Technology Collaboration Programme
by iea

Evaluating technology options to mitigate greenhouse gas emissions

6th International Workshop on Offshore Geologic CO_2 Storage

IEAGHG Technical Review 2023-TR06 December

IEA GREENHOUSE GAS R&D PROGRAMME

Acknowledgements & Citations

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This work reports on the 6th in a series of international workshops on the offshore geological storage of CO2 which was hosted in Aberdeen by the University of Aberdeen with sponsorship from STOREGGA. This report was prepared by Phoebe Sleath and Francisca Robledo Carvajal, and edited by Nicola Clarke, Tim Dixon and Katherine Romanak.

IEAGHG would like to thank the Steering Committee for their efforts in facilitating this workshop:

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About IEAGHG

Blazing the way to net zero with leading CCS research. *We advance technology to accelerate project development & deployment.*

We are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

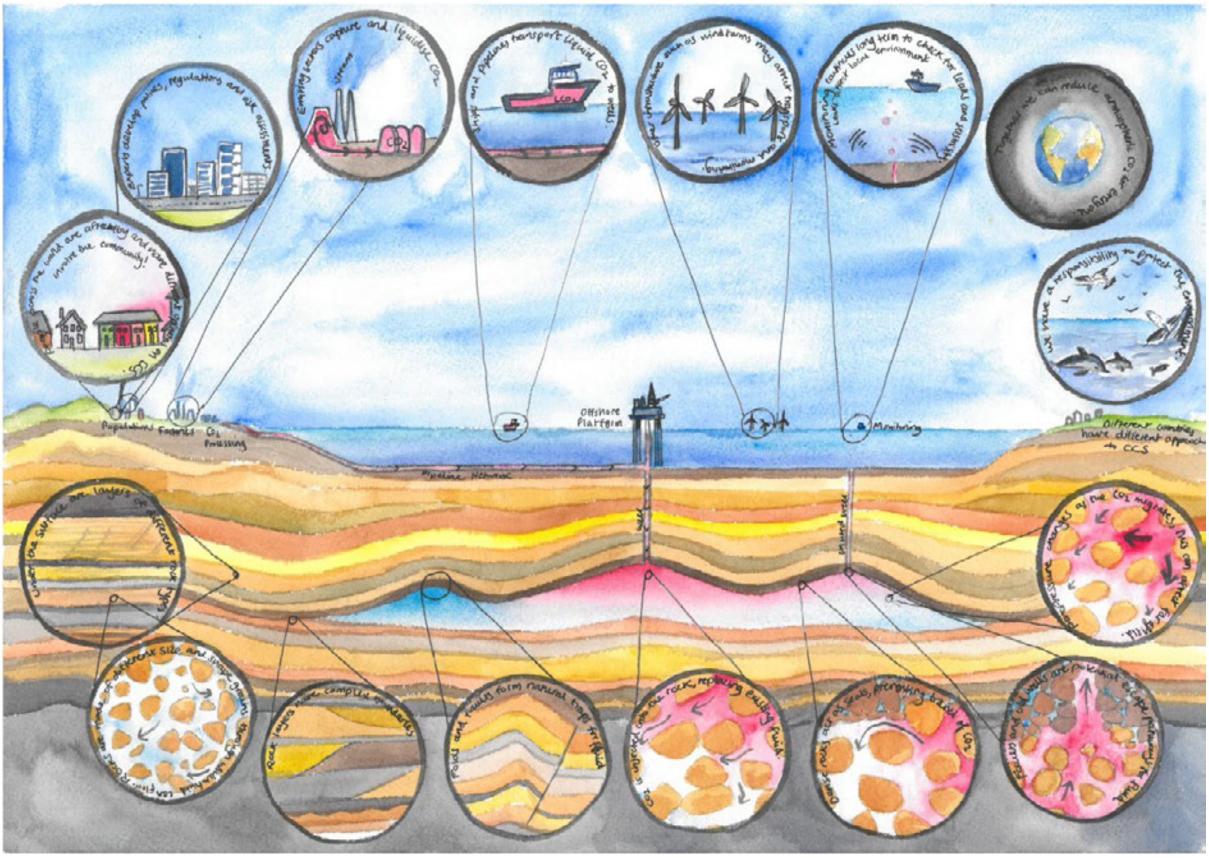
International Workshop on Offshore Geologic CO_2 Storage

6th International Workshop on Offshore Geologic CO_2 Storage

Organised by GCCC, BEG at the University of Texas, with IEAGHG

The Sir Duncan Rice Library, The University of Aberdeen
13-14th September 2023

Hosted by The University of Aberdeen. Sponsored and supported by Storegga



Artwork created by Phoebe Sleath during the workshop – (please note that scales are figurative).

