EAST CO2AST CLUSTER

# CCS Corrosion and materials selection overview and challenges, the approach of an integrated energy company

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# Abstract

$CO_2$ capture and sequestration (CCS) is an important technology for reducing the amount of $CO_2$ that is emitted into the atmosphere. One of the critical aspects of CCS is corrosion management and materials selection especially when $CO_2$ is in contact with water or when there are different impurities in the $CO_2$ stream. There has been a lot of work on CCS corrosion and materials selection but there are still several gaps that need to be addressed. There is extensive experience in $CO_2$ transport and downhole injection for $CO_2$ from natural sources, but information about corrosion management and materials selection for anthropogenic $CO_2$ with impurities such as $NO_x$, $SO_x$, $O_2$, etc is limited.

The intention of this presentation is to discuss some of the industrial challenges for CCS Corrosion management and materials selection, review some of the work that has been done on this topic so far, and remaining gaps that need attention.

This presentation will also discuss some of the learnings from the Northern Endurance Partnership (NEP) project.

# Outlines

- East Coast Cluster Overview.
- CCUS Technical Challenges (focused on Corrosion)
- Highlights of approach
- Gaps to be addressed within the Corrosion (and Materials) Community

# East Coast Cluster Overview

## AIMS

- remove almost 50% of the UK’s total industrial cluster $CO_2$ emissions
- create and protect thousands of jobs (an average of 25,000 jobs per year between 2023 and 2050)
- establish the Teesside and Humber regions as globally competitive climate-friendly hubs for industry and innovation

## Highlights

- unparalleled and diverse mix of low-carbon projects (e.g., industrial carbon capture, low-carbon hydrogen production, negative emissions power, and power with carbon capture)
- essential for the UK to meet its net zero targets

## Timeline

- March 2023: the Department for Energy Security and Net Zero (DESNZ) selected 3 East Coast Cluster projects – Net Zero Teesside Power, H2Teesside and Teesside Hydrogen $CO_2$ Capture
- first commercial operations in 2027
- new process later in 2023 to enable further expansion of the East Coast Cluster, beyond the initial deployment, identifying and selecting projects to be operational by 2030

**The East Coast Cluster aims to capture and store an average of around 23 million tonnes of $CO_2$ per year by 2035.**

# The East Coast Cluster Explained

The East Coast Cluster (ECC) is a set of carbon capture, usage and storage (CCUS) projects, which serves the industrial powerhouse regions of Teesside and the Humber.

Across Teesside and the Humber, there is a diverse range of businesses who wish to connect to the East Coast Cluster infrastructure to decarbonise their operations.

These carbon capture projects are deemed by DESNZ to fit into four broad categories – power with carbon capture, industry with carbon capture, Hydrogen and BECCs.

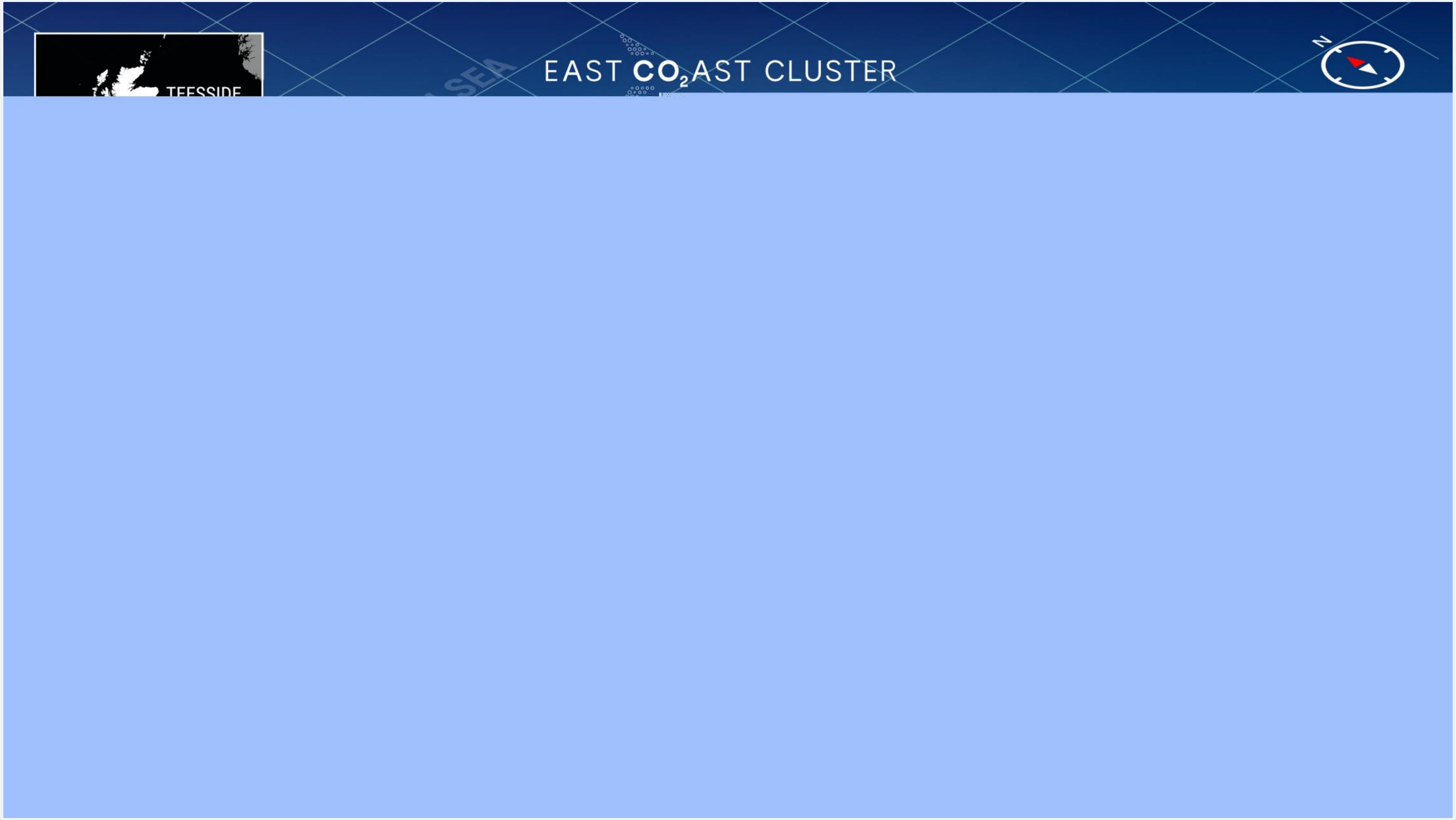
The Northern Endurance Partnership is the CO2 transportation and storage (T&S) provider for the ECC, and will build the onshore and offshore T&S infrastructure to serve the ECC carbon capture projects.

