated CCUS value chain connecting the Central Belt to CO_2 storage facilities[237].

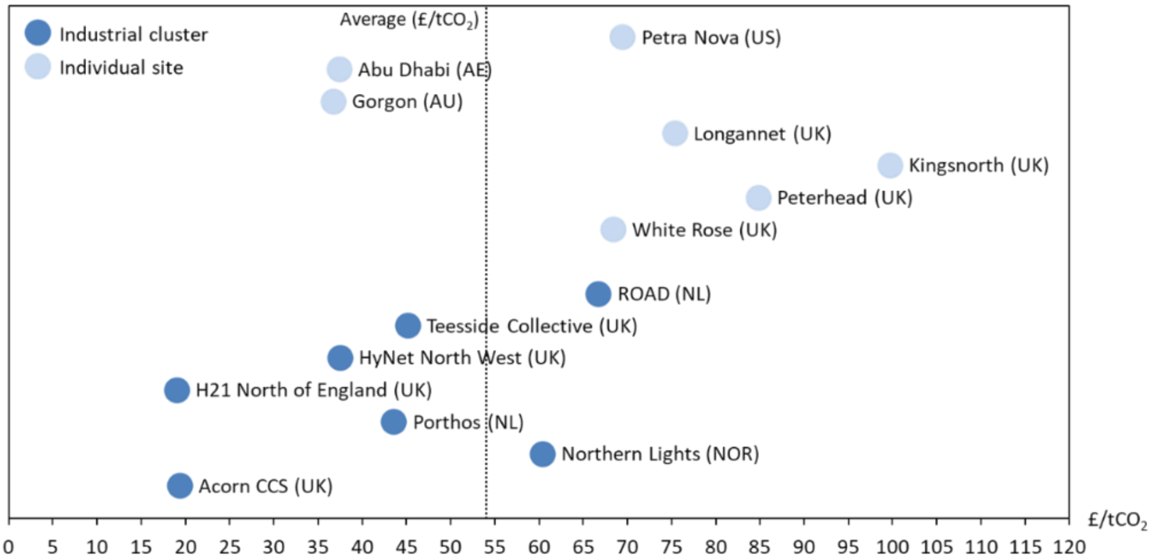

Figure 8-2: Comparison of the T&S fees for international CO_2 storage projects, industrial clusters vs. one-site projects[238]. Dashed line represents the average T&S fee.

- Funding in the form of grants could be directed **towards large-scale projects around potential transport infrastructure** to i) create “anchor projects”, facilitating the early financial viability of T&S infrastructure and ii) create a backbone that would minimise cross-chain risks as well as planning requirements and futureproof the investment, allowing later connection to CO_2 collection networks. This will have the added advantage of mitigating some economic risks associated with earlier carbon capture FOAK projects and also help accelerate the rate at which valuable learnings and additional experience is gathered to materialise cost reductions. **The level of funding required would potentially be project-specific,** and some sectors would require increased support based on:
    - The total project costs of capture, a £/tCO_2 or similar basis (refer to Figure 5-3).
    - The distance relative to transport infrastructure, as dedicated pipeline connections would add up to the project costs, on top of carbon capture costs. If the case that the CO_2 is transported by ship, emitter-port pipeline connections would be needed too.
- To minimise cross-sector work, both the carbon capture and T&S elements must be aligned in maturity and deployment timeframes. Significant previous work has been conducted on Feeder 10 feasibility; however large emitters in Scotland have not conducted site-specific feasibility studies to the same level of

[237] UK Government is planning on investing £1bn by 2025 in order to facilitate CCUS in two industrial clusters in 2020s and a further two by 2030 to capture 10 $MtCO_2$/yr. however, strong competition is expected with other UK industrial clusters.
[238] Formatted and adapted from Xodus Advisory for The Dutch Ministry of Economic Affairs and Climate Policy, Porthos CCS – Transport and Storage Tariff Review (2020). Acorn CCS is based on PBD Acorn CCS D17 Report, 2018 and refers to the cluster ambition.

detail. **Policy should thus recognise the maturity gap on the emitter site**, whilst not undermining the remaining work required for Feeder pipeline FID.

- This may also require **financial assistance to operators** such as National Grid (which are a regulated entity) to accelerate engineering works required to further assess the suitability of existing transmission assets to be repurposed for both CO_2 and hydrogen transport.

Ensure connections between supply and demand (short and medium term)

Willingness to deploy hydrogen and CCUS should not be limited by a lack of integration of the CCUS value chain. The intention of many Scottish sites in industry and power is to decarbonise but **infrastructure needs to be there to ensure project progression**:

- Scottish Government needs to **support alliances which are actively exploring the topic of value chain integration**. Providing resources to cross-sector organisations such as SNZR and Scotland Net Zero Infrastructure is an effective way for Scottish Government to understand the needs and willingness of stakeholders in different regional cluster groups to progress projects.
- Scottish Government needs to leverage its position to **create a level playing field and bring all stakeholders of CCUS value chains together, from CO_2 source to sink**. Potential supply, transport and demand stakeholders need to be connected and make investment decisions forward together in order to ensure alignment on infrastructure development timeframes[239].
- In addition, support for early deployment of key infrastructure will enable better connectivity between supply and demand, especially for the hydrogen market. The report concluded that two areas are expected to show early large-scale availability of blue hydrogen: **St Fergus/Aberdeen**, due to the Acorn Hydrogen project, and **Grangemouth**, due to the large industrial demand and vicinity to large population centres. It is thus **key that support for infrastructure is focused on these two main areas in the short and medium term**. In the longer term, further support will be needed to connect the two points of supply, for example, via an intra-Scotland hydrogen pipeline, enabling large-scale adoption.

Mandate future industrial projects to have a clear decarbonisation strategy (short and medium-term)

Future industrial and power projects in Scotland collocated next to infrastructure could benefit from some of the most cost-competitive T&S fees in the UK.

- Scottish Government, as the main approver of industrial projects in Scotland, could **mandate that all future industrial projects in Scotland provide in their planning proposals a clear decarbonisation strategy** designing the long-term emissions reduction strategy with an emissions reduction pathway set out, in alignment with Scotland's decarbonisation targets. This would support CCUS most if such projects included decarbonisation strategies via blue hydrogen and carbon capture, albeit other pathways do exist. This could lead to future industrial projects considering the proximity of T&S infrastructure when planning for location of industrial project.

Create a freeport model which truly supports trade of CCUS and hydrogen (short-term)

In 2021, Scotland announced the development of freeports in Scotland. Freeports are custom zones located at ports where relaxed custom/duty rules and lower import taxes apply. In this model, goods entering the port

[239] An analogue from a similar industry would be the Hydrogen Energy Supply Chain Pilot Project, an initiative by the Japan and Australia Governments. It is a joint federal, state and industry project where academia, hydrogen producers, and hydrogen transport operators have partnered with Japan and Australia Governments to demonstrate the feasibility of shipping liquefied hydrogen from Australia to Japan in 2021.

would only pay the established custom duties if these enter the domestic market. Freeports could benefit the international trade industry in Scotland by attracting new investment, as long as the future underlying green freeport model supports Scotland's Net Zero targets and does not lead to relocation of industrial activity.

- Many of the details on operation of freeports in Scotland are to be defined. Throughout its conversations with the UK Government, **Scottish Government can ensure that the Scottish freeport model considers exempting of tax responsibilities for important energy trade flows** such as CO_2 imports as well as renewable offshore electricity, which could be used for the on-site production of green hydrogen to be later exported.

Reduce administrative burdens and accelerate project deployment (short, medium and long-term)

Government action on project scheduling should not be the critical path. Scottish Government **can fast track the pace at which planning permission, environmental permits and consenting awards are provided** to relevant energy infrastructure such as:

- Developers of carbon capture projects in sectors such as industry and DACCS, to minimise progress time towards successful Final Investment Decision stages.
- Land-based gas pipelines for the transport of CO_2 and H_2, by collaborating with local authorities as well as gas-DNOs potentially running both future CO_2 collection pipelines as well as repurposed natural gas networks.

Develop a clear CO_2 transport strategy for pipeline and shipping (short, and medium-term)

Analysis highlighted i) the higher costs associated with intra-Scotland CO_2 shipping compared to onshore transport, and that ii) the CO_2 unit costs required to establish a CO_2 import value chain are lower than those for intra-Scotland shipping. However, there are signals suggesting that CO_2 shipping may be required as a form of system safety net:

- Scottish Government could liaise with CCUS stakeholders to quantify the value and benefits of CO_2 transport system resiliency provided by shipping, as CO_2 shipping could enable more ambitious carbon capture projects to deploy the technology ahead of pipeline conversion[240]. This would help develop a **clear CO_2 transport system strategy**, which helps determine whether investment for intra-Scotland CO_2 shipping is justified.
- This strategy would also require investigating **the synergies of CO_2 shipping with the export of hydrogen**, and potential integration in a UK-wide CO_2 shipping network.