Some of the in-person attendees at the 6th International Workshop.

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Executive Summary

The 6th International Workshop on Offshore Geologic CO_2 Storage was held in Aberdeen on 13-14 September. Organised with the University of Texas and hosted by the University of Aberdeen. The location was very appropriate as we were co-hosted and sponsored by Storegga who leads the Acorn project nearby in Scotland. This project had been recently announced by the UK government as a Track 2 Cluster project. This 6th workshop had 190 delegates (60 in-person and 130 virtual) from 35 countries, with a good mix of industry, researchers and regulators.

In a very packed agenda of some 44 presentations, it also included time for discussions. What struck everyone again was the number of new projects with offshore storage being progressed. As well as the number, it was the diversity of the projects that was impressive, covering many industry sectors, storage in depleted hydrocarbon fields and deep saline formations, and different transport means to storage. Once the project updates had been covered, the workshop got into more technical details, such as impacts and screening of legacy wells, storage capacity, regulations, interaction with other users of the seabed, transport and infrastructure, stakeholder engagement, monitoring, and environmental aspects. Transport developments included ship CO_2 capture by Shell and the importance of pressure management in pipeline networks.

Of particular interest with respect to the workshop location, the workshop heard from the North Sea Transition Authority (NSTA) about the UK's first-ever CO_2 storage licencing round. The announcement was made by NSTA the day after the workshop of 21 new licences being accepted by operators, mostly in the North Sea. Delegates heard from some of these licence holders on their project plans. NSTA is also working with a 'co-location forum' to coordinate with other uses of the seabed.

Conclusions and recommendations were agreed at the end of the workshop. These include the welcoming of "Just Transition" being included in UK and US projects, the maturing of MMV plans and their approval by regulators, the careful evaluation and allocation of storage resources contingent on well density and pressure space, and that community benefits are just as critical in the offshore (they just differ from the onshore), transparency and method of communicating risk is important. Recommendations include developing monitoring techniques for use around wind farms. Basin-wide management is an emerging topic with ways to manage the 'commons' or pressure space seen as a pressing need i.e. who is responsible for this and does the first mover win? There is a clear need to improve public knowledge, know your local community and collaborate with them, positive engagement with the media is also imperative. Clarity is needed over the way we license. The more licences are granted, the shorter this process will become. Protocols for how to assess and monitor legacy wells were also a theme. Lastly, knowledge transfer, especially to the Global South in countries without a mature hydrocarbon industry, was required.

Overall, there is impressive progress in developing CCS projects offshore, and much knowledge was shared in this workshop. Thanks to Storegga for sponsoring and co-hosting, and to the University of Aberdeen for hosting. The presentations will be available on the GCCC website at BEG Global Offshore Initiative | Bureau of Economic Geology (utexas.edu).

DAY 1

Session 1: Welcome and Scene Setting

A welcome was given by Clare Bond (University of Aberdeen), Nick Forsyth (Vice Principal Research, University of Aberdeen), Steve Murphy (Chief Commercial Officer, Storegga), Tim Dixon (IEAGHG) and Katherine Romanak (University of Texas at Austin). This is the 6th International Workshop on Offshore CCS. The workshop series was initiated by the University of Texas Bureau of Economic Geology (BEG) and co-organised with IEAGHG following a recommendation by the CSLF Task Force on Offshore Storage in 2015. Reports of each workshop are published by IEAGHG. There is a strong emphasis at these workshops on international cooperation and sharing of knowledge with developing countries.

Aberdeen was chosen to host the 6th workshop as the city is well established as the Energy Transition Capital of Europe, and the nearby North Sea is host to several offshore CCS projects.

