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Accelerating Low carboN Industrial Growth through CCUS

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Summaries of UK case studies to reduce the cost of CCUS deployment in the Teesside and Grangemouth industrial clusters

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Written By	Maxine Akhurst, Erica Greenhalgh, Karen Kirk, Jonathan Pearce, Hayley Vosper, Gareth Williams, John Williams, (BGS), Belinda Perriman, Sarah Tennison (TVCA), Zhengang Nie, Yu Zhang, Sevket Durucan, Anna Korre (ICL), Ward Goldthorpe, Lionel Avignon, Austin Goldthorpe (Sustainable Decisions Limited).	30th November 2020
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Executive summary

This report highlights the research completed within ALIGN-CCUS (ALIGN) by the UK case studies to advance the development of full-chain Carbon Capture Utilisation and Storage (CCUS) at the Teesside and Grangemouth industrial clusters. The specific objective is to undertake research and development activities, supported by the ALIGN project that will reduce the cost of CCUS deployment in the Teesside and Grangemouth industrial clusters.

The UK case study focuses on reducing costs of Carbon Capture and Storage (CCS) deployment at the Grangemouth and Teesside clusters and increasing certainty in provision of sufficient geological storage capacity. It includes the following research and development objectives:

- Identify cost reduction opportunities around CCUS for the Teesside and Grangemouth industrial clusters, including the production of clean hydrogen for use in industrial heating;
- Develop and test options to meet North Sea storage demand for the two UK CCUS clusters;
- Present optimal CCS transport and storage options, including transport by shipping, for a UK CO_2 transport and storage network for Teesside and Grangemouth, with expansion options to other industrial hubs;
- Determine optimal business models for growth and expansion of UK CCUS clusters beyond initial investment from the UK Government's Department for Business, Energy and Industrial Strategy (BEIS), and understand relevant regulatory and liability constraints (including State Aid) relevant to UK CCUS clusters.

Summaries from the UK case studies research deliverables are compiled as chapters in this short report:

Scenarios for future storage requirements in the United Kingdom (Pearce and Akhurst, 2019, D5.1.4a; Pearce and Akhurst, 2020, D5.1.4b);

A CO_2 storage network for enabling decarbonisation of the Teesside industrial cluster (Williams et al., 2019a, D3.2.2);

Modelled CO_2 storage options for the Teesside industrial cluster (Williams et al., 2020, D5.1.2a);

A CO_2 storage network for enabling decarbonisation of the Grangemouth industrial cluster (Williams et al., 2019b, D3.2.3);

Modelled CO_2 storage options for the ALIGN-CCUS Grangemouth industrial cluster (Vosper et al., 2020, D5.1.2b);

Suitability of infrastructure for re-use: UK case study (Greenhalgh et al., 2019, D3.3.2);

Summary of outcomes of TVCA planning for the Teesside industrial CO_2 capture cluster relevant to the offshore transport and storage network (Perriman and Tennison, 2020, D5.1.1);

Scenarios analysis and guidelines for the development of flexible transport and storage network for the Grangemouth and Teesside clusters (Nie et al., 2020a, D5.1.4d);

Business and investment models for UK CCUS storage cluster options (Goldthorpe et al., 2020, D5.1.3).

A bibliography of the UK case study research deliverables summarised in this report and other ALIGN research deliverables cited is presented.

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1 Introduction

This report highlights the research completed within the ALIGN project to advance the development of full-chain CCUS at the Teesside and Grangemouth industrial clusters. The specific objective is to undertake research and development activities, supported by the ALIGN project that will reduce the cost of CCUS deployment in the Teesside and Grangemouth industrial clusters.

Tees Valley, north-east England, is amongst the largest and most densely clustered sites of manufacturing industries in the UK. ALIGN research has built on the existing plans for CO_2 capture, conditioning and compression from energy-intensive industry, costing of CO_2 transport and storage underlying the North Sea, and potential financing mechanisms. Over half of the UK's hydrogen is currently produced at Teesside, and CCS to store the CO_2 produced and provide further 'clean hydrogen' is part of the collective plan at Teesside. Teesside is also the initial recommended site for hydrogen production to replace natural gas for domestic use in UK households.

The Grangemouth industrial cluster is focused around the Ineos refinery complex, which annually produces approximately two million tonnes of chemical products and is Scotland's sole crude oil refinery. The Grangemouth site, central Scotland, is connected to the North Sea oil and gas pipeline terminus at St Fergus which is the location for the planned Acorn full-chain CCS and hydrogen infrastructure project[1].

The UK case study focuses on reducing costs of CCS deployment at the Grangemouth and Teesside clusters and increasing certainty in provision of sufficient geological storage capacity included the following research and development objectives:

- Identify cost reduction opportunities around CCUS for the Teesside and Grangemouth industrial clusters including the production of clean hydrogen for use in industrial heating;
- Develop and test options to meet North Sea storage demand for the two UK CCUS clusters;
- Present optimal CCS transport and storage options, including transport by shipping, for a UK CO_2 transport and storage network for Teesside and Grangemouth, with expansion options to other industrial hubs;
- Determine optimal business models for growth and expansion of UK CCUS clusters beyond initial BEIS investment and understand relevant regulatory and liability constraints (including State Aid) relevant to UK CCUS clusters.

The research proposed early in January 2017 gained support of national and European Commission and commenced in August of that year. During the ALIGN-CCUS research, completed in November 2020, there has been a wider recognition of the adverse impact on the environment of carbon dioxide in the atmosphere and increased UK strategic support for emissions reduction. Accommodation of the increased ambitions for CCS in the UK within the planned ALIGN-CCUS outputs, to ensure the research findings remained relevant, was by agreement between the national funders and researchers.

Summaries from the UK case studies research deliverables are compiled as chapters in this short report. Links between UK case study research activities are highlighted and where there has been input from research and tools developed in the wider ALIGN project.

The case study commenced with receipt of plans for deployment of CCS at Teesside which informed the assessment of required storage capacity. National and industry plans for CO_2 capture and CCS deployment in future decades were reviewed for Grangemouth and Teesside. The profile of planned CO_2 supply was plotted, in collaboration with the ACT ELEGANCY Project[2], to set the challenge for the CO_2 storage research (Chapter 2).

Storage options in the Southern North Sea with sufficient capacity to enable decarbonisation at Teesside, from present day to 2100, were selected (Chapter 3) and the proposed storage network options were evaluated for technical feasibility (Chapter 4).

[1] https://theacornproject.uk/

[2] ELEGANCY – Enabling a low-carbon economy via hydrogen and CCS

Storage options in the Moray Firth area of the Central North Sea were selected for Grangemouth (Chapter 5) and simulated for technical feasibility (Chapter 6).

Existing offshore infrastructure was considered, suitability screening criteria identified, relevant UK legal and commercial matters highlighted and actions recommended to enable re-use for CO_2 transport and storage (Chapter 7). The re-use screening criteria were applied to the storage options selected for Teesside and Grangemouth.

Increased aspirations to achieve net-zero emissions reduction, announced by the UK Government in November 2018, included a greater role for large-scale hydrogen production with CO_2 storage. Updated plans for Net Zero Teesside were received in 2020 (Chapter 8) and subsequently a second review of the future CO_2 storage requirements was completed (Section 2.4).

An analysis and guidelines for the development of flexible transport and storage network was modelled for both the Grangemouth and Teesside clusters, including the increased CO_2 capture rate by Net Zero Teesside (Chapter 9).

The development of the business case for the Teesside and Grangemouth industry clusters was analysed to address the impact of the characteristics of phased or evolutionary storage network development and operation on business models and investability (Chapter 0). The analysis incorporates the network optimisation modelling performed in the UK case studies (Chapter 9).

