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Integration of cement plants into CCUS hubs and clusters in Europe: case study from United Kingdom

Master thesis

Student: Glea Habicht, 192230LARM

Supervisor: Alla Šogenova, Department of Geology, senior researcher

Study program: Georesources

2021

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Tsemenditehaste integreerimine CCUS-sõlmpunktidesse ja klastritesse Euroopas: juhtumiuuring Ühendkuningriigist

Magistritöö

Üliõpilane: Glea Habicht, 192230LARM

Juhendajar: Alla Šogenova, Geoloogia Instituut, vanemteadur

Õppekava: Maapõueressursid

2021

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Abstract

Carbon capture, utilization, and storage (CCUS) is one of the most effective climate mitigation technologies that can provide 15% reduction of the world's CO_2 emissions. In the UK, the Climate Change Act of 2008 commits the government to reduce national greenhouse gas emissions by at least 100% (net zero) by 2050.

The UK has enough CO_2 storage capacity to fully support the UK's needs for hundreds of years of demand. Several CCUS cluster projects are under development in the country. The presented case study includes three clusters Net Zero Teesside (NZT), Zero Carbon Humber (ZCH) and HyNet North West (HNW) to help the UK to reach their strategical climate targets.

The aim of this work was to integrate suitable cement plants and industrial CO_2 emitters into the prospective CCUS cluster projects in UK. Technical and geological information about cluster projects were collected and integrated into ArcGIS program as multi-layered maps supported by numerous parameters for every project and storage location.

The first CCUS scenario includes CO_2 storage in the Southern North Sea saline aquifer in the Endurance structure. This structure is a storage site for NZT and ZCH projects. In this scenario calculated CO_2 storage capacity in the 245 m thick Early Triassic Olenekian Bacton Group Bunter Sandstone Formation reservoir, occured at the depth of more than 1 km, is 570 Mt. The estimated duration of the project is 43 years for the planned and proposed by author CO_2 emission sources, which produced 13.3 Mt of CO_2 in 2020.

The second CCS scenario includes CO_2 storage into the depleted oil and gas fields Lennox, Hamilton and Hamilton North in the Irish Sea, which are prospective storage sites for the HNW cluster project. Calculated CO_2 storage capacity in the 212-265 m thick Early Triassic Olenekian Sherwood Sandstone Group Ormskirk Sandstone Formation reservoir, occured at the capacity will be enough for 89 years for the planned and proposed emission sources, which produced 2.58 Mt of CO_2 in 2020.

All the studied projects are planning green and blue hydrogen production and transport combined with CCS. These scenarios will help to decarbonise three major UK industrial areas. Integrating additional CO_2 emitters, including cement industry, makes CO_2 storage for the projects more economic, considering sharing of transport and storage infrastructure. Additional storage sites could be included in both projects in future stages by demand.

During this work, Heidelberg Cement Group signed a memorandum to include its Padeswood Works CP to the HNW project. In this work I have added two CEMEX production units into my scenarios. In May 2021, CEMEX also announced that it will start decarbonization of its cement plants.

Cooperation of CO_2 producers in several CCUS cluster and hubs in UK and sharing transport and storage infrastructure is a great example for the Baltic and all European countries in reaching carbon neutral economy.

Some of these results are included in the poster presentation presented at the IEA Greenhouse Gas Technology Conference (GHGT-15) in March 2021, and were included in the article, published in the conference proceedings.

This study was supported by the CLEANKER project, which has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement nr. 764816.

Annotatsioon

Süsiniku sidumine, kasutamine ja säilitamine (CCUS) on üks tõhusamaid kliimamuutuste leevendamise tehnoloogiaid, mis võib vähendada maailma CO_2 heitekogust 15%. Suurbritannias kohustab 2008. aasta kliimamuutuste seadus valitsust vähendama riiklikke kasvuhoonegaaside heitekogust aastaks 2050 vähemalt 100%.

Ühendkuningriigil on piisavalt süsinikdioksiidi ladustamise mahtu, et rahuldada oma vajadusi mitme sajaks aastaks. Riigis on väljatöötamisel mitu CCUS-i klastriprojekti. Käesolev juhtumiuuring hõlmab kolme klastrit Net Zero Teesside (NZT), Zero Carbon Humber (ZCH) ja HyNet North West (HNW), et aidata Ühendkuningriigil saavutada oma strateegilised kliimaeesmärgid.

Selle töö eesmärk oli integreerida sobivad tsemenditehased ja tööstuslikud CO_2- emissiooni tootjad tulevastesse CCUS-i klastriprojektidesse Ühendkuningriigis. Klastriprojektide kohta koguti tehnilist ja geoloogilist teavet ning see integreeriti ArcGIS-i programmi mitmekihiliste kaartidena, millele on lisatud iga projekti ja ladustuskoha parameetrid.

Esimene CCUS-i stsenaarium sisaldab süsinikdioksiidi ladustamist Põhjamere lõunaosas asuvas soolase põhjaveekihis nimega Endurance. See struktuur on NZT ja ZCH-i projekti ladustamiskoht. Esimese stsenaariumi korral ladustatakse CO_2 esimeses Varase Triiase Olenekian Bacton Groupi Bunteri liivakivi reservuaari, mis on rohkm kui 1 km sügavusl. CO_2 ladustamise maht on arvutuste kohaselt 570 miljonit tonni ning planeeritud ja autori poolt pakutud heiteallikate korral projekti kestuseks 43 aastat.

Teine CCUS-i stsenaarium koostati süsinikdioksiidi säilitamiseks Iiri mere ammendatud nafta- ja gaasiväljadesse Lennox, Hamilton ja Hamilton North, mis on HNW projekti ladustamiskohad. Selle stsenaariumi CO_2 ladustamise kohaks on Varase Triiase Olenekian Bacton Groupi Bunteri liivakivi reservuaar. CO_2 ladustamise maht on arvutuste tulemusena 229 miljonit tonni ning planeeritud ja autori poolt pakutud heiteallikate korral on arvutatud projekti kestuseks 89 aastat.

Kõik uuritud projektid hõlmavad rohelise ja sinise vesiniku tootmist ja transporti koos CCS-i stsenaariumiga.Modelleeritud NZT, ZCH ja HNW CCS-i stsenaariume võrreldakse nende hinnangulise ladustamise perioodiga Endurance'i, Lennoxi, Hamiltoni ja Hamilton Northi struktuurides. Need stsenaariumid aitavad dekarboniseerida Suurbritannia kolme peamist tööstuspiirkonda. Mõlemasse projekti on võimalik tulevikus lisada nõudlusel vastavalt täiendavaid CO_2 ladustamise kohti.

Selle töö koostamise ajal allkirjastas Heidelberg Cement Group memorandumi oma Padeswood Worksi tsemenditehase kaasamiseks NHW projekti. Selles töös olen oma stsenaariumidesse lisanud kaks CEMEX-i tootmisüksust. 2021. aasta mais teatas ka CEMEX, et hakkab oma tsemenditehaseid dekarboniseerima. CO_2 tootjate koostöö mitmes Suurbritannia CCUS-i klastris ning transpordi- ja ladustamistaristu jagamine on Baltikumi ja kõigi Euroopa riikide jaoks suurepärane näide süsinikuneutraalse majanduse saavutamisest.

Osa neist tulemustest on lisatud 2021. aasta märtsis IEA kasvuhoonegaaside tehnoloogiakonverentsil (GHGT-15) stendiettekandele ja konverentsi materjalides avaldatud artiklisse.

Seda uuringut toetas projekt CLEANKER, mis on saanud toetuse Euroopa Liidu teadus- ja innovatsiooniprogrammist Horisont 2020 toetuslepinguga nr. 764816.

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Abbreviations, terms and units

Parameters

h - average thickness of the reservoir in the trap

H_2 - hydrogen

M_{CO2t} - storage capacity

Min-max (mean) - minimum-maximum (average)

N_{cond} - Cumulative condensate production

NG - net to gross ratio of the aquifer in the trap (%)

S_{ef} - storage efficiency factor (for the trap volume, %)

S_w - reservoir water saturation

V_{iw}- the volume of injected water

V_{pw} - the volume of produced water

ρ_{CO2} - elevated temperature

ϕ - porosity (%)

Abbrevitations

3D - 3-dimensional

A - reservoir area

ACT - Accelerating CCS Technologies

ACTL - Alberta Carbon Trunk Line

BSF - Bunter Shale formation

BSL - British Steel Limited

CCC - Committee on Climate Change

CCS - CO_2 capture and storage

CCU- carbon capture and utilization

CCUS - Carbon capture, utilization, and storage

CGR - Condensate-gas ratio

CGS - CO_2 geological storage

CO_2 - carbon dioxide

CP - cement plant

EOR - enhanced oil recovery

ESE- east-southeast

ETI - Energy Technologies Institute

ETS - Emission Trading System

EU - European Union

GGBS - Ground Granulated Blast-furnace Slag

GSP - Government Support Package

H2H - Hydrogen to Humber

HCG - Heidelberg Cement Group

HGV - heavy goods vehicle

HNW - HyNet North West

ICC - Industrial Carbon Capture

IDCF - Industrial Decarbonisation Challenge Fund

IEA - International Energy Agency

ISCF - Industrial Strategy Challenge Fund

JLR - Jaguar Land Rover

NDC - nationally determined contribution

NEP - Northern Endurance Partnership

NIA - Network Innovation Allowance

NZNS - Net Zero North Sea Storage Limited

NZT - Net Zero Teesside

NTG - Net-to-gross

OGA - Oil and Gas Authority

PCI - Project of Common Interest

SE - south-east

SMC - Stanlow Manufacturing Complex

SNS - Southern North Sea

ZCH - Zero Carbon Humber

TVDSS - true vertical depth sub-sea

UK - The United Kingdom

UK SAP - Storage Appraisal Project in the United Kingdom

UKCS - UK Continental Shelf

WNW - west-northwest

Units

atm - unit of pressure (1 atm = 101 325 Pa)

g – grams

g/l - gram per litre

GW – gigawatt

kg - kilogram

km - kilometre

km^2 - squire kilometre

Kt - kilotonnes

Kt/y - kilotonnes per year

m – metre

m^3 - squire metre

mD - Millidarcy

mm - millimetre

MPa - megapascal (unit of pressure)

Mt - million tonnes

MW - megawatts

t - tonnes

T, ˚C - temperature by Celsius

Wh – watts per hour

1 Introduction

This Master thesis work was supported and initiated by the CLEANKER Project, funded by EU Horizon 2020 Programme. CLEANKER project is coordinated by LEAP (Italy) and integrates 13 research organizations from seven countries (Cleanker, 2020). The main goal of the EU Horizon 2020 project CLEANKER is to use a calcium looping technology to capture CO_2 emissions from the cement industry. One of the additional objectives and tasks was to find cement plants suitable for exploration of the Ca-looping CO_2 capture technology among Buzzi Unicem (BU) and HeidelbergCement Group (HCG) plants around the world, based on the transport and storage opportunities of operating and developing CCUS clusters mainly described in (IEA GHG, 2015).

I took part in the last mentioned task of the project for several months, collecting technical and geological information into the datasets developed for the CLEANKER ArcGIS database (Shogenova & Shogenov, 2020) about CO_2 emissions sources, storage sites and transport opportunities of the European cluster projects.

The Paris Agreement, which was ratified at the Paris Climate Conference in December 2015, is the first-ever universal, legally binding global climate change agreement. The European Union (EU) and its member states among 197 countries have ratified the Paris Agreement. The Paris Agreement established a worldwide basis for avoiding harmful climate change by keeping global warming far below 2°C and pursuing measures to keep it below 1.5 °C, compared to pre-industrial times. It also helps to improve countries' capability to cope with climate change's effects and to assist them in their efforts to create a climate neutral planet by mid-century in order to meet this long-term temperature target (UNFCCC, 2020).

The EU submitted its revised and upgraded nationally determined contribution (NDC) in December 2020, with a goal of reducing pollution by at least 55% from 1990 levels by 2030, as well as information to facilitate clarity, transparency and understanding of the NDC (Paris Agreement, 2021).

1.1 CCUS technology

Carbon capture, utilization, and storage (CCUS) is a critical emissions control technology that can be used in the energy grid. Carbon dioxide (CO_2) is captured from fuel combustion or manufacturing operations, transported by ship or pipeline, and then used as a resource to produce useful materials or stored permanently deep underground in geological formations. When CO_2 comes from bio-based systems or directly from the environment, CCUS technologies provide the basis for carbon reduction or "negative emissions" (IEA, 2020), (Figure 1).

Carbon capture is the only solution for reducing large-scale emissions at a relatively low cost while maintaining the value of fossil fuel sources and current infrastructures, for both the power sector and industry. To make a meaningful contribution to CO_2 reduction, thousands of large-scale CCUS projects will need to be developed globally over the next several decades, which would require a collective initiative by businesses and policymakers. National demonstration projects are a necessary engine of emerging technology growth. The United States and China are the leading countries in terms of major demonstration projects, with various projects documented. A variety of ambitious projects have been built in other regions, such as Australia and Europe, in recent years. There are three major CO_2 capture systems, represented by post-combustion, pre-combustion, and oxy-fuel combustion that can be incorporated into both power plants and industrial plants, as well as the natural CO_2 capture that could happen in some industrial processes and during biofuel production (BCC Research, 2020).

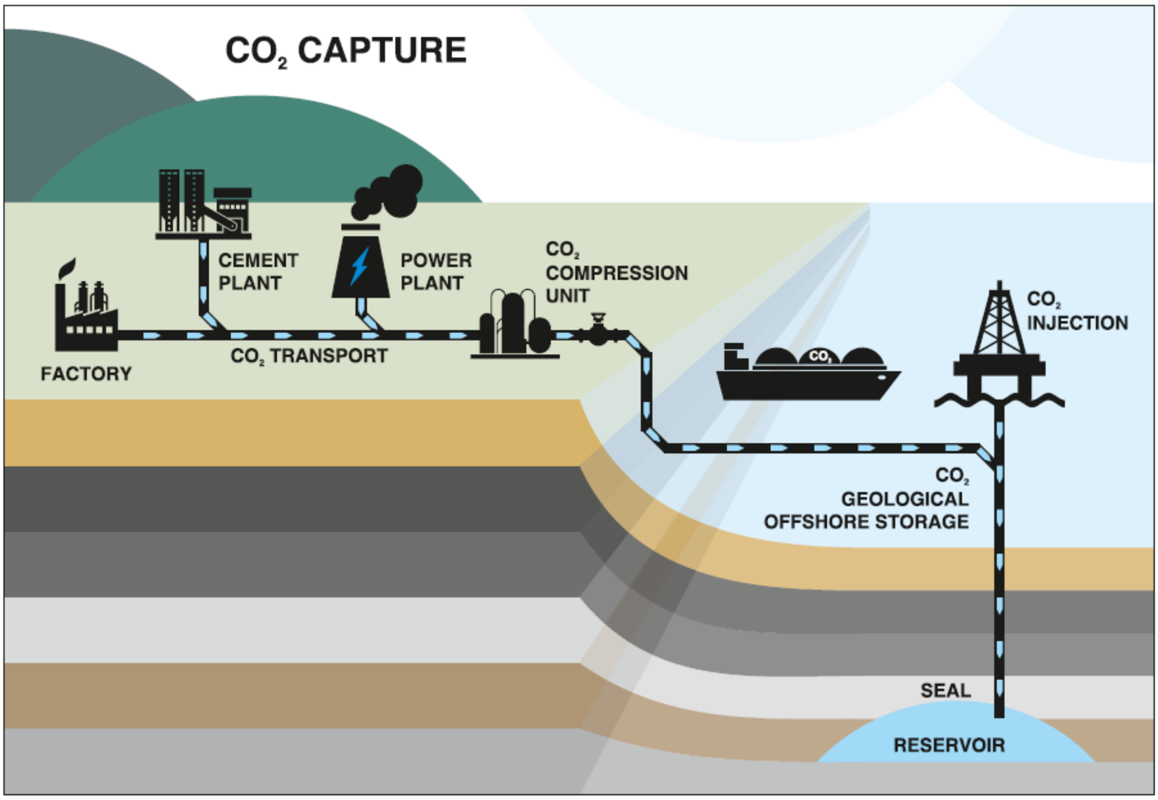


Figure 1. CCUS technology approach used in the UK cluster projects (figure constructed by author using CorelDraw software).

In total, CCUS contributes nearly 15% of the cumulative reduction in CO_2 emissions worldwide compared with the Stated Policies Scenario, which takes into account current national energy- and climate-related policy commitments. The contribution of CCUS to the transition to net-zero emissions grows over time, accounting for nearly one-sixth of cumulative emissions reductions to 2070 (IEA, 2020), (Figure 2).

There are only around 20 commercial CCUS operations in the world today. In the last three years, more than 30 commercial CCUS facilities have been revealed (mainly in Europe and the United States, but also in Australia, the China, Korea, the Middle East and New Zealand). Currently, there are projects with a potential investment of about USD 27 billion. If CCUS is required to achieve energy and environment targets, cross-border cooperation and collaboration between government and industry are essential. Now, governments and industry have the opportunity to join together to realise the environmental and economic advantages of CCU (IEA, 2020).

Without CCUS innovations that lead to clean energy transitions in many strategic ways, reaching net zero would be almost impossible. Emissions from existing energy systems are being tackled. Existing power and industrial facilities that will otherwise produce 600 billion tonnes of CO_2 over the next five decades can be retrofitted with CCUS. It is a solution to some of the world's most challenging emissions. Today, heavy industries account for about 20% of global CO_2 emissions. CCUS is practically the only technology that can reduce cement production emissions significantly. In certain countries, it is still the most cost-effective way to avoid emissions in the iron and steel and chemical industries. Captured CO_2 is an important component of the supply chain for synthetic CO_2 and hydrogen fuels, which are one of the few low-carbon options for long-distance transportation, especially aviation. A cost-effective method for producing low-carbon hydrogen. CCUS will help accelerate the production of low-carbon hydrogen to satisfy existing and potential demand from emerging technologies in transportation, manufacturing, and buildings. CCUS is an effective technical solution for eliminating carbon and providing a net-zero electricity system for emissions that cannot be avoided or decreased directly (IEA, 2020).

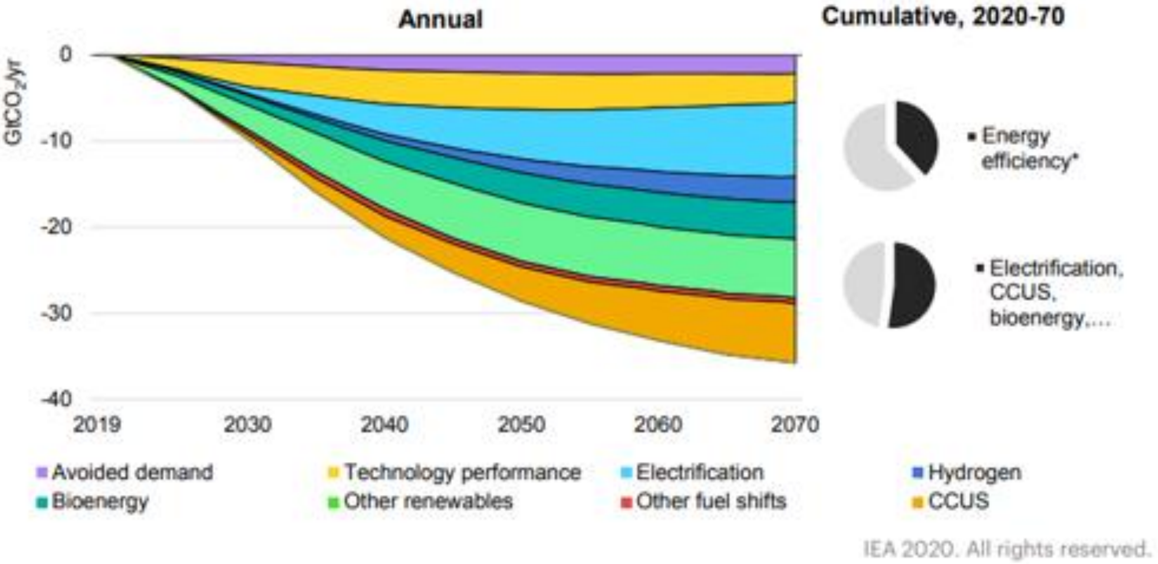


Figure 2. Global energy sector CO_2 emissions reductions by measure in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-2070 (IEA, 2020).