DESNZ has put in place a process – The Cluster Sequencing Process for CCUS – through which carbon capture projects are selected by UK Government for sequenced connection to the East Coast Cluster.

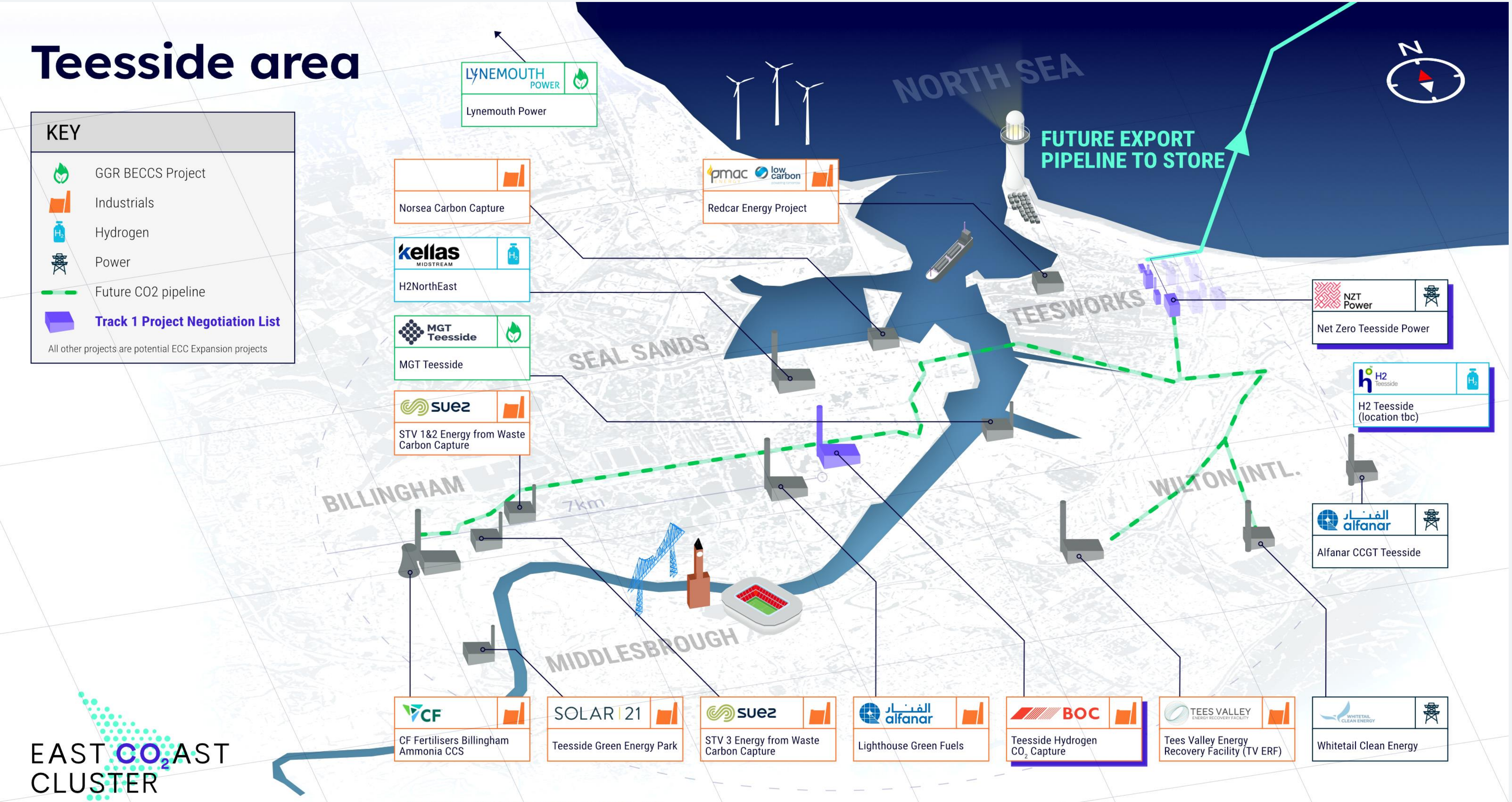
Represents the opportunity to capture 50% of the UK's total industrial cluster emissions and protect thousands of jobs across the Humber & Teesside