A bibliography of the UK case study research deliverables summarised in this report and other ALIGN research deliverables cited is presented (Chapter 11).

2 Scenarios for future storage requirements in the United Kingdom

Estimates of possible rates of CCS deployment to 2050 and beyond are required to identify credible options for geological storage of CO_2. ALIGN research has reviewed and summarised available estimates of CCS development for low-carbon industrial operations and large-scale hydrogen production to achieve continuing reduction of CO_2 emissions to meet national targets in future carbon budgets (Pearce and Akhurst, 2019). The estimates were combined to develop a range of CO_2 capture rates for two industrial regions, Grangemouth and Teesside, to identify the required storage capacity that will be needed in future decades. The estimates were presented as input data to inform research in the ACT ELEGANCY Project and, in collaboration, with ALIGN UK case studies to reduce the cost of deployment of CCUS at the two industrial sites.

2.1 Background

The UK Clean Growth Strategy, published in October 2017 by the United Kingdom's Department for Business, Energy and Industrial Strategy (BEIS), set out actions that the UK Government can take to increase economic growth with lower carbon dioxide emissions. The UK has legally binding carbon budgets which have been fixed over five-year periods, with the first period from 2008-2012. The UK is in its third carbon budget period, from 2018 to 2022. Whilst the UK has met its targets in each of the first three periods, meeting the target in the subsequent fourth and fifth periods will require further significant technological transitions across many key sectors. These technology changes are most notable in the industrial, transport and heating sectors. Analysis by the UK Government Climate Change Committee indicates that the use of capture and storage of CO_2 from industrial sources will be required as part of a portfolio of options, to enable the UK to meet its fourth and fifth carbon budgets. The emissions reduction would be achieved by conventional power generation with CCS (up to 4-7 GW electricity generated) and capture of CO_2 from industrial plants (3-5 million tonnes (Mt) CO_2 per year) by 2035. This review extends the timescale to 2100 since it is expected that once investments are made the infrastructure will provide low-cost options for continued CO_2 reduction in the latter half of this century.

2.2 Methodology

An estimate of the potential magnitude and rate of future CCS deployment was presented, based on industry predictions of CO_2 capture from industrial sources and implementation of hydrogen reformation with CCS available to May 2018. Providing this estimate allowed CO_2 supply curves to be defined and a portfolio of suitable storage sites with matched capacity to be selected and appraised. However, assessing the future growth in energy demand must incorporate a range of factors including: future scale and locations of industrial emissions; proportion of fossil-based power and heating that might contribute to meet industrial demand; and possible rates of hydrogen replacement of natural gas for heating or transport. Since these factors carry large uncertainties, a scenario-based approach has been taken, whereby studies undertaken elsewhere have been reviewed and combined to develop an estimate of possible future CCS deployment, with a focus on the Teesside and Grangemouth industrial clusters.

2.3 Scenarios of CO_2 supply

Regional CCS deployment concepts were integrated and mapped onto a low-carbon development pathway at the Teesside and Grangemouth industrial clusters. In order to encompass different possible rates of CCS deployment in the UK, three variants along the pathway were defined with low, intermediate and high rates of CCS deployment. The variants reflect both increasing capture of CO_2 from industrial sources across a wider catchment surrounding the industrial clusters at Teesside and Grangemouth and increasing production of hydrogen from methane with CCS. The pathway progresses from an '*initial projects*' phase through a '*growing projects*' phase to a '*maturing projects*' phase, to help achieve a low-carbon economy in the UK. Development considers the parallel operation of several CCS projects with progressively increasing cumulative geographical extent with increasing annual volumes of CO_2 stored. The 'maturing projects' phase will be further developed to consider future UK storage of CO_2 captured and transported from Europe.

Low rates of CCS deployment during the *initial projects* phase includes CO_2 capture rates at Teesside of 0.7 Mt per year and at Grangemouth of 1.7 Mt per year. Storage capacities required for these initial projects are approximately 23 Mt and 61 Mt by 2055, respectively.

At intermediate rates of CCS deployment during the g*rowing projects* phase there would be industrial capture from more emitters and at higher rates together with increasing hydrogen production. Annual CO_2 capture rates would increase to approximately 14 Mt per year at Teesside and 8.6 Mt per year at Grangemouth. Growing projects would require the provision of a total CO_2 storage capacity of 309 Mt for Teesside and 267 Mt for Grangemouth and Central Scotland by 2055. Assuming constant capture thereafter to 2100, the combined required storage capacities would increase to a total of 1248 Mt.

At high rates of CCS projects deployment, with increased hydrogen production, the average rate of CO_2 captured for storage in England would be 59 Mt per year. The CO_2 storage capacity required in 2050 would be approximately 852 Mt. Assuming constant capture rates thereafter, the required storage capacity would be 2557 Mt by 2100 for England. In this scenario, high rates of deployment for Scotland are being addressed by the ACT Acorn Project[3].

The UK has an estimated theoretical potential CO_2 storage capacity of 78,000 Mt, well known from hydrocarbon exploration and production, underlying its immediately adjacent seas[4]. The three variants on the pathway to a UK low-carbon economy were investigated by the ALIGN-CCUS project for flexible storage options for growth of the Teesside and Grangemouth industrial clusters. The ACT ELEGANCY project used the same pathway to examine seasonal and operational variations in CO_2 supply and composition associated with large-scale hydrogen production.

2.4 Updated review of CO_2 storage estimates for the UK to meet net-zero emissions targets

Subsequent to the CO_2 supply profiles developed at the beginning of the ALIGN research project, a second review of the potential storage requirements was considered necessary to take account increased UK ambitions for emissions reduction and the role of hydrogen (Pearce and Akhurst, 2020). New and additional studies available from May 2018 to December 2019 were reviewed that analysed the potential roles of hydrogen production with CCS and 'carbon-negative solutions' such as direct air capture (DACCS) and bio-energy CCS (BECCS). These technologies all rely on CO_2 storage and are considered necessary to achieve net-zero emissions by 2050. Increased aspirations for industrial CO_2 emissions reduction and ambitions for low-carbon gas by hydrogen production and CCS were being made publicly available during 2018. In late 2018 the UK Government's action plan for a CCUS Deployment Pathway[5] and Climate Change Committee recommendation of net-zero emissions by 2050 in May 2019[6] galvanised renewed industry plans for CO_2 emissions reduction. These studies have clearly indicated that further storage capacity is likely to be needed to meet potential capture rates in the 2030s to 2050s and beyond. Further analysis is needed to both define the storage capacities required, as industry, 'carbon-negative solutions', heating and transport decarbonises across the UK. Analysis must include decarbonisation of industrial regions in neighbouring countries who might wish to use UK storage capacity where this is at lower cost or available at an earlier date.

2.5 Estimated CO_2 capture rates for the Grangemouth and Teesside industry clusters: key points

A CO_2 supply profile was presented from review of national and regional plans for capture of CO_2 from industrial processes, and strategies to use hydrogen for heating and transport in the UK (England, Scotland and Wales).

The duration of the profile is from the present day to 2100. It is informed by national and regional plans and strategies extending to the 2050s and then extrapolations at constant, increasing or decreasing rates from 2055 to 2100.

[3] ACT Acorn Project. A scalable full-chain industrial CCS Project. https://www.actacorn.eu/

[4] Bentham et al., 2014. CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas. Energy Procedia, 63, 5103 – 5113 doi: 10.1016/j.egypro.2014.11.540

[5] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759637/beis-ccus-action-plan.pdf

[6] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Studies by UK government and industry, mostly focused around the Teesside and Grangemouth industrial clusters, have been mapped and combined to present scenarios of increasing low-carbon industrial growth and increasing geographical extent.