1.2 CCUS for the cement industry

Originally, CCS technology was developed for large power plants in the energy sector. The global production of cement reached 4.2 Gt in 2019 (Edwards, 2019). Cement is the most commonly used building material in the world, but it is also one of the most significant sources of greenhouse gas emissions, accounting for 8% of global emissions (Bellona, 2020). Cement kilns, which cook ground limestone with sand and clay at high temperatures, emit carbon dioxide during the production process. CO_2 is released during this process, both from the combustion of these fuels to heat the kilns and from the gas emitted from the limestone during the calcination process. The CO_2 concentration in cement plant exhaust is very high, making carbon capture much easier. In an optimized engineering design, Carbon Clean's technologies can absorb and store more than 90% of CO_2 (Gomez, 2021).

Per one tonne of cement made, up to 0.95 t of CO_2 is emitted. The real carbon footprint is calculated by many factors, including the clinker-to-cement ratio, the production process (dry or wet), the degree of heat recovery, the fuel used, the moisture content of the raw materials, and the plant's capacity. Process emissions account for about 60% of direct CO_2 emissions, while fuel combustion accounts for the remaining 40% (ECI, 2020).

Heidelberg Cement has committed to decrease its specific net CO_2 emissions per ton of cement manufactured by 30% by 2030, compared to 1990 levels, and to reach carbon neutral concrete by 2050 at the very latest; it is the first cement company in the world to gain approval for science-based CO_2 reduction targets (Beumelburg, 2019).

By rising the percentage of CO_2-neutral feed materials and combustibles, arriving at lower clinker cement classes, and using CCUS, HeidelbergCement hopes to achieve net zero carbon footprint (Plaza, 2020), (Figure 3).

Given the large share of process emissions in the cement sector, the role of CCUS in achieving carbon neutrality by 2050 would be even greater, as this is required to achieve deep levels of decarbonization. CCUS technologies are unquestionably needed in the cement industry. Although there are no yet large-scale CCUS facilities in the cement industry, there are CCUS facilities in the power and industrial sectors that can produce annually up to 40 Mt CO_2 (GCCSI, 2021).

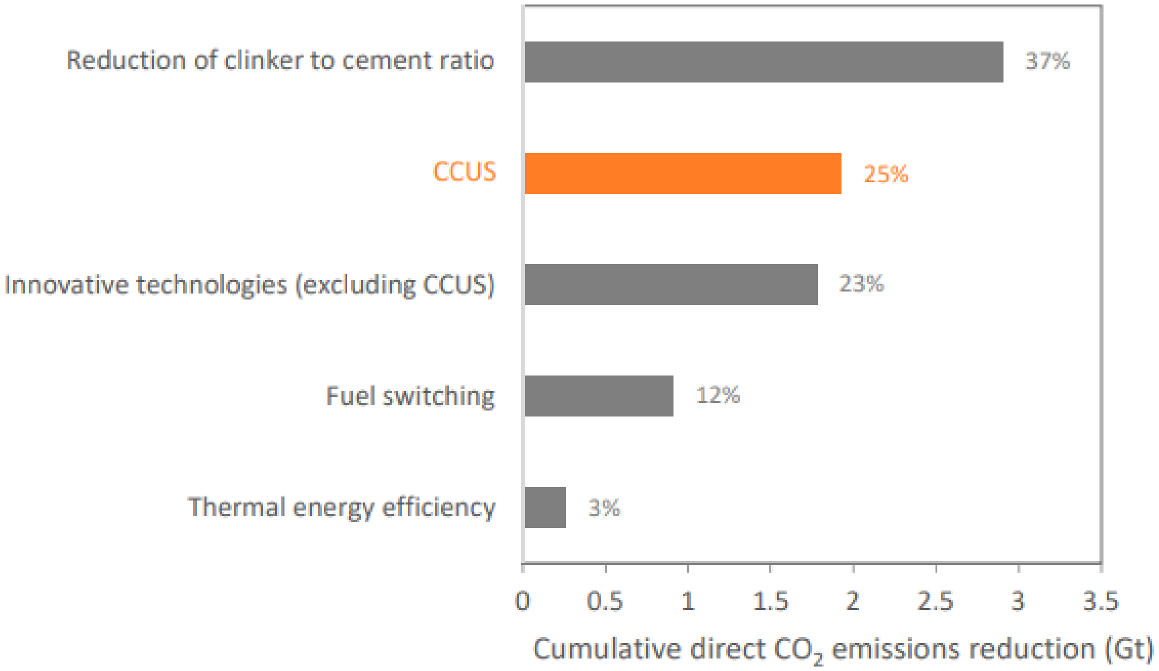


Figure 3. Global cumulative CO_2 emissions reductions by 2050 (Plaza, 2020).

1.3 CCUS hubs and clusters

CCUS, like most sectors, benefits from economies of scale. Compression, dehydration, pipes, and handling on a broader scale result in substantial cost savings per tonne of CO_2. Early CCS innovations adopted a point-to-point concept, which preferred conditions in which a single large emitter (such as a power plant or a gas processing plant) was located within a suitable distance of a large storage location. CO_2 streams from clusters of facilities are collected, compressed, dehydrated, and transferred via hubs. There are substantial cost savings to be had, particularly in the capital costs of compression plants (up to around 50 MW of power consumption) and pipelines (up to around 10-15 Mtpa of capacity). This industrial system, which includes several CCUS service customers and vendors, also helps to mitigate risks. Hubs also help carbon capture plants and storage resources properly balance their sources. They allow for greater turndown than would be possible with individual compression plants at each source, making more flexible compression operations (GCCSI, 2021).

The development of CCUS hubs, which are industrial centers that share CO_2 transport and storage facilities, could help to speed up development by lowering costs. At least 12 CCUS hubs are currently under development around the world, including Australia, Europe and the United States, with all of them related to low- carbon hydrogen production. Today's 19 major industrial projects have a total annual CO_2 capture capacity of 34 Mt (IEA, 2020).

Following are some of the most important industry achievements accomplished in the past year: In March 2020, the Alberta Carbon Trunk Line (ACTL) started operation. This main infrastructure for Canadian industry transports CO_2 for EOR storage in Central Alberta and has a capacity of 14.6 Mt of CO_2. It's the world's highest-capacity CO_2 transportation infrastructure, and it was designed with long term in mind. The Northern Lights Project is one of the most advanced construction hubs. This Norwegian CCS hub in the North Sea aggregates CO_2 streams, starting with foundation sources from waste to energy and cement plants (combined capacity of 0.8 Mtpa of CO_2. The project, which is being developed by Equinor, Shell, and Total, will compress and liquefy CO_2 at source plants before transporting it to a storage site through a dedicated CO_2 ship. The project is planned to be completed in 2024. Northern Lights, a large offshore CO_2 storage plant in the North Sea, may also provide a solution for emissions from neighboring countries (GCCSI, 2021, IEA, 2020, Shogenova et al, 2021), (Figure 4).

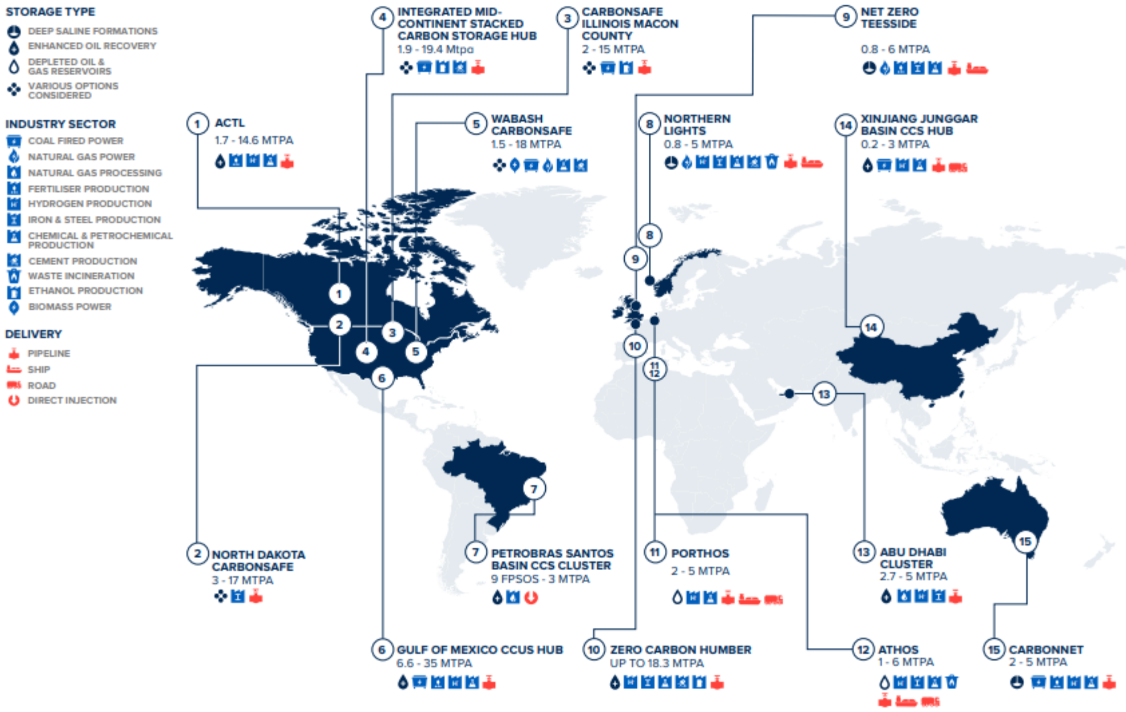


Figure 4. Hubs and clusters over the world (Global CCS Institute, 2021).

1.4 UK clusters

The UK has enough CO_2 storage capacity to fully support the UK's needs for 100s of years of demand (CO_2 Stored, 2015, Oil & Gas Authority, 2021). Several projects have been set up for CO_2 capture and storage. All UK cluster projects are listed below.

Net Zero Teesside (NZT)

Net Zero Teesside is a CCUS plant located in Teesside, England (Figure 5). By 2030, it plans to decarbonize a cluster of carbon-intensive enterprises. The project aims to capture up to 10 Mt of CO_2 emissions, which is the annual energy use of over 3 million UK homes. Teesside's location provides to access in the southern North Sea for CO_2 storage. Teesside industries account for 5.6% of industrial emissions in the UK and the site is home to 5 of the UK's top 25 CO_2 emitters (Net Zero Teesside, 2021).

Zero Carbon Humber (ZCH)

ZCH project is developing CCUS and low carbon hydrogen technology. The project is located in Humber area (Figure 5). ZCH is planning to capture CO_2 at scale from electricity generation, hydrogen production and industrial processes around the estuary via pipelines and transport the emissions to permanent storage in an aquifer under the southern North Sea (Zero Carbon Humber, 2021).

HyNet North West (HNW)

HNW is a project based on the production of hydrogen from natural gas. Project is located in Chester region (Figure 5). It includes the development of a new hydrogen pipeline; and the creation of the CCS infrastructure. The project is planning to storage CO_2 in the East Irish Sea oil and gas fields. Cadent is leading the development of the hydrogen pipeline and Progressive Energy is leading the development of the low-carbon hydrogen production plant and CO_2 pipeline (HyNet, 2020).

Acorn

The Acorn CCS Project is being developed by Pale Blue Dot Energy. By 2023, the Acorn project is aiming to have a low-cost CCS system in place in north east Scotland (Figure 5). To shift the Acorn project from proof-of-concept to design studies, ACT Acorn improves on existing research, such as an appraisal of potential CO_2 storage sites and ways to re-use oil and gas assets. The project centers around the St Fergus Gas Terminal, north of Aberdeen It is linked to a network of offshore pipelines, three of which could be repurposed. St Fergus is also connected to the UK National Gas Grid and has its own pipeline to the Central Belt, where the Caledonia Clean Energy plant near Edinburgh is being proposed. The project will begin with CO_2 capture and storage at the gas terminal, then look into expanding to other large-scale sources of emissions in the area, as well as inbound shipping tankers. The key focus of the project will be on repurposing existing facilities, not only for the implementation of Acorn in the UK, but also for the creation of policy guidelines for the preservation of essential infrastructure in the North Sea area (Acorn, 2021).

South Wales Industrial Cluster

The Cluster is in its starting phase. The project wants to show UK Government an effective option for reducing CO_2 emissions. The Progressive Energy initial is helping to carry out development activities. Project is waiting for vision and guidance of the Welsh Government for 2050. The estimated amount of CO_2 captured is 5Mt CO_2/yr (SWIC, 2021).

This study includes three of these clusters, as they are the most suitable for integration of the cement plants according to their location and CO_2 storage capacity.

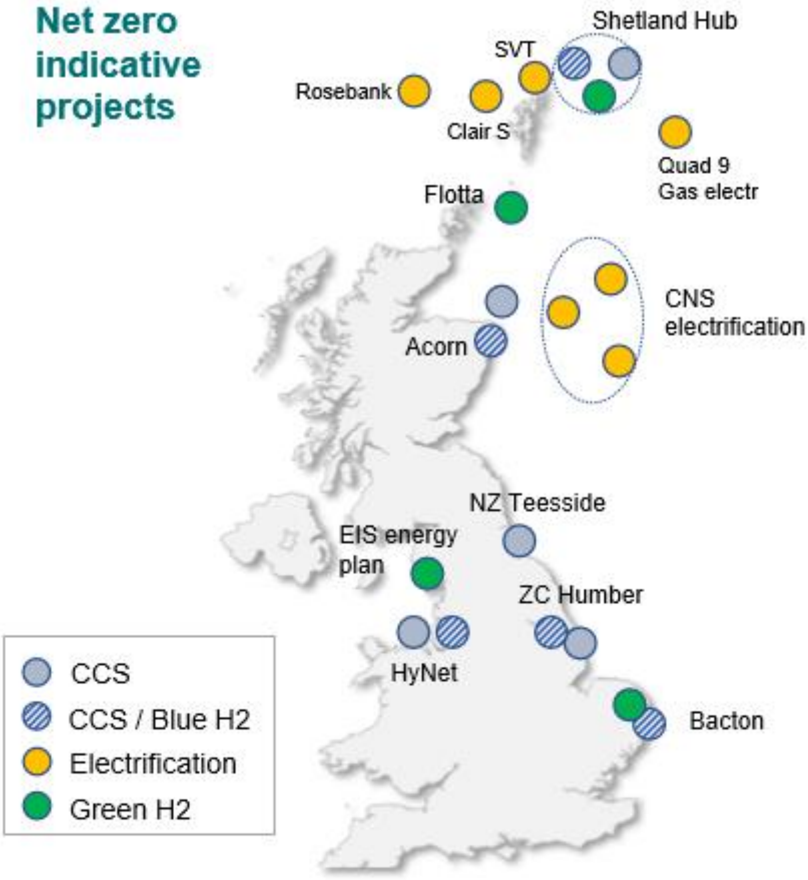


Figure 5. Planned cluster projects in the United Kingdom (Oil & Gas Authority, 2021).

1.5 National climate strategy and CCS regulations in The United Kingdom

The Climate Change Act of 2008 is a key piece of climate change legislation in the United Kingdom. It commits the government to reducet national greenhouse gas emissions by at least 100% of 1990 levels (net zero) by 2050, and to agree on interim five-year "carbon budgets" that would bring the country closer to that target at the lowest possible expense. This act contains the first legally binding national commitment to reduce greenhouse gas emissions in the world. The majority of policy initiatives are focused on energy, especially electricity. Energy is one of the largest sources of UK pollution, and both energy production and demand include cost-effective low-carbon technologies. Governments shall set legally binding "carbon budgets" under the UK Act. Each budget places a five-year limit on total greenhouse emissions; these caps should not be met in order to achieve the UK's carbon mitigation targets. The carbon budgets are proposed to the government by the Climate Change Committee (CCC), which was formed by the Act. They are planned for about a decade in advance to ensure that the necessary strategies and investments are in place. The budgets, when put together, demonstrate the most cost-effective approach to the 2050 target. The Committee submits a periodic report to Parliament on the success of the administration. Climate change action can be categorized into steps to minimize greenhouse emissions and facilitate cleaner energy sources; to support energy efficiency; to encourage corporate monitoring of carbon emissions; and to support climate action in other countries (Climate Change Commitee, 2019, ECI, 2020).

The United Kingdom's government has stated to a number of principles that will guide their approach that includes: a whole-government approach, being facilitative, inclusive, fair, outward-looking and act sustainably. The current requirement that no new coal plant be constructed without demonstrating CCS technologies will be reinforced by an Emissions Performance Standard (HM Goverment, 2020). In March 2020, government announced its commitment to invest GBP 800 million (USD 995 million) in CCUS infrastructure. Starting in 2020, the EUR 10 billion Innovation Fund in Europe will be able to finance CCUS projects (as well as other clean energy technologies) (IEA, 2020).

To get started on, national goal is to have a CCUS sector that can capture 10 Mt of CO_2 per year by 2030. This equates to about four million cars' worth of annual emissions, or the Humber's current industrial emissions. To accomplish this, the UK will spend up to £1 billion to help develop CCUS in four industrial clusters, resulting in the creation of multiple ‘SuperPlaces' (NIS, 2020). Clean industry, power, hydrogen, and transport can all be brought together in locations like the North East, the Humber, the North West, Scotland, and Wales. UK intends to develop CCUS in two industrial clusters by the mid-2020s, and in two more industrial clusters by 2030, and use customer subsidies to help build at least one power CCUS plant by 2030 The role of CCUS in achieving net zero is stated in the Ten Point Plan, Energy White Paper, and National Infrastructure Strategy. The goverment wants to make sure that the industry is prepared so that they can start deploying CCUS in the mid-2020s. That is why, as business models are being developed, they are providing £130 million in funding to help initiatives on front end project development activities such as planning, design, and readiness for implementation process through the Industrial Strategy Challenge Fund and Industrial Decarbonisation Challenge Fund. In addition, a Government Support Package is being proposed to resolve high-impact, low-probability threats to the Transport and Storage network, such as stranded properties and CO_2 leakage risk from storage facilities. The proposed Industrial Carbon Capture business model is intended to promote the use of carbon capture technologies by industrial consumers who, in many situations, have no other alternative for deep decarbonization (Department for Business & Energy , 2020, Frontier Economics, 2020, The Energy White Paper, 2020, The Ten Point Plan, 2020).

As the nationUK's post-Brexit emissions trading scheme (ETS) launched for the first time on 19 May, the UK's carbon price hit £50. The price is almost £5 higher than what is currently trading in the EU's ETS, which is the world's biggest ETS and which the UK left as part of the Brexit process, in December 2020 . On the morning of May 19, 2021, trading prices per tonne of carbon in the EU ETS stood at €52.40, which is about £45.25. Power plants and other high-emitting enterprises will be charged for every tonne of CO_2 they produce above a certain amount under the UK ETS. They will also be able to benefit from excess reductions by selling them to other businesses that haven't met their specific targets. In its first year, the ETS is expected to cover 155 Mt of CO_2 emissions. The ETS will be implemented in the United Kingdom soon after the Committee on Climate Change (CCC) recommendation on the Sixth Carbon Budget is adopted. This binds the UK to reducing net emissions by 78% by 2035, compared to 1990 levels (Edie, 2021).

2 Data and methods

This thesis was supported by CLEANKER project and methodology developed by CLEANKER project was applied (Shogenova & Shogenov, 2020). At first information about cluster projects were collected into the datasets developed in MS Excel datasheets. These Excel datasheets include general project information, project partners, geological data for storage site reservoir and cap rocks parameters, CO_2 emission sources, including cement plants and types of fuels used by the cement plants and CO_2 transport.

I used Geographic information System ArcGIS, version 10.8, to create CCUS cluster projects maps and measured distances between emission sources and CO_2 storage sites. The use of the program was provided by TalTech. All collected data were integrated into ArcGIS program as multi-layered maps supported by numerous parameters for every project and storage location. Constructed ArcGIS layers include location of: CO_2 emission sources already in every project, additional CO_2 emission sources proposed by me, including cement plants, planned hydrogen plants involvd in the clusters, geological storage sites and pipelines and ship routes for CO_2 transport.