Support key stakeholders enabling a future hydrogen economy (short, medium and long-term)

In its Hydrogen Policy Statement, Scottish Government sets out a comprehensive approach to initiate a hydrogen economy in Scotland. Whilst many of the regulatory and legislative levers needed to enable this transition require collaboration with UK Government, Scottish Government can support key areas through its 2021 Hydrogen Action Plan (besides those mentioned as part of other recommendations):

- In collaboration with SGN, **Scottish Government can prepare a hydrogen conversion program of distribution networks ahead of the timelines for hydrogen conversion** envisioned in this study. Preparing in advance of the switchover will help ensure a smooth transition to hydrogen and reduce costs. The conversion program could include the planning to fit hydrogen meters and sensors in every

[240] The Porthos project, with similar project infrastructure components as those of Acorn CCS, is expected to have an annual system downtime of around <250hr/year.

building to be switched as well as mandating all future domestic boiler sales to be compatible with pure blends of natural gas and hydrogen.

- Low-carbon hydrogen can struggle to compete with natural gas prices, especially in industry. In collaboration with UK Government, Scottish Government can ensure that **industrial use of hydrogen is incentivised, whilst minimising possible carbon leakage** may require a subsidy via Subsidy Control which reduces the gap of operational costs. A portion of the £100mn available to support hydrogen projects, to come as part of the Hydrogen Action Plan, could be used to support early movers.

Influence future reviews of UK ETS to include DACCS (short-term)

Currently, CO_2 removal through DACCS and BECCS is not part of the UK and EU's climate policy nor carbon accounting taxonomy yet[241]. In the UK, the response to the UK Carbon Pricing consultation concluded that, as of 2020, offsets from GGRs will not be permitted in the early stages of UK ETS Phase I[242]. This is partly because the standards required to introduce offsets cannot be delivered by the time Phase I is implemented in 2021:

- UK Government and Devolved Administrations may consider during the two whole-system review points in 2023 and 2028 the inclusion of offsets in the UK ETS. It is critical for early DACCS deployment in Scotland that the **Scottish Government supports the inclusion of negative emission credits in such whole-system reviews**, as DACCS projects are in the pipeline in Scotland for as early as 2026. However, based on CCC comments that inclusion of GGRs in an ETS could start only in 2030 (once technology maturity is increased), it is possible that no credits are available for early DACCS projects in Scotland, thus **potentially requiring a substitute support mechanism to see early projects move forward, such as subsidies.** To justify investment, Scottish Government could target those solid or liquid DACCS technologies with more significant cost reduction potential/offering lower costs of capture.
- The UK Government is open to linking the UK ETS internationally and is currently exploring a range of options, but no decision on preferred linking partners has yet been made[155]. In parallel to the recommendation above, Scottish Government can ensure that **selection of future linking partners considers their potential and interest in offsetting emissions with DACCS technology.** In this selection process, it is important that Scottish Government **emphasises to possible partners the role which DACCS may play in the future in Scotland** as a tool to offset emissions in other regions.

Incentivise the CCU route (medium and long-term)

Manufacture of products via CCU pathways are on most occasions less cost-effective and face increased commercialisation barriers relative to their counterfactuals:

- **Scottish Government can carry out demand side interventions by policy design to promote an "added value" of commodities produced through CCU pathways**. Certification, product labelling and green procurement are support mechanisms which could protect CCU derived products with improved climate benefits against other products with lower retail price e.g., low-carbon cement, fertiliser, methanol.
- Scottish Government can also support testing work in order to provide evidence and ensure that CCU products achieve the same quality standards than counterfactuals by **supporting the development of a CCU hub in the Central Belt of Scotland** to scale-up technologies and improve TRLs by

[241] At an EU level, the negotiation of the EU ETS Directive concerning the Phase IV 2021 to 2030 period was not consequential with carbon dioxide removal.
[242] HM Government, The future of UK carbon pricing, UK Government and Devolved Administrations' response (June 2020)

providing targeted funding for CCU options which are i) closest to technological maturity and ii) for which local market for CCU products already exist. In regards of CCU use in distilleries, **Scottish Government can work with Scotch Whisky Association** to familiarise the Speyside region with the technology for fertiliser production. Common and parallel action is required in the region, as the provision of CO_2 from Speyside distilleries for fertiliser production would have to be sufficient so as to justify investment in the fertiliser manufacturing plant.

Support Scotland in becoming a carbon management economy (medium and long term)

This study estimates that CO_2 imports, hydrogen exports and others could be a valuable contributor to Scotland's CCUS value chains. The earlier trade starts, the more the benefits there will be. Scottish Government can support this by:

- **Supporting CO_2 storage operators to gain additional storage contracts from CO_2 imports to instil confidence.** This is because there is still uncertainty about the precise location of CO_2 import sources, due to the lack of existing CO_2 shipping contracts as well as defined shipping routes. This would improve the CO_2 storage contracting clarity for operators and help increase the financial viability of storage in Scotland by accelerating the commissioning of cost-effective storage in East Mey. This can be pursued, for instance, by **promoting, and raising awareness of, Scotland's cost-effective shipping CO_2 import plans** through international channels in climate change conferences and events.
- **Increase the infrastructure investment in Scotland's main CO_2 import hub location:** Peterhead Port. This investment could build on top of current financial support being provided to the Port coming from prominent funding programmes such as Connecting Europe Facilities. The investment could focus on funding next steps for a CO_2 port value chain, supporting deployment of CO_2 offloading equipment.
- Scotland is envisaged to produce low-carbon commodities such as blue and green hydrogen, low-carbon steel and low-carbon cement. **Scottish Government can assist UK Government in developing and signing future bilateral agreements through Free Trade Agreements (FTAs) with other regions** to ensure that Scotland's future low-carbon products can compete in international markets for commodities and industrial products. Scottish Government could also use its diplomatic channels in international delegations to **promote Scotland's potential for DACCS deployment**.
- Certain corporations are establishing pledges of carbon removal by offsetting part of their direct emissions. **Scottish Government can undertake outreach initiatives with the private sector to attract capital for earlier DACCS projects in Scotland**. International cooperation is instrumental to establish DACCS standards, and working with private stakeholders can help reduce the capital investment gap which could otherwise have to be filled by additional public investment.

9 Appendix: Key modelling assumptions

9.1 Identification of sites suitable for CCUS

Nine industrial sites were deemed eligible for carbon capture after applying the criteria outlined in Section 3.1. The assumed deployment of carbon capture at these sites is summarised in Table 7. For the refinery, it was assumed that carbon capture deployment would occur sooner on the SMR than on other emission sources.

Table 7: Timeline of carbon capture deployments in industry

Cluster	Source	$ktCO_2$ baseline	$ktCO_2$ captured		Deployment year	
			Core	Ambition	Core[243]	Ambition
St Fergus / Peterhead	St Fergus Terminals	>300	>300	>300	2024	2024
Grangemouth	Kinneil Terminal	345	17	17	2028	2028
	Refinery SMR	189	189	-	2028	-
	Olefins plant	522	367	462	2030	2030
	Refinery Furnaces	897	330	-	2032	-
	Power station	429	-	386	-	2035
	CHP	641	-	576	-	2043
Fife/East Coast	Fife ethylene plant	680	414	601	2034	2034
Upper Forth	Alloa glass plant	148	-	134	-	2034
Other	Dunbar cement plant	559	491	491	2037	2037
Total		**4,725**	**2,109**	**2,968**		

It should be noted that other factors may influence and constrain the viability of carbon capture; for instance, the extent to which industrial processes would be disrupted by the installation of carbon capture equipment, or whether enough space is available on site. These and other barriers are reviewed in the Element Energy study on deep decarbonisation pathways for Scottish industries.

However, not all of these emissions from the nine sites identified in Table 7 are captured in the scenarios considered. This is down to two reasons. First, as per the third bullet above, fuel switching is assumed to be preferable to decarbonise emission sources (e.g., some of the refinery furnaces, as outlined in Box 1, or the for the compressor at the Kinneil gas terminal). Second, capture rates are always lower than 100%; for the purposes of this analysis, it was assumed that 10% of the emissions from sources with low CO_2 purity escape capture[244].

9.2 Hydrogen uptake in industry

The Ambition scenario is the only scenario where the gas grid is assumed to be progressively converted to hydrogen, which enables smaller sites to fuel switch to hydrogen. In all other scenarios, it is assumed that only large sites that can be grouped within sufficiently large clusters can fuel switch to hydrogen. For these large

243 Deployment timelines and volumes captured in the Carbon Management and Soft Start scenarios are assumed to be the same as those in the Core scenario.

244 This includes all burners, heaters, and furnaces, which typically yield flue gases with CO_2 concentrations of around 10%. The capture rate from high-purity sources like the refinery SMR as well as the CO_2 separation processes at gas terminals was instead assumed to be 100%.

sites, hydrogen uptake is assumed to take place over a 10-year period starting when hydrogen becomes first available from local production projects, and the uptake trajectory is assumed to roughly follow an ‘S-curve’, as can be seen in Figure 3-3. Conversely, hydrogen uptake across smaller sites (in the Ambition scenario only) is assumed to follow a linear trajectory, linked to the progressive conversion of the gas grid.