The CO_2 supply profile has been used in two projects funded by the Accelerate CCS Technologies (ACT) programme; the ALIGN-CCUS project has investigated storage capacity for different rates of CO_2 supply and the ELEGANCY project has considered variations in CO_2 production and composition associated with large-scale hydrogen production.

The pathway for UK low-carbon growth progresses from initial industry CCS projects, through project growth by addition of CO_2 sources from within the surrounding regions, including from increased hydrogen production, to import of CO_2 attracted to maturing projects.

Initial CCS projects at Teesside and Grangemouth have a combined capture rate of 2.4 Mt CO_2 per year and will require a cumulative storage capacity of approximately 23 Mt and 61 Mt by 2055 respectively.

Increased capture rates during projects growth, including from large-scale hydrogen production, are an average of 59 Mt per year at Teesside and 8.6 Mt per year at Grangemouth, requiring 309 Mt capacity at Teesside and 267 Mt for Grangemouth and central Scotland by 2055. Extending the storage period between 2055 and 2100, the additional capacity required for Teesside is 286 Mt and 387 Mt for Grangemouth. The total required storage capacity to 2100 would be 1248 Mt.

At high rates of CCS deployment, and particularly large-scale hydrogen production, average annual CO_2 capture is estimated as 59 Mt per year in England requiring a total CO_2 storage capacity of 852 Mt in 2050. Assuming constant high capture rates thereafter, the required storage capacity solely for England would be 2557 Mt in 2100. High rates of deployment for Scotland are investigated by the ACT Acorn project.

Project updates in 2020 include details of revised annual capture rates that approximate or exceed the ‘Projects Growth’ scenario for capture and storage at both the Teesside and Grangemouth clusters.

The study has evaluated the potential storage requirements for two industrial clusters, set within a national context. The Industrial Strategy Challenge has identified five clusters which will create a greater requirement for appraisal of UK storage capacity.

3 A CO_2 storage network for enabling decarbonisation of the Teesside industrial cluster

The rationale for storage site selection, to enable CO_2 emissions reduction from the Teesside industrial cluster by CCS is described by Williams et al. (2019a). The sites selected comprise a network of storage options. The selection considers the time-dependent rate of CO_2 supply matched to suitable storage sites assessed against the following criteria:

- Sites should provide adequate storage capacity;
- Injectivity of the storage reservoirs should be sufficient to meet the CO_2 supply profiles for Teesside of Pearce and Akhurst (2019);
- Sites should be within relatively close proximity to the Teesside industrial cluster;
- The network of storage sites should have the potential for future expansion to accommodate CO_2 captured from additional clusters of industrial sources in the north of England and/or CO_2 imported for UK storage by ship from other sources e.g. Rotterdam;
- Sites have been characterised to suitable Storage Readiness Levels, as developed in ALIGN-CCUS (Bentham et al., 2019), during the planned early injection period;
- Existing 3D geological models and/or data are available or obtainable within project resources, to enable detailed simulation and verification of the storage scenarios;
- Sites should have the potential to be included in an integrated storage network.

Key decisions for Teesside network site selection include:

- Two separate storage networks should be developed for each of the industrial clusters considered in ALIGN-CCUS, Teesside and Grangemouth, to enable future low-carbon growth through the 2030s;
- A multi-site storage network will be required to meet future decarbonisation ambitions at Teesside;
- Sites within the northern part of the UK Southern North Sea (SNS) Basin are prioritised for selection of options for storage of CO_2 from the Teesside industrial cluster;
- Storage sites evaluated by previous commercial and feasibility studies should be prioritised for initial development, in preference to sites that have not received sufficient assessment to be considered as a contingent resource;
- Only sites with existing geological models that are available for research will be investigated in the ALIGN-CCUS UK case study for storage of CO_2 from the Teesside industrial cluster;
- Initial storage site development for the Teesside storage network should be within the Endurance structure to enable CO_2 storage from 2024;
- Bunter Closure 36 will act as the second anchor site, linked to the Endurance site by a CO_2 transportation corridor, to develop a Teesside storage network from 2029/2030;
- Expansion of the Teesside storage network should incorporate development of Bunter Closure 37 followed by Bunter Closure 39 during the 2030s, according to CO_2 supply scenario, although local pressure constraints may require additional storage sites;
- The Hewett and Leman gas fields will not be considered within the Teesside storage network owing to their distance from Teesside and greater suitability for decarbonisation of London and the south-east of England;
- Wider expansion of the Teesside network in a scenario of mature CCS projects development should first include Bunter Closure 26, followed by Bunter Closures 40 and 5, if required due to pressure limitations;
- The Viking Gas Field and overlying Bunter Closure 3 may be suitable sites for expansion of the Teesside storage network, if required, due to pressure increase within the Bunter Sandstone closures proposed for the Teesside storage network;
- Development of a 'free-standing' storage complex for import of CO_2 via shipping should consider the Viking Field and Bunter Closure 3.

A conceptual illustration of the proposed mature storage network for Teesside in the SNS includes the addition of a separate conceptual storage network for south-east England and potential opportunities for further storage network development (*Figure 1*). Potential options for import of CO_2 from Germany and Belgium exported via the Port of Rotterdam is also illustrated.

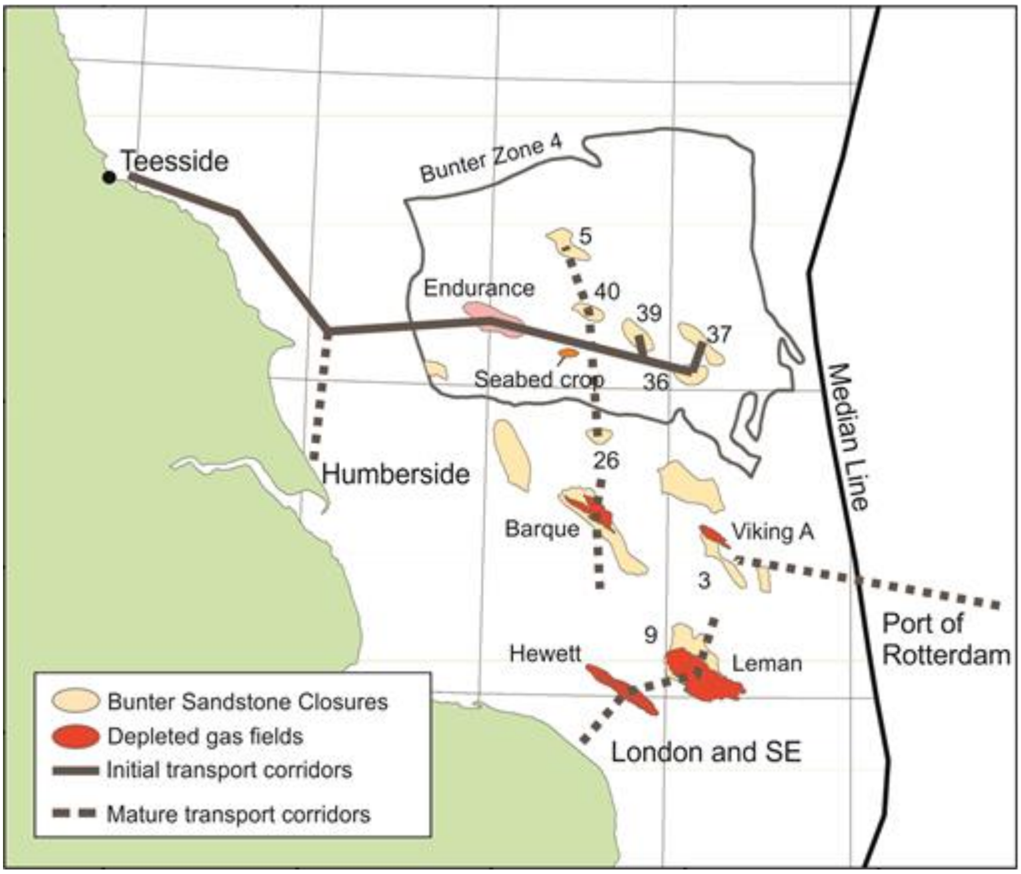

Figure 1 ALIGN-CCUS proposal for initial and mature storage networks in the Southern North Sea, including separate storage networks for the Teesside industrial cluster and the south-east of England.