A scene-setting presentation was given by Owain Tucker (Shell) on the geology, infrastructure, economics, and environment of the North Sea and the fundamental differences between working offshore compared to onshore. The North Sea is a long-established fishing and hydrocarbon basin with a very challenging and higher-cost operating marine environment. Geological targets remain the same as onshore, and although an offshore environment reduces stakeholder concerns it comes with its own challenges working in such remote locations.

Monitoring for containment, conformance, and confidence can be simpler than onshore, but with other marine activity and competition for seabed space ramping interference between activities can pose issues.

Working offshore provides huge opportunities, but we must keep in mind the significant differences that come with this.

Session 2: Project Roundup | Chairs- Tim Dixon and Clare Bond

Acorn, UK | Iain Morrison, Storegga

Acorn has two projects in the North Sea off the coast of Aberdeen: Captain Fairway and East Mey. Within the Lower Cretaceous is a high-quality sandstone unit which provides a potential CO_2 store for more than 20 years. Captain Fairway is in the initial stage of development, it is a combination of aquifer and structural traps. The project is in an unusual position of being able to reuse the Goldeneye Pipeline. East Mey is in phase 2 of development, it is an aquifer store with minimal structural trapping. It uses the 30" Miller Offshore Pipeline. The aquifer has a low storage efficiency, so a large area is required. Acorn has applied for additional licenses; so far it is in Track 2 of the UK Government Programme.

Prinos, Greece | Nickolas Rigus, Energean

Energean is a Mediterranean-focused gas company which is moving into the energy transition. Their main operations are in Israel, Greece and Italy. They currently run Prinos - the only gas field in Greece, for which they were awarded the exploration license in 2022 which can be transferred to CO_2 storage in future. Greece is concerned with a lack of CO_2 sites, Prinos is the only site. The plan for CO_2 storage is a first phase of local CO_2 emissions, a second phase of liquid CO_2 (2026) and a third phase aims to store 3 MTpa of CO_2 for countries across the Mediterranean (2028). Energean then plans to replicate this process with other licenses. For their other operations, they believe Israel is poised to decarbonise and is a big target for the company, Egypt has no CCS potential and regulations are not yet in place, and Italy is working on it. In total from their assets, they have 100 million tonnes of storage capacity and are currently oversubscribed to store CO_2.

Corpus Christi, USA | **Katherine Romanak**, University of Texas for Tip Meckel

Corpus Christi, located on the Gulf Coast of Texas, is the largest port in the USA by annual revenue tonnage. It offers many opportunities for commercial partnerships in carbon capture and storage (CCS). The Biden Administration has established a CCUS Federal Lands and Outer Continental Shelf Permitting Task Force to develop rules and regulations for offshore CCS projects in the outer continental shelf. The Port Corpus Christi has also signed a unique memorandum of understanding (MOU) with the Port of Rotterdam, the largest port in Europe, to exchange technical information and focus on navigational safety and environmental protection. Moreover, Port Corpus Christi has a strong priority on collaborating with the Texas General Land Office to co-develop the CCS potential in the Coastal Bend of Texas, a region that includes Corpus Christi and its surrounding counties. Currently, two discrete CCS projects in the area have received funding from the US Department of Energy, totalling USD 16.4 million to further the development of CCS in this area.

Viking CCS, UK | Andrew Hood – Harbour Energy

Viking CCS Transport & Storage is a joint venture run primarily by Harbour Energy and BP. It is anchored in the Humber region (20MT pa emissions), with well-developed capture projects and is the first mover at-scale CO_2 shipping capacity in the UK. The licences target deep storage in Leman Sandstone depleted gas fields. The reservoir is overlain by the Zechstein salt, termed a super seal, and takes high pressures. A secondary reservoir in the Bunter Sandstone will act as a backup. The Humber is a dense industrial zone. Viking CCS are aiming for 300MT of storage capacity.

The project has moved quickly through licensing and was the first to complete the competent person report and was selected as a Track 2 cluster, opening negotiations for Economic Licence. FID timing is dependent on the government timeline until Track 2 is finalised and the emitters selected.