NEP enables the East Coast Cluster by providing the common infrastructure needed to transport $CO_2$ from emitters in the Humber & Teesside to secure and scalable offshore storage in the North Sea

# East Coast Cluster carbon capture projects on Teesside and the Humber

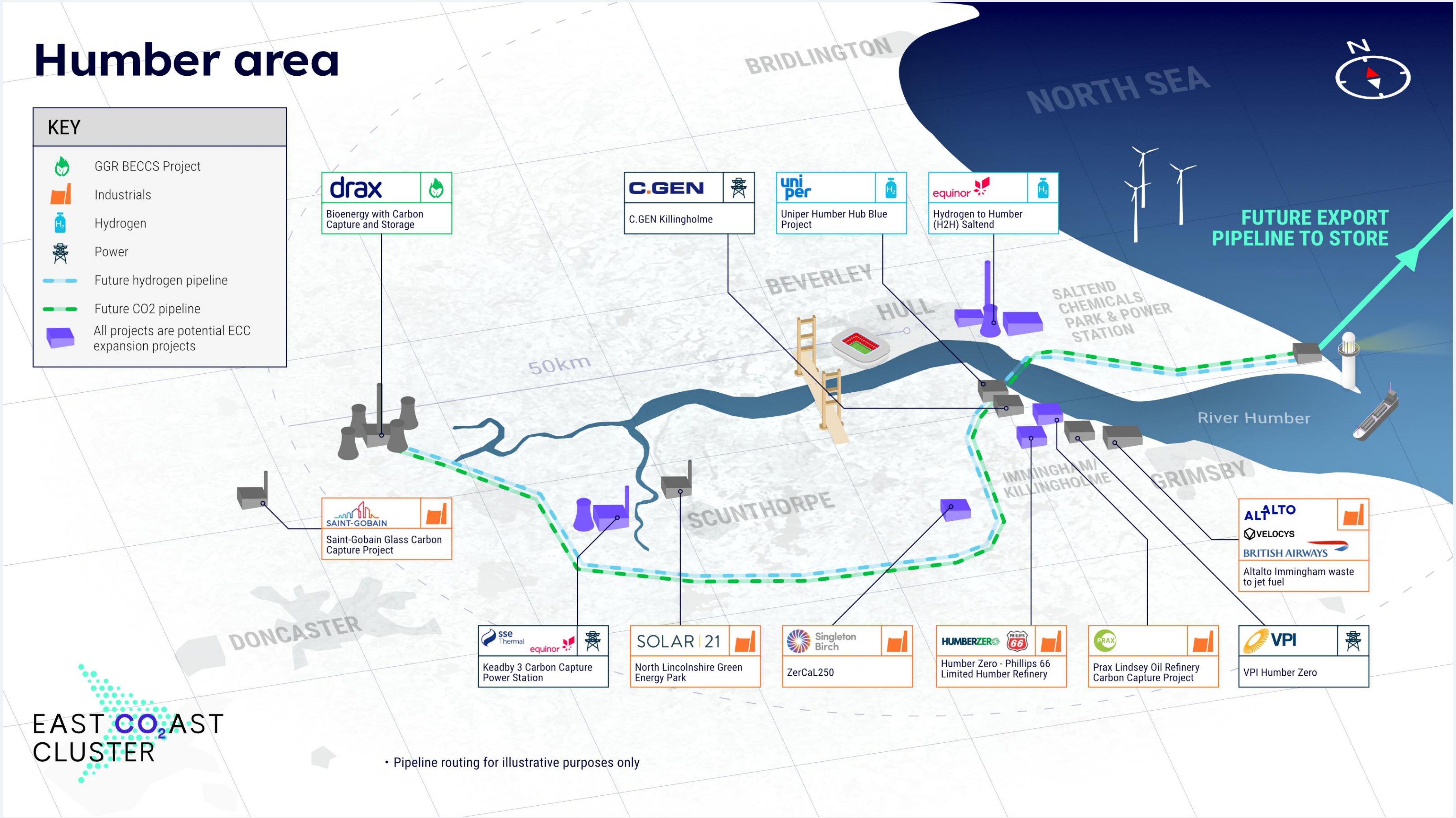


# East Coast Cluster carbon capture projects on Teesside




• Pipeline routing for illustrative purposes only

# East Coast Cluster carbon capture projects on the Humber




• Pipeline routing for illustrative purposes only

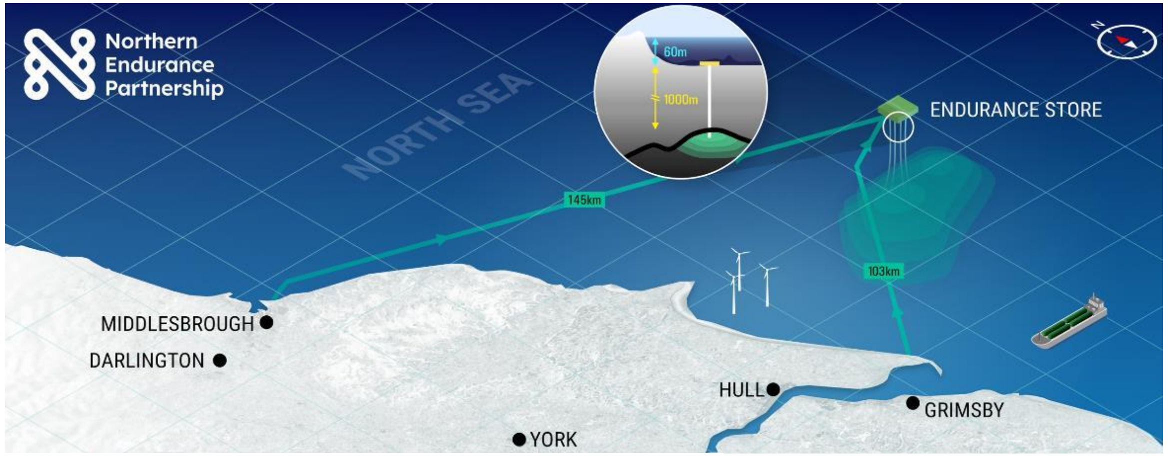
# The NEP is developing a wide portfolio of CO2 stores – ready to serve the ECC expansion

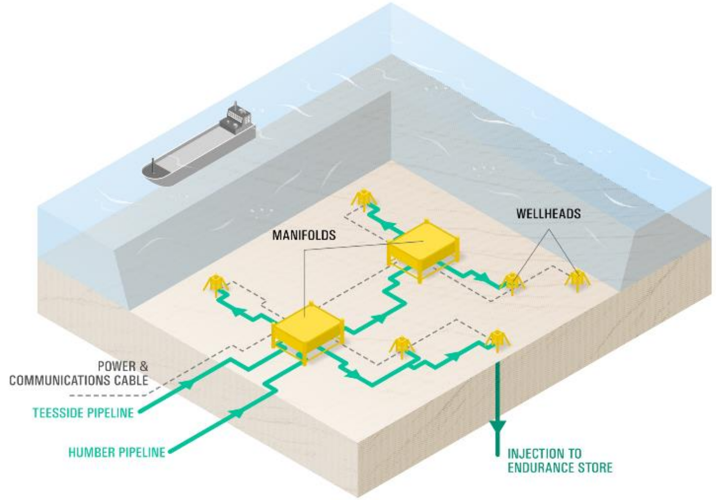
## Our Ambition

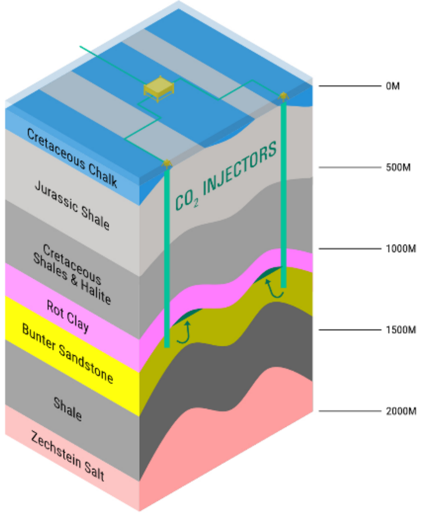
- DESNZ have selected 3 projects - Net Zero Teesside Power, H2Teesside and Teesside Hydrogen CO2 Capture – who will connect first to the East Coast Cluster – subject to business model negotiations.
- An average of around **4.1 million tonnes of CO2 per year** will be captured and stored from these projects from first cluster operations **in 2027**.
- The NEP is investing to develop at pace our portfolio of storage sites which will more than double annual CO2 storage to an average of around **10mtpa by 2030** – ready to serve the expansion projects from both Teesside and the Humber as they are selected by DESNZ.
- The NEP hold a storage licence for the Endurance Store, and two expansion store licenses – giving access to a total of up to 5 stores. We are also awaiting the outcome of our application to the NSTA for a further licence.
- The NEP aims to capture and store an average of **23mtpa by 2035**.