The storage concepts presented were investigated by dynamic simulation of CO_2 injection (Williams et al., 2020), and network and economic modelling (Nie et al., 2020a) in the ALIGN-CCUS UK case studies for Teesside.

4 Modelled CO_2 storage options for the Teesside industrial cluster

Estimates of the CO_2 storage capacity of the Bunter Sandstone Formation in the UK SNS are required to provide technically credible storage options for CO_2 from Teesside and North of England region. The feasibility of storage scenarios incorporating CO_2 from industrial operations and large-scale hydrogen production and selected storage options presented as components of ALIGN-CCUS project research (Pearce and Akhurst, 2019; Williams et al., 2019a) were modelled by Williams et al. (2020). A reservoir model was constructed and parameterised using available rock property data. This model formed the basis for a range of simulations designed to test the storage capacity of five large anticlinal dome structures with favourable flow properties for CO_2 storage.

Three CO_2 storage scenarios have been investigated, based on industry plans for CCS project deployment at the Teesside industrial cluster. The 'Initial Project' injection scenario (Pearce and Akhurst, 2019, Scenario 2.2) has been designed to store around 428 Mt of CO_2 over a 76-year injection period, at a rate of approximately 5.6 Mt of CO_2 per year. A 'Project Growth' scenario of captured CO_2 supply increased to around 7.8 Mt of CO_2 per year and total target storage volume to 595 Mt (Pearce and Akhurst, 2019, Scenario 2.3). The injection profile for the 'Mature Project' scenario (Pearce and Akhurst, 2019, Scenario 5.1) assesses storage of a total of around 3118 Mt of CO_2 in nine target sites in the UK SNS. Five sites are selected, with a total target storage of 1976 Mt CO_2, and modelled in this study for the Mature Project scenario and, subsequently, for the TVCA Teesside Base Case (Perriman and Tennison, 2020).

A series of model runs were conducted to assess the impact of selection of input modelling parameters to address uncertainties in the volume of CO_2 that can be safely injected into the Bunter Sandstone within the area modelled. A conservative 'low storativity' case was designed to assess the low-end CO_2 storage capacity, incorporating parameter estimates at the lowest end of the measured range. A 'base case' scenario represents regional storage parameters currently thought to be representative for the Bunter Sandstone in this region. A 'high storativity' scenario assumes optimistic input parameters, in which the maximum amount of CO_2 storage would prove possible. Modelling input parameters and associated range of values used to address uncertainties in the dynamic simulations are shown in ***Table 1***.

Table 1 Modelling input parameters and associated range of values used to address uncertainties in the dynamic simulations.

Grid property	**Low storativity case**		**Base case**		**High storativity case**	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Porosity (%)	18.0	18.0	18.0	23.0	23.0	23.0
Horizontal permeability (milliDarcy)	55.0	55.0	55.0	270.0	270.0	270.0
Ratio of vertical to horizontal permeability	0.05	0.05	0.35	0.35	0.85	0.85
Pore compressibility, per bar of increased pressure	$2.5x10^{-5}$	$2.5x10^{-5}$	$5.0x10^{-5}$	$5.0x10^{-5}$	$8.5x10^{-5}$	$8.5x10^{-5}$
Fracture pressure gradient (bars/metre) and % of the lithostatic pressure gradient.	0.16 (70%)	0.16 (70%)	0.18 (80%)	0.18 (80%)	0.2 (85%)	0.2 (85%)
Connected aquifer volume (cubic kilometres)	1.0	1.0	2.0	2.0	4.0	4.0
Relative permeability dataset	Viking II	Viking II	Viking II	Endurance	Endurance	Endurance
Result	Failed to meet any of the proposed storage scenarios		Easily accommodated Initial and Growth scenarios and just met Mature Project scenario		Easily accommodated all storage scenarios	

The modelling demonstrated it is theoretically possible to store around 1900 Mt of CO_2 in the Bunter Sandstone aquifer in the model area. This figure is based on CO_2 injection into five structural closures, with an in-situ reservoir permeability in the range 50 to 270 milliDarcy and a regionally extensive connected aquifer with a volume of more than 2000 cubic kilometres. It is important to note, however, that injecting these volumes of CO_2 increases hydraulic pressure in the aquifer to more than 70% of fracture pressure across a large area. The pressure increase is mitigated by brine flow through a hydraulically connected seabed outcrop in the simulations, which is modelled as open to fluid flow. If this outcrop is closed to flow, then a significant number of water production wells will be required to provide pressure relief to multiple large-scale storage operations.

The study also identified key risks to development of a successful large-scale CO_2 storage operation in the Bunter Sandstone of the UK SNS to be mitigated by additional investigations. The presence of existing and abandoned hydrocarbon exploration wells, and increased certainty in the regional hydraulic connectivity and intrinsic permeability properties of the wider aquifer should be analysed further. It is recommended that:

1. A second phase of Bunter Sandstone aquifer appraisal would begin with an analysis of the location, age and completion status of all known hydrocarbon wells in the region.
2. This study would also incorporate a regional history matching exercise, in an attempt to link observed pressure measurements in exploration wells throughout the region with natural gas production data from the Esmond hydrocarbon complex.

A successful history match would give increased confidence that the bulk regional flow properties of the model were broadly representative of the aquifer, prior to simulating CO_2 injection.

5 A CO_2 storage network for enabling decarbonisation of the Grangemouth industrial cluster

The rationale for storage site selection, to enable CO_2 emission reduction from the Grangemouth industrial cluster by Carbon Capture and Storage (CCS) is described by Williams et al. (2019b). The sites selected comprise a network of storage options. The selection considers the time-dependent rate of CO_2 supply matched to suitable storage sites assessed against the following criteria:

- Sites should provide adequate storage capacity;
- Injectivity of the storage reservoirs should be sufficient to meet the CO_2 supply profiles for Grangemouth identified in ALIGN-CCUS Task 5.1 (Pearce and Akhurst, 2019);
- Sites should be within relatively close proximity to the Grangemouth industrial cluster;
- The network of storage sites should have the potential for future expansion to accommodate CO_2 captured from additional clusters of industrial sources in Scotland;
- Sites have been characterised to suitable Storage Readiness Levels, as developed in ALIGN-CCUS (Bentham et al., 2019), during the planned early injection period;
- Existing 3D geological models and/or data are available or obtainable within project resources, to enable detailed simulation and verification of the storage scenarios;
- Sites should have the potential to be included in an integrated storage network.