Table 8: Hydrogen uptake assumptions

Site type	Portion of energy demand met via hydrogen in 2050		
	Core / Carbon Management	**Soft Start**	**Ambition**
Large sites that also implement carbon capture[245]	Cement plant: 20%[246] Refinery: 59%[247] Other sites: 35% Weighted average: 43%	As in Core scenario, but delayed uptake	Cement plant: 20%[32] Other sites: 0%[248] Weighted average: 1%
Other large sites	Sites within key clusters[249]: 35% Other sites: 0% Weighted average: 17%	As in Core scenario, but delayed uptake	Sites in the Shetlands[250]: 0% Other sites: 65% Weighted average: 64%
Smaller sites	0%	As in Core scenario	Sites in the Shetlands: 0% Sites near clusters[251]: 65% Other sites: 50% Weighted average: 52%

Differences in hydrogen uptake across scenarios

Two key factors explain this significant difference in hydrogen uptake between scenarios:

- First, the cumulative energy demand from the multitude of small sites that are not listed on the SPRI is estimated to have been over 15,000 GWh in 2019, or 37% of the total estimated energy demand from the industrial and commercial sector in 2019. Of this, 8,000 GWh are assumed to be met via hydrogen by 2050, but only in the Ambition scenario.
- Partly counteracting the above, hydrogen uptake within the Grangemouth cluster reduces visibly in the Ambition scenario (from 4,800 GWh/year to 435 GWh/year, by 2050). This is due to: i) the assumed transformation of the refinery into a blue hydrogen production facility (see Box 1) which implies that no hydrogen is demanded from the refinery itself, and ii) the assumed deployment of carbon capture on the boilers and CHP units.

245 Percentages relating to this site category refer to the total energy demand that is not already decarbonised with CCUS.
246 A mixed-fuel kiln burning 20% hydrogen is assumed to be used to decarbonise cement production.
247 See Box 1.
248 All of the relevant emission sources are assumed to be decarbonised via CCUS in this scenario.)
249 I.e., St Fergus/Peterhead, Grangemouth, Upper Forth, Fife/East Coast. Sites in the West and Shetlands regions see no hydrogen uptake in this scenario.
250 It is assumed that no *blue* hydrogen will be used in the Shetland. Even though some green hydrogen may be used, this would not bear any impact on the Scottish carbon management sector.
251 Clusters include St Fergus/Peterhead, Grangemouth, Upper Forth, West, Fife/East Coast.

9.3 Hydrogen infrastructure availability

Table 9: Hydrogen infrastructure availability. Small industrial sites gain access to hydrogen via conversion of the gas grid. Large industrial sites in selected regions deploy designated hydrogen connection to producers.

Region	Core	Soft Start	Ambition			Carbon Management
			Large Sites	Small Sites		
				Conversion Starts	Conversion Ends	
St Fergus/Peterhead	2026	2029	2026	2032	2033	2026
20% H_2 in Aberdeen(shire)	2026	2029	2026	N/A	N/A	2026
100% H_2 in Aberdeen(shire)	2032	2035	2032	2032	2034	2032
Fife/East Coast/Upper Forth	2031	2034	2031	2033	2036	2031
Grangemouth	2029	2032	2029	2031	2034	2029
West	N/A	N/A	N/A	2034	2037	N/A
Other	N/A	N/A	N/A	2033	2045	N/A
Dunbar (green H_2)	2032	2035	2033	N/A	N/A	2032

Geographical availability for the different regions follows a geographical expansion approach, where hydrogen availability grows outwards from the two main areas of large-scale blue hydrogen production: the Grangemouth industrial cluster and St Fergus. This geographical expansion can be differentiated for the large industrial sites and small sites. The large industries gain access to hydrogen via direct connections to closest hydrogen producers in all scenarios. In the Ambition scenario, the Scotland-wide conversion of the gas networks allows for small industries (and the residential sector) to gain access to hydrogen as gas networks get converted. The conversion process of the gas networks of each region have been assumed to take 2-3 years to fully convert. The Dunbar cement plant is deemed to be too far from Grangemouth as to connect directly via dedicated pipeline. As a result, a three-year lag relative to Grangemouth is assumed, where hydrogen becomes available either i) through green on-site hydrogen deployment or ii) through trailer delivery.

9.4 Additional supporting information

Table 10: CO_2 volume from each sector, for key years ($MtCO_2$/year)

Scenario	Core			Soft Start			Ambition			Carbon Management		
Year	2030	2040	2045	2030	2040	2045	2030	2040	2045	2030	2040	2045
Power	1.3	1.3	1.3	1.3	1.3	1.3	2.0	2.0	2.0	1.3	1.3	1.3
Bio-CCS	-	-	-	-	-	-	1.0	1.0	1.0	-	-	-
DACCS	1.0	2.0	2.0	0.5	1.0	1.0	1.0	2.0	3.0	1.0	2.5	4.0
Industry	0.9	2.1	2.1	0.9	2.1	2.1	0.8	2.4	3.0	0.9	2.1	2.1
CO_2 imports	3.0	5.0	5.0	0.5	5.0	5.0	3.0	5.0	5.0	4.0	9.0	12.0
Blue H_2	0.6	1.6	1.6	0.3	1.1	1.1	3.9	6.8	6.8	1.3	2.3	2.3
TOTAL	**6.8**	**12.0**	**12.0**	**3.5**	**10.5**	**10.5**	**11.7**	**19.2**	**20.8**	**8.5**	**17.2**	**21.7**

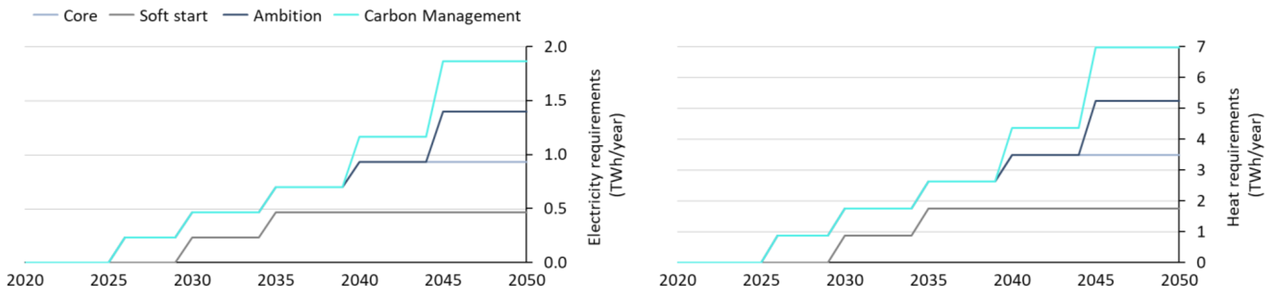

Figure 9-1: Annual electricity and heat requirements for DACCS deployment in various scenarios

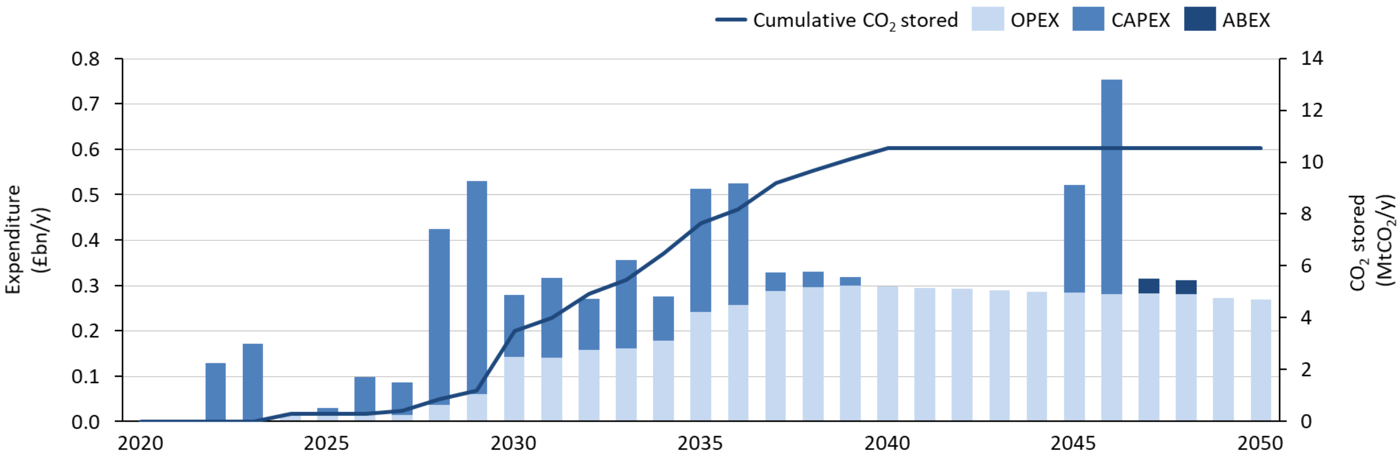

Figure 9-2: Annual investment in the CCUS value chain required in the Soft Start scenatio (left y-axis) against the annual CO_2 volume being stored (right y-axis).