## Our Infrastructure

- First-of-a-kind offshore low carbon CCS infrastructure in the UK.
- Largest saline aquifer in southern North Sea – capacity to store 450m tonnes of CO2 with potential to extend capacity to around 1 billion tonnes with nearby stores.
- Includes CO2 pipelines from Teesside and the Humber.
- Compression and pumping systems to a common subsea manifold and well injection site at the Endurance store.



# CCUS Technical Challenges (focused on Corrosion)

## General Context

- Dry (pure) $CO_2$ is not corrosive
- Industrial $CO_2$ contains impurities which might trigger corrosion mechanisms
- Definition of $CO_2$ entry composition is key to address and resolve corrosion threats
- Main corrosion mechanism:
  - <u>$CO_2$ corrosion</u> (needs just water)

  => Dense phase $CO_2$ corrosion modelling (to be expanded to account for the effect of water chemistry and pH change for fixed volume of water and large surface area of steel). This will help to define the maintenance pigging and inspection requirement.

  - <u>Strong acid corrosion</u> (triggered by $H_2O$, $O_2$, $SO_x$, $NO_x$ and $H_2S$, it doesn't necessarily need free water)

  => Effect of combination of different impurities at different concentrations on acid and water drop out. How to manage different impurities excursions?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# Highlights of approach

- Definition of CO2 entry composition is key to address and resolve corrosion threats (from literature) and protect Carbon Steel Pipeline selection
- Test the validity of the developed CO2 entry spec at all operating conditions through:
- Modelling activities
  - Use of best in class software, updated to address corrosion in dense CO2 with impurities
  - It only accounts for thermodynamics, not kinetics
  - Conservative
- Participation to key JIPs
  - develop safe entry specifications for CO2 pipeline transportation
  - Tests carried out using an autoclave in which different CO2 / impurities mixtures can be reproduced
  - It accounts for kinetics, limited information on quantitative corrosion measurement
- Testing at specific NEP conditions
  - aligned with classic qualification approach for material selection validation
  - direct assessment of corrosion rate
  - critical NEP validation point in calibrating:

*Model vs Observation vs Quantification*

Table 77: Verified impurity concentration (VIC) for $CO_2$ transport based on experimental testing at 25 °C and 100 bar. Numbers in brackets are verified based on experiments with only chemical analyses but not visual observation [69].

| No. | Maximum impurity content (ppm-mol) | | | | | Observation |
|---|---|---|---|---|---|---|
| | $H_2O$ | $H_2S$ | $SO_2$ | $NO_2$ | $O_2$ | |
| 1 | 2500* | | | | | Negligible corrosion with under-saturated water. * |
| 2 | 1900* | | 80** | | 240** | Slight corrosion for water > 1900 ppm-mol (about 4 µm/y). * |
| 3 | 200 | | 1000 | | 100 | Slight corrosion, less than 10 µm/y. |
| 4 | 250 | | | 70** | | Significant corrosion with 670 ppm-mol water. |
| 5 | 100 (300) | 35 (100) | 35 (100) | | 60 (350) | Visual observations indicated no corrosion or chemical reactions. (Nonreactive experiment, but no visual conformation.) |
| 6 | 50 | | 35 | 30 | 80 | Visual conformation and nonreactive experiment. |
| 7 | 200 | 20 | 20 | 10 | 20 | Formation of $H_2SO_4$ and $HNO_3$ if ($SO_2$+$H_2S$) > 60 ppm-mol. |

[69] B. H. Morland, A. Dugstad, G. Svenningsen, Experimental based CO2 transport specification ensuring material integrity, *International Journal of Greenhouse Gas Control*, 119, (2022) p. 103697.