Key decisions for Grangemouth network site selection include:

- Two separate storage networks should be developed for each of the industrial clusters considered in ALIGN-CCUS, at Grangemouth and Teesside, to enable future low-carbon growth through the 2030s;
- A multi-site storage network will be required to meet future decarbonisation ambitions at Grangemouth;
- Sites within the Moray Firth are prioritised for selection of options for storage of CO_2 from the Grangemouth industrial cluster;
- Storage sites evaluated by previous commercial and feasibility studies should be prioritised for initial development, in preference to sites that have not received sufficient assessment to be considered as a contingent resource;
- Only sites with existing geological models that are available for research will be investigated in the ALIGN-CCUS UK case study for storage of CO_2 from the Grangemouth industrial cluster;
- The initial storage site development for the Grangemouth storage network should be within the Captain X region[7] [8] [9] [10] of the Captain Sandstone Fairway to enable CO_2 storage during the earliest 2020s;
- A second injection site to the east of the depleted Goldeneye Gas Condensate Field will act as the second anchor site to develop a Grangemouth storage network;
- Expansion of the Grangemouth storage network should incorporate development of the Forties 5 Site studied by the UKSAP project, as required to meet the growth and mature scenarios of CCS projects development;
- In the mature scenario, water production or an alternative development scenario will be required to maximise the storage capacity of the Forties 5 site;
- The ACT Acorn storage development of the East Mey Site[11] is included to reduce the injection rate and volume at the Forties 5 site[12] for the mature scenario.

A concept of the proposed storage network for the initial and growth CCS projects scenarios and for the mature projects' scenarios for Grangemouth in the Central North Sea is illustrated in *Figure 2*.

[7] ACT Acorn. 2018a. D04 Site Screening Methodology. 10196ACTC-Rep-07-01. January 2018.

[8] ACT Acorn. 2018b. D05 Site Selection Report. 10196ACTC-Rep-08-01. January 2018.

[9] Pale Blue Dot. 2016a. D04 WP3 – Initial Screening & Down-Select. 10113ETIS-Rep-03-2.0.

[10] Pale Blue Dot. 2016b. D13: WP5D – Captain X Site Storage Development Plan. 10113ETIS-Rep-19-03.

[11] ACT Acorn. 2018c. D08 East Mey CO_2 Storage Site Development Plan. 1019ACTC-Rep-26-01. October 2018.

[12] Pale Blue Dot. 2016c. D11: WP5B – Forties 5 Site 1 Storage Development Plan. 10113ETIS-Rep-18-03.

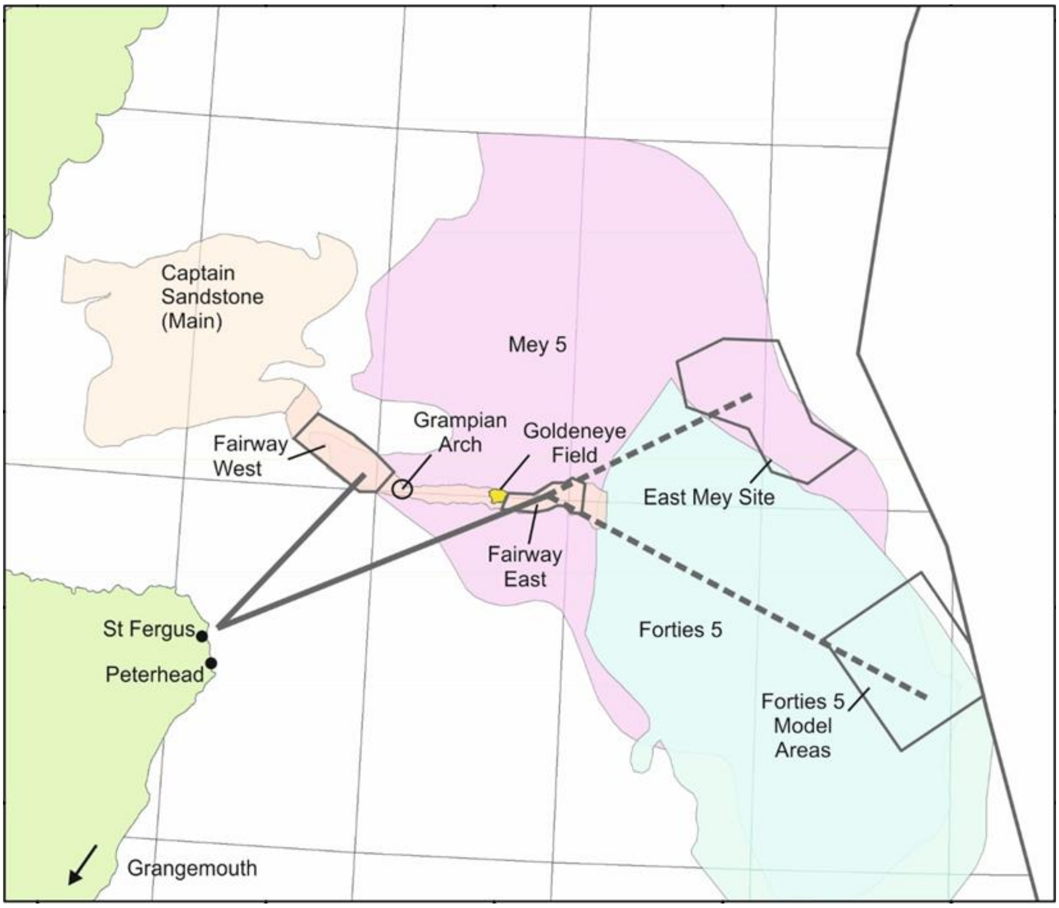

Figure 2 ALIGN-CCUS concept for networks to store CO_2 within two sites in the Captain Sandstone for the initial and growth scenarios, shown in solid lines. The storage network is extended, shown in dashed lines, to store CO_2 in the Forties 5 and East Mey sites for the latter growth, and mature projects development scenarios for the Grangemouth industrial cluster and other sources in central and eastern Scotland.

The storage concepts presented were investigated by dynamic simulation of CO_2 injection (Vosper et al., 2020), network and economic modelling (Nie et al., 2020a) in the ALIGN-CCUS UK case studies for Grangemouth.

6 Modelled CO_2 storage options for the ALIGN-CCUS Grangemouth industrial cluster

A network of storage sites underlying the North Sea will be required to meet the demands of planned and future industrial decarbonisation projects. Vosper et al. (2020) investigated the technical feasibility of sites with sufficient CO_2 storage capacity for emissions captured for permanent geological storage at the Grangemouth site and central Scotland. Possible offshore storage options have been identified that might comprise the transport and storage network to provide sufficient CO_2 storage capacity (Pearce and Akhurst, 2019; Williams et al., 2019b). Simulations of the volume and rate of CO_2 supply injected into the identified storage options are presented. The flow simulations investigated which of the possible options would have sufficient capacity and securely contain the envisaged supply of CO_2 for storage and so achieve permanent emissions reduction.

Three scenarios of CCS project deployment were investigated (Pearce and Akhurst, 2019). The Initial Projects injection scenario supplies 1.7 Mt CO_2 per year, as planned for the Caledonian Clean Energy Project (CCEP) at Grangemouth, requiring a total storage capacity of 136 Mt CO_2. The Projects Growth injection scenario supplies CO_2 planned by CCEP, additional Grangemouth industrial sources and hydrogen reformation for heating, at a rate of 8.6 Mt per year and requiring a total storage capacity of 654 Mt CO_2. The Mature Projects injection scenario commences at 4 Mt per year in 2030, increasing to 8 Mt per year in 2031 and to 16 Mt per year in 2032. The Mature Projects injection scenario includes additional development by the ACT Acorn project and hydrogen production for industrial purposes in central Scotland and requires a total cumulative storage capacity of more than 1000 Mt CO_2.

A review of available and appropriately appraised sites with good proximity to the CO_2 transport and storage infrastructure planned by the Acorn Project, linking Grangemouth to St Fergus and North Sea CO_2 storage, was undertaken by the UK case study (Williams et al., 2019b). Three saline aquifer sandstone storage sites were selected that are known from previous simulation studies and so have higher Storage Readiness Levels, and where model files are available: Captain Fairway, ACT Acorn Project[10]; East Mey, ACT Acorn Project[11]; and Forties 5, Strategic Storage Appraisal Project[12]. An Eastern Captain Fairway site was also simulated, building on the CO_2MultiStore[13] investigation of two sites in the Captain Sandstone, with the second site lying east of the Goldeneye Field. Further numerical simulations address a faster rate of CO_2 injection for a shorter duration at both the Acorn Project Captain Fairway and the Eastern Captain Fairway sites.