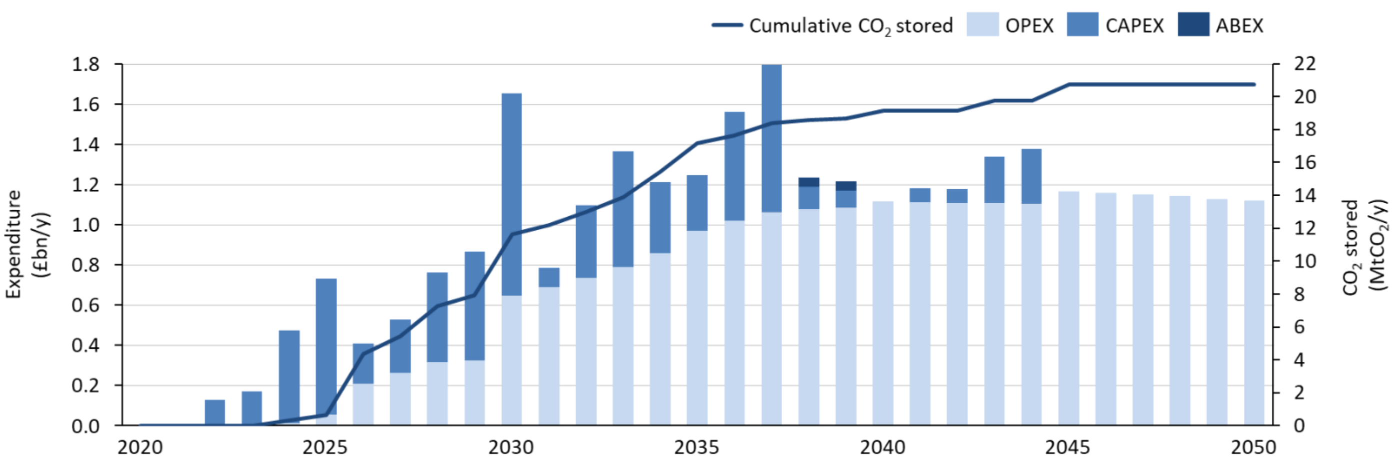

Figure 9-3: Annual investment in the CCUS value chain required in the Ambition scenario (left y-axis) against the annual CO_2 volume being stored (right y-axis).

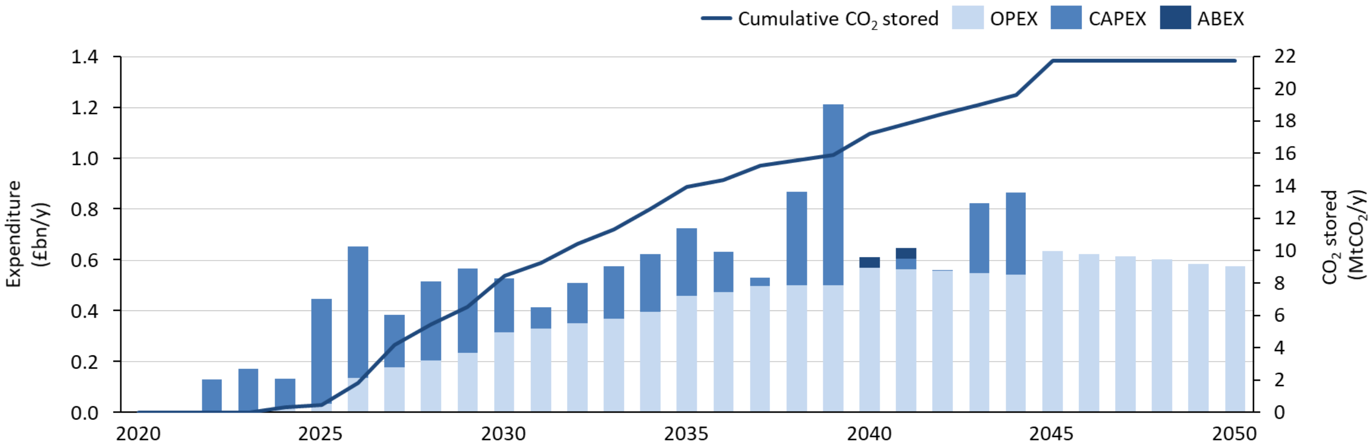

Figure 9-4: Annual investment in the CCUS value chain required in the Carbon Management scenario (left y-axis) against the annual CO_2 volume being stored (right y-axis).

General assumptions

- Commissioning and decommissioning of new and repurposed CCUS infrastructure assets (for CO_2 capture, T&S) has been assumed to be **2 years**, with the exception of compressors and injection wells (**1 year**).
- The useful lifetime of CO_2 capture and transport hardware is assumed to be of **30 years**.

Capture

General assumptions for the study are: to include asset life, undiscounted, inclusion of costs directly related to the deployment of CCUS and blue hydrogen infrastructure.

Table 11: Summary of key cost assumptions used in capture stage

Cost component and source	Cost type	Description and assumptions
CO_2 capture for industry, power and bio-CCS[252]	CAPEX & OPEX	Capture technology used is advanced amines or blends (which have high retrofit potential) and FOAK, SOAK and NOAK progression as mentioned in Section 4.5. Capture rates depend on capture process. Output atmospheric pressure.
DACCS[253]	CAPEX & OPEX	Due to uncertainties, costs used here are the average for the two technologies considered in the paper. Assumption of linear decrease for the costs reported between now (2020 - £165/tCO_2) and long-term (2050 - £90/tCO_2).
Blue hydrogen production[254]	CAPEX & OPEX	Assumes CAPEX of ATR production and of carbon capture as well as OPEX for separation and conditioning, electricity and natural gas.

Transport and storage of CO_2

Cost data for the different CO_2 T&S infrastructure components shown in Table 12 has been taken from a variety of sources specified below. Cost data comes from techno-economic models, for which specific parameters can be introduced to yield cost data, as well as from previous reports for specific CO_2 T&S projects.

[252] Element Energy, Carbon Counts, PSE, Imperial College, & University of Sheffield's Demonstrating CO_2 Capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A techno-economic study (2014)
[253] Keith, David W., et al. "A process for capturing CO_2 from the atmosphere." Joule 2.8 (2018): 1573-1594.
[254] Element Energy for Pale Blue Dot Energy, Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero (2020)

In the latter case, costs have been sized by calculating a unit cost per cost component using and appropriate scaling factor e.g., $MtCO_2$ or $MtCO_2$/year.

Table 12: Summary of key cost assumptions used in CO_2 T&S stage

Cost component and source	Cost type	Description and assumptions
Offshore CO_2 T&S (mostly repurposed assets)[255]	CAPEX, OPEX & ABEX	Includes CAPEX for FEED, pipeline repurposing and acquisition; umbilical, manifold, wells and measurement, monitoring and verification facilities. OPEX for transport and subsea equipment operation, monitoring and Crown Estate rent. ABEX for abandonment of Acorn CO_2 storage site, post closure and handover. Minimal remediation of pipelines is assumed.
Offshore CO_2 T&S (new assets)[256]	CAPEX & OPEX	Length of new offshore pipelines is assumed to be 100 km and 200km for Acorn CO_2 and East Mey, respectively. Pipelines to the former store have a throughput of 5 $MtCO_2$/year and 10 $MtCO_2$/year for the latter.
Feeder 10 pipeline[257]	CAPEX & OPEX	CAPEX includes transfer of asset for CO_2 transport, repurposing work and additional in-line compression when needed. OPEX includes pipeline operation and potential fees.
Onshore CO_2 transport (new assets)[256]	CAPEX & OPEX	Length of new onshore pipelines from Peterhead Port to PPS is 2 km and from PPS to St Fergus is 20 km.
Compression[256]	CAPEX & OPEX	CAPEX CO_2 compressors in PPS, Peterhead Port and for injection in St Fergus. OPEX for PPS, Peterhead Port, Feeder 10 compression as well as injection in St Fergus.
CO_2 shipping[256]	CAPEX & OPEX	Includes CAPEX and OPEX for liquefaction (electricity powered), loading, temporary CO_2 storage in origin ports and unloading and conditioning in destination ports. Cost of ships include a CAPEX and both fixed and variable OPEX. No harbour fee included.

Value chain implications and calculation of the required shipping fee for the described intra-Scotland CO_2 Firth of Forth - Peterhead shipping volumes between are provided below for the Carbon Management scenario:

- The maximum cargo capacity for a MP CO_2 ship which minimises the number of trips is 21,000tCO_2, based on the discussed allowable limits in Peterhead Port.
- The distance between the two ports is approximately 200 km, which is covered in 8 hours at a cruise speed of 28 km/h[256]. In both the origin and destination ports, it takes a total of 19 hours to enter the port, load/unload the 21,000t of CO_2 and exit the port. This means that the total time for a full CO_2 shipment cycle, the total time is approximately 2 days and 6 hours. At a 100% ship availability, over 160 return trips can theoretically be completed. However, annual requirements are close to 2.8$MtCO_2$/year, meaning that the dedicated ship has an utilisation rate of 70% (as presented in discussion in Section 4.2).
- For intra-Scotland CO_2 shipping requirements from Firth of Forth and Dunbar, excluding CO_2 imports, Peterhead Port availability for CO_2 shipping needs to be around 25%.

[255] Accelerating CCS Technologies Studies: Acorn CCS: D03 Basis of Design for St Fergus Facilities, Acorn CCS: D16 Full Chain Development Plan and Budget and Acorn CCS: D16 Full Chain Development Plan and Budget.
[256] Element Energy for BEIS, CO_2 Shipping Study (2018). Additional cost assumptions can be found in the Excel model.
[257] Accelerating CCS Technologies: Acorn Project: D17: Feeder 10 study, ACT Acorn Project (2017).

Outside of scope cost components

Some elements secondary to the CCUS supply chain have not been included:

- **Hydrogen:** Conversion and operation of the transmission and distribution network, intraday and interseasonal storage. New domestic and industrial appliances, turbine replacements, and fuel cells for transport. Green hydrogen infrastrcutre, such as electolysres and supporting renewble energy capacity.
- **CCUS:** Extension of the tanker jetty to accommodate for additional CO_2 imports, possible buffer storage tanks for CO_2 in St Fergus, fuel costs of carbon capture.
- **Wider economy technologies:** Electrification, electric appliances, heat pumps

Breakdown of blue and green hydrogen production

As described earlier, Table 13 below has been estimated on the basis of regional hydrogen projects as well as on the hydrogen suitability for end-use e.g., blue hydrogen production in Grangemouth to supply to industry.