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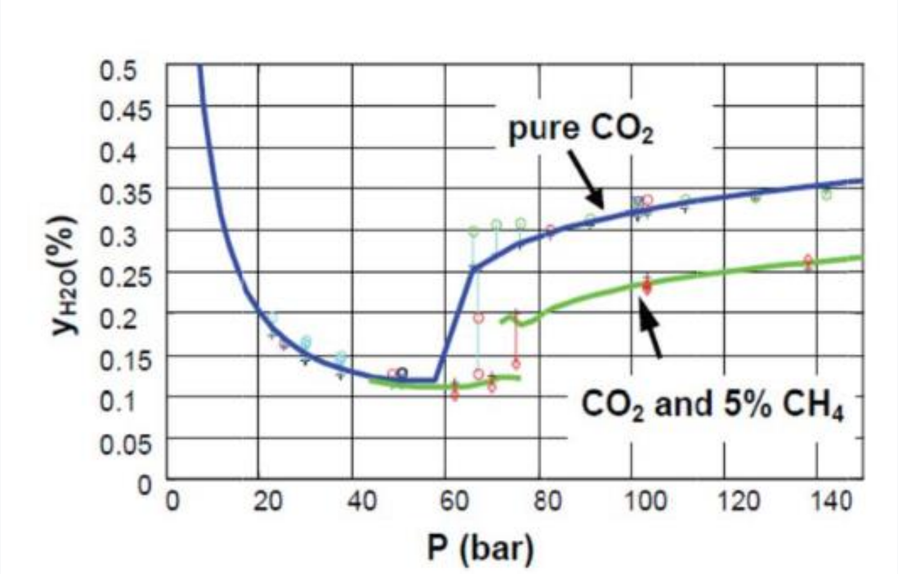
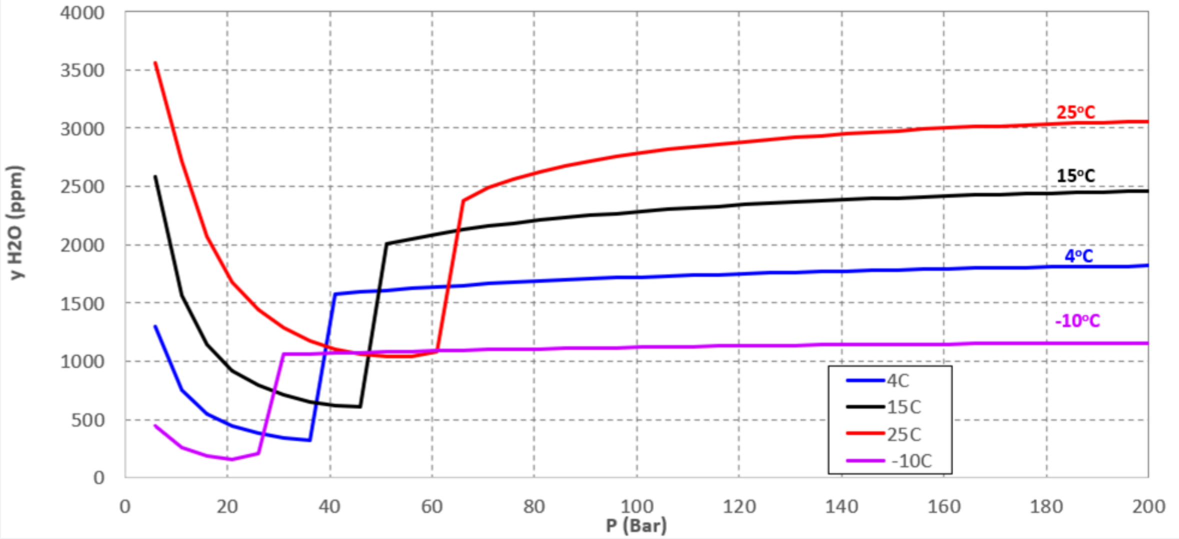
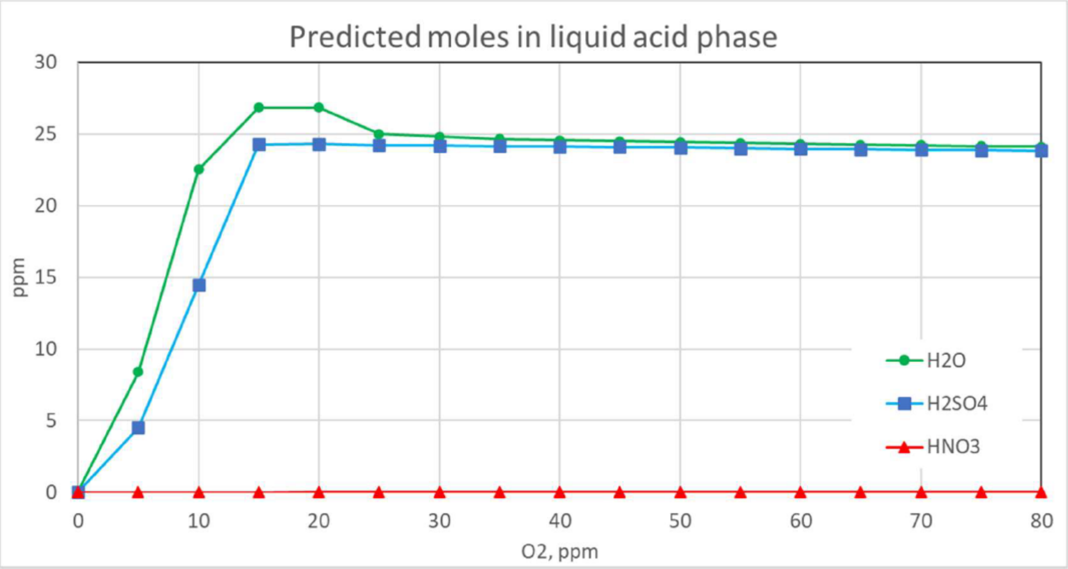
# Highlights of approach

- Modelling activities




Dugstad, A., & Halseid, M. (2012, March). Internal corrosion in dense phase CO2 transport pipelines-state of the art and the need for further R&D. In CORROSION 2012. OnePetro.