For the Initial Projects scenario, a single well within the Acorn Project Captain Fairway site was sufficient to inject all the supplied CO_2 given best-fit parameters. A 'low storativity' case with pessimistic parameters required four injection wells and a water production well to store the CO_2 inventory within pressure constraints.

Three approaches, A to C, were investigated for the Projects Growth scenario.

Approach A commences with the Acorn Project Captain Fairway and East Mey Sandstone sites operating concurrently, with the Forties 5 Sandstone site operational in the 2050s when the Acorn Project site capacity is reached. This is a conservative approach and provides greater capacity than required. A constraint is that the East Mey Sandstone would need to be operational as a storage site by 2025.

Approach B operates two sites in the Captain Sandstone, the Acorn Project and Eastern Captain Fairway sites. There would be sufficient capacity until 2047 when the East Mey and Forties 5 sandstones sites would become operational. This approach is reliant on the Captain Fairway for the first 20 years of operations. Commencing operations in two additional sites, as the Captain Fairway sites reach capacity, may need to be staggered to ensure a smooth transition.

Approach C stores solely in the East Mey Sandstone. The ACT Acorn project modelled CO_2 storage capacity significantly exceeding 500 million tonnes. If the entire inventory is stored in the East Mey Sandstone no infrastructure at other sites would be required, however, it would need to be operational by 2025.

[13] SCCS, 2015. Optimising CO_2 storage in geological formations; a case study offshore Scotland. CO_2Multistore Project. Scottish Carbon Capture and Storage. September 2015.

The Mature Projects scenario requires storage in the four sites considered here and an additional 10% of the currently modelled capacity. The ACT Acorn project findings indicate this additional capacity may be met within the East Mey Sandstone, possibly using additional injection sites.

Proposed timelines for the distribution of captured CO_2 to the storage sites investigated (Vosper et al., 2020) informed assessment of a cost-effective flexible transport and storage network in the ALIGN Project UK case study (Nie, et al., 2020a).

7 Suitability of infrastructure for re-use: UK case study

The UK sector of the North Sea is a mature petroleum province with declining rates of exploration and production and is expected to enter a large-scale decommissioning phase within the next few years[14]. The process of decommissioning presents opportunities to adapt existing infrastructure to support the deployment of UK Carbon Capture, Utilisation and Storage (CCUS) networks. Re-using existing oil and gas infrastructure for CO_2 transportation and injection can help to reduce the cost of full-chain carbon capture, utilisation and storage projects[15].

Technical and non-technical criteria for infrastructure re-use relevant to the UK are considered by Greenhalgh et al. (2019). Non-technical issues were reviewed and the highest priority legal and commercial matters specific to the UK infrastructure re-use are highlighted. UK legal and regulatory organisations, documents and tools relevant to infrastructure re-use are listed.

The ALIGN-CCUS methodology of technical assessment for re-use (Grimstad et al., 2019) was applied to UK infrastructure. The criteria considered include location, timing of availability, remaining lifespan, capacity, and materials. Technical criteria bounds, from published sources, were applied to infrastructure in the vicinity of prospective CO_2 storage sites for the industrial clusters at Grangemouth and Teesside. The assessment informed the transport and storage network modelling for the two UK case study industrial clusters (Nie et al., 2020a). Testing of the published criteria on selected UK infrastructure has enabled the effectiveness of the criteria to be assessed when used in screening for infrastructure re-use. Integrity of the infrastructure was not considered by Greenhalgh et al. (2019) owing to the requirement for a detailed site-specific investigation to inform the appraisal. A recommendation from this work is that provision of data which is currently more difficult to access, including from infrastructure operators, should be collated as part of a national strategy for infrastructure re-use.

Addressing non-technical considerations is essential for UK infrastructure to be re-used for a CO_2 transport and storage service. The UK has a mature and relatively flexible regulatory framework for governing oil and gas activities. There are, however, some important practical legal and commercial matters to be addressed to facilitate the timely conversion of assets from oil and gas service to use for CO_2 transport and storage operations. The priorities among these include:

- Implementing a strategic approach to identifying physical assets for re-use combined with integrated planning in the marine environment to overcome barriers to re-use;
- Managing the consequences of the temporal gap of potentially long duration between cessation of hydrocarbon production and commencement of CO_2 operations, including mothballing and maintenance of facilities, and transferring or restructuring ownership;
- Dealing with decommissioning liabilities.

To achieve these priority actions, a mandated entity, which could be public or private, was recommended to co-ordinate and manage the transition of assets from hydrocarbon to CO_2 operations. These actions were raised in the 2019 Department for Business, Energy and Industrial Strategy (BEIS) consultation on developing a policy for the re-use of oil and gas assets for CCUS projects.

Where infrastructure meets all other technical and non-technical criteria for re-use, a detailed site-specific assessment of hardware integrity is required to confirm its suitability for re-use. Commissioning of detailed studies of integrity is recommended for infrastructure identified as suitable and of potentially strategic importance as part of a future national network asset for CO_2 transport and storage.

A strategic approach for selection of UK infrastructure for re-use is recommended. Technical suitability, legal and commercial issues, whether in the vicinity of potential storage sites and/or in geographical proximity of a current or planned source of CO_2 capture, should all be included in the assessment.

[14] Oil and Gas Authority. 2016. Decommissioning Strategy

[15] IEA GREENHOUSE GAS R&D PROGRAMME. 2018. Re-use of oil and gas facilities for CO_2 transport and storage.

The strategy should incorporate the concept of a transition, to enable continuity of revenue or minimise a potential temporal gap, from hydrocarbon production, through enhanced recovery where appropriate, to a CO_2 storage service. Both a transition from hydrocarbon production to CO_2 storage and also a period of suspension when CO_2 storage does not directly follow the end of hydrocarbon production should be considered.

An appraisal of infrastructure for re-use should be undertaken early in the planning phase of decommissioning. This is imperative to avoid additional costs and potential weakening of integrity associated with mothballing of infrastructure.

8 Summary of outcomes of TVCA planning for the Teesside industrial CO_2 capture cluster relevant to the offshore transport and storage network

Twenty reports were received from Tees Valley Combined Authority (TVCA) in August 2017 at commencement of research in ALIGN-CCUS project (Akhurst, 2018). The majority of the reports were publicly available and document the outcomes of TVCA's detailed planning for the Teesside industrial CO_2 capture cluster with a synthesis of design constraints relevant to the offshore transport and storage network. Other information was received in confidence for analysis within the UK case studies of the ALIGN-CCUS project. The information received from TVCA early in the project was input to the assessment of CO_2 supply in the UK case studies for Teesside (Pearce and Akhurst, 2019).

At the end of 2019, Net Zero Teesside was launched, and the Hydrogen Vision for Teesside was presented to UK industry and government members of the UK CCUS Advisory Group and made public. Volumes of the CO_2 planned for capture and geological storage were updated, collated and presented by Perriman and Tennison (2020).

The ALIGN-CCUS case study of the industrial cluster at Teesside focuses on assessing the UK's prolific storage potential to reduce the cost of CCS, not only for the UK, but also for countries around the North Sea Basin. There are many aspects to accelerating industrial CCS in the ALIGN-CCUS Project research, but the update by TVCA (Perriman and Tennison, 2020) specifically focuses on transport and storage network development in the North Sea area.