CorelDRAW and Adobe Photoshop graphic design software were used in order to create CCUS technology approach used in the UK cluster projects figure and to modify several other figures.

Number of public databases were used to collect data for this thesis:

- CO_2 emissions for each source were obtained from European Union Emissions Trading System (EU ETS, 2021).
- The CO_2 Stored database was used to collect geological information of the storage sites (CO_2 Stored, 2015).
- Storage sites coordinates are taken from The Oil and Gas Authority Wellbore Dataset (Oil and Gas Authority, 2021).

The static capacity of saline aquifer structure was calculated using (Equation 1) for the estimation of the capacity of structural traps (Bachu et al, 2007).The data for the calculation were collected in the CO_2 Stored database (CO_2 Stored, 2015).

$$M_{\mathrm{CO2t}} = A \times h \times NG \times \varphi \times \rho_{co2r} \times S_{ef} \qquad \text{Equation 1}$$

Where:

M_{CO2t} - storage capacity (kg)

A - the area of the reservoir in the trap (m^2)

h - the average thickness of the reservoir in the trap (m)

NG - an average net to gross ratio of the reservoir in the trap (decimal)

ϕ - the average porosity of the reservoir in the trap (decimal)

ρ_{CO2r} - the in situ CO_2 density in reservoir conditions (kg/m^3)

Sef - the storage efficiency factor (for the trap volume, decimal).

CO_2 density in reservoir conditions is estimated as a function of temperature and storage pressure in the reservoir. I used pressure from the middle of the well in my calculations. The CO_2 storage efficiency factor is the volume of CO_2 that could be stored in the reservoir per unit volume of original fluids in place. S_{ef} is estimated according to (Bachu et al., 2007, Vangkilde-Pedersen et al., 2009). Optimistic CO_2 storage capacity is calculated with formula (1) and using optimistic storage efficiency factor (S_{ef}). CO_2 storage capacity is calculated using CO_2 datasheet average results and was added to the Excel datasheet (Shogenova & Shogenov, 2020).

Equation 2 was used for calculating the CO_2 storage capacity in oil and gas reservoirs. It is based on the geometry of the reservoir (areal extent and thickness), as given in CO_2Storaged database (Bachu, 2008).

$$M_{\mathrm{CO2t}} = \rho_{co2r} \times [Rf \times A \times h \times \varphi \times (1 - S_w) - V_{iw} \times V_{pw}] \qquad \text{Equation 2}$$

Where:

ρ_{CO2r} - CO_2 density in reservoir conditions (kg/m^3)

Rf - recovery factor (decimal)

A - reservoir area (m^2)

h – reservoir thickness (m)

ϕ - reservoir porosity (decimal)

S_w - reservoir water saturation (decimal)

V_{iw} and V_{pw} - the volumes of injected and produced water, respectively.

CO_2 storage capacity is calculated by using average results from the CO_2 Stored database.

3 Results

3.1 Integration of cement plants into the cluster projects by CLEANKER project

The aim of this study was to identify suitable Buzzi Unicem and HeidelbergCement Group plants for CO_2 capture in Europe, North America, and Asia-Pacific based on well-documented transport and storage opportunitities of CCS clusters. Initially, cement plants were planned to be integrated into 12 cluster projects stated in the IEAGHG 2015 report (IEA GHG, 2015). However, not all of the projects are still operational. The most advanced EU project, ROAD, which received the first EC storage permit, was cancelled, and the Netherlands is now working on a new PORTHOS project. The Collie Hub cluster project in Australia was discontinued due to a lack of suitable cap rocks (Geoff, 2014). As a result, the study included the Carbon Net Cluster Project in Victoria, Australia (Shogenova et al., 2021).

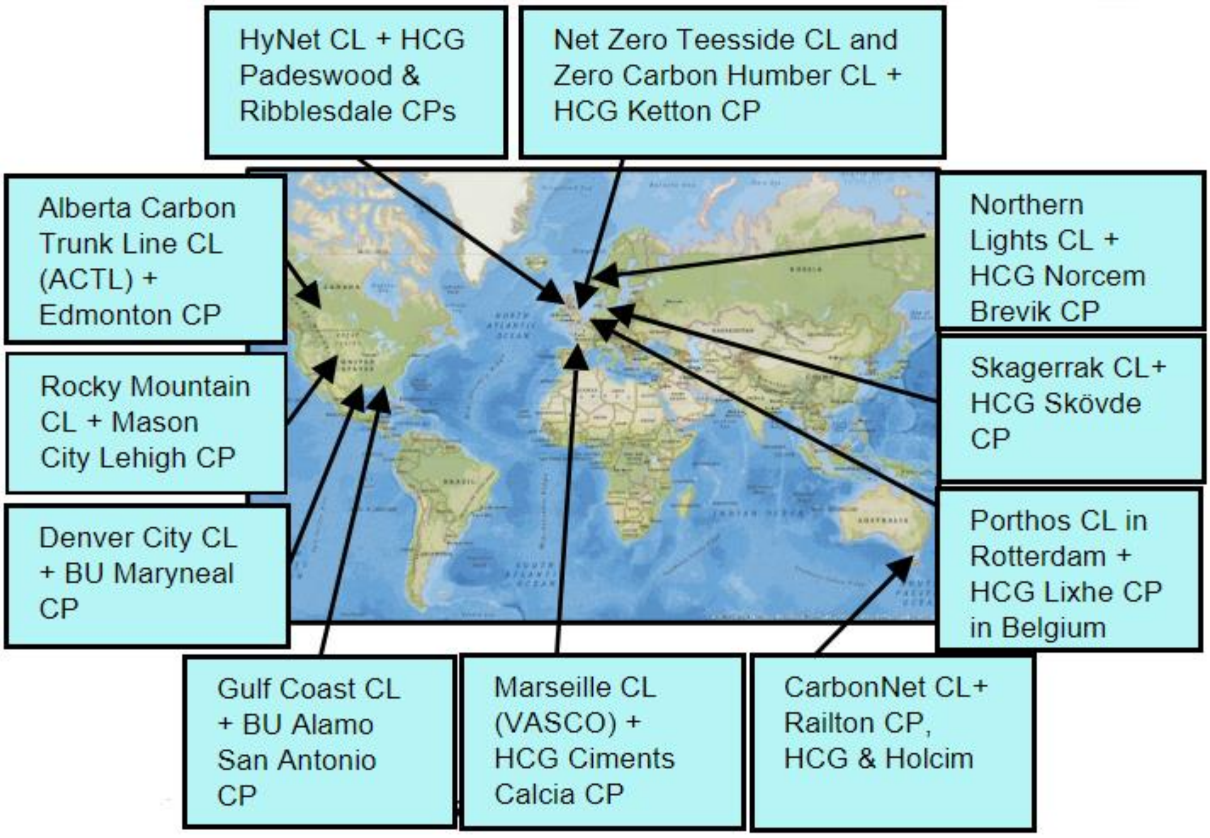


Figure 6. Cluster prjojects studied in CLEANKER Project with Buzzi Unicern and HCG cement plants integrated (Shogenova et al., 2021).

In the Nordic countries, the Skagerrak/Kattegat cluster project was a study that was partially initiated within the Northern Lights Project in Norway, and another Skagerrak project in this region is under discussion and development in Denmark and Norway. The Northern Lights Project, represented by HCG Brevik Norcem CP, was included in the study as the first and only emerging European cluster and PCI project (European Project of Common Interest) with a cement plant (Shogenova et al., 2021), (Figure 6).

The HCG Norcem Brevik cement plant (CP) is the first CP in the world with Northern Lights facilities integrated into the Longship project. The second potential candidate is HCG Edmonton CP, which is located 170 km from the ACTL project's Clive DOF in Alberta, Canada. BU Maryneal CP, located 81 km from Sacroc DOF in the Denver City project in Texas, is the best choice for incorporation among three operational CO_2-EOR cluster projects in the United States. All of the CPs suggested for inclusion in European projects are situated within 50-300 km of the storage sites. This rule has also been followed in this work when adding to CP into clusters (Shogenova et al., 2021).

3.2 Net Zero Teesside cluster

NZT is a CCUS project located in Teesside, in Durham County, North Yorkshire, England (Figure 7). NZT seeks to develop a network that will enable the decarbonization of a cluster of carbon-intensive businesses on Teesside by 2030 (NetZeroTeesside, 2021).

3.2.1 CO_2 emission sources

NZT has confirmed three production units of the partners involved in the project including: CF Fertilisers UK Ltd Billingham Manufacturing Plant, BOC Limited Teesside Hydrogen Plant and SembCorp Utilities Ltd Wilton Power Station both in Middlesbrough (NetZeroTeesside, 2021), (Figure 7).

Table 1. CO_2 emissions produced in 2018-2020 by plants (EU ETS, 2021) and hydrogen production planned for Net Zero Teesside cluster (Net Zero Teesside, 2020)**.**

Plant name	CO_2 emissions, 2018 , Kt	CO_2 emissions, 2019, Kt	CO_2 emissions, 2020 , Kt	Planned Hydrogen, Kt	Source of energy
Billingham Manu-facturing Plant	837.16	820.3	803.4	-	Gas
Teesside Hydrogen Plant	204.34	200.2	196.1	32	Gas, biomass, wind, water and solar energy
Wilton Power Plant	38.939	37.5	36.120	-	Gas, biomass, waste
Total CO_2 emissions	1080.4	1058	1035.6	32	

1 CF Fertilisers UK Ltd

CF Fertilisers is the leading fertiliser manufacturer in the UK, producing annually over 1.5 Mt of fertiliser, accounting for 40% of the UK's fertiliser demands. Along with this, Teesside industries benefit from the production of half a million tonnes of chemicals and the supply of utilities (CF Fertilisers, 2021).

The Billingham Site is an integrated processing and storage facility that produces chemicals, utilities, and ammonium nitrate fertilizers. The Billingham plant, which employs 190 employees, located at the center of the Teesside Chemical Industry, with many close links to nearby chemical companies that use ammonia and nitric acid as key raw materials (CF Fertilisers, 2021).

2 Sembcorp Energy UK

Sembcorp Energy UK is an integrated energy company that offers flexible energy services and sustainable solutions to help the UK achieve Net Zero energy, with a 968MW portfolio of energy generation and battery storage in operation. Wilton International provides energy resilience, stability, and cost advantages to energy-intensive industrial companies on the site by supplying private wire power, world-scale utilities, and specialist services. Sembcorp Energy's Wilton 10 Biomass Power Plant uses low-grade recycled wood with no other practical use. Wilton 11 Energy from Waste facility utilises household residual waste after recyclable components have been eliminated, which would otherwise result in 440 Kt of landfill waste each year. In contrast to fossil-fuel-based power generation, these facilities save about 330 Kt of carbon per year (Sembcorp Energy, 2021, Wilton International, 2020). CO_2 emissions in 2018, 2019 and 2020 for Wilton 10 and Wilton 11 facilities, jointly shown in the Table 1 under Wilton Power Plant, decreased from about 39 Kt in 2018 to 36 Kt in 2020. (Figure 7, Table 1).

CO_2 emissions produced by Billingham Manufacturing Plant are slightly decreased from 837.2 Kt in 2018 to 803.4 Kt in 2020 (Figure 7, Table 1).

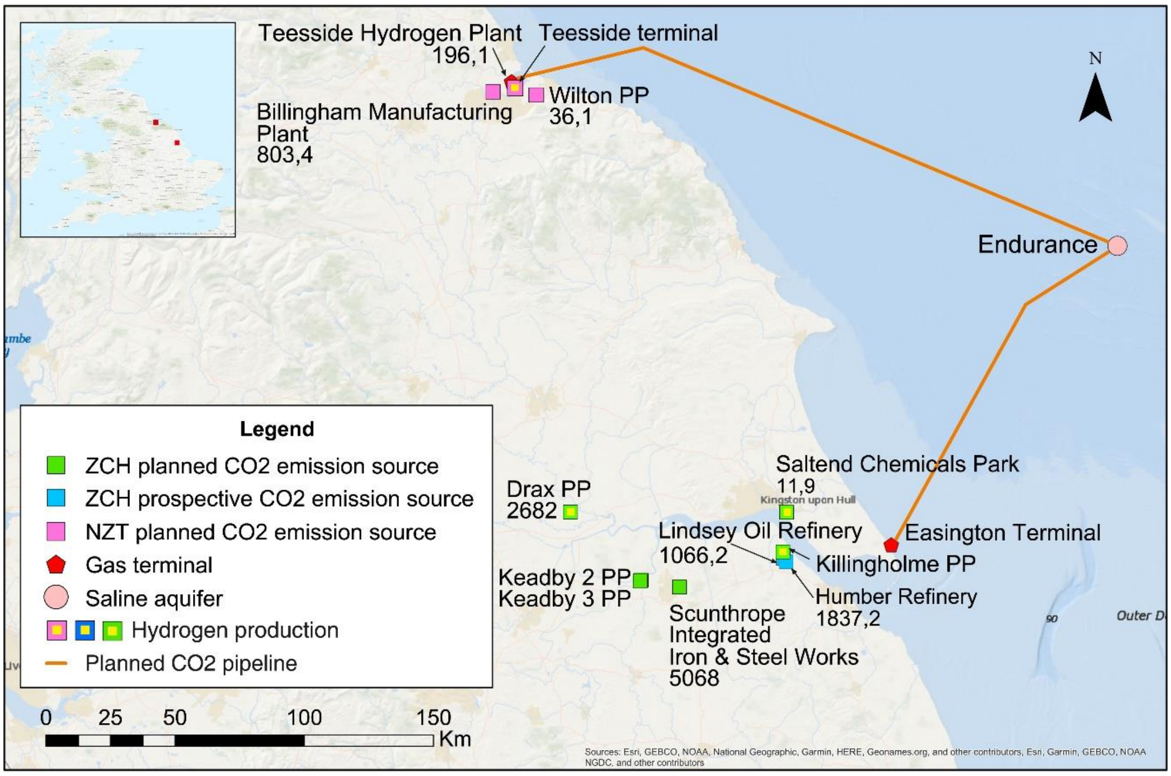


Figure 7. Map of Net Zero Teesside and Zero Carbon Humber cluster projects (constructed using ArcGIS 10.8). CO_2 emissions produced in 2020 are shown in Kt, according to data collected from EU ETS, 2021.

3.2.2 Hydrogen Production

The importance of CCUS is also emphasized in terms of capturing CO_2 from non-renewable energy production and hydrogen production (given the ambition to transition to a hydrogen economy, which a crucial part of reaching net zero). Net Zero Teesside project has collaborated with one hydrogen plant. It is the BOC Limited Teesside Hydrogen Plant in Middlesbrough (Net Zero Teesside, 2020), (Figure 7).

BOC ’s parent company Linde is actively advancing technology to maximize the share of renewable hydrogen produced in the future, based on these conventional hydrogen production techniques and the company's more than 100 years of H_2 production experience. The long-term goal is to greatly expand the share of renewable energy sources in the hydrogen mix, such as wind, water, and biomass. Electrolysis of water using wind, water, or solar power, as well as biogas reforming, are currently viable options for a zero-emission hydrogen energy cycle (BOC, 2021).

Teesside Hydrogen Plant has planned hydrogen production of 32 Kt/y (BOC, 2021). Since the Teesside Hydrogen Plant uses biomass, wind power, water power, solar energy, it produces green hydrogen using electrolysis splitting. The only elements that are produced are hydrogen and oxygen. Without harming the environment, hydrogen may be used to release oxygen into the atmosphere. Electrolysis requires a lot of energy and power. The green hydrogen production process is driven by renewable energy sources such as wind and solar. Green hydrogen, as a result, is the most environmentally sustainable option: hydrogen produced from clean energy sources with no CO_2 emissions as a by-product. A cleaner-than-grey manufacturing process known as "blue hydrogen" holds promise in the short and long term to fill the gap between grey and green hydrogen processing (Van Cappellen et al., 2018, Gielen et al., 2020).

Future plans for the Teesside area include the construction of a new hydrogen plant. The planned development is named H_2 Teesside and it will begin production in 2027 and aim to produce 1GW of hydrogen by 2030. A feasibility study is currently underway for the project, which will help the city achieve its goal of being a renewable energy powerhouse for the UK, while also assisting other local industries in switching to hydrogen over natural gas and other energy sources (Tees Valley Combined Authority, 2021).

3.2.3 CO_2 Transport

Northern Endurance Partnership (NEP) submitted a bid for funding through Phase 2 of the UK Government's Industrial Decarbonisation Challenge, with the aim of accelerating the construction of an offshore pipeline network to transport collected CO_2 emissions from both NZT and ZCH to Endurance storage site (Equinor, 2020).

Net Zero Teesside project captured CO_2 will be transported to Endurance storage field by a offshore pipeline. The diameter of the pipe is 609.7 mm (NetZeroTeesside, 2020). The gas terminal from which the CO_2 is transported along the offshore pipeline is located in Middlesbrough. In the case of short-distance, less than 1000 km, offshore CO_2 transportation is effective by pipelines. The offshore pipelines connecting the gas terminal at Middlesbrough and the Endurance storage site shown on the map is about 144 km long- according to the measurement made by the autor in the ArcGIS system (Figure 7).

The equipment needed for the high-pressure compression of CO_2 from the power station and local industries, as well as the onshore CO_2 pipeline network, will be installed, operated, and decommissioned by NZNS Storage. NZNS Storage will also be in charge of NZT's offshore elements, which include the pipeline that will carry CO_2 to the Endurance storage site in the North Sea, as well as supporting infrastructure (NetZeroTeesside, 2020).

The CO_2 transport offshore pipeline will start in the location of the former SSI steel works site in Redcar, before heading offshore (Teesside terminal)controlled by the STDC (Figure 7). The Oil and Gas Authority (OGA) regulates offshore pipelines and carbon dioxide transportation and storage (NetZeroTeesside, 2020).

CO_2 can be transported in two phases: gaseous and dense. The advantages of dense phase CO_2 transportation far outweigh the disadvantages:

- higher flow capacity per unit cost;
- increased capacity outweighs additional cost of increased pressure requirement;
- lower pressure drop per unit mass of CO_2;
- ease of operation and benefits of the use of pumps rather than compressors (Hafez & Fateen, 2016).

The use of dense phase also eliminates the need for injection compressors on the offshore platform, so booster pumps will be located onshore; the dense phase pipeline can be made of carbon steel (rather than high-cost chrome/nickel alloy steel); and CO_2 purity will be tightly controlled and dehydrated to less than 50 ppm to avoid corrosion and hydrogen embrittlement (Hafez & Fateen, 2016, White Rose, 2016).

CO_2 can also be liquefied as an alternative. CO_2 that has been liquefied will be exported by marine tankers. Natural gas is converted to LNG (Liquefied Natural Gas) and then transported via tankers, which is a similar technique used in the oil and gas industry. This method is particularly appealing when the fluid is carried over long distances that are much greater than the distances covered by pipelines. However, it should be acknowledged that CO_2 liquefaction is a costly operation. Furthermore, the tankers must be specially constructed and refrigerated to ensure that the CO_2 stays in liquid form, increasing the cost of CO_2 transportation (Lee et al., 2012, Metz et al., 2005).

Since CO_2's critical temperature is 31°C, liquefaction typically takes place at or below room temperature, with pressures ranging up to 70 bar. The temperature must be preserved during shipping to prevent the liquefied CO_2 from evaporating (Bennaceur, 2014, Hafez & Fateen, 2016).

With the existing concentration of industries located within a relatively compact area, captured CO_2 can be gathered and transported to an offshore storage site relatively easily (NetZeroTeesside, 2020).

3.3 Zero Carbon Humber Cluster

Zero Carbon Humber (ZCH) is a Carbon Capture, Utilization, and Storage (CCUS) and low carbon hydrogen technology project located in Humber, Yorkshire and North East Lincolnshire (Figure 7), on the east coast of England (Zero Carbon Humber, 2021).

3.3.1 CO_2 emission sources

1 Saltend Chemicals Park

Saltend Chemicals Park Limited includes: Tricoya Technologies Ltd., bp, Vivergo Fuels, Air Products, INEOS, Yara, Soarnol and Triton Power (Saltend Chemicals Park, 2021).