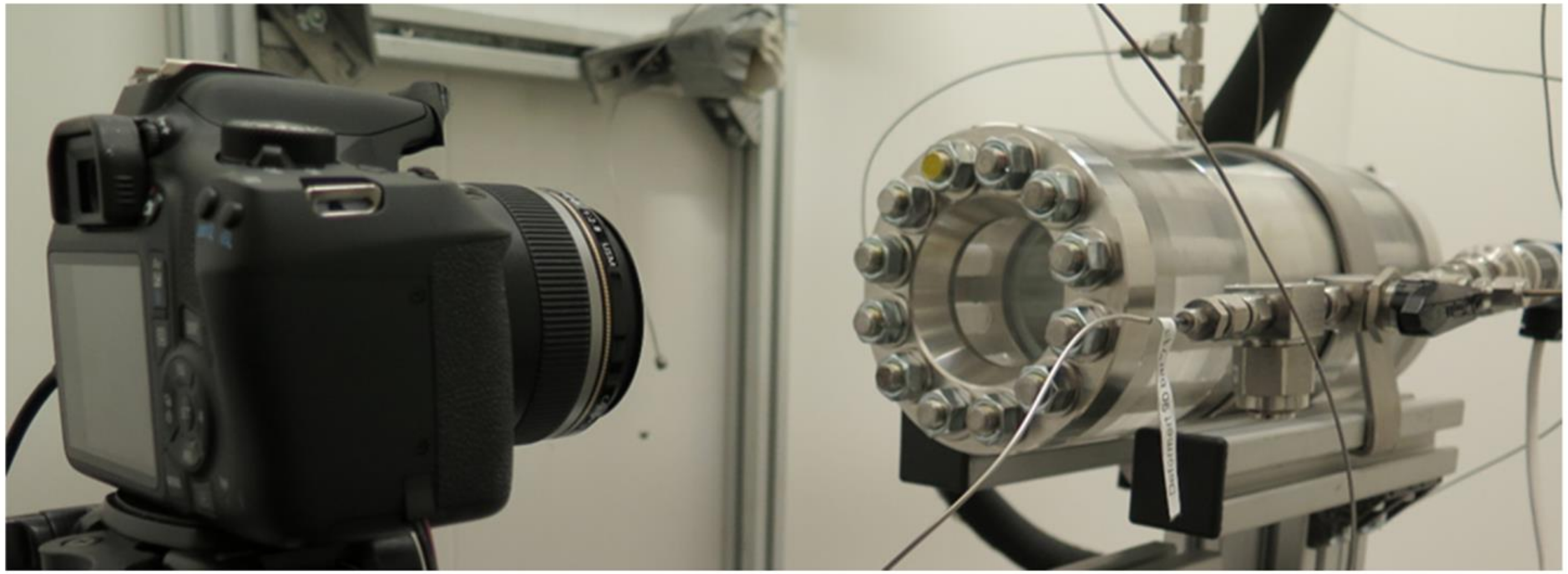



# Highlights of approach

- Participation to key JIPs

$$2\,H_2S + SO_2 \rightarrow 3/x\,S_x + 2\,H_2O$$
$$2\,H_2S + 3\,O_2 \rightarrow 2\,SO_2 + 2\,H_2O$$
$$H_2S + 2\,NO_2 \rightarrow \tfrac{1}{2}\,SO_2 + 2NO + H_2O + \tfrac{1}{2}\,S$$
$$2\,NO + O_2 \rightarrow 2\,NO_2$$
$$NO_2 + SO_2 + H_2O \rightarrow NO + H_2SO_4$$
$$SO_2 + \tfrac{1}{2}\,O_2 + H_2O \rightarrow H_2SO_4$$
$$2\,NO_2 + H_2O \rightarrow HNO_2 + HNO_3$$
$$H_2S + H_2SO_4 \rightarrow S + SO_2 + 2\,H_2O$$
$$H_2S + HNO_3 \rightarrow 3S + 2\,NO + 4\,H_2O$$
$$SO_2 + H_2O \rightarrow H_2SO_3$$
$$4\,NO_2 + O_2 + 2\,H_2O \rightarrow 4\,HNO_3$$

Dugstad, A., Halseid, M., & Morland, B. (2014). Testing of CO2 specifications with respect to corrosion and bulk phase reactions. Energy Procedia, 63, 2547-2556.