The North Sea Basin between the UK and Norway is particularly well mapped due to half a century of oil and gas industry seismic surveys, drilling, production data and sub-surface modelling activities. The UK with 80 gigatonnes and Norway with 70 gigatonnes have similar, high confidence (75-100%) mapped carbon dioxide (CO_2) storage volumes (**Fout! Verwijzingsbron niet gevonden.**), but UK water depths are generally shallower than Norwegian water depths. In addition, the sub-surface drilling depths of many suitable storage sites are shallower than other parts of the North Sea Basin. Hence, the CO_2 injection wells can be both drilled and maintained, over their multi-decade lifetimes, at lower cost in UK waters. With 27% of Europe's high confidence total CO_2 storage potential, the UK can provide a cost-effective CO_2 storage service to the North Sea Basin.

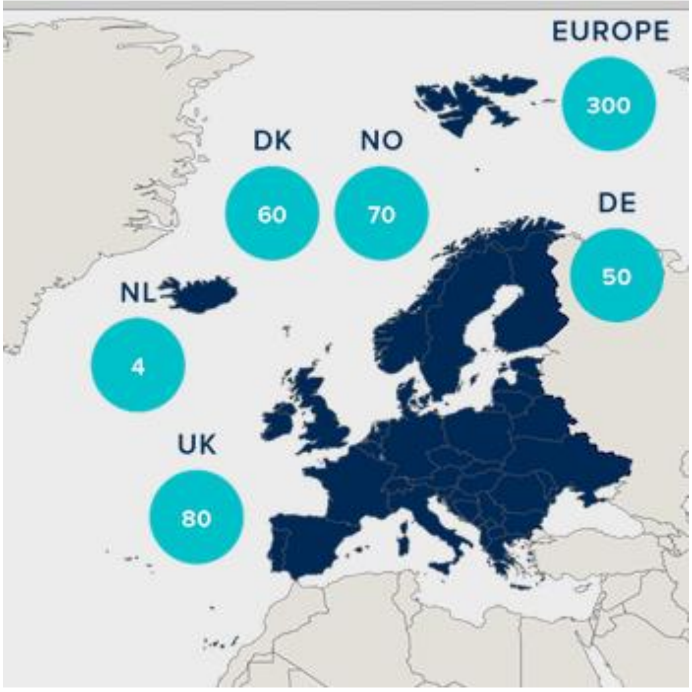

Figure 3 Global CCS Institute map showing the storage capacity (in gigatonnes of CO_2) for the UK and other European countries

In some cases, North Sea oil and gas pipelines, platforms and wells can be reused to allow for the injection of CO_2 rather than the production of oil and gas (i.e. the directions of flow for CO_2 injection being reversed relative to oil and gas production). Asset reuse can both reduce cost and reduce the carbon footprint of the development of CCS. Asset reuse is currently planned for one of the two CO_2 stores being developed in the UK Case Study.

Whilst the case study starts with decarbonizing the Grangemouth and Teesside industrial clusters, there is potential to store CO_2 from industrial clusters across the whole of the UK and to take CO_2 volumes from multiple countries around the North Sea Basin. An update of the estimates of CO_2 that are currently planned to be captured on Teesside itself is provided and compared to the volumes presented in the East Coast Study[16] that was issued when the ALIGN-CCUS Project commenced. The evidence presented by Perriman and Tennison (2020) showed that the early 2020 estimates of total volumes of CO_2 from Teesside to be geologically stored by 2050 are very similar to the volume estimates made in the 2017 East Coast Study, upon which the CO_2 supply profiles compiled for the ALIGN-CCUS UK case study were based (Pearce and Akhurst, 2019).

There are different technology routes to both decarbonize existing industry and to stimulate new, low-carbon industry. The mix of technologies planned on Teesside is continuing to evolve, particularly as decisions are made on the business models that are being encouraged in the various energy sectors. The envisaged breakdown between CO_2 volumes produced from: a) the manufacture of hydrogen (for large volumes, the lower cost route being reformation of natural gas) for industrial and domestic heat, transport and dispatchable power; b) the CO_2 volumes captured, post-combustion, from industry; and c) the volumes of CO_2 captured from combustion of biomass for energy, are different in the latest estimate and in the East Coast Study. But put simply, the technology used to arrive at very large volumes of CO_2 for geological storage each year is not of significance for the cost-effective storage assessment.

The early 2020 assumptions are presented, in which three scenarios of varying CO_2 capture rate are described for Teesside: Base Case; High Case; Low Case. The TVCA Teesside Base Case of Perriman and Tennison (2020) was modelled by simulation of CO_2 injection by Williams et al. (2020) and for techno-economic network development by Nie et al. (2020a).

[16] Clean Air-Clean Industry-Clean Growth, Caledonia Energy and Summit Power project, October 2017

9 Scenarios analysis and guidelines for the development of flexible transport and storage network for the Grangemouth and Teesside clusters

Decarbonisation of industry and power will require deployment of CCUS technologies and development of cost-effective low-carbon industrial clusters in the UK, such as at Grangemouth and Teesside. The modelling tool developed in the ALIGN Project (Nie et al., 2020b) was successfully used to devise optimal CCS transport and storage value chains and appraise the costs and real options value of Grangemouth and Teesside CO_2 storage cluster; individual site uncertainties and flexibility in operation and design were incorporated. The optimisation modelling implemented was based on the individual storage site simulation results and scenario design from ALIGN-CCUS project research (Williams et al., 2020; Vosper et al., 2020). The stochastic optimisation model quantitatively identified optimal investments under significant uncertainty, given the information available currently for the Grangemouth and Teesside CO_2 storage clusters. Two business models, which describe the transport and storage company's approach to going to market and how it will create real value for customers and partners, were used. Business model 1 assumes government pays financial support to CO_2 emitters, who in turn pay fees to companies for their CO_2 transport and storage service. The service fees are paid at a price per tonne CO_2 injected to guarantee the companies operate at an 8% internal rate of return. Business model 2 assumes direct payment by government to the transport and service company of 100% of both capital (CAPEX) and operating (OPEX) expenditure.

The results from the scenarios analysis carried out and guidelines for the development of flexible transport and storage networks for the Teesside and Grangemouth clusters are summarised as follows:

- The optimal CCS networks for deterministic scenario analysis carried out have the same configurations and network evolution for both Business model 1 and Business model 2. This provided robust evidence that the CCS network evolution is mainly driven by geological and regional geographical constraints and the engineering designs relying on them.
- The choice of business model significantly affects the economics for operators and the government. Business model 2 requires less government support overall, as it only covers CAPEX and OPEX and offers no profits. Business model 1 requires an internal rate of return at 8%, which is higher than the weighted average cost of capital set at 5%. This means that transport and storage operators have profits. However, Business model 2 requires more upfront support from government.
- Individual storage sites have significantly different cash flows, dictated by their physical characteristics and the injection concept chosen.
- The results show that the multi-store CCS network costs are mainly driven by storage costs. Transport costs account for around 22-30% of overall costs, as the transport distance is relatively short for both the Grangemouth and Teesside clusters.
- Storage capacity and CO_2 supply (or CO_2 mitigation target) are the main uncertainties for a multi-store CCS network. The quantitative stochastic optimisation model indicates a better understanding and modelling of these uncertainties can significantly reduce the storage network costs. This implies that a clear government CO_2 mitigation target and appraisal of potential CO_2 storage sites can jointly significantly reduce the uncertainty and hence the costs of CO_2 transport and storage.
- Infrastructure re-use can reduce overall costs but only slightly, though transportation costs are considerably reduced.