Hydrogen to Humber, led by Equinor (H2H) is the anchor project for ZCH. At px Group's Saltend Chemicals Park, it will build the world's largest hydrogen production plant with carbon capture. Both CO_2 captured will be compressed and stored under the southern North Sea using offshore facilities shared with the Teesside industrial cluster at Centrica Storage's Easington sitegas terminal. Equinor has a long history of storing CO_2 at North Sea fields like Sleipner, and it will build on that knowledge as it participates in the creation of full value chains for carbon capture and storage, such as their partnership with Shell and Total and Northern Lights JV (Equinor, 2020), (Figure 7).

The H2H Saltend project serves as the gateway for a National Grid Ventures-developed carbon dioxide and hydrogen pipeline network that will link energy-intensive industrial sites throughout the region, giving companies the opportunity to capture CO_2 emissions directly or switch to hydrogen as a fuel (Saltend Chemicals Park, 2021, Zero Carbon Humber, 2021). The H2H Saltend Chemicals Park produced in 2019 - 2020 about 12 Kt of CO_2 emissions (Table 2).

Other ZCH partners will connect their infrastructure, which is currently in development, to the pipelines when this shared infrastructure is delivered. In addition to the partners already approved by the ZCH project, it is very likely that more companies will join the project in the future. As there is a large potential for CO_2 storage in the Endurance storage site, ZCH is planning to find more project partners. Two suitable companies could be Total Lindsey Oil Refinery Limited and Phillips 66 Limited (Saltend Chemicals Park, 2021, Zero Carbon Humber, 2021).

2 Drax Power Station

Drax Group is a green energy firm based in the UK. The company develops renewable power, produces sustainable biomass, and sells renewable electricity to companies. Drax has four sites in England and Scotland where it operates a generation portfolio of sustainable biomass, hydroelectric, and pumped hydro storage assets. It is the UK's primary renewable energy source (Drax, 2020).

Drax Power Station near Selby has confirmed joining the ZCH project. The DPS is striving to become a carbon negative power station by 2030. Thanks to the use of sustainably sourced wood pellets, DPS is the UK's biggest single producer of renewable energy. The CO_2 captured by the forests from which biomass is generated is equal to the emissions released as the biomass is used to produce electricity. When bioenergy is combined with CCUS technology (known as BECCS technology), the overall electricity generation process removes more CO_2 from the atmosphere than it releases, resulting in negative emissions power (Zero Carbon Humber, 2021)(Figure 7).

DPS CO_2 emissions decreased about two times from 2018 to 2019 (from 4.1 Mt to 2 Mt) and increased again in 2020 up to 2.7 Mt of CO_2 (Table 2).

3 Uniper's Killingholme plant

Uniper is an international energy company that generates, trades, and markets energy on a large scale. We also procure, store, transport, and supply commodities such as natural gas, liquefied natural gas, and coal as well as energy-related products (Uniper Energy, 2021).

Uniper’s Killingholme plant is located in Immingham, East Riding of Yorkshire, Lincolnshire. The plant is one of the very first gas-fired power stations in the UK. The site is close to and has existing connections to offshore wind production facilities in the North Sea, which could enable the production of green hydrogen from renewable electricity (Uniper Energy, 2021), (Figure 7).

Killingholme PP is not included in the CO_2 emissions table since the emissions data of this facility were not available in the EU ETS database.

4 SSE Thermal

Keadby 2 Power Plant

SSE Thermal is a leading renewable energy producer in the UK and Ireland, and one of the country's biggest power network providers. To help the zero-carbon transition, company builds and runs it's own low-carbon infrastructure. SSE Thermal has also confirmed joining the ZCH project (SSE Thermal, 2021).

The pipeline network will pass through SSE Thermal's Keadby site, where Keadby 2 power plant (PP) is located. Siemens Energy is currently building Keadby 2, a new 840MW gas-fired power station in North Lincolnshire. The project is located next to the Keadby 1 PP, which is currently operating. SSE Thermal has teamed up with Siemens Energy to bring to the UK a first-of-its-kind, high-efficiency gas-fired generation technology. Keadby 2 is planned to be Europe's cleanest and most efficient gas-fired power station once completed. The station received a 15- year capacity agreement at a de-rated capacity of 803.7 MW via the UK's Energy Auction process in March 2020 (SSE Thermal, 2020), (Figure 7).

SSE Thermal Keadby 3 Power Plant

SSE Thermal is building a second PP, Keadby 3, near Keadby 2. Keadby 3 PP is currently under construction. It will be one of the emission sources to join the ZCH CCUS network. SSE Thermal has committed to develop PP that have a direct path to decarbonization. Keadby 3 PP will use natural gas as its fuel and will be equipped with a carbon capture plant to remove CO_2 from its emissions. It will have an electrical capacity of up to 910 MW. By the mid-2020s, this will be the UK's first gas-fired PP with carbon capture technology, delivering decarbonised flexible power to complement intermittent renewables generation while maintaining supply reliability. The network will also pass through Immingham, where Uniper plans to expand its European hydrogen ambitions by developing clean hydrogen production at its Killingholme site, in line with the company's commitment to be carbon neutral in Europe by 2035 (Zero Carbon Humber, 2020, SSE Thermal, 2021), (Figure 7).

Keadby 2 and Keadby 3 power plants are not included in the CO_2 emissions table since they are in construction.

5 British Steel Scunthorpe Integrated Iron & Steel Works

British Steel Limited (BSL) is a construction industry supplier to a wide variety of structural sections. Generate process gases as by-products of blast furnace ironmaking, basic oxygen steelmaking, and coke processing are all carried out at the Scunthorpe plant. (British Steel, 2021). British Steel, as one of the UK's largest steel producers and a major employer in the region, could benefit from the ZCH infrastructure as part of its efforts to reduce emissions. ABP, the region's main port and logistics provider, will support the global reach of Scunthorpe and Saltend's low-carbon products and chemicals (British Steel, 2021, Zero Carbon Humber, 2021).

Scunthorpe's 2,000- acre site is an integrated site of BSL. The Scunthorpe site deals with refining the raw materials, iron making and continuous casting. Steel production raw materials are transported to the site, where they are eventually converted to steel (British Steel, 2021). Scunthorpe Integrated Iron & Steel Works' CO_2 emissions decreased from 5.6 Mt in 2018 to 5 Mt in 2020 (Figure 7, Table 2).

6 Total Lindsey Oil Refinery

Total is a multinational energy corporation that produces and sells fuels, natural gas, and electricity (Total, 2021).

Total Lindsey Oil Refinery Limited has Lindsey Oil Refinery in North Killingholme, Immingham , which is within the Zero Carbon Humber project area (Total, 2021), (Zero Carbon Humber, 2021). Lindsey Oil Refinery's emissions decreased from 1.1 Mt in 2018 to 1.07 Mt in 2020 (Figure 7, Table 2).

Table 2: CO_2 emissions produced in 2018-2020 by plants (EU ETS, 2021) and hydrogen production planned for the Zero Carbon Humber cluster.

Plant name	CO_2 emissions, 2018, Kt	CO_2 emissions, 2019, Kt	CO_2 emissions, 2020, Kt	Source of energy
Drax PP*	4139	1958	2682	Coal, biof uel
Scunth-orpe Int. Iron & Steel Works	5620.3	5507.1	5068	Coal
Saltend Chemicals Park*	-	12.187	11.9	-
Total planned CO_2 emissions			7761.94	
Lindsey Oil Refinery (proposed)	1111	1088.7	1066.2	Oil
Humber Refinery (proposed)	1914.4	1875.9	1837.2	Oil
Total proposed CO_2 emissions			2903.4	
Total planned and proposed CO_2 emissions	12784.7	10441.82	10665.32	

***Planned hydrogen production.**

7 Phillips 66 Limited Humber Refinery

Phillips 66 is an energy manufacturing and logistics company with a wide range of products. The company produces, transports, stores, and markets fuels and products around the world through its Midstream, Chemicals, Refining, and Marketing and Specialties businesses (Phillips 66, 2021).

The Humber Refinery is located in South Killingholme, Northern Lincolnshire, United Kingdom. It mainly processes crude oil from the North Sea, which includes light, low, and medium-sulfur, as well as acidic crude oils. Humber produces a significant amount of oil, diesel, and aviation fuel. Because of its fluid catalytic cracking unit/thermal cracking/coking configuration, large quantities of other feedstocks, such as low-sulfur fuel oil and vacuum gas oil, can be processed alongside crude oil to completely use Humber's conversion capabilities (Phillips 66, 2021).

Phillips 66 Limited's Humber Refinery CO_2 emissions decreased from 1.91 Mt in 2018 to 1.84 Mt in 2020 (Figure 7, Table 2).

8 Cement Plants

8.1 Hanson UK Heidelberg Ketton Works cement plant (CP)

Hanson UK, as a leading provider of building materials, provides a diverse variety of cement products, ranging from general purpose to waterproof, quick dry, pre-mixed, and ready mix cement. Portland Cement, White Portland Cement, GGBS, and Fly Ash are among the unrivalled product categories (Hanson UK, 2021).

The Hanson UK Heidelberg Ketton Works CP could be integrated into the ZCH cluster (Shogenova et al., 2021). The Heidelberg Ketton Works is a complex with a big cement plant and quarry in Stamford, UK (Hanson UK, 2021). Heidelberg Cement Group (HCG) company produces ready-mixed concrete, asphalt, cement, cement-related materials and aggregates. It is a division of the HCG, a leading producer in aggregates, cement, and concrete (Hanson UK, 2021), (Figure 8).

8.2 CEMEX South Ferriby and Rugby Cement Plants

As ZCH will add more CO_2 producers to the project in the future, I propose to add another cement plant located in the middle of the Humber region. In addition to the Hanson UK Heidelberg Ketton Works cement plant (proposed by the CLEANKER project, (Shogenova et al., 2021), I would also add CEMEX South Ferriby CP and CEMEX Rugby CP. As these plants produce clinker and have relatively high emissions, it would be reasonable to join the project.

CEMEX generates produces readymixed concrete, cement and aggregates they also supply and install asphalt materials, manufacture concrete block pavings, rail products, bespoke pre-cast and concrete blocks. The South Ferriby Cement plant is based in Barton-upon-Humber in North Lincolnshire. It provides cement and cementitious solutions to businesses in the Lincolnshire region (CEMEX, 2021).

The South Ferriby Cement plant CO_2 emissions are relatively stable and decreased only from 438 Kt in 2018 to 420 Kt 2020 are shown in the (Figure 8, Table 3).

The CEMEX Rugby Works cement plant is located in Rugby, eastern Warwickshire. The plant provides cement and cementitious solutions to businesses in the region. Cement is produced for use in small, medium, and large construction projects (CEMEX, 2021), (Figure 8, Table 3).

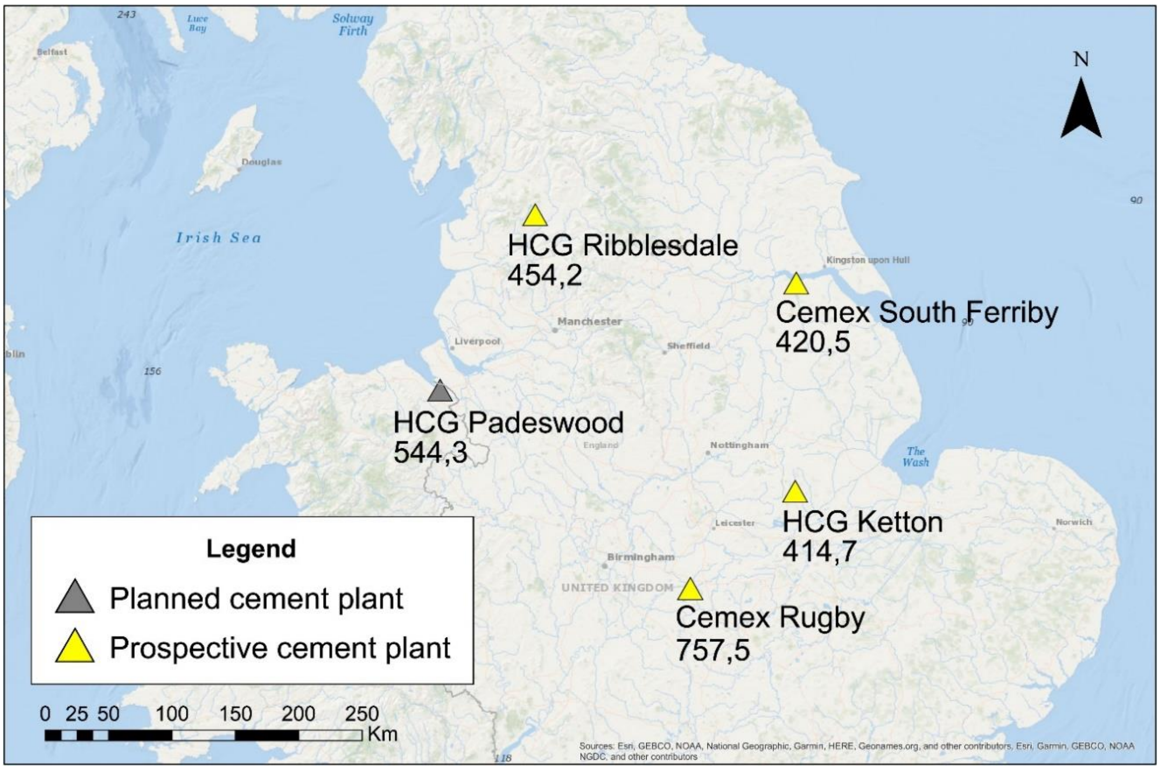


Figure 8. Map of the planned and prospective cement plants (constructed using ArcGIS 10.8). CO_2 emissions produced in 2020 are shown in Kt, according to data collected from EU ETS, 2021.

Ketton Works CP could be integrated into the ZCH cluster (Shogenova et al., 2021). The Heidelberg Ketton Works CO_2 emissions decreased from 725 Kt in 2018 to 415 Kt in 2020 (Table 3).

Table 3. CO_2 emisions produced by cement plants in 2018-2019 (EU ETS, 2021).

Project partner name	Plant name	Plant location (town)	CO_2 emissions, 2018, Kt	CO_2 emissions, 2019, Kt	CO_2 emissions, 2020, Kt
Castle Cement Ltd	Ketton Works	Stamford	725.32	423.41	414.67
Cemex UK Cement Ltd	South Ferriby Works	Barton upon Humber	438.18	429.35	420.5
Cemex UK Cement Limited	Rugby Works	Rugby	789.34	773.45	757.5
Total CO_2 emissions					1592.67

3.3.2 Hydrogen Production

The hydrogen economy will be a key component of the Humber and wider Yorkshire region decarbonisation. Hydrogen is one of the primary fuels for the future in the Humber area and beyond. The hydrogen can be combined to reduce the carbon footprint of domestic heating and more in industrial production where high temperatures are needed, including steel and chemical products. The decrease CO_2 emissions in heating will have a significant effect on the emissions overall, opening up new possibilities in an increasingly environmentally aware world market for greener steel and chemicals to become competitive. Furthermore, hydrogen is being tested as a low-carbon substitute to oil-based fuels in a variety of forms of transportation. Hydrogen-powered trains have recently completed their first trials on UK railways, and hydrogen cars are now available from a number of suppliers. Hydrogen-powered ferries are also currently being tested (Zero Carbon Humber, 2021).

The ZCH offers low carbon blue hydrogen production via the H2H Saltend site, as well as Drax Power Station and multiple other sites along the pipeline infrastructure’s route in the future (Zero Carbon Humber, 2021), (Figure 7).

Uniper’s Killingholme site is in early development phase to to produce blue and green hydrogen in the future (Zero Carbon Humber, 2020).

Electrolysis is being used to develop green hydrogen production at Saltend Chemicals Park. Expansion of hydrogen output and transmission system to Drax and Ferrybridge in the west. At SSE Keadby Clean Power Hub, transmission of hydrogen produced at Saltend would provide a decarbonization alternative. Saltend's hydrogen production capacity is being expanded (fuel switch at Triton to 100% hydrogen). Electrolysis is being used to develop green hydrogen processing at Saltend Chemicals Park. Hydrogen is an obtion to help decarbonize British Steel, one of the UK's two steel works (Equinor, 2021), (Figure 7).

Uniper’s Killingholme site in Immingham is planning to add, clean hydrogen production, in line with the company’s pledge to be carbon neutral in Europe by 2035 (Zero Carbon Humber, 2021), (Figure 7).

3.3.4 CO_2 storage site

Net Zero Teesside and Zero Carbon Humber have decided to jointly store their captured CO_2 emissions in the Southern North Sea in the Endurance structure (Figure 7).

1 Geological background

In the Triassic Southern North Sea (SNS) basin several large-scale saline aquifer structures have been identified as potential storage sites in the UK's Southern North Sea (SNS). These structures can be found at depths of over 1000 meters in the Early Triassic Olenekian Bacton Group Bunter Sandstone Formation (BSF) (Brook et al., 2003, White Rose, 2016).

The Endurance structure is located in blocks 42/25 and 43/21, on the western side of the Bunter province in the Southern North Sea. There is a cluster of abandoned gas fields and tested structures in the Triassic Bunter Sandstone Formation (BSF), (Gluyas & Bagudu, 2020).

The Triassic is divided into three stratigraphic groups at Endurance. The Triassic Bacton group, which includes red sandstones, shales, and mudstones, includes Top Bunter, which is mostly coarse-grained. A basal seal is provided by the Bunter Shale formation (BSF), which lies underneath the BSF. The Bunter Shale Formation, which is dominated by mudstones, was deposited in the Early Triassic Induan time and is overlain by the Olenekian Bunter Sandstone Formation reservoir interval (White Rose, 2016).

At the base of the the Haisborough group lies the Rot Halite member, which is well formed in the Southern North Sea (SNS) basin. Rot Halite is located directly on top of the Endurance structure and is considered to be quite large. The Penarth group in the top Triassic represents the marine transgression that marks the transition from the Triassic to the Jurassic (Balson et al., 2001, (Glennie & Boergner, 1981, Gluyas & Bagudu, 2020, Henni et al., 2002).

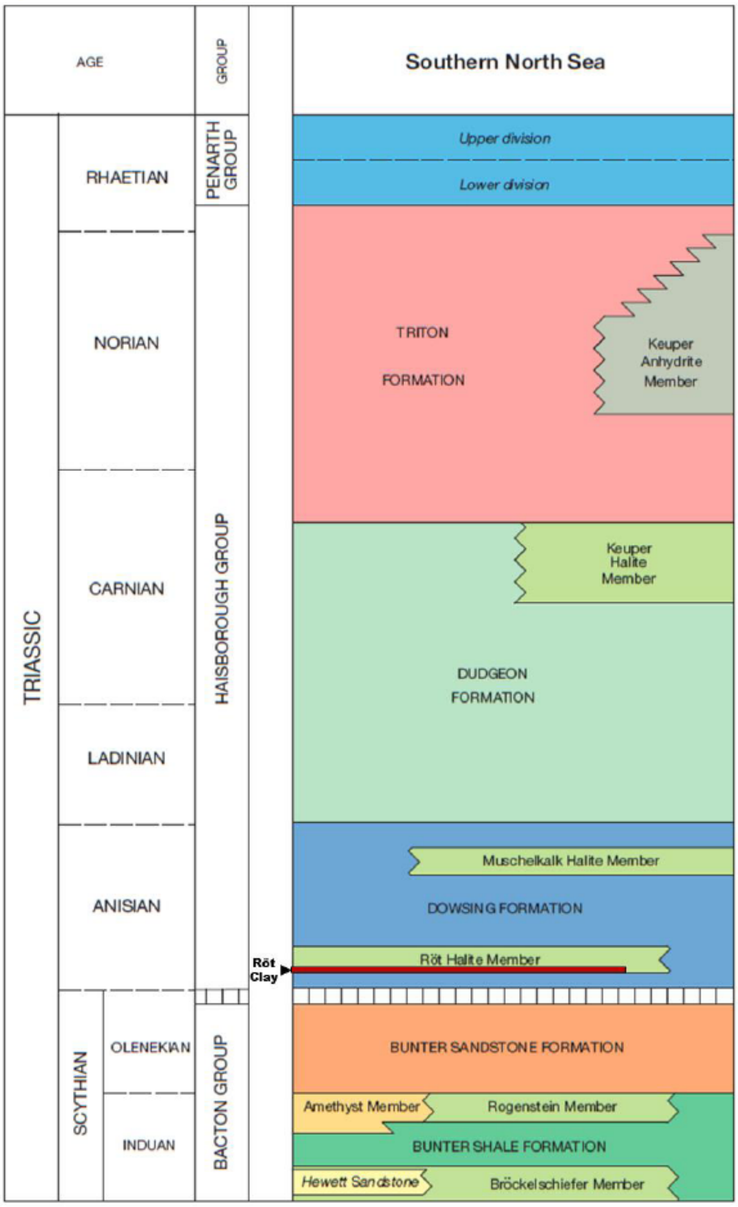


Figure 9. Lithostratigraphic nomenclature scheme for the Triassic of the Southern North Sea (White Rose, 2016).