Pilot Strategy, Portugal | Maria Helena Caeiro, University of Évora

PilotStrategy is an EU Horizon 2020 funded project that runs until mid-2026 and aims to investigate promising geological storage sites in industrial regions of Southern and Eastern Europe to support the development of CCS. This project accounts with several research, industrial and social science partners. The multidisciplinary scope of PilotStrategy encompasses technical evaluation, legal framework, safety and performance risk assessment, investment proposal and pilot life-cycle, communication and dissemination, social engagement and stakeholders' participation.

In Portugal, an offshore location with commercial scale potential has been selected after a judicious analysis of a few onshore and offshore options. The selected Portugal offshore location has the potential to store up to 30 Mt of CO_2 in an approximately 900m deep reservoir in the Lower Cretaceous. The selected location is set in a privileged location close to CO_2 emitters from hard-to-decarbonise sectors, such as cement and lime and glass sectors, shows high reservoir quality, has good data quality and coverage, low active seismicity and other prospects exist nearby, allowing to upscale the storage site. Engagement with stakeholders and social acceptance from the local community is promising. Impacts of implementation are promising and PilotSTRATEGY is actively engaging the industrial players, local authorities and national policymakers to set the way for this project.

Northern Lights, Norway | Catalina Acuna, Northern Lights

Northern Lights Project is a CO_2 transport and storage company set up as a joint venture by the Norwegian Government, Equinor, Shell and Total. The Longship project comprises the full CCS value chain with onshore capture facilities that will feed the Northern Lights (transport & storage component of Longship). Together they plan to collect CO_2 emissions from all around Norway and northern Europe.

Onshore facilities are progressing according to plan and the site will be ready for operation in 2024. They awarded two ship-building contracts in 2021 and 2023 with a cargo size of 7,500m^3. The ships are purpose-built medium-pressure cargo containment. The ships are being built in China and they still need additional vessels. The exploration well was drilled in 2019 with an injection test to be performed imminently and planned operations start in 2024. Operations have a 3-phase capacity to meet storage resources. Phase 1: 37MT in 25 years and Phase 2 more than 100MT contingent storage resources, Phase 3 has an undisclosed resource.

Northern Lights is focused on delivering an economic business model delivering CO_2 storage as a service with a focus on servicing industrial emitters in hard to abate sectors across Norway and Europe.

South Korea | Axel Lemus, Korea CCUS Association

The Donghae CCS Project utilizes a depleted gas field located in the East Sea and has a goal of sequestering 1.2 MT of CO_2 pa. The budget is estimated at approximately KRW 2 trillion (approx. USD $1,5Bill). CO_2 is collected from industrial and power sectors in South Korea's south eastern coast – where there are intensive industries including petrochemical complexes , power plants, etc. This project will include a hub terminal, with onshore (15km) and offshore pipelines (60km). The CO_2 storage injection system will use an offshore platform with a subsea injection facility. KNOC and Hyundai E&C have signed a contract to conduct a pre-FEED study earlier in July. The pre-FEED runs parallel to government plans to advance the project and focuses on existing and new facilities to obtain design specifications, conceptual designs, standards, etc.

Porthos, Netherlands | Kike Beintema, EBN

Porthos is a depleted gas field, with capture and a collective pipeline and compressor station through the Rotterdam port area. The goal is to capture and store 2.4Mt/yr CO_2 for 20 years. This represents 14% of national CO_2 emissions. Other CCS projects in the Netherlands include the Aramis project and large-scale transport projects. The Delta corridor connects Rotterdam to the German Hinterland. Porthos is now ready for FID, the FEED engineering is done, the storage licence obtained, environmental permits received, and now ready for shareholder FID. Pre-FID investment in key infrastructure. They are preparing for shareholder approval and construction phase. The first CO_2 injection is due in 2026.

Liverpool Bay, UK CCUS project | Manotti Matteo – ENI

Eni UK is the nominated lead for the CO_2 transportation and storage component of the HyNet NW Project, which was chosen by the UK Government for Track 1 Cluster Sequencing in 2021, enabling the creation of one of the first UK low-carbon clusters contributing to UK carbon neutrality targets to limit global warming. Eni UK will develop and operate the transportation network from emitters and store the CO_2 in three depleted Liverpool Bay fields: Hamilton, Hamilton North and Lennox, identified as excellent storage sites.