Table 13: Percentage of green hydrogen penetration in new built capacity (%) deployed beyond initial deployment of Acorn Hydrogen (i.e. outside St Fergus)

Scenario	2030	2035	2040	2045
Core	10%	20%	100%	100%
Soft Start	100%	20%	100%	100%
Ambition	40%	50%	100%	100%
Carbon Management – Non-Acorn deployment	10%	20%	100%	100%
Carbon Management - Exports	0%	100%	100%	100%

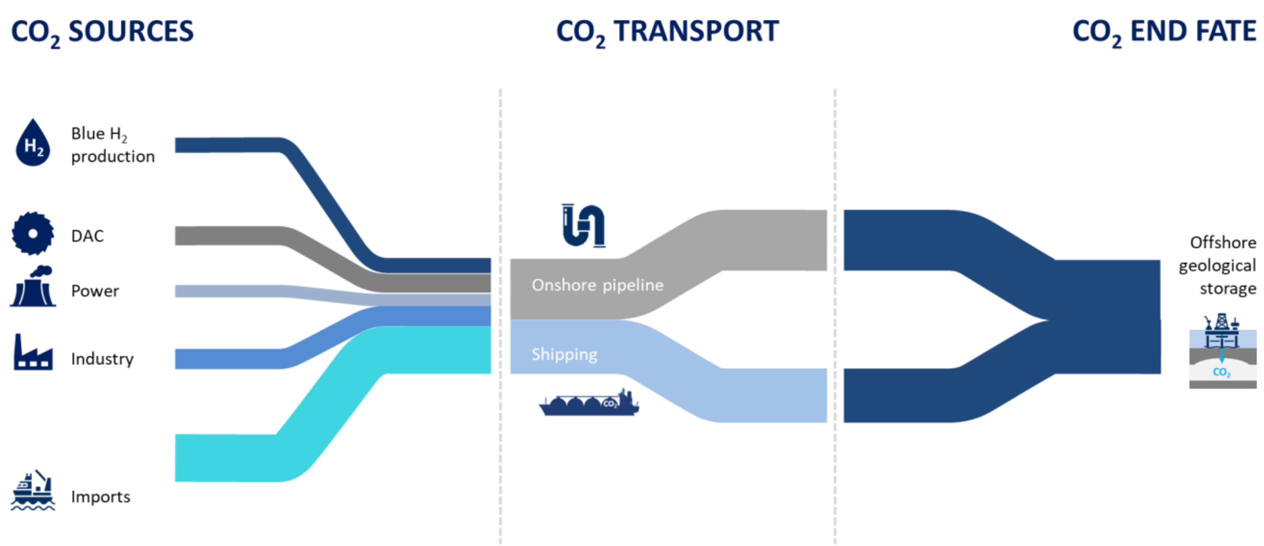

Figure 9-5: Breakdown of the CO_2 flows from the six emitting sectors and across different transport modes for the Core scenario in 2050

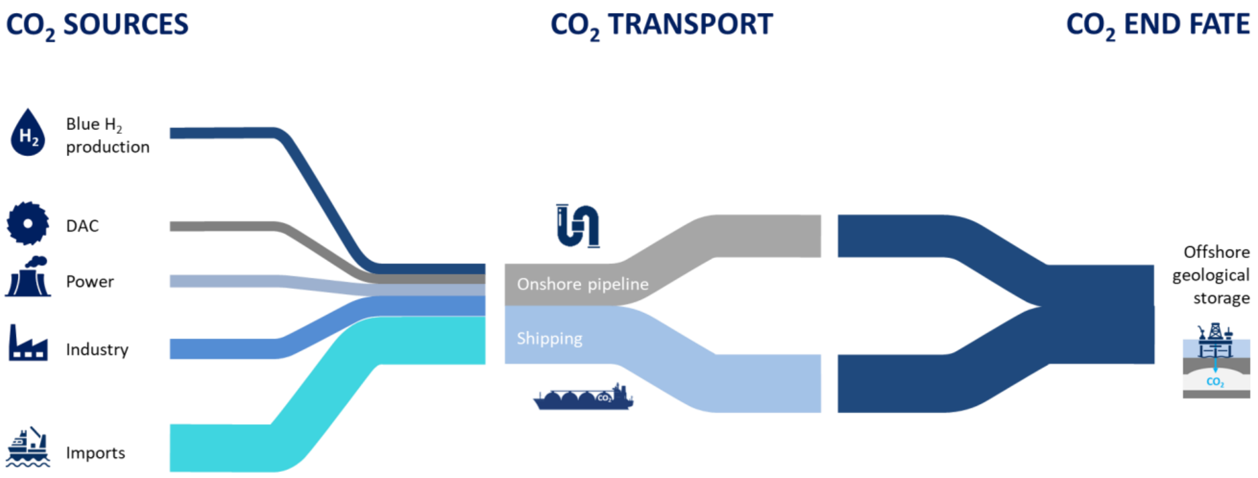

Figure 9-6: Breakdown of the CO_2 flows from the six emitting sectors and across different transport modes for the Soft Start scenario in 2050

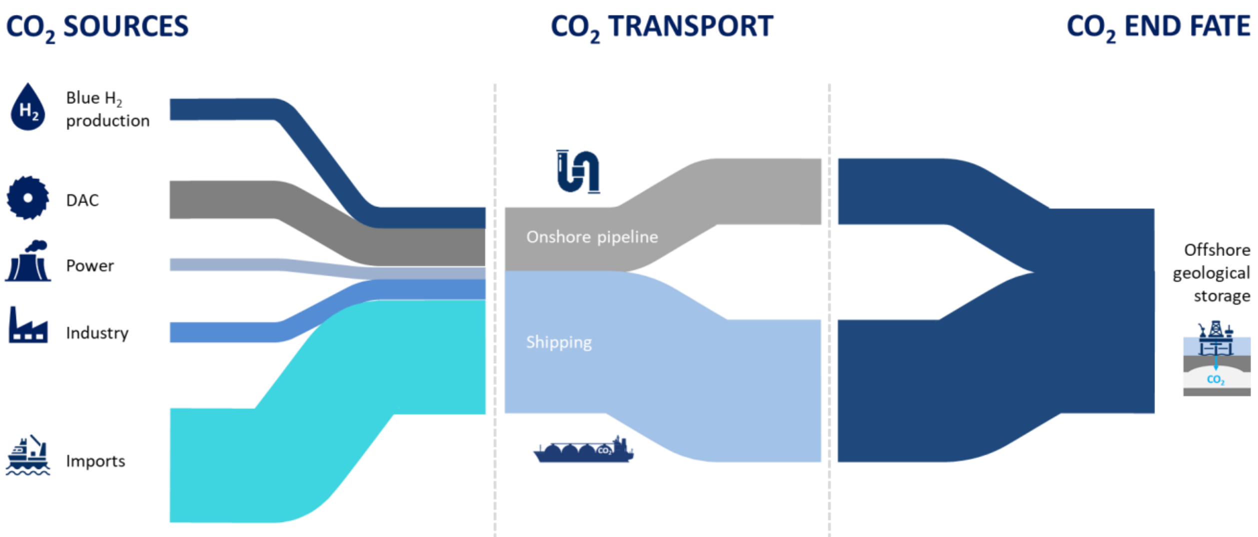

Figure 9-7: Breakdown of the CO_2 flows from the six emitting sectors and across different transport modes for the Carbon Management scenario in 2050

9.5 Economic assessment methodology

9.5.1 ViEW

This section describes ViEW, the model used to analyse the impact of deploying CCS on the Scottish economy and its sectors.

ViEW is an economy-wide, recursive dynamic model of economic activity, energy production and carbon dioxide emissions that can model the impacts of low carbon technologies and energy policies on the economy and its individual sectors. As a CGE model, the model provides detailed insights into both economy-wide as well as sectoral effects, can incorporate feedback loops and thus help to highlight potential spill overs and indirect effects of the policies.

ViEW is an appropriate tool to model all sectors of the economy that are affected by the CCUS uptake. ViEW allows for an in-depth and rigorous view of both energy and non-energy sectors and is highly tailored to study the long-term impacts of the CCUS uptake. Energy production in ViEW includes three resource extraction sectors (coal, crude oil, and natural gas), and multiple electricity generation technologies (electricity from coal, natural gas, nuclear, hydro, biomass, wind and solar). ViEW also can represent non-energy sectors in detail, including agricultural, manufacturing and service sectors, as well as economic agents such as government, firms, and households. Figure 9-8 gives a schematic overview of how ViEW represents the economy.