The Dowsing, Dudgeon, and Triton formations cover the Haisborough group (Glennie et al., 1981), (Figure 9). Mudstone dominates the remaining Middle Triassic and Late Triassic strata, with subordinate evaporites. Non-marine sedimentary rocks make up the whole Triassic interval. The Bunter Sandstone Formation was deposited by a mixture of braided, ephemeral fluvial channels and braidplains with aeolin dunes. The sediments originated from the London Brabant Massif to the south, and were overlain by Lower Jurassic marine mudstones, which also covered the seabed (Gluyas & Bagudu, 2020), (Figure 10).

Top Bunter is mainly coarse-grained and is made of the Early Triassic Olenekian Bacton Ggroup, which includes red sandstones, shales, and mudstones (Gluyas & Bagudu, 2020).

The Haisborough Group immediately overlies the Bacton Group, which consists primarily of alternating beds of fine-grained clastics and evaporates that serve as excellent top seals for CO_2 injected into the Endurance structure (White Rose, 2016).

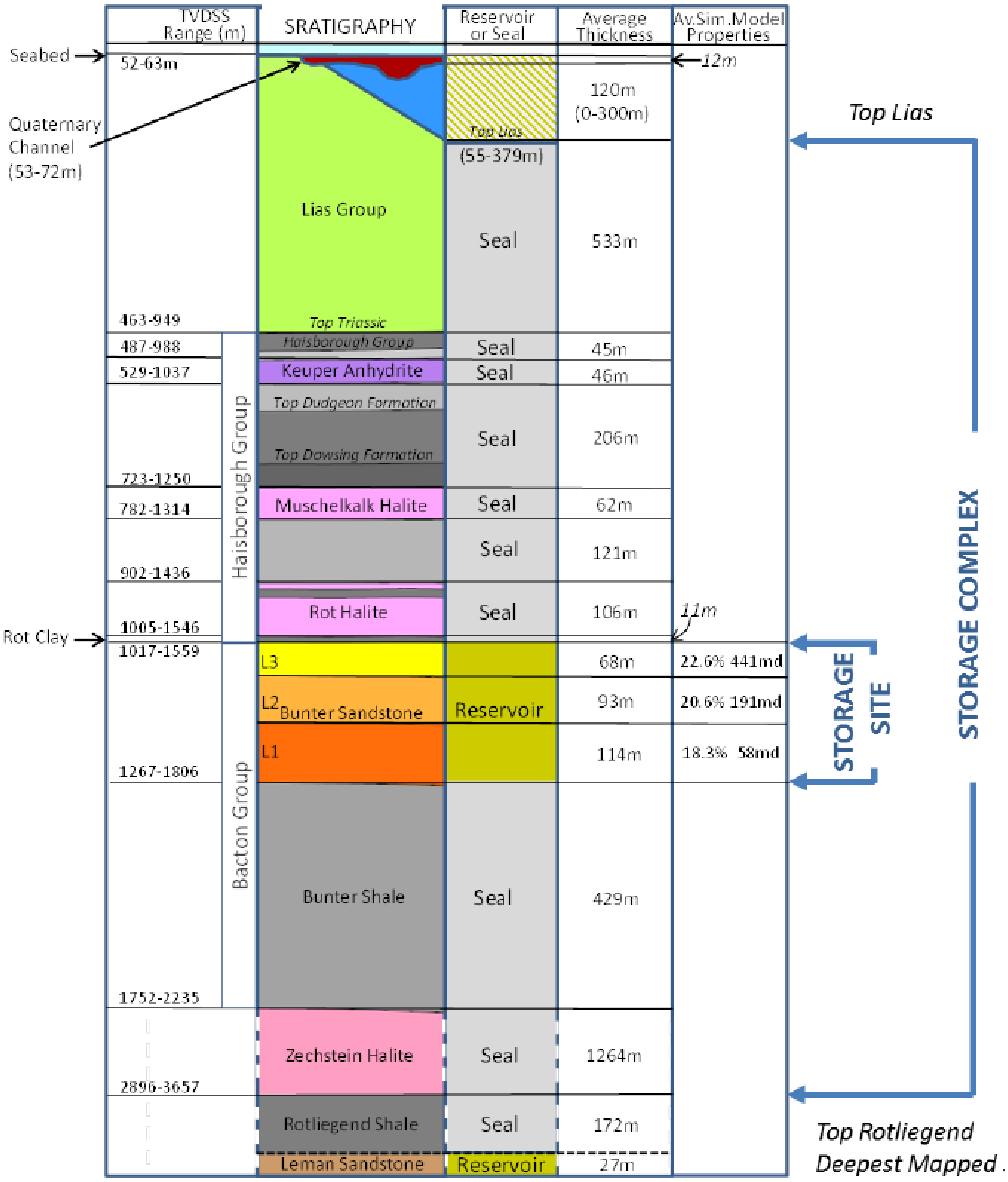


Figure 10. Lithostratigraphy of the Storage Site and complex (White Rose, 2016).

2. Storage reservoir in Endurance structure

The area of interest (identified as "Endurance" and officially as "5/42") is a four-way dip-closure in the Southern North Sea's Bunter Sandstone Formation.It's a freshwater aquifer that's 22 km deep, 7 km high. The crest of the reservoir is at the depth of about 1020 m below the seabed. Endurance field was productive between 1970 and 2013, three exploration and appraisal wells were drilled between Blocks 42/25d and 43/21. National Grid Carbon and partners Capture Power drilled 42/25-3 in 2013 to appraise Endurance for geostorage of CO_2 (Brook et al., 2003, Gluyas & Bagudu, 2020).

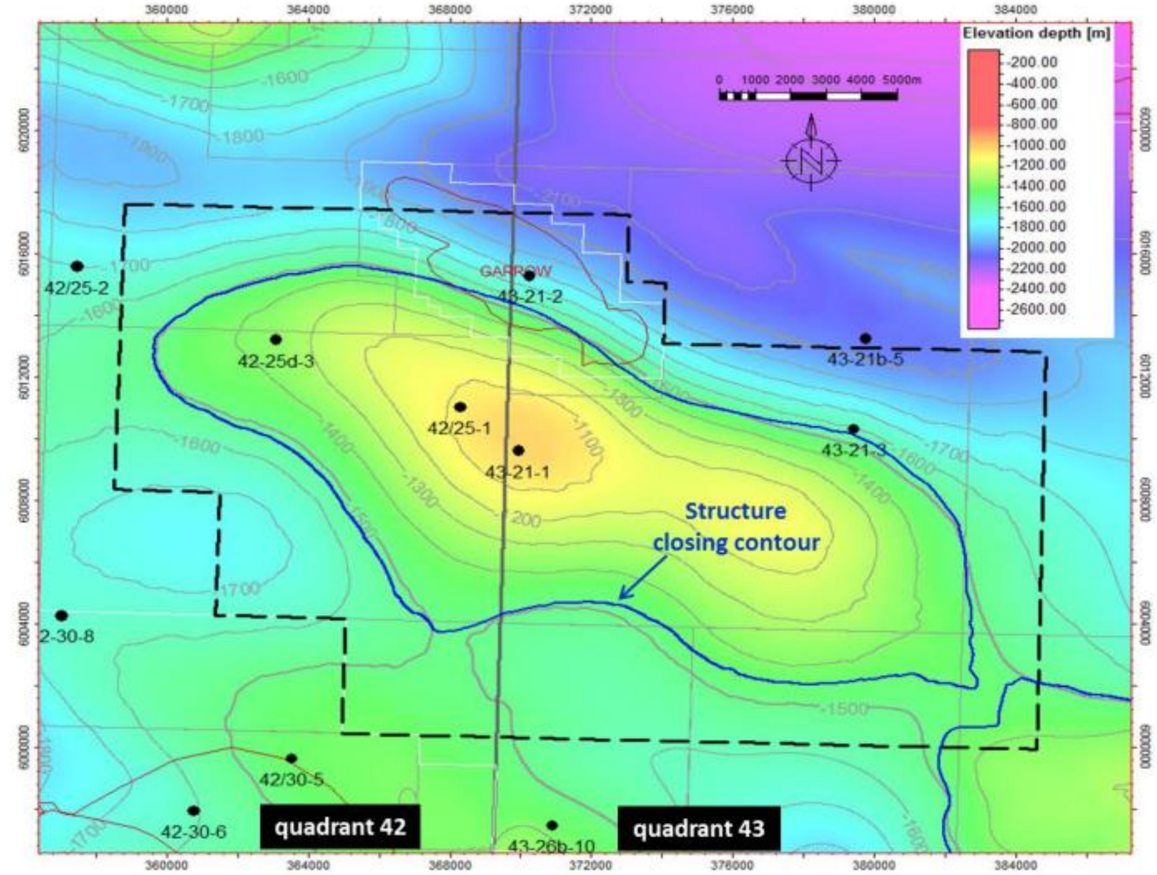
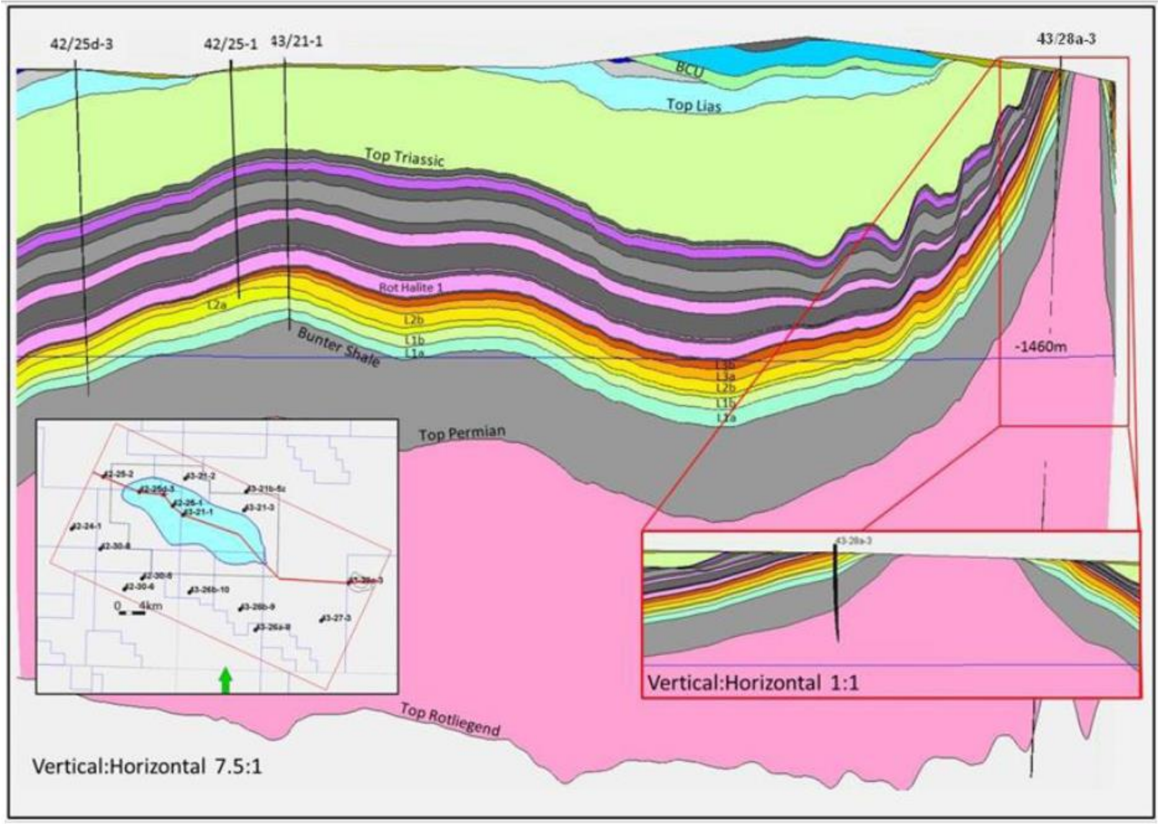


Figure 11. Structure map of the top of the Bunter Sandstone Formation in the Endurance Storage Site showing licence block boundaries (broken black line) and exploration and appraisal wells. Only wells 42/25d-3, 42/25-1, and 43/21-1 have penetrated the Endurance structure (White Rose, 2016).

The Endurance structure (Figure 11) is one of multiple BSF structural closures located in the Triassic SNS basin. It is a broad four-way dip closure that formed its current structural configuration as the underlying Zechstein Halite diapir formed (White Rose, 2016).

The Endurance reservoir is completely contained within the Early Triassic Olenekian Bacton Group. The BSF is made up of fluvial and aeolian sandstones of very fine to fine grain size and is approximately 245 m thick in and beyond the Endurance structure. Individual sandstones are grouped into large-scale fining-upward units, with fluvial and aeolian sandstones at the bottom and silistone and playa lake claystone alternations at the top. The BSF's finer-grained lithologies are more prevalent in the lower section, while the coarser-grained deposits are more common in the middle and upper regions (Gluyas & Bagudu, 2020). Measured from the appraisal well, the pressure of the reservoir is 138 atm and and temperature 57°C, respectively, at a datum level of 1300 m below the mean sea surface level. Because of the depth, and hence the pressure, which would reach more than 100 bars, any injected CO_2 will be supercritical at reservoir conditions (Brook et al., 2003), (Table 4).

Sandstone is generally weakly cemented and friable as found outcropping in eastern England. Calcite, other carbonates, anhydrite, quartz and feldspar overgrowths are cementing the shallow subsurface along the basin's margins. Furthermore, due to the presence of secondary halite cement in the pore spaces, the porosity and permeability of the Bunter Sandstone in the southern North Sea vary greatly. When halite is present in pores, almost no porosity is preserved; where it is absent, porosity may be as high as 25% conditions (Brook et al., 2003), (Figure 12).



Frigure 12. WNW-ESE cross-section through Endurance structure and salt diapir to SE (White Rose, 2016).

Since the CO_2 storage capacity was calculated with various parameters applied, I presented data available from two projects and my own calculations of theoretical storage capacity (Table 5). I calculated the CO_2 storage capacity according to Formula 1, using only average values of all parameters.

For CO_2 Stored the results of the generic and detailed models were integrated to develop methods for 'correcting' static capacity estimates for dynamic effects in all defined units. Static and theoretical capacity was calculated based on these models (Gammer & Green, 2011). In the CO_2 Stored database the Endurance structure capacity for CO_2 storage is 533 Mt (CO_2 Stored, 2015).

Table 4. Reservoir parameters of the Endurance structure (CO_2 Stored, 2015).

	CO_2 STORED DATA		
Parameters	Min	Max	Average
Trap area, km^2	142.29	173.91	158.1
Shallowest depth of the top, m	961.54	1111.54	1061.54
Thickness, m	199.43	279.02	245
Porosity, decimal	0.05	0.26	0.26
Permeability, mD	200	1500	400
Net to gross ratio	0.71	1	0.91
Salinity, (g/l)			180
Reservoir pressure at shallowest depth, atm			103.6
In situ CO_2 density, kg/m^3	700	780	750
Reservoir temperature at shallowest depth, °C	40.4	50.5	45.4
Storage efficiency for opened reservoir, %	5.42	22.18	11.72
Theoretical CO_2 Storage capacity, Mt	233	1253	533

Table 5. Reservoir parameters of the Endurance structure and CO_2 storage capacity estimated by author.

Parameters	Average
Trap area, km^2	158.1
Shallowest depth of the top, m	1020
Thickness, m	245
Porosity, decimal	0.26
Permeability, mD	400
Net to gross ratio	0.91
Salinity, (g/l)	180
Reservoir pressure at the depth 1143 m depth, atm	124
In situ CO_2 density, kg/m^3	621.9
Reservoir temperature at 1143 m depth, °C	49
Storage efficiency for opened reservoir, %	10
Theoretical CO_2 Storage capacity, Mt	570

3 Primary and Secondary Seals

The main cap rock or seal over the aquifer is a layer of mudstone identified as the Röt Clay. This covered by a salt layer known as the Röt Halite, which is more than 90 m thick and has extra sealing capabilities. A thick series of shales and evaporites belonging to the Haisborough Group lies above the Bunter Sandstone, forming the main regional sealing. The lithologies of the overburden formations are consistent, with only minor thickness differences. A fault visible on the seismic is blamed for Muschelkalk thinning in 43/21-1. The Röt Clay Member, which lies at the base of the Haisborough Group and directly overlies the Bunter sands, is approximately 10 m thick over the Endurance structure. The cap rock and primary seal are formed by this, which is immediately overlain by the Röt Halite Member, which includes interbedded shales and halite layers. The Röt Halite is at the base of an 800 m thick sequence of anhydrites and shales that includes the Muschelkalk Halite, the Dowsing Shale, the Dudgeon Formation, and the Keuper Anhydrite, among others. Long-term exposure of the Röt Clay to a CO_2 cap is predicted to induce marginal diffusion and no detectable migration beyond the Storage Site, as well as no alteration in the Röt Clay's mechanical properties (White Rose, 2016).

4 Static model

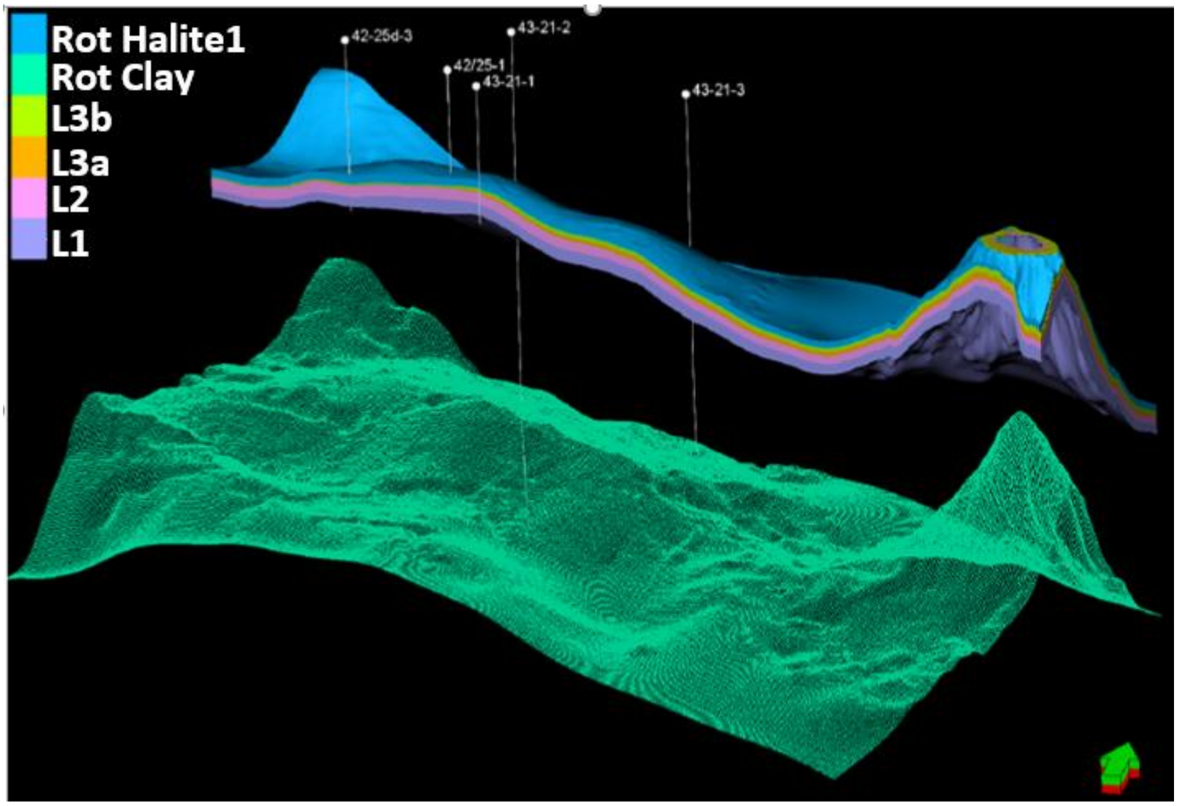


Figure 13. Static Model Geometry. The Bunter Sandstone and Top Bunter have been divided into units units based on sedimentology, adapted from (White Rose, 2016).