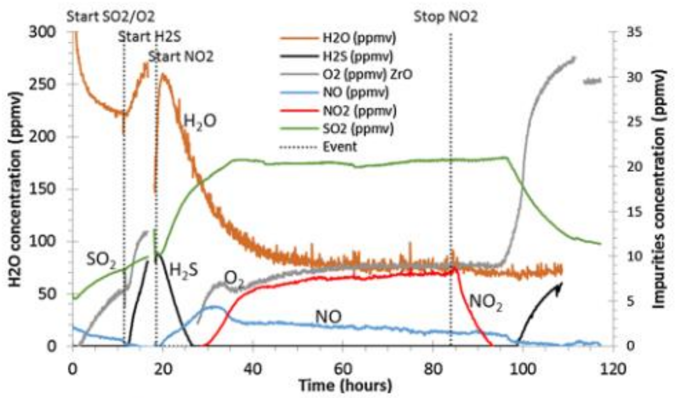



**Fig. 6.** Analysis of exhaust gas from Hub02.

Morland, B. H., Tjelta, M., Norby, T., & Svenningsen, G. (2019). Acid reactions in hub systems consisting of separate non-reactive CO2 transport lines. International Journal of Greenhouse Gas Control, 87, 246-255.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# Highlights of approach

- Testing at specific NEP conditions, highlights:
  - Fast depressurization can lead to greater aggressiveness of the system -> free water condensation
  - Oxygen concentration affects the susceptibility of the material to localized corrosion
  - It appears that both the TOP and the BOTTOM of the line can be subjected to the corrosion. More work is needed to reveal the mechanism.

# Summary

- Modelling predicting only low concentrations of strong acids (equilibrium conditions)
- Laboratory testing suggesting that strong acid may not actually form (possibly due to slow kinetics)
- Laboratory testing showing very low corrosion rates


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# Gaps to be addressed within the Corrosion Community

- Define guidelines for agreed and reliable testing
- Sour service qualification for extreme low pH conditions
- CRA and Non-metallic materials performance in CCUS service
- Corrosion inhibitor performance in CCUS conditions (possible contingency plan during water spec excursion?)
- Low temperature toughness requirements
- …


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# CO2 Pipeline Failure Data (PHMSA report of USA data) 2010-2021

- In the United States, CO2 has been transported by pipeline in support of EOR since 1972 (~5000 miles of pipeline as of 2020).

| Year | Number | UNINTENTIONAL RELEASE_BBLS | INTENTIONAL RELEASE_BBLS | Cost |
|---|---|---|---|---|
| 2010 | 6 | 329 | 70191 | $212,521 |
| 2011 | 4 | 2542 | 43198 | $168,770 |
| 2012 | 2 | 19 | 0 | $5,823 |
| 2013 | 5 | 52 | 52118 | $270,387 |
| 2014 | 5 | 2190 | 3694 | $32,948 |
| 2015 | 7 | 1281 | 3513 | $67,224 |
| 2016 | 9 | 1709 | 12247 | $71,029 |
| 2017 | 9 | 218 | 13970 | $132,993 |
| 2018 | 5 | 406 | 47393 | $299,047 |
| 2019 | 4 | 480 | 9909 | $375,395 |
| 2020 | 6 | 50903 | 22246 | $4,035,553 |
| 2021 | 4 | 787 | 2 | $66,184 |
| **Grand Total** | **66** | **60917** | **278481** | **$5,737,874** |

**Note:** No fatality. No injuries since 2007.

| Cause of Failure | Number of Failures | UNINTENTIONAL RELEASE_BBLS | INTENTIONAL RELEASE_BBLS |
|---|---|---|---|
| "CONSTRUCTION-, INSTALLATION-, OR FABRICATION-RELATED" | 4 | 64 | 51943 |
| "DAMAGE BY CAR, TRUCK, OR OTHER MOTORIZED VEHICLE/EQUIPMENT NOT ENGAGED IN EXCAVATION" | 1 | 1208 | 306 |
| "FAILURE OF EQUIPMENT BODY (EXCEPT PUMP), TANK PLATE, OR OTHER MATERIAL" | 1 | 1 | 1 |
| "VALVE LEFT OR PLACED IN WRONG POSITION, BUT NOT RESULTING IN A TANK, VESSEL, OR SUMP/SEPARATOR OVERFLOW OR FACILITY OVERPRESSURE" | 1 | 70 | 0 |
| ENVIRONMENTAL CRACKING-RELATED | 1 | 106 | 10292 |
| EQUIPMENT NOT INSTALLED PROPERLY | 1 | 1 | 0 |
| EXTERNAL CORROSION | 7 | 219 | 16237 |
| HEAVY RAINS/FLOODS | 1 | 9532 | 21873 |
| MALFUNCTION OF CONTROL/RELIEF EQUIPMENT | 12 | 44554 | 1725 |
| MISCELLANEOUS | 3 | 302 | 0 |
| NON-THREADED CONNECTION FAILURE* | 16 | 4193 | 38795 |
| ORIGINAL MANUFACTURING-RELATED (NOT GIRTH WELD OR OTHER WELDS FORMED IN THE FIELD) | 4 | 121 | 114847 |
| OTHER EQUIPMENT FAILURE | 5 | 133 | 0 |
| OTHER INCORRECT OPERATION | 4 | 338 | 22450 |
| THREADED CONNECTION/COUPLING FAILURE | 1 | 1 | 0 |
| WRONG EQUIPMENT SPECIFIED OR INSTALLED | 4 | 75 | 12 |
| **Grand Total** | **66** | **60917** | **278481** |

***** Most of non-threaded connection failures are related to O-ring or gasket failure in valve.