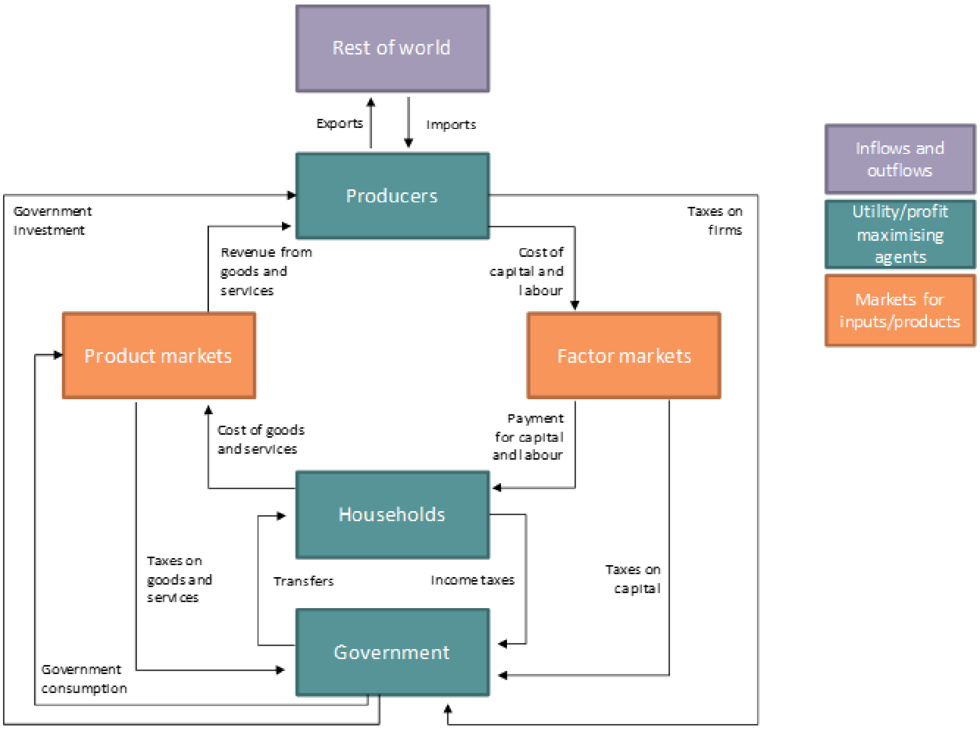

Figure 9-8: Overview of the ViEW model[258]

The model's complexity requires assumptions that need to be considered when interpreting the results. The focus on the long run means that the results pertain to horizons beyond which short run effects, such as nominal rigidities and demand and supply imbalances, e.g., labour market frictions and unemployment, dissipate. Furthermore, ViEW has been calibrated to reflect the changes in economic sectors at a high level, but changes in smaller subsectors might not be fully represented. Lastly, not all government policies in the UK and in the rest of the world can be represented entirely.

The model offers a robust representation of the differential impacts of the CCUS uptake on a range of key economic indicators at an aggregate and sectoral level, but the results must be interpreted with caution. The model delivers economic outcomes at an aggregate and sectoral level across a range of the CCUS uptake scenarios. These outcomes are not offered as forecasts: the analysis focuses on the differences in economic outcomes between a scenario of the future of the UK economy with and without the CCUS uptake to evaluate the impacts of CCUS. The results intend to illustrate potential scale and direction of differences between scenarios rather than exact numbers.

ViEW has previously been used to analyse the impacts of climate policies in various jurisdictions. It was successfully applied in similar projects such as a study on carbon pricing design in Turkey and Sri Lanka,

[258] The rest of the world is modelled here as an aggregate of all other countries contained in the GTAP database. The UK is modelled explicitly in ViEW (Source: Vivid Economics)

on carbon leakage risk in Mexico, decarbonisation pathways in New Zealand, and ETS and carbon tax interactions in Ukraine.

9.5.2 Aggregation, calibration, and data inputs

Aggregation

ViEW uses economic, energy and emissions data from the GTAP database. In addition to economic trade data, this database includes CO_2 emissions by fuel, user and region from the IEA, which constitute the emissions included in the model. The GTAP version 10 database, based on 2014 data, is used to set up the model, while more recent data and forecasts from the UK and international sources are used to calibrate the model until 2050.

The GTAP version 10 database's primary purpose is to provide expansive and granular bilateral industrial sector linkages and relationships of the agents in the economy, such as firms, households and government. In particular, the current GTAP 10 database features 65 sectors.[259] ViEW further disaggregates the electricity generation sector into eight sectors. The model also represents households, firms and government as economic agents. It can be calibrated to any chosen form of aggregation of these sectors. In this way, it can model impacts in the sectors of interest in detail while aggregating those not of interest together such that the model remains tractable and easy to use.

Table 14 summarises the regions, sectors and greenhouse gases represented in ViEW for this analysis.

Table 14: Overview of ViEW aggregation[260]

Category	Aggregation
Regions	The UK
	Rest of the world
Sectors	Power generation: • Gas electricity • Oil electricity • Coal electricity • Wind and solar electricity • Hydro electricity • Nuclear electricity • Biomass electricity • Other electricity • Electricity transmission and distribution
	Industry: • Oil extraction • Natural gas extraction

[259] A full list of GTAP version 10 sectors is available here: https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx
[260] Source: Vivid Economics

Category	Aggregation
	• Coal extraction • Oil refining • Natural gas processing • Chemical industry • Non-Metallic Minerals (e.g. cement, lime, glass, ceramics) • Iron and steel • Pulp and paper • Motor vehicles and parts • Food and beverages • Other manufacturing (including textiles, Non-ferrous metals, other mining)
	Other sectors: • Road transport • Air transport • Water transport • Agriculture • Services
Greenhouse gases	CO_2 emissions from combustion
	CO_2 process emissions from natural gas processing

For this study, ViEW is extended to include the CCS, blue hydrogen, and green hydrogen technologies across the Scottish economic sectors. The sectors in ViEW are provided access to these technologies based on the sectoral CCS, blue hydrogen, and green hydrogen uptake in the four CCUS uptake scenarios developed in Chapter 3, as shown in Table 15.

Table 15: Economic sectors that can deploy CCS, blue hydrogen, and green hydrogen[261]

Category	Sectors
Sectors that deploy CCS	Power generation: • Gas electricity • Biomass electricity Industry: • Oil refining • Gas processing • Chemicals

[261] Vivid Economics and Element Energy's CCUS update scenarios

Category	Sectors
	• Non-metallic minerals
Sectors that use blue hydrogen as energy input	Industry: • Chemicals • Paper and pulp • Non-metallic minerals • Food and beverages • Road transport • Services
Sectors that use green hydrogen as energy input	Industry: • Chemicals • Paper and pulp • Non-metallic minerals • Food and beverages • Road transport • Services • Households

Calibration

The Baseline describes the development of the UK economy under its 2050 net zero target and assumes high electrification and green hydrogen use, but no CCS uptake. This allows the model to contrast the four CCUS uptake scenarios to a baseline with no CCS uptake and hence quantify the economic impact of CCS fully. As far as known to us, BEIS, the CCC and other government institutions has not modelled a net zero scenario for the UK that does not contain CCS. To bridge this gap, we create our bespoke baseline using Consumer Transformation Scenario from National Grid's FES 2020 as the starting point.[262] At the UK level, the scenario assumes high electrification across the economic sectors and has the lowest level of CCS uptake among the available alternative scenarios of FES 2020. The scenario is further altered to replace BECCS and blue hydrogen with electricity generation with renewables and green hydrogen to achieve a baseline with no CCS uptake. Table 16 presents the data inputs used for the calibration of the Baseline scenario.

Table 16: Data inputs for the Baseline calibration[263]

Category	Source
GDP growth	BEIS, 2018 Updated energy & emissions projections, v1.0 published on 16/05/2019[264].
Electricity generation by technology	Consumer Transformation Scenario from National Grid's Future Energy Scenarios 2020[265]; adjusted using National Statistics, Energy trends – UK

[262] https://www.nationalgrideso.com/document/174016/download
[263] Source: Vivid Economics based on National Grid's FES 2020
[264] https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2018#history
[265] https://www.nationalgrideso.com/document/174016/download

Category	Source
	renewables[266]; further altered to replace BECCS and blue hydrogen with electricity generation with renewables and green hydrogen to achieve a baseline with no CCS uptake.
Combustion emissions by sector	GTAP version 10 database[267]; the benchmark year is 2014.
Process emissions by sector	BEIS, Final UK greenhouse gas emissions national statistics 1990 – 2018[268]; the benchmark year is 2014.
Oil prices	International Energy Agency's World Energy Outlook 2019[269]
Autonomous energy efficiency improvements	Assumed 0.3% per year for fuels in electricity generation, and 1% per year for fuels used elsewhere. These are consistent with what is used in other models, e.g. the MIT-EPPA model[270].
Net zero target	The UK Government[271], The Scottish Government[272].
Potential negative emissions in Scotland by 2050	Vivid Economics (2019). A climate of possibility: harnessing Scotland's natural resources to end our contribution to climate change. For World Wide Fund for Nature (WWF)[273].

Running the CCUS uptake scenarios in ViEW

The data provided by the CCUS uptake scenarios are dialled into ViEW to model the economic impact of CCS uptake on the UK economy and its sectors. The data provided by the CCUS uptake scenarios are first scaled up from the Scottish level to the UK level. The data provided by the CCUS uptake scenarios and used in ViEW include: CCS uptake, OPEX and CAPEX of CCS, blue and green hydrogen demand, OPEX and CAPEX of blue and green hydrogen production, distribution of these over the respective value chain components, value of energy inputs needed per value of blue and green hydrogen output, natural gas replacement cost ratio for blue and green hydrogen in 2020, OPEX and CAPEX of CO_2 shipping infrastructure, and OPEX and CAPEX of CO_2 transmission and storage. The data are by sector and over 2020 – 2050 where applicable.