The static model covers a wide area due to all regional wells that constrain stratigraphy and provide information for rock property modeling. The model contains five facies models or sensitivity cases. Because of the absence of a meaningful correlation between the primary depositional facies and the reservoir quality, a set of "electro facies" was defined based on wireline log data alone and was used in the facies modelling. Six electro facies were picked on the gamma-ray, sonic and resistivity logs in 13 wells within the greater Endurance area and interpreted for trends that could be then used for modelling. The facies are interpreted to relate primarily to post-depositional diagenetic processes that occlude the original porosities (White Rose, 2016).

The porosity parameters are conditioned to the facies, resulting in five porosity models. Each pair of facies and porosity has three NTG parameters: low, reference, and high, which correspond to different porosity cut-offs. The model includes zones: Röt Halite 1, Röt Clay, Bunter L3b, L3a, L2 and L1, each of them further divided in layers. The lateral resolution is 100 m x 100 m with an average layer thickness of just over 1 m (White Rose, 2016), (Figure13).

3.3.4 CO_2 transport

The National Grid Ventures pipeline network is developed to connect the H2H Saltend with other selected industrial sites across the region, enabling further decarbonisation by capturing a minimum of 17 Mt of CO_2 each year from projects across the Humber area and providing up to 10 GWs of hydroge by the mid-2030s. The CO_2 will be compressed at Centrica Storage's Easington site and deposited by NEP (with Equinor and National Grid as two partners) in the Southern North Sea, and shared with NZT (in which Equinor is a partner). NZT and the NEP made separate bids to the same fund but are closely aligned because of their shared offshore infrastructure and storage (Zero Carbon Humber, 2021), (Figure 7).

The onshore CO_2 pipeline will be placed next to a hydrogen pipeline, enabling industrial consumers both to capture their emissions and to use low-carbon hydrogen produced locally (Zero Carbon Humber, 2021). British Steel, as one of the largest steel producers in the UK- , could benefit from the ZCH infrastructure. The global reach of the low carbon products and chemicals produced at the Scunthorpe site and Saltend area will be supported by ABP, the region's major ports and logistics provider. The Drax Power Station in Selby, North Yorkshire, would link to the completed CO_2 pipeline network, enriching the ZCH scheme with bioenergy and carbon capture and storage (BECCS). The pipeline network will also pass through SSE Thermal’s Keadby site, where SSE Thermal is developing Keadby 2 and Keadby 3. The pipeline network will also pass through SSE Thermal's Keadby site, where Keadby 2 and Keadby 3 are being built. The network will also run through Immingham, where Uniper intends to expand its European hydrogen plans by developing clean hydrogen production at its Killingholme facility (Zero Carbon Humber, 2021).

3.3.5 CCUS scenario

CCUS scenario for NZT and ZCH includes CO_2 capture from power production, industrial and cement plants, blue and green hydrogen production with CCS, CO_2 compression and transport to the offshore Endurance storage site.

NZT is planning now to include Billingham Manufacturing Plant, Wilton Power Plant and Teesside Hydrogen Plant which produced together 1.04 Mt CO_2 in 2020 (Figure 7, Table 1, Table 6). In future NZT is planning to increase annually captured CO_2 up to 10 Mt.

ZCH has already included Drax PP, Scunthorpe Int. Iron & Steel Works and Saltend Chemicals Park planning to produce hydrogen. Together they produced 7.77 Mt CO_2 in 2020. Additionally I have proposed to include into ZCH cluster two refineries (Lindsey Oil Refinery and Humber Refinery) which produced 2.9 Mt CO_2 in 2020 (Table 2, Figure 7) and three cement plants. These plants includes HCG Ketton CP and CEMEX South Ferriby and Rugby CPs, which together produced 1.6 Mt CO_2 in 2020 (Figure 14, Table 6).

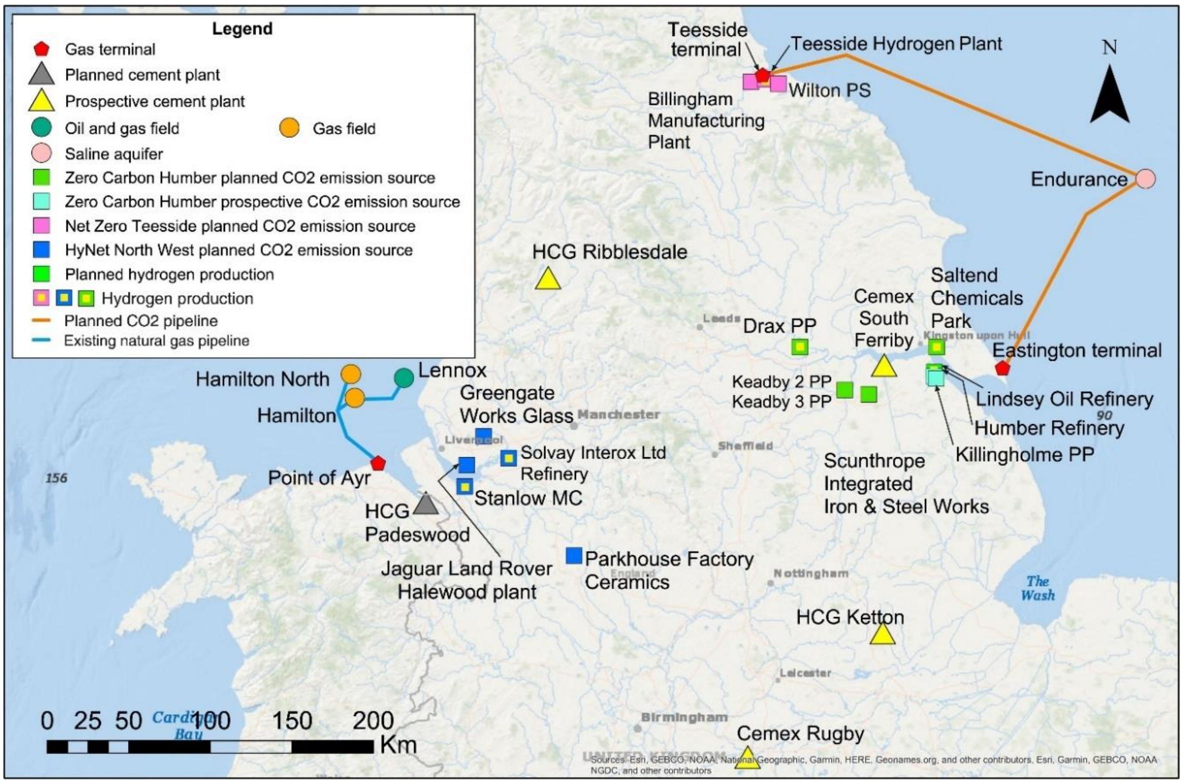


Figure 14. Map of the three clusters.

Produced hydrogen will be transported using onshore pipelines. Captured CO_2 will be transported using onshore pipelines to the Teeside terminal for NZT cluster and to Eastington terminal for ZCH cluster. Onshore pipelines will be built along available natural gas pipelines, or along the roads. From the terminals CO_2 emissions will be transported by offshore pipelines and ships to the Endurance storage site.

In the Immingham area there are also Total Lindsey Oil Refinery and Phillips 66 Humber Refinery that could also be quite easily added to the transport network. The distance between the Ketton CP and the The Phillips 66 Humber Refinery is 140 km by measurments in ArcGIS. The transport could be carried out by trucks or new onshore pipelines (Shogenova et al., 2021).

Zero Carbon Humber project uses Centrica Storage's Easington site gas terminal (Figure 14) that is connected with the Endurance storage site via offshore pipeline wich is 85 km by ArcGIS measurements.

The estimated average storage capacity of the Endurance reservoir (570.2 Mt) will be enough for about 65 years for the storage of the already included and planned by clusters CO_2 emissions. For the total planned and additionally proposed emissions from refineries and cement plants the storage capacity of the Endurance will be enough for about 43 years.

Table 6. CCUS Scenario for Teesside and ZCH clusters.

Parameters	Clusters		
	NZT	ZCH	Total
Planned annual CO_2 emissions (2020), Mt	1.04	7.77	8.81
Proposed annual CO_2 emissions total (2020), Mt	0	4.50	4.50
Planned and proposed annual CO_2 emissions, Mt	1.04	12.27	13.31
CO_2 storage capacity in Endurance, Mt			570.2
Project duration for planned CO_2 emissions, years			**64.7**
Project duration for planned and proposed CO_2 emissions, years			**42.9**

3.4 HyNet North West Cluster

HNW is a low-cost, deliverable project that tackles the main challenges of reducing carbon emissions from industry, domestic heating, and transportation (HyNet, 2020). The projct is located around Liverpool Bay in a bay area and the Irish Sea, between northeast Wales, Cheshire, Lancashire and Merseyside (Figure 15).

3.4.1 CO_2 emission sources

HyNet North West has confirmed Essar Oil UK Limited’s Stanlow Manufacturing Complex, Jaguar Land Rover Limited’s Halewood Body & Assembly, Solvay Interox Limited’s Solvay Interox Limited site, NSG Pilkington Greengate Works St Helens site and Ibstock Brick Limited’s Parkhouse Factory confirmed to capture and store CO_2 from their production units (HyNet, 2021).

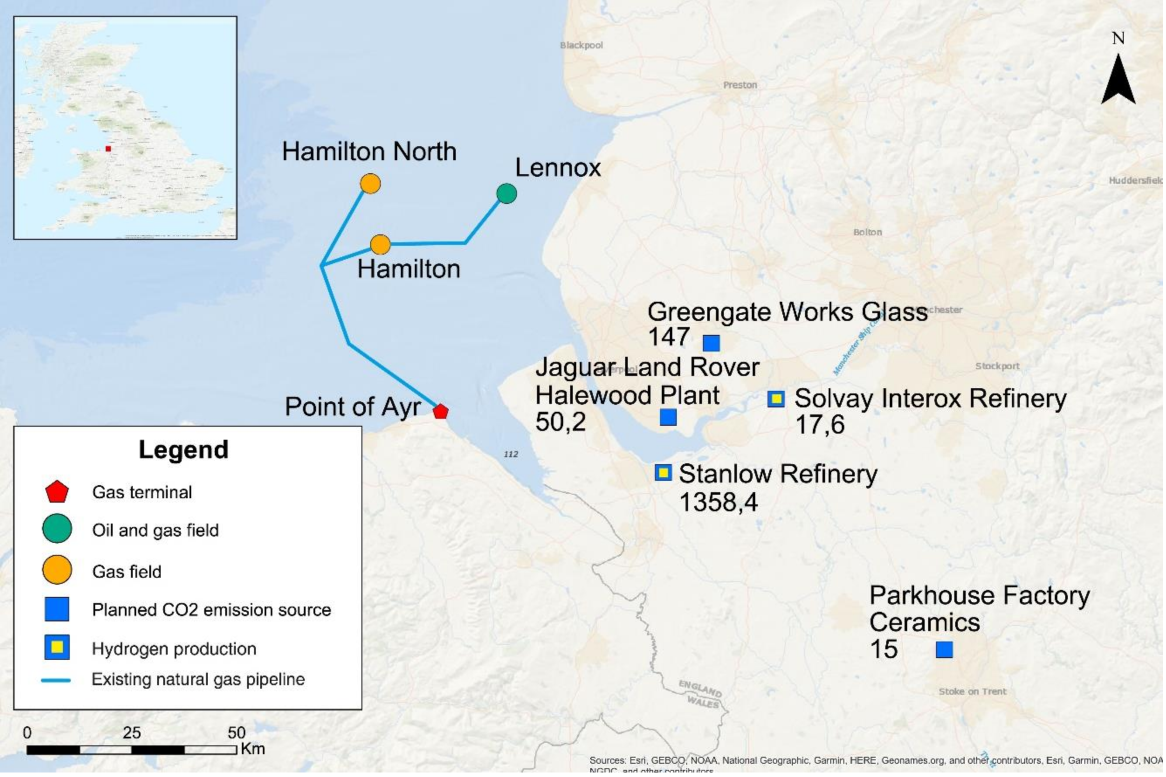


Figure 15. HyNet North West project CO_2 emission sources in 2020.

1 Essar Oil UK Ltd

Essar Oil is a major supplier in North-West England with customers including most of the major retail brands operated by the international oil companies and the hypermarkets, Manchester Airport and the region's trains and buses. The Stanlow Manufacturing Complex (SMC), located on the south side of the Mersey Estuary near Liverpool, is owned and operated by Essar Oil Limited. Stanlow contributes significantly to the national economy, supplying over 16% of the UK's transportation fuels (Essar Oil, 2021).

SMC has a highly efficient distribution capability for refined end products: The Stanlow Terminals Road Terminal which has substantial spare capacity which provides supply resilience for the region; a direct connection via the UK Oil Pipeline through to Kingsbury, Northampton and beyond towards London; a pipeline connection to the UK's busiest regional airport at Manchester and six berths on the Manchester Ship Canal handling export parcels of up to 10,000 tonnes. SMC produces: 4.4 billion litres of diesel every year, 3 billion litres of petrol a year and 2 billion litres of jet fuel a year (Essar Oil, 2021).

Essar Oil Stanlow Manufacturing Complex' CO_2 emissions decreased from 1,6 Mt in 2018 to, 1,3 Mt in 2020 (Figure 15, Table 7).

2 Jaguar Land Rover Limited - Halewood Body & Assembly

Jaguar Land Rover (JLR) has been a wholly-owned subsidiary of Tata Motors, in which Tata Sons is the largest shareholder, since 2008. JLR manufactures luxury vehicles. The company aims to to achieve net zero carbon emissions across our supply chain, products and operations by 2039 (Jaguar Land Rover, 2021).

Halewood Body & Assembly is a JLR automobile production facility in Halewood, Merseyside. Ford completed a contract to sell Jaguar and Land Rover to Tata Motors, a part of the Indian-based Tata

Group, which is one of the world's largest commercial vehicle manufacturers, in March 2008. Ford retained ownership of Halewood's transmission facility, which it maintains in partnership with Getrag, under the terms of the agreement (Jaguar Land Rover, 2021).

Halewood Body & Assembly'S CO_2 emissions decreased over 2000 Kt from 2018 to 2020 (Figure 15, Table 7).

3 Solvay Interox Limited

Solvay is a science company focused on Materials, Chemicals, and Solutions. Solvay solves vital manufacturing, social, and environmental issues by using advancements in aircraft, vehicles, batteries, smart and medical devices, water and air treatment, and other areas (Solvay, 2021).

The Solvay Peroxides Global Business Unit includes Solvay Interox facility in Warrington. The facility produces Hydrogen Peroxide in a number of grades for use in pulp and paper bleaching, disinfection, environmental treatment, chemical synthesis, and aquaculture, among other applications. The site produces paramove, a special grade of hydrogen peroxide used in the fish farming industry (Solvay, 2021).

The Warrington site's CO_2 emissions decreased 0,742 Kt from 2018 to 2020 (Figure 15, Table 7).

4 Pilkington United Kingdom Limited

NSG Group is one of the world's largest manufacturers of glass and glazing products for architectural, automotive and established creative technology to support nsg group's future growth (NSG, 2021).

NSG Pilkington Greengate Works (PGW) is located in St Helens, Merseyside. As part of the NSG Group, Pilkington has been manufacturing glass and glazing solutions for nearly 200 years. In 2020 NSG started testing the use of hydrogen as a furnace fuel in the Pilkington Greengate Works site (Pilkington, 2021).

NSG Pilkington Greengate Works site's CO_2 emissions decreased 6,18 Kt from 2018 to 2020 (Figure 15, Table 7).

5 Ibstock Brick Limited

Ibstock Brick is a manufacturer of clay facing bricks with 21 factories across the UK. Ibstock Brick has been acktive in brick making and industrial activity since the 1800s. Ibstock Brick has confirmed the integration of Parkhouse Factory in East Newcastle-under-Lyme, Staffordshire into the HNW project (Ibstock Brick, 2021).

Parkhouse Factory's CO_2 emissions decreased 0,629 Kt from 2018 to 2020 (Figure 15, Table 7).

Table 7. HyNet North West project CO_2 emission sources in 2020.

Plant name	CO_2 emissions, 2018, Kt	CO_2 emissions, 2019, Kt	CO_2 emissions, 2020, Kt	Planned Hydrogen production, Kt	Source of energy
Stanlow Manufacturing Complex (SMC)	1638.57	1605.58	1358.38	Planning	Oil, waste
Halewood Body & Assembly	52.334	51.280	50.222	-	Wind power, solar energy
Solvay Interox	18.379	18.009	17.637	Yes	Coal, gas
NSG Pilkington Green-gate Works	153.181	150.096	147.001	-	Gas, oil
Park-house Factory	15.595	15.281	14.966	-	Gas, oil
Total CO_2 emissions	1878.06	1840.25	1588.2		

6 Hanson Heidelbergcement Group (Hanson HCG) Cement plants

Ribblesdale Works cement plant (RWCP)- is located on the edge of Clitheroe, Ribblesdale. The principle purpose of the plant is to manufacture cement. RWCP is testing the use of a combination of 70% biomass, 20% hydrogen and 10% plasma energy with cement and lime kilns to operate with a net zero carbon fuel mix. Company is applying for a hazardous substance consent as part of a demonstration using hydrogen in combination with biomass to fuel the kiln (Hanson, 2020, Castle Cement, 2016), (Figure 8, Table 8).

Table 8. Emissions of the Hanson UK Ribblesdale Works, Padeswood Works and CEMEX UK Cement Limited Rugby Works cement plants in 2028, 2019 and 2020 (EU ETS, 2021).

Project partner name	Plant name	Plant location (town)	CO_2 emissions, 2018, Kt	CO_2 emissions, 2019, Kt	CO_2 emissions, 2020, Kt
Hanson UK	Ribblesdale Works	Clitheroe	473.27	463.74	454.18
Hanson UK	Padeswood Works	Mold	567.2	555.78	544.32
Total CO_2 emissions			1040.47	1030.47	998.5

Padeswood Works cement plant is located in Mold Flintshire, northeastern Wales. The cement plant uses Limestone as the main raw material from a local quarry. This material is used to produce cement (Hanson, 2020), (Figure 8, Table 8).

After proposal made in 2020 by the CLEANKER Project to include three HCG cement plants into the UK clusters, the decision was taken by HCG and and in March 2021 has signed memorandum of ubderstanding with HyNet North West Project was signed for the Padeswood Works CP (HyNet, 2021).

3.4.2 Hydrogen Production

HNW is based on the production of hydrogen from natural gas. Progressive Energy, Essar, Johnson Matthey, and SNC Lavalin have been awarded £7.5 million from the government to do a 'FEED' study on a hydrogen production plant that would use Johnson Matthey's patented technologies to produce low carbon hydrogen from natural gas. The ultimate project, which would be based at Stanlow Refinery, could involve up to three plants generating up to 18TWh of low-carbon hydrogen per year (HyNet, 2021).

Since blending up to 20% hydrogen does not necessarily require improvements to boilers or cookers, it is possible to decarbonize buildings while causing minimal disruption to households and businesses. To achieve net zero, all buildings must drop fossil-fuel-based heating. HNW will supply 100 % hydrogen to heat buildings by converting relevant parts of the existing gas distribution network in the 2030s to achieve this target. Hydrogen combined with electrification of heating would be the most cost-effective option for households and companies. Hydrogen is likely to be found in both standalone hydrogen boilers and hybrid solutions that have electric heat pumps (HyNet, 2020).

Progressive Energy is actively partnering with Cadent to further develop the design of the HyNet hydrogen distribution network, as well as its operational philosophy, which is financed by the Network Innovation Allowance (NIA). The network's integration with storage sites is especially significant because it provides the grid with the required level of flexibility, enabling it to satisfy current and potential heat demand as well as future demand for flexible power generation (HyNet, 2021).