For the Grangemouth CO_2 transport and storage cluster:

- Higher weights (probabilities) were assigned to the Growth Scenarios (Vosper et al., 2020). The stochastic optimisation results demonstrated that it is optimal to develop Captain West and East Mey sites first, which will stabilise the CCS network evolution and provide flexibility.
- The optimisation results suggest pipeline development, from the start of the planning horizon (2020), linking St Fergus to Captain West, then via Captain East to East Mey. The pipeline passes Captain East but this storage site is not recommended for development during the first period of the CCS network construction. This pipeline, however, provides important flexibility to open Captain East for storage during later periods, if necessary.

- The optimisation results suggest initial development of a pipeline with small capacity (10 Mt/year) during period 1, driven by the higher probability assigned to the rates of supply for the Growth scenarios rather than the Mature scenarios. The analysis suggests additional pipeline capacity should be added after Period 1 for the Mature scenarios of CCS project deployment.
- In order to meet the fixed 8% internal rate of return, the CO_2 transport and storage service fees for individual storage sites display a significant range. In most cases, the required service fees are lower than €25 per tonne of CO_2 stored.

For the Teesside CO_2 transport and storage cluster:

- Higher weights (probabilities) are assigned to the Teesside low CO_2 supply scenarios (Williams et al., 2020). The stochastic optimisation results demonstrate that it is optimal to first develop storage in the Endurance structure and then Bunter Closure 36, which will stabilise the CCS network evolution and provide flexibility.
- The optimisation results suggest development of a trunk line from the start of the planning horizon (2020), linking Teesside to the Endurance storage site, with a flow rate capacity 25 Mt per year, which can meet the maximum flow rate required by Teesside base CO_2 supply scenario. This trunk line, however, provides important flexibility to further reach and open sites in Bunter Closure 36, Bunter Closure 39 and Bunter Closure 40 during later periods, if necessary.
- It is also important to note the initial trunk line development between Teesside and Endurance should be of high capacity (25 Mt/year). This is driven by the high probability (40%) assigned to Teesside base CO2 supply scenario. Although the CAPEX of the high capacity trunk line is considerably higher than a pipeline with capacity 15 Mt per year, such a development during period 1 avoids the need to build additional pipelines at higher cost in a later period between Teesside and Bunter Closure 35.
- The statistical analysis of likely network costs cluster around 1,900-2,350 million Euro, scenario predicted at around 90% likelihood. This finding is driven by the assignment of higher weight (probability) to Teesside low supply and Teesside base supply, with the levelized cost per tonne CO_2 ranging between €17 and €20 per tonne CO_2.
- In order to meet the required 8% internal rate of return, the CO_2 transport and storage service fees for individual storage sites range significantly. In most cases, the required service fees are lower than €25 per tonne CO_2.

10 Business and investment models for UK CCUS storage cluster options

Aspects of business case development for the offshore CO_2 storage clusters that could service the decarbonisation of the Teesside and Grangemouth onshore industrial clusters using CCS has been analysed by Goldthorpe et al. (2020). The primary objective of their work is to address the impact of the characteristics of phased or evolutionary storage network development and operation on business models and investability.

Key areas of study included:

- Assessing applicability to phased storage development of commercial, financing and business model earning for transport and storage infrastructure for Teesside and Grangemouth;
- Analysing the interdependencies of technology and operational characteristics on investment, commercial and contractual arrangements for phased expansion, and handling of storage liabilities, risk sharing and performance obligations; and
- Developing the system-level cluster business case, which will specify the approach to public-private risk share, assess the effect on the business model and identify barriers to implementation.

The semi quantitative heuristic assessment undertaken for both offshore storage clusters is based on the detailed network optimisation modelling on the planning a transport and storage network performed in the UK ALIGN case studies (Nie, et al., 2020b). Nie et al. (2020a) applied the modelling tool developed in the CO_2 transport research activity to model an optimal CCS transport and storage value chain and appraise the costs of offshore CO_2 storage clusters incorporating individual site uncertainties and flexibility in operation and design.

The business assessment for the UK case study storage clusters presented in this report has been undertaken at the 'concept definition' level. Nevertheless, this report presents a very detailed analysis of the investment barriers and collaborative public-private system business models required for delivering the first investments of each of the modelled storage cluster networks. These business models also provide the necessary flexibility and optionality to enable subsequent investment decisions for expansion. The recommendations should assist the establishment of an enduring government policy and support framework that can facilitate the development of, and decisions for, both the onshore cluster decarbonisation and the offshore storage clusters.

For both the Grangemouth and Teesside storage clusters the analysis directs towards a preference for a cluster business model with a greater public sector ownership for the initial investment stage. For example, one choice would be a joint venture with a combination of public sector and private sector ownership and a flexible shareholder structure that could adapt over time to the actual circumstances that emerge. This would be both in terms of supply/market development and technical performance to manage the operational delivery and remuneration risks. In such a joint venture the government's initial investment over and above a point-to-point private sector project would be the cost of the real option of all the future possibilities for the phased expansion of the cluster that would go together with government management of market development. This would mitigate the government overpaying for a private sector regulated asset business with oversized infrastructure at risk of not being fully utilised.

The analysis by Goldthorpe et al. (2020) has:

1. Summarised the commercial, financing and business model learning from previous Teesside and Grangemouth studies applicable to phased transport and storage development.
2. Addressed the difference between the technical and commercial characteristics of a single point-to-point transport and storage project versus the evolutionary expansion in phases of an offshore storage cluster.
3. Provided a summary background of the concepts, terminology and methods for handling of storage liabilities, risk sharing and performance obligations during phased transport and storage expansion. The work is based on the risk assessment methodology developed in the ERA-Net ACT ELEGANCY project. That work in turn is based on stakeholder interviews and workshops conducted

jointly with the ALIGN project and the European Zero Emissions Platform. The methodology is applied in this report to the UK Grangemouth and Teesside storage cluster case studies.

4. Listed the recommended split of investment barriers and risks between the public and private sectors for facilitating the investment in, operation and phased expansion of, transport and storage infrastructure to support the decarbonisation of the Grangemouth and Teesside industrial clusters.
5. Presented the methodology developed by Sustainable Decisions Limited to assess the impact of technology and operational aspects of storage cluster system components, and their interaction, on business models for the phased development of a T&S infrastructure network.
6. Applied the methodology developed to the key system components for the Grangemouth case study: the CO_2 supply scenarios, offshore storage options, and the main characteristics of the Grangemouth storage cluster in the Central North Sea. A detailed assessment of each of the transport and storage network scenarios modelled by Nie et al. (2020a) is followed by a system interaction analysis and conclusions about business model impacts for phased expansion of the T&S cluster for Grangemouth.
7. Applied the methodology developed to the key system components for the Teesside case study: the CO_2 supply scenarios, offshore storage options, and the main characteristics of the Teesside storage cluster in the Southern North Sea. A detailed assessment of each of the transport and storage network scenarios modelled by Nie et al. (2020a) is followed by a system interaction analysis and conclusions about business model impacts for phased expansion of the T&S cluster for Teesside.
8. Developed potential conceptual business models for Grangemouth and Teesside CO_2 storage clusters that can accommodate the uncertainty in supply scenarios and technical characteristics of the proposed storage and pipeline developments. A system analysis of the UK policy and investment environment is carried out and used in combination with the findings of previous chapters to make recommendations on risk allocation between the public and private sectors. Recommendations are also made on the commercial structures that would enable the T&S cluster evolution through phased development.

The ACT ELEGANCY risk assessment methodology is briefly summarised and supporting information underlying the analysis of Goldthorpe et al. (2020) is listed as appendices as follows:

- Investment barriers: mitigation led by public sector;
- Business risks: allocated jointly to public and private sectors;
- Business risks: allocated to private sector;
- Business risks: allocated to the public sector.

11 Bibliography of UK ALIGN-CCUS research report deliverables

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