The top-down ViEW model and the bottom-up CCUS uptake scenarios complement each other and allow for a complete whole-economy analysis. ViEW is well suited to assess the whole economy impacts of CCS as it models the interactions between the economic sectors and agents and accounts for feedback loops between these. However, ViEW's disaggregation of the economic sectors lacks granularity, and it represents each sector as one firm only, missing within-sector nuances. As bottom-up scenarios, the four CCUS roll-out cases account for sectoral details and within-sector nuances in detail, while they miss the whole-economy impacts and intertemporal optimisation over time considered by ViEW. Combining the two approaches leverages their strengths and addresses their individual shortcomings.

However, aligning ViEW and the CCUS uptake scenarios is not straightforward. The two approaches assess the economic impacts and project CCS and hydrogen uptake from two opposite angles. They have

[266] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/925976/Renewables_ODS.ods
[267] https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx
[268] https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2018
[269] https://www.iea.org/reports/world-energy-outlook-2019
[270] https://globalchange.mit.edu/research/research-tools/eppa
[271] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
[272] https://www.gov.scot/news/reaching-net-zero-1/#:~:text=The%20Climate%20Change%20Act%202019,gases%20are%20emitted%20by%20it.
[273] https://www.wwf.org.uk/sites/default/files/2019-01/WWF_Report_VIVID_Jan_2019.pdf

different underlying modelling dynamics and assumptions, making it difficult for ViEW to hit all CCS and hydrogen uptake targets. Ideally, ViEW and the CCUS uptake scenarios would be iterated multiple times to achieve a full alignment. However, the timeline and scope of this project allowed for a one-way approach instead. The scenarios are fed into ViEW, but the ViEW outputs are not fed back to the CCUS uptake scenarios. CCS use and blue and green hydrogen production in the CCS uptake scenarios are dialled into ViEW by choosing costs for these technologies so that they are profitable and introducing resource constraints so that the equilibrium production from these technologies in ViEW match those in the CCS uptake scenarios. Costs are adjusted in ViEW by scaling up or down CAPEX and OPEX costs by equal proportions.

Lowering the CCS uptake costs and fuel replacement costs for blue and green hydrogen results in conservative GVA estimations for sectors that uptake CCS and hydrogen. In social accounting matrix terms, GVA of a sector is the sum of the payments to the factors of production, such as capital, labour, land, and natural resources. The approach described above lowers costs and hence capital investment in sectors that uptake CCS and hydrogen. This in return lowers payments to capital in these sectors and thereby their GVA. However, the model tends to overestimate the sectoral GVA impacts in the other sectors. Because less capital is needed for CCS and hydrogen uptake, more capital is available to support other economic activities, boosting GVA in the other sectors. At the whole economy level, as ViEW is a full employment model, lower the CCS and hydrogen costs does not impact the employment of labour and capital in the economy; however, by the lower demand for factor of production will lower the unit returns to these factors and ultimately lead to lower GVA, relative to if the same quantity of CCS and hydrogen output had been simulated in the model at higher CCS and hydrogen costs.

9.5.3 Discrepancies between our analysis and previous studies

A comparison of our results with previous studies have shown discrepancies. It is important to note that the results intend to illustrate potential scale and direction of differences between the CCUS uptake scenarios and the Baseline rather than exact numbers. Our study takes a different approach compared to previous studies that quantify the economic impacts of CCS and hydrogen. Deploying a CGE model, our study considers the whole system impact of the CCS uptake rather than just the gross impacts produced by multiplier-based input-output models. Models deploying the two approaches produce a wide range of results. Results from CGE models tend to sit at the lower end, whereas results from the multiplier-based input-output models are at the higher end of this range.

The discrepancy between the results of CGE and by multiplier-based input-output models can be explained by:

- **Scarcity**: a key reason is that in CGE models sectors compete for primary factors. In other words, the available primary factors are limited in amount, and every activity in a CGE model has an opportunity cost. That is, primary factors used to produce certain quantities of CCS and hydrogen inputs are redirected from other sectors in the economy, decreasing economic activity in the latter. In multiplier-based input-output models, there is no competition for primary factors. The approach assumes that these are abundant and additional, without considering that these must be diverted from another productive activity. In other words, adjustments in other sectors are not required to accommodate output from new technologies.
- **Attribution**: in CGE models, if CCS and hydrogen would not be available, most of the economic activity supported by them would still materialise as sectors would replace these technologies and inputs with others available in the market. So, not all economic activity supported by CCS and hydrogen is attributed to them, resulting in low GVA. In multiplier-based input-output models, all economic activity supported by CCS and hydrogen is attributed to them. Assuming the economic activity is fully additional results in high GVA.

9.5.4 Pre- and post-processing

ViEW applies a top-down approach and runs at the UK level, while pre-processing inputs and post-processing outputs at the Scotland level. The top-down approach is preferable because the UK and Scottish economies are strongly linked. Running ViEW at the UK level accounts for UK policies and hence avoids large leakages of economic activity from Scotland to the rest of the UK that may result from policy differences. Potential leakages could distort the modelling results and conclusion derived from these. The top-down approach follows five steps:

1. Calibrate the ViEW baseline at the UK level;
2. Scale up the CCS and hydrogen deployment targets from the CCUS uptake scenarios from the Scotland level to the UK level using the sectoral GVA ratios of the two levels, also called pre-processing;
3. Dial in the scaled-up CCS and hydrogen deployment targets into ViEW;
4. Scale down the ViEW outputs from the UK level to the Scotland level using sectoral GVA and GDP ratios of the two levels, also called post-processing; and
5. Compare the results from the CCUS uptake scenarios to the results from the baseline.

Table 17 presents the sources used to calculate GVA and GDP ratios. We compiled the Input-Output Analytical Tables from Office for National Statistics and Scottish Government and mapped these to the GTAP sectors used in ViEW. Where there is a mismatch between the sectors of the Input-Output Analytical Tables and GTAP, we used simple assumptions to breakdown the sectoral figures further. For the electricity sector, we leveraged the electricity generation fuel mix data for the UK and Scotland for this purpose.

Table 17: Data sources used to calculate the sectoral GVA ratios[274]

Data	UK source	Scotland source
GVA by sector	2016 Input-Output Analytical Tables from Office of National Statistics[275]	Input-Output tables/multipliers for Scotland 1998-2017 from SG[276]
GTAP sectors	GTAP version 10 database[277]	
Electricity generation by technology	Energy trends: UK electricity, Table 5.1 from National Statistics[278]	Scotland, electricity generation fuel mix from Scottish Government[279] [280]

9.5.5 Employment impacts

As a CGE model, ViEW assumes full employment over the modelling period. Following a shock, such as the introduction of the CCS and hydrogen technologies to the economy, the model works its way always back to natural employment. As a result, if one sector gains employment, other sectors need to lose employment, keeping the total employment at the same level. There also are no labour market frictions and costs when reallocating the workforce between the sectors.

[274] Source: Vivid Economics
[275] https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed
[276] https://www.gov.scot/publications/about-supply-use-input-output-tables/pages/developments/
[277] https://www.gtap.agecon.purdue.edu/databases/v10/v10_sectors.aspx
[278] https://www.gov.uk/government/statistics/electricity-section-5-energy-trends
[279] https://www.gov.scot/Resource/0054/00549213.pdf
[280] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

ViEW keeps the total employment at the same level over the modelling period. Based on Scottish Annual Business Statistics 2018[281] and the Scottish Parliament's industry overview[282], the study assumed the total employment in Scotland as 2.5mn in 2016 and over the modelling period. National Records of Scotland[283] estimates that the Scottish population will increase from 5.44mn in 2018 to 5.57mn in 2043. We assume the aging population will counterbalance the slight population increase, keeping the level of the total employment as it is. This feature of the model also leads to significant labour productivity increases across all economics sectors considered in ViEW.

To calculate the employment by sector,

- We compile the sectoral 2016 employment numbers from Scottish Annual Business Statistics 2018.
- We calculate a factor payment for labour index for each sector. We assumed 2016 as the base year and divided the annual factor payment for labour in a given year by the 2016 factor payment for labour.
- Then, we multiply the index of factor payments for labour for each sector with the 2016 employment of that sector.
- We then rescaled the total employment in a given year to ensure that the total employment in Scotland remains constant over time.

9.5.6 Off-model calculations

We complement the ViEW runs with off-model calculations to consider the GVA and job impacts of CCU, carbon imports, and direct air capture (DAC). This section presents the methodology we applied in detail.

CCU

We quantify the direct and indirect GVA and job impacts of 0.1 $MtCO_2$/year CCU deployment in FOAK plants to produce synthetic fuels, methanol and aggregates. The calculations are done for 2030 using the data shared by Element Energy and ViEW outputs. The former includes hydrogen consumption, electricity consumption, output, annual CAPEX and annual fixed OPEX for the FOAK plant of each commodity. Element Energy also provides a 2030 price estimate for hydrogen and the three commodities. The 2030 electricity price is taken from the Green Book.[284] ViEW and 2018 Scottish Annual Business Survey provide the GVA and job multipliers for electricity generation and hydrogen production.