HNW has confirmed two hydrogen producing sites to be in the cluster: Solvay Interox Refinery and Stanlow Refinery (Figure 15).

3.4.3 CO_2 and hydrogen transport

HNW is constructing a hydrogen pipeline network to supply local industries with hydrogen and to combine hydrogen with natural gas in local networks. With 77% of gas pipelines recently replaced to enable hydrogen transportation, the North West's gas network is becoming "hydrogen ready“ (HyNet, 2020).

Planned Hydrogen Pipeline parameters:

- Total length of pipelines = 109km
- Diameter of 'trunk' pipeline = 45.72-60.96 cm
- Pressure range of trunk pipeline = 20-45bar

- Diameter of ‘spur’ pipelines = 15.24-30.48 cm
- Pressure range of spur pipelines = 14.8-39.5 atm
- Total pipeline network linepack = 1.5 GWh (HyNet, 2021).

HNW is going to use existing offshore and onshore natural gas pipelines repurpocing them for transporting of CO_2 and will build new onshore CO_2 and hydrogen pipelines along existing natural gas pipelines and/or roads. CO_2 storage can be made by repurposing existing offshore platforms. CO_2 will also be transported by ships. The offshore pipeline is 33 km long and onshore pipeline is 27 km long (HyNet, 2021), (Figure 15).

Planned CO_2 Pipeline parameters:

- Total CO_2 transported = 1.5 Mtpa
- 50.8-60.9 cm diameter at 29.6- 12.3 atm
- 33km of repurposed offshore pipeline
- 27km of repurposed onshore pipeline
- 31km of new onshore pipeline (HyNet, 2021).

3.4.4 CO_2 storage sites

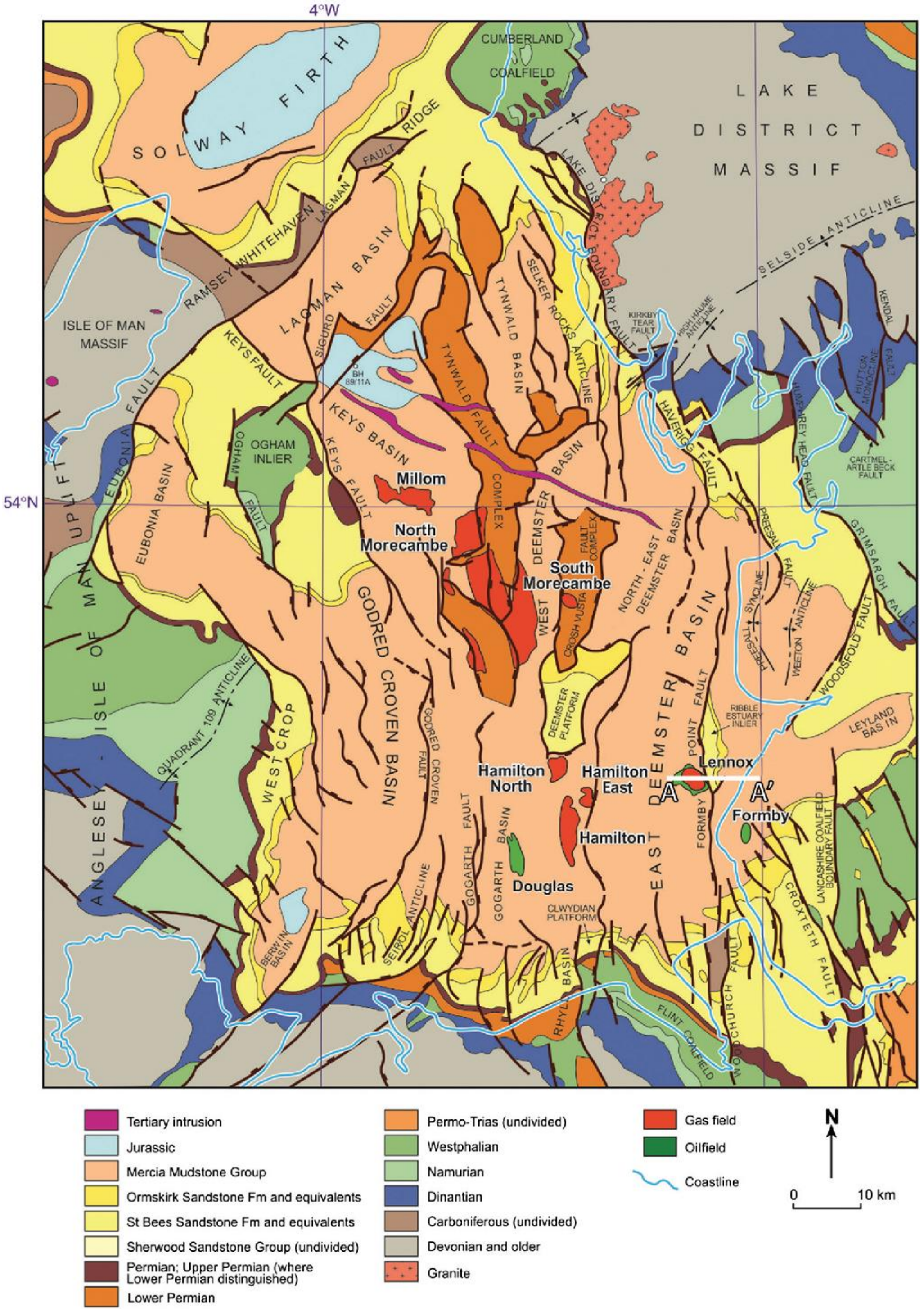
Three hydrocarbon fields have been selected for the HyNet North West project targeted storage sites, which are Hamilton gas field, Hamilton North gas field and Lennox oil and gas field. Since the storage sites are located very close to each other, since they are located in similar geological, stratigraphic and structural settings (Figure 15).

1 Introduction

The Hamilton and Hamilton North Gas Fields are located in the East Irish Sea's Block 110/13a, approximately 13 km off the Lancashire coast, in a depth of 30 m. The Lennox Field, a saturated oilfield with a significant primary gas cap at initial conditions, is located in the East Irish Sea within Blocks 110/14c and 110/15a (Pale Blue Dot, 2016).

The Hamilton depleted gas field is one of the largest of a number of fields in the East Irish Sea's Liverpool bay area. A group of E-W trending faults, which are antithetic to the main east-west boundary fault to the Deemster Platform, are gradually down-faulting the northern part of the region (Yaliz & Taylor, 2003).

The Lennox Field was discovered in 1992, while first oil was achieved in February 1996. The Lennox structure is a rollover anticline formed in Permo-Triassic sediments in the Fomby Point Fault's hanging wall. The reservoir consists of sandstones from the Triassic Sherwood Sandstone Group. The gas column reaches a height of c. 259 m and overlays a 44 m oil column. Oil initially-in-place is estimated to be 202 MMbbl. There are a total of 17 wells in the region and 11 of them have high-quality data on the target reservoir, with four of them providing core sample data (Pale Blue Dot, 2016), (Figure 16).



■	Tertiary intrusion
■	Jurassic
■	Mercia Mudstone Group
■	Ormskirk Sandstone Fm and equivalents
■	St Bees Sandstone Fm and equivalents
■	Sherwood Sandstone Group (undivided)
■	Permian; Upper Permian (where Lower Permian distinguished)
■	Lower Permian
■	Permo-Trias (undivided)
■	Westphalian
■	Namurian
■	Dinantian
■	Carboniferous (undivided)
■	Devonian and older
▨	Granite
■	Gas field
■	Oilfield
~	Coastline

Figure 16. Major structural elements of the East Irish Sea Basin, adapted from (Bunce, 2020).

2. Stratigraphy

The Carboniferous Namurian Graven Group Hollywell Shale Formation, which is predominantly clastic with deep water shales deposited by a vast fluvio-deltaic regime that existed throughout north and east England during the Namurian, is the oldest rock penetrated in the area. The Hollywell Shale is the area's source soil. Above a significant unconformity, the overlying Permian consists of desert sandstones (Early Permian Collyhurst Sandstone Formation) and red mudstones (Late Permian Manchester Marl Formation) (Bunce, 2020), (Figure 17).

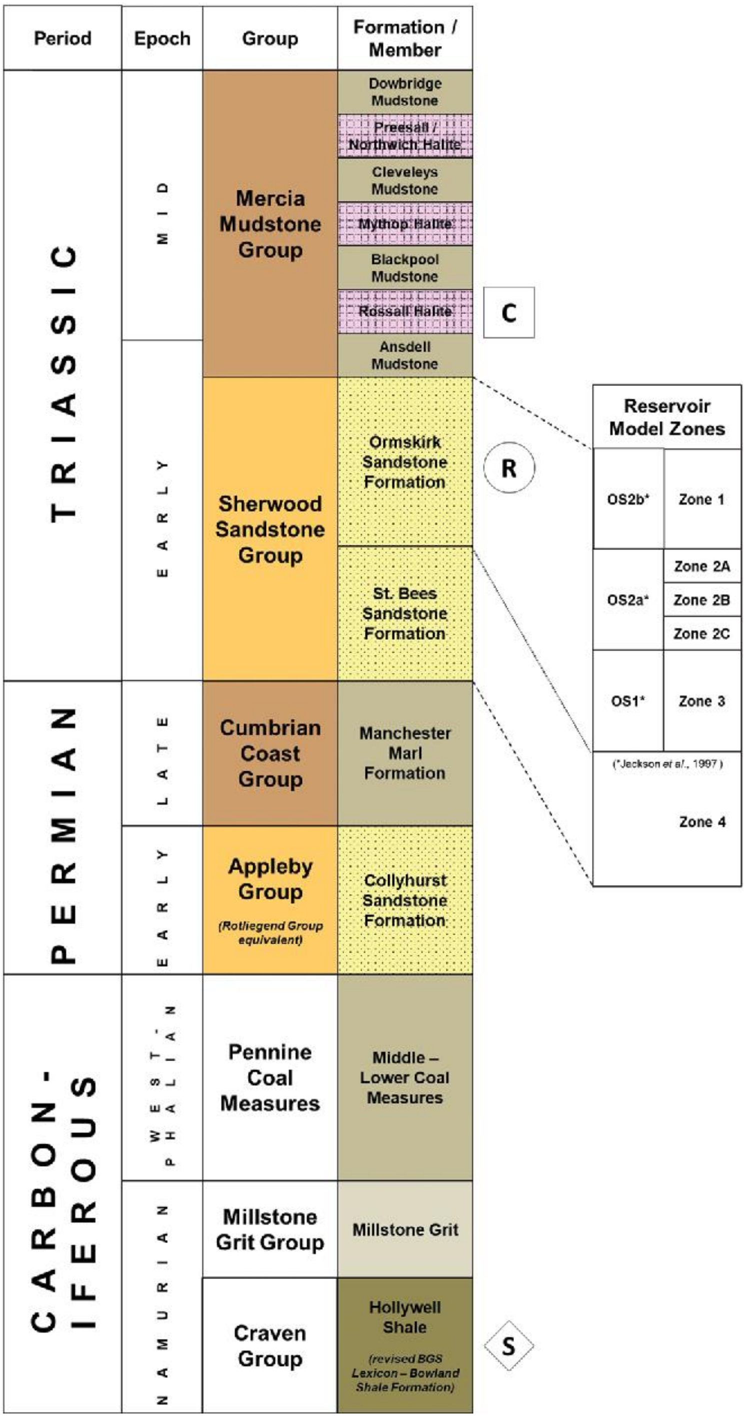


Figure 17. Source to seal stratigraphy for the East Irish Sea Basin (Bunce, 2020).

The Sherwood Sandstone Group and the Mercia Mudstone Group are both part of the Triassic. The former is made up of semi-arid sandstones, siltstones, and mudstones, while the latter is composed of shales and thick halite units deposited in lakes subject to periodic flooding and desiccation, and forms a laterally extensive and competent seal over the Hamilton and Hamilton North Fields. The Rossall and Mythop halites are both about 15 m high, while the Preesall Halite is between 152 and 223 m thick (Haig et al. , 1997, Jackson et al., 1997, Meadows & Beach, 1993), (Figure 17).

3 Structure of Hamilton, Hamilton North and Lennox fields

The Hamilton tructure is characterized by major faults to the North and West (Figure 18). The gas is trapped in the Early Sherwood Sandstone Group Triassic Ormskirk Sandstone Formation, which is highly efficient. The gas-water contact is at 886 m in the Hamilton Field and 964 m in the Hamilton North Field, and the reservoir depth is shallow (701-792 m). Formation contains a small amount of gas (Yaliz & Taylor, 2003).

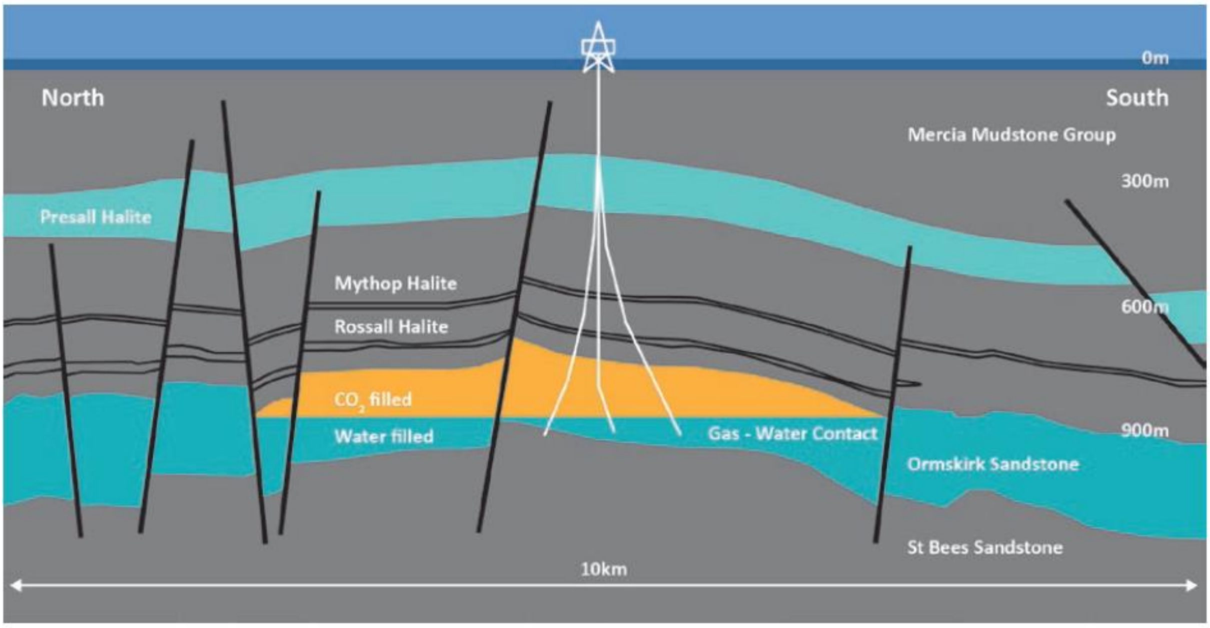


Figure 18. The Hamilton Field structure (Pale Blue Dot, 2016).

Based on the vertical distribution of sedimentary lithofacies, the Ormskirk Sandstone Formation has been divided into three distinct zones: Zone I, Zone II, and Zone III (Figure 17). The uppermost reservoir unit is primarily made up of aeolian dune and sabkha sandstones and has a thickness of 42-51 m. In the center of the district there is a thin unit (5-6 m) of fluvial sandstones. The upper parts of aeolian dune and sabkha sandstones become fluvial-dominated towards the southern areas of the Hamilton Sector. Zone II consists primarily of fluvial sandstones formed as a stacked series of channel deposits, with thicknesses ranging from 50 to 78 m. Zone III is a mixed sequence of aeolian dune, aeolian sabkha, and small fluvial channels with a thickness ranging from 50 to 59 m. It has a uniform thickness of 70 m in the Hamilton North Sector. Zone IV is made up of a stacked series of fluvial channel deposits with a thickness of 61 m or more with an average porosity value of 18.6%. Zone I has the highest reservoir quality. The quality of the reservoirs in Zone II is low, with average porosity ranging from 11 to 13 % across the area. In both directions, the average porosity in Zone III is about 17.5%. In both sectors, the net/gross sand ratio is very high, ranging between 80 and 100%. The only possible permeability obstacles are fluvial abandonment and playa lake facies. However, pressure data shows that the reservoir has been depleting uniformly, showing that no permeability baffles or barriers occur in the entire field. Minor eastwest and north-south faulting cut the structure, which runs north-south. Both faults in the field have sand-to-sand connection and do not function as gas flow barriers. Dip closure provides the trap to the north and south. The structure's crest is about 701 m TVDSS at the reservoir level, with the gas-water contact at 887 m TVDSS (Yaliz & Taylor, 2003), (Figure 18, Table 9).

The Lennox structure is a rollover anticline formed in Permo-Triassic sediments in the Fomby Point Fault's hanging wall. The reservoir consists of sandstones from the Triassic Sherwood Sandstone Group. The gas column reaches a height of 259 m and overlays a 44 m oil column. Oil initially-in-place is estimated to be 202 MMbbl, whilst total gas initially-in-place is 521 bcf. The field has been developed by a wellhead platform tied-back to the neighbouring Douglas Oil Field Complex (Bunce, 2020, Haig et al., 1997), (Figure 16, Figure 19).

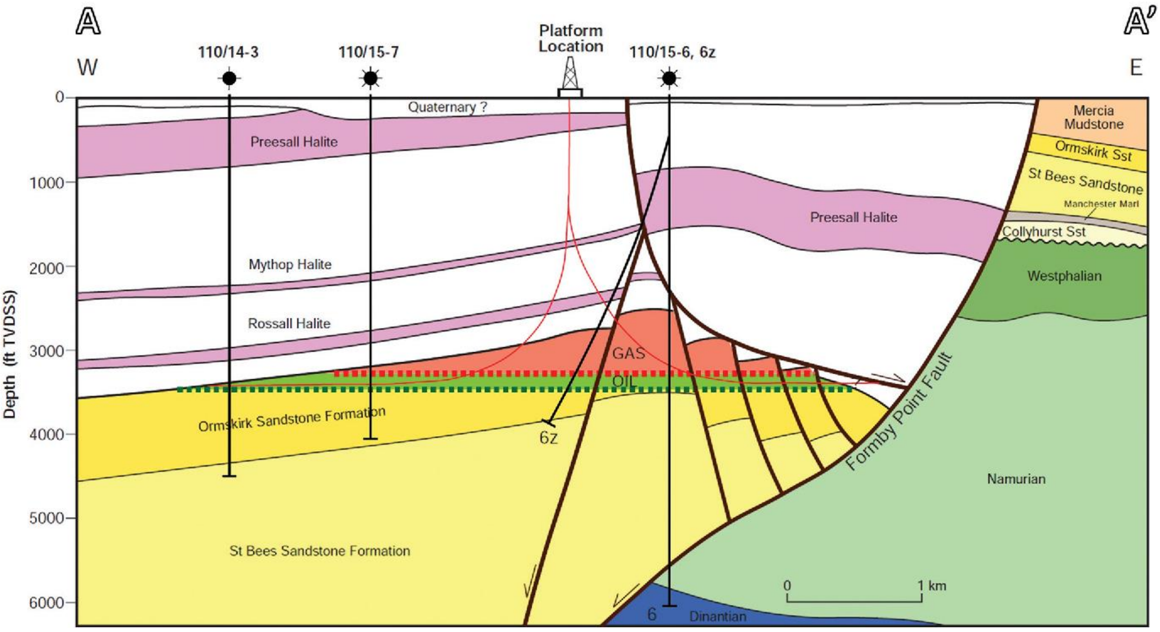


Figure 19. Westeast structural cross-section through Lennox Field. The location of the cross section is shown in Figure 16 (Bunce, 2020)**.**

In the CO_2 Stored database the structure capacity for CO_2 storage is 72.7 Mt in Lennox, 122.1 Mt in Hamilton and 38.5 Mt in Hamilton North (CO_2 Stored, 2015), (Table 9).

4. Storage reservoir

The targeted storage reservoirs are in the Ormskirk sandstone from the Triassic age. It is part of the Sherwood Sandstone Group, which is the equivalent of the Bunter Sandstone in the Southern North Sea. The Ormskirk Sandstone is 226 m thick in the Hamilton Field, 211.7 m in the Hamilton North Field and 265 m thick in the Lennox Field. The reservoir quality is "very good," with nearly 80% of the Ormskirk Sandstone thickness considered effective reservoir. Porosity of the rock accounts for 15%, and its average permeability reaches 778 mD in Hamilton, 308 mD in Hamilton North and up to 5 D in the Lennox field (Pale Blue Dot, 2016), (Table 9).

The Ormskirk Sandstone Formation is divided into three members; OS1, OS2a and OS2b, which were formerly known as Thurstaston, Delamere and Frodsham. The OS1 Member includes a mixed sequence of aeolian dunes and sandsheets. The OS2a Member is predominantly fluvial with some aeolian facies. The uppermost OS2b Member represents predominantly aeolian conditions but towards the south of the Hamilton Field fluvial facies replace the aeolian sandstones at the base of the unit. (Jackson et al., 1997, Meadows & Beach, 1993). The target Ormskirk Sandstone storage reservoir is a faulted structure with a crest 700 m below sea level and a area of 15 km2 in Hamilton. Although some of the structure's faults extend to the seabed in areas, they have shown to be effective at trapping natural gas under pressure and are predicted to be equally effective for CO_2 (CO_2 Stored, 2015, Pale Blue Dot, 2016), (Figures 17, 18, 20, 21).

Table 9. Reservoir parameters of the Lennox, Hamilton and Hamilton North structures (CO_2 Stored, 2015, Yaliz & Taylor, 2003) with CO_2 capacities estimated by author.

Parameters	Lennox field	Hamilton field	Hamilton North field
CO_2 storage capacity, Mt	77.9	103	48
Trap area, km^2	9.3	15	8
Depth, m	993	793	884
Thickness, m	265	226	211.7
Porosity, decimal	0.16	0.15	0.14
Permeability, mD	5025	778	308
Net to gross ratio	0.95	0.95	0.95
Recovery factor, decimal	0.45	0.45	0.45
Reservoir pressure, atm	110.2	96	104.4
In situ CO_2 density, kg/m^3	790	780	781
Reservoir temperature, °C	37.9	34	36.3
Storage efficiency, decimal	0.2	0.2	0.2

In the Lennox reservoir a thin oil column is overlain by a thick gas cap in the Lennox oil field. The total amount of gas initially in place is expected to be 521 bcf, whilst the amount of oil initially in place is expected to be 202 MMbbl (Bunce, 2020, Haig et al., 1997). The precipitation of illite within the pore spaces is the most significant diagenetic effect. Thin illite crystals can expand perpendicular to the grain faces of sandstone, making fluid passage through the reservoir more difficult. They clog the pore throats, impacting the reservoir's permeability rather than its porosity (Ebbern, 1981, Kirk, 2005), (Figure 22).

CO_2 storage capacity estimations by CO_2 stored Project were for the Hamilton storage site 122.1 Mt, for Hamilton North storage site 38.5 Mt and for Lennox 72.7 Mt (CO_2 Stored, 2015).

The calculated by author theoretical CO_2 storage capacity of the Hamilton storage site is 103 Mt, for Hamilton North storage site 48 Mt and for Lennox 77.9 M t (Equation 2, Table 9).

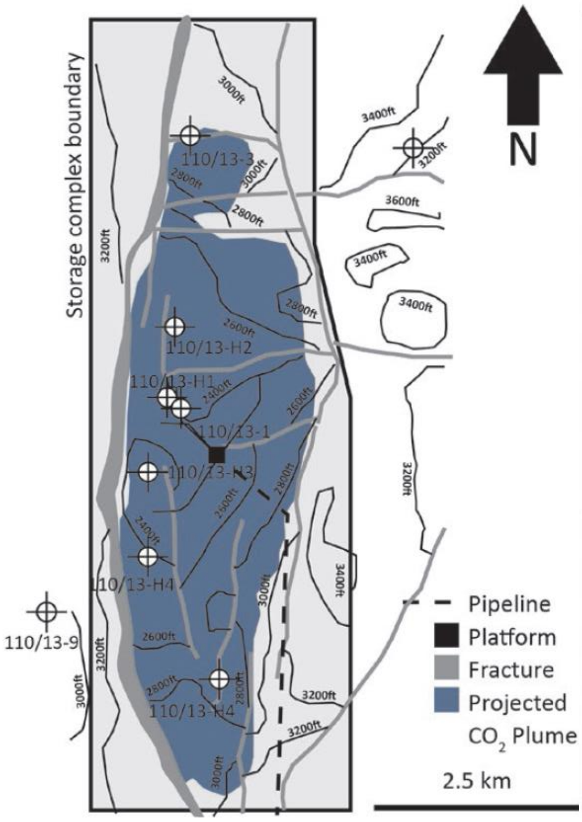


Figure 20. Storage complex boundary of Hamilton field (Pale Blue Dot, 2016).

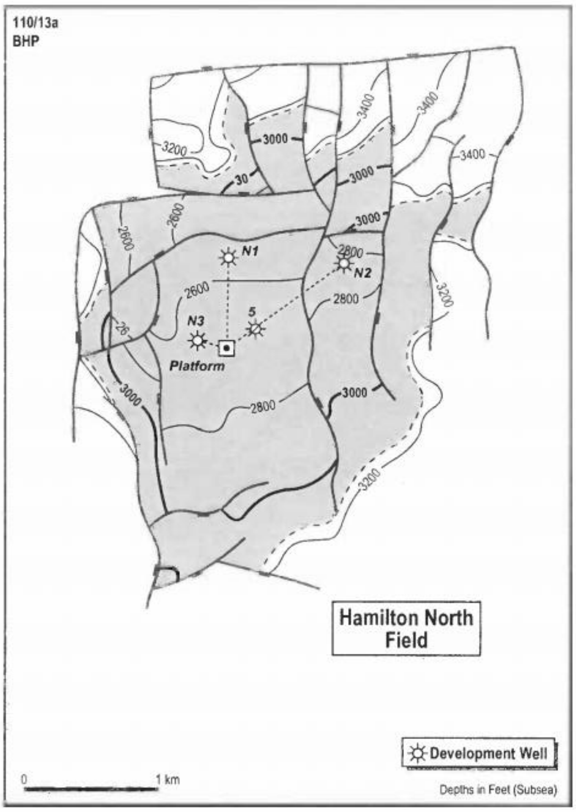


Figure 21. Top reservoir depth structure maps of the Hamilton North Field, development well locations (Yaliz & Taylor, 2003).

5 Primary and secondary seal

The Mercia Mudstone Group, which is built up of five cycles of alternating red mudstones and thick rock salt deposited in desert lakes that dry out periodically, is the primary caprock. The Mercia Mudstone Group consists of a cyclic sequence of sandy mudstones and halites. The Rossall and Mythop halites are each less than 15.2 m thick and the Preesall Halite has a thickness of between 152.4 and 223 m. Many of the East Irish Sea's oil and gas fields; are effectively sealed by these caprocks. Nearly all of the water-bearing Triassic sandstones in the East Irish Sea region were cemented. The pore space is filled with illite, a clay mineral that decreased permeability by up to two orders of magnitude. As a result, the deeper water-bearing sandstones serve as excellent sealing formations with little to no storage space. This provides the storage site with an effective low permeability base. Under pressure flowing, the mudstone, especially the halite in the overlying cap rock, seals any potential migration routes to the surface along the faults. It is an ideal cap rock for that reason (Kirk, 2005, Meadows & Beach, 1993, Pale Blue Dot, 2016).

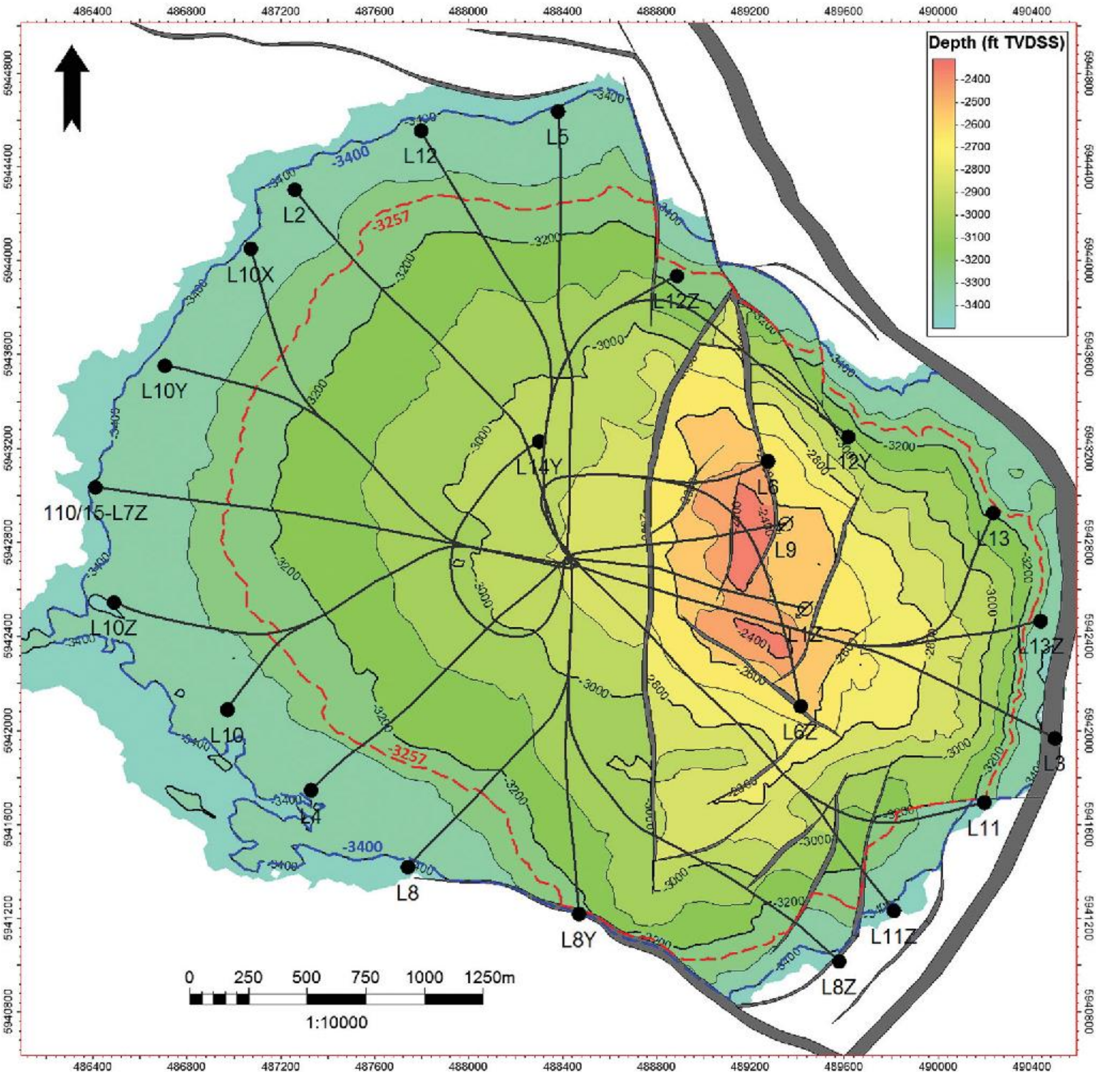


Figure 22. Top Ormskirk Sandstone Formation top depth structure map of Lennox Field, showing the locations of the horizontal development wells and the original field fluid contacts (Bunce, 2020).

3.4.5 CCUS scenario

HNW project partners Encirc 360, Inovyn, Nestle, Progressive Energy and Unilever, which of Pilkington, NSG Group, Essar Oil, Jaguar and Land Rover and Ibstock Brick Limited confirmed to capture and store CO_2 from their production units (HyNet, 2021).

The projeect is based on hydrogen production from natural gas. It entails the construction of a new hydrogen pipeline as well as CCS infrastructure. HNW hydrogen network will produce, store and distribute hydrogen to decarbonise the North West of England and North Wales (HyNet, 2021), (Figure 15).

The site, which is owned by ENI, has a CO_2 storage capacity of 130 million tonnes, and gas production is expected to end within the project's deadline. For many factors, re-use of the site is a good, low-cost option for CCUS: it can prevent or delay significant decommissioning expenses for the fields, which would be paid by government and industry; it is closer to the coast than other potential CCS sites, which reduces costs; and early technological cooperation would maximize the benefit from re-use of infrastructure (e.g. pipeline and rigs) (HyNet, 2021).

Greater CO_2 storage (up to 1 billion tonnes) is readily accessible in the surrounding region at the Morecambe Bay gas fields, which provide a long-term option for major infrastructure expansion by 2030. Other industries, power producers, and the manufacture of low-carbon transportation fuels could all benefit from this resource. These technologies, when combined with CCS, have the ability to minimize CO_2 emissions by 10 million tonnes a year by 2030, the equivalent of removing four million cars from the road (HyNet, 2021).

CCUS scenario for HNW includes CO_2 capture from car manufacturer, glass and ceramics production, industrial and cement plants and transport to the offshore Lennox, Hamilton and Hamilton North storage sites.

HNW is planning now to include Stanlow Manufacturing Complex, Jaguar Land Rover Halewood Body & Assembly, Solvay Interox refinery, Greengate Works glass production unit and ceramics producing Parkhouse Factory. Project has also planned to include Padeswood Works CP. Together all these six sites produced 2.13 Mt CO_2 in 2020 (Figure 8, Figure 15, Table 7, Table 8). In future HNW is planning to increase annually captured CO_2.

ZCH has already included Solvay Interox refinery and Stanlow Manufacturing Complex planning to produce hydrogen. Together they produced 1.38 Mt CO_2 in 2020. Additionally I have proposed to include into ZCH cluster Ribblesdale Works cement plant which produced 0.45 Mt CO_2 in 2020 (Figure 15, Table 7, Table 8).

Table 10. CCUS Scenario for HyNet North West cluster.

<table>
<tr><td colspan="4">CO_2 storage capacity, Mt</td></tr>
<tr><td>Lennox</td><td>Hamilton</td><td>Hamilton North</td><td>Total</td></tr>
<tr><td>77.9</td><td>103</td><td>48</td><td>228.9</td></tr>
<tr><td colspan="4">Total annual CO_2 emissions, Mt</td></tr>
<tr><td>Planned</td><td>Proposed</td><td>Proposed for cement plants</td><td>Total planned and proposed</td></tr>
<tr><td>2.13</td><td>0.45</td><td>0.45</td><td>2.58</td></tr>
<tr><td colspan="4">Project duration, years</td></tr>
<tr><td colspan="2">For planned plants</td><td colspan="2">Total for planned and proposed</td></tr>
<tr><td colspan="2">107.46</td><td colspan="2">88.72</td></tr>
</table>

Produced hydrogen will be transported by constructed hydrogen pipeline onshore and offshore. Captured CO_2 will be transported by repurpocing existing onshore and offshore natural gas pipelines. The onshore pipelines run to the Point of Ayr terminal that is connected with Lennox, Hamiltin and Hamilton North storage sites via offshore pipeline which is 36 km by ArcGIS measurements.

The estimated average storage capacity of the Lennox, Hamiltin and Hamilton North reservoirs (228.9 Mt) will be enough for about 107 years for the storage of the already included and planned by clusters CO_2 emissions. For the total planned and additionally proposed emissions from refineries and cement plants the storage capacity of the Endurance will be enough for about 89 years (Table 10). If additional plants will be included into the cluster with total capacity of 10 Mt, then this storage capacity will be enough for about 23 years. Additional economic benefits will arise from this cluster project, if owner of the gas fields (ENI) will use CO_2 for enhanced gas and oil recovery and storage.

4 Discussion and conclusions

For the estimation of the CO_2 storage capacity of the Endurance saline aquifer all needed parameters were taken from CO_2 Stored database and calculated with equation for theoretical CO_2 storage capacity in saline aquifers (Table 9). The average theoretical capacity of the Endurance structure estimated study is more than four times lower than the capacity that had been estimated in previous White Rose report (2800 Mt) (White Rose, 2016) and 37.2 Mt higher than estimated CO_2 Stored average theoretical CO_2 storage capacity (533 Mt) (CO_2 Stored, 2015). The White Rose project reported so much larger capacity because it was calculated for a larger area. The difference with CO_2 Stored is caused by some variations in the applied parameters, such as storage efficiency and CO_2 density. CO_2 storage capacity for Lennox, Hamilton and Hamilton North structures was calculated with equation for oil and gas reservoirs, based on the geometry of the reservoirs (Table 7). The calculations were made with average units from the database. The capacity of Lennox structure is 77.9 Mt, which is 5.2 Mt larger than stated at the CO_2 Stored database. The capacity for Hamilton and Hamilton North is according to my calculations 103 Mt and 48 Mt and by CO_2 Stored 122.1 Mt and 38.5 Mt. The difference in this case is also caused by the difference in the CO_2 density applied.

In total for two scenarios 21 emission sources were included in the United Kingdom CCUS scenario in order to decrease costs for the industrial project partners.

The first CCUS scenario is proposed for two major industrial areas in the UK- Teesside and Humber. For Net Zero Teesside 3 CO_2 emission sources produced by industrial facilities and for Zero Carbon Humber 8 industrial facilities and 3 cement plants, overall 14 emission sources with total calculated CO_2 emissions of 13.31 Mt in 2020. The emissions are transported for CO_2 storage to the Southern North Sea saline aquifer in the Endurance structure. This structure is a storage site for NZT and ZCH projects. In this scenario calculated CO_2 storage capacity in the 245 m thick Early Triassic Olenekian Bacton Group Bunter Sandstone Formation reservoir, occured at the depth of more than 1 km, is 570 Mt. Tthe estimated duration of the project is 43 years for the planned and proposed by author CO_2 emission sources.

The second CCUS scenario involves capturing CO_2 emissions from manufacturing facilities designed and suggested for the HyNet North West cluster. According to the EU Emissions Trading System, the 5 production units and 2 cement plants produced 2.58 Mt of CO_2 in 2020 and will have storage in the Lennox, Hamilton and Hamilton North storage sites for the duration of about 89 years.

The cement industry has only recently joined CCUS technology, but now more and more cement manufacturers are joining CCUS clusters. During the time of writing this work, the Heidelberg Cement Group has confirmed that it will merge its Padeswood Works CP to the HyNet North West project. CEMEX also announced in May 2021 that it is planning to decarbonise its production facilities through CCUS technology.

When comparing scenarios, then Hynet North West is more economic, as it will repurpose and reuse immediately all available oil and gas infrastructure, after the gas production has stopped. Also HNW cluster will be able to use CO_2 for enhanced hydrocarbon recovery to produce more revenues for the project. The advantage of the first scenario is that Endurance has larger storage capacity hence more CO_2 production units can take part in the project. Although storage in the Endurance will be more expensive, as the distance to transport CO_2 is longer and not all infrastructure is vailable yet.

All the studied projects are planning green and blue hydrogen production and transport combined with CCS. These scenarios will help to decarbonise three major UK industrial areas. Integrating additional CO_2 emitters, including cement industry, makes CO_2 storage for the projects more economic, considering sharing of transport and storage infrastructure. Additional storage sites could be included in both projects in future stages by demand.

This work will help to address poorly-known aspects of CCUS technologies and the integration of cement plants into CCUS clusters.

The scenarios discussed in this work are a great example for Estonia, Baltic and European countries of how it is possible to cooperate in clusters and hubs to achieve carbon neutrality while not eliminating the production and consumption of fossil fuels. Estonia is a small country and the cooperation between NZT and ZCH is a good example of how Estonia, Latvia and Lithuania, could work together. The two large clusters combined their resources to make storage more economical.

Some of the results of this master thesis are included in the poster presentation presented at the IEA Greenhouse Gas Technology Conference (GHGT-15) in March 2021, and were included in the article, published in the conference proceedings (Shogenova et al., 2021).

5 Acknowledgements

This work was supported by the CLEANKER project, which has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement n. 764816. Author is grateful for the supervisor, Alla Shogenova, for involving the author in the CLEANKER project and for the topic of the dissertation and also giving advice and direction, instructions and overall help with writing this thesis. Author would also like to thank Tõnno Habicht, who made it possible to use the CorelDRAW software and and Maarja Möldre, who who helped to check the spelling of Estonian abstract.

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