- **Direct impacts:** we use the data shared by Element Energy to calculate the GVA impacts of producing the three commodities as the difference between total revenue and input costs. For the job multiplier for the three commodities, we use the chemicals sector as proxy and use the 2018 Scottish Annual Business Survey as the primary source. Note that the analysis considers the direct impacts from the OPEX phase only given the long-term focus of the study.
- **Indirect impacts:** the three commodities are energy intensive and consume large amounts of electricity and/or hydrogen as their primary inputs. That's why, the analysis focuses on GVA and jobs supported by electricity generation and hydrogen production as the indirect impacts. As mentioned above, the GVA and job multipliers for these two sectors are employed for the calculations.

[281] https://www.gov.scot/publications/scottish-annual-business-statistics-2018/
[282] https://digitalpublications.parliament.scot/ResearchBriefings/Report/2017/10/13/Scotland-s-Employment-by-Industry-and-Geography#Industry-overview
[283] https://www.nrscotland.gov.uk/files/statistics/population-projections/2018-based/pop-proj-2018-scot-nat-pub.pdf
[284] Traded central scenario in Tables 9-13, long run variable costs of energy supply (real 2019 prices), Central & Industrial from Green Book supplementary guidance. Available at https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

Carbon imports

The total GVA and jobs supported by carbon imports from the EU have three components:

- **Shipping:** ViEW calculates the GVA impact on an increase on domestic water transport activity due to carbon imports. We then calculate the job impact using the approach described in Section 9.5.6.
- **T&S:** We used the GVA and job multipliers provided by Element Energy to calculate the GVA and jobs impacts of transmission and storage of carbon imports. These include direct as well as indirect impacts.
- **Cost differential between the UK and the EU:** The cost data provided by Element Energy shows that storing CO_2 in Scotland will be significantly cheaper than storing CO_2 in the EU, such as in its leading Northern Lights project. We assume that the carbon storage market will be a seller market, and hence Scotland will be able to charge a fee for carbon imports just under the cost of transporting and storing CO_2 in Northern Lights. We then multiply these price differentials with projected carbon imports in the CCUS uptake scenarios to calculate the supported GVA. There is no job impact originating from the cost differential.

DACCS

We quantify the direct and indirect GVA and job impacts of the DACCS deployment in Scotland based on the levels stated in the CCUS uptake scenarios.

- **Direct impacts:** to calculate the GVA impact of DACCS, for each year, we take the difference of the UK carbon price from the Green Book[285] and the total levelized costs of DACCS shared by Element Energy and then multiply this difference with the total CO_2 captured by DACCS. To calculate the job impact of DACCS, we refer to the job multipliers of Rhodium Group.[286] They estimate a single DACCS plant with 1 $MtCO_2$ capture capacity can support around 3,070 jobs during its construction phase and 278 jobs during the operations & maintenance phase (excluding the jobs supported by the energy and chemicals demand of the DACCS plant). We assume a lifetime of 20 years and distribute the jobs supported in the construction phase over the lifetime of the DACCS plant.
- **Indirect impacts:** as an energy intensive process, DACCS relies on chemicals reactions to remove CO_2 from the atmosphere and consumes large amounts of electricity during this process. That's why, the analysis considers chemicals and electricity consumed by DACCS to quantify the indirect impacts. For chemicals, the job multiplier comes from Rhodium Group, whereas the GVA multiplier is compiled from Scottish Annual Business Survey 2018.287 For electricity, ViEW provides the GVA multiplier, while the job multiplier is calculated using Scottish Annual Business Survey 2018. It is assumed that all chemicals needed by DACCS are produced in Scotland.

9.6 Methodology used for supply chain gap analysis

In order to understand the potential gap in the size of the 2045 Scottish CCUS industrial supply chain, we conducted the following analysis:

- The revenue which the Scottish O&G supply chain captures today was calculated from the EIC SupplyMap supply chain database.
- This value was then translated to a 2045 potential revenue for the Scottish O&G supply chain, by applying a percentage change in the size of the Scottish O&G sector from today to 2045, from ViEW modelling.

[285] Traded central scenario in Table 3 from Green Book supplementary guidance. Available at https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal
[286] Rhodium Group (2020). Capturing new jobs. Available at https://rhg.com/wp-content/uploads/2020/06/Capturing-New-Jobs-Employment-Opportunities-from-DAC-Scale-Up.pdf
[287] https://www.gov.scot/publications/scottish-annual-business-statistics-2018/

- The potential revenue which the Scottish CCUS supply chain could capture in 2045 was calculated from the EINAs CCUS report.
- The difference in potential revenue between the 2045 Scottish O&G and CCUS supply chains was classified as the potential gap in the size of the 2045 Scottish CCUS industrial supply chain.

The revenue which the Scottish O&G supply chain captures today, was determined as follows:

- First, the EIC SupplyMap database was filtered for Scottish companies with revenues between £1mn and £1bn. This revenue range was felt to be appropriate given the size of contracts which would be expected to be tendered for participation in the supply chain of CCUS projects being planned in Scotland.[288]

- Second, the products (goods and services) of these companies were classified into one of the five main categories in the CCUS supply chain. These categories are 1) capture and pollution control, 2) conversion and generation, 3) T&S, 4) measuring, monitoring and verification and 5) EPCm. This categorisation reflects the fact that the very same companies providing goods and services classified under 'capture and pollution control' in O&G for example, should also be able to provide 'capture and pollution control' goods and services for CCUS. This step captured the opportunity for these companies in the O&G supply chain to provide goods and services in CCUS, despite the CCUS industry being nascent.

- Third, to determine how much of this revenue is actually from UK based activity, the total revenue of all companies in each of the five CCUS supply chain categories was multiplied by an average historic market share of UK companies in EU-level trade statistics. For example, historic trade statistics from PRODCOM show that the UK was able to capture an average of 5-6% of EU level trade in 'capture and pollution control' equipment (in O&G or other sectors) between 2016 and 2018. The average across all five CCUS supply chain categories was broadly stable over the period 2016 and 2018 and was approximately 5%. The assumption that all revenue for UK based companies is from the UK or EU, was made because it was not possible to apportion revenue for UK companies in the EIC SupplyMap database, to countries outside of the EU.

Finally, to determine how much of this revenue is able to accrue to Scotland (for wider spending in the Scottish economy), the total revenue of all companies in each of the five CCUS supply chain categories, was multiplied by the current ratio of Scottish O&G sector turnover, to UK O&G sector turnover (78% in 2018). This reflects the fact that the Scottish O&G industry is a disproportionate size of total UK O&G turnover and that being so well established, we would expect it to continue to capture a disproportionate size of UK CCUS turnover in the future.

The 2045 potential revenue for the Scottish O&G supply chain was determined as follows:

- First, CGE modelling results for Task 1.4 of this study were used to determine the potential GVA of the 2045 Scottish O&G industry, in the presence of CCUS. We used the Ambition scenario from Task 1.4, because it represents the greatest level of deployment of CCUS in the O&G sector and therefore the most productive deployment of *existing* O&G infrastructure, all else equal. Additionally, it is the scenario with the largest change in the size of the Scottish O&G sector relative to today. The gap therefore represents capacity constraints for deployment of CCUS in other industries, with the concomitant gaps in skilled labour to ensure the deployment can take place. Figure 7-9 of the report shows that CCUS enables an increase in GVA in the Ambition scenario by 2045, of ~£0.6bn (2019£), relative to the Baseline of no CCUS.

[288] EICSupplyMap does not contain details of any companies in the UK with revenue less than £1m.

- Second, the potential GVA of the 2045 Scottish O&G industry was translated to a percentage change relative to 2019. The total GVA in 2019 of the Scottish crude oil, gas and refining sectors was ~£2.3bn (2019 £). Therefore, this percentage change was 0.6/2.3 =~26%.
- Finally, this percentage change was applied to the Scottish O&G revenue today, in all five categories of the CCUS supply chain. This reflects the change in the potential revenue which all five CCUS supply chain categories supplying goods and services into the O&G industry, could expect to capture in 2045.[289]

The potential revenue which the Scottish CCUS supply chain could capture in 2045 was determined as follows:

- First, data from the CCUS EINAs report was used to determine the size of the tradeable market for the activities in the CCUS supply chain in 2050. These activities corresponded to the exact same five CCUS supply chain categories mentioned above, ensuring a fair comparison between O&G and CCUS sectors.
- Second, to determine how much of this market could potentially be captured by UK companies in the form of revenue, the size of the tradeable market was multiplied by estimated 2045 market shares in EU trade taken from the EINAs CCUS report, for each of the five CCUS supply chain categories. Because the EINAs CCUS report provides market shares for 2050, we linearly interpolated market shares from 2050 down to 2045 levels.
- Finally, to determine how much of this revenue might be able to potentially accrue to Scotland (for wider spending in the Scottish economy), the total revenue of all companies in each of the five CCUS supply chain categories, was multiplied by the current ratio of Scottish O&G sector turnover, to UK O&G sector turnover (78% in 2018). This reflects the fact that the Scottish O&G industry is a disproportionate size of total UK O&G turnover and that being so well established, we would expect it to continue to capture a disproportionate size of UK CCUS turnover in the future.

The difference in potential revenue between the 2045 Scottish O&G and CCUS supply chains was determined as follows:

- The difference between 2045 Scottish O&G and CCUS supply chains was calculated. This was classified as the gap.[290]

[289] It was not possible to split the percentage change into each of the supply chain categories individually
[290] Uncertainty in future sectoral wages meant that we did not convert the gap in potential revenue, into GVA or jobs.