The project entails the drilling of 8 injectors and 3 monitoring wells, in addition to utilising 2 existing wells (sentinel) as supplementary monitoring points until a CO_2 breakthrough occurs. Redevelopment plans include the existing gas terminal and three platforms, with the possibility of reusing an existing pipeline. The process to secure a storage permit commenced in October 2020 and the project is progressing towards its final milestone, the 'End Define Phase' which is crucial to achieving the Storage Permit Award and reaching Cluster FID by Q3-4 2024.

Deep C Store, Australia | Daein Cha – Deep C Store

Deep C Store “dCS” is Australia’s CCS developer, Offshore Australia, working with multinational partners. dCS offtakes CO_2 from industrial emitters in Australia and the APAC region and obtains CO_2 storage acreage in offshore Australia for deploying ~ 3 MTPA commercial-scale floating CCS hub - “CStore 1”. Currently at the Pre-FEED Phase 2 stage, having already identified ~15MTPA of CO_2 to underpin CStore 1, mainly coming from Japan’s largest emitting facilities such as Kansai Electric Power and Nippon Steel Corporation. A joint bid was submitted with JX Nippon O&G for GHG acreage in offshore Australia. dCS aims for FID by the end of 2026. Government subsidies cover some options but hopefully, more support will be drawn up. Community support is in the early days and more projects and community engagement are needed. A bill has been introduced to parliament to ratify the London Protocol and declare acceptance of the 2009 amendment to allow CO_2 storage offshore.

Taiwan | Cheryl Yang, ITRI

In March 2022 Taiwan released a GHG reduction and management plan as a response to Net Zero reductions. The new Climate Change Response Act includes CCS in articles 39 and 40. Two field test sites were announced: the Taichung power plant field test site and the Tiehchenshan gas field test site. With injection of 2000 tonnes per year at the first site and 10,000 tonnes per year for three years on the second site is planned. A two-well carbon storage research project is proposed, a 3000 m deep injection well, with proposed capacity of 2000 tonnes per year. An EIA update of the carbon storage site is being developed. CCS research in ITRI has reviewed the storage capacity and updated the site assessment. They have also developed distributed fibre optic sensing for CCS site monitoring.

Poseidon & Orion, UK | Nick Terrell, Carbon Catalyst

Poseidon and Orion projects are two independent transport and storage projects awarded licences in the UK first Carbon Storage Round run by Perenco and Carbon Catalyst. Located 50-60 km off East Anglia, Poseiden is a Gigaton storage project. Orion is closest to the Humber cluster.

Poseidon is a world-class CCS project with a storage capacity of 935 Mt and a target first injection in 2029. Currently, it’s targeting FID by ~2027. Centred on the Leman Field which is the UK’s largest legacy gas field, and overlying BC-9 saline aquifer closure. Injection should last for 30 to 40 years. The project is focussed on domestic emitters in East Anglia, London and the Southeast of England, and also the significant international market across continental Northwest Europe.

Orion is strategically positioned to decarbonise Humberside, the UK’s largest industrial cluster. It has a storage capacity of 126 Mt and the target first injection is in 2031. It is also targeting FID by ~2029. It is centred on the high-quality reservoirs of the decommissioned Amethyst field cluster and depleted West Sole Field. Injection should last for around 30 years.

Gulf of Mexico, USA | Rahul Umrani, Talos Energy

Rahul presented on an Area Of Review (AOR) generation workflow. The Gulf Coast has 100 + facilities and is a world-class storage region with >30 gigatons of potential capacity. With the context of permitting Class VI, the main motivation for this work is the critical pressure concept of AOR. Critical Pressure Calculation can be calculated with analytical equations.

Pre-Salt play, Brazil | Ana Paula Musse, Petrobras

Santos Basin, a pre-salt oil field is located 300km from the coast, with 136 wells, producing 3.3 million boe/day, with high CO_2 content. The CO_2-rich gas is stripped and reinjected back into the reservoir. Petrobras and its partners are committed to avoiding CO_2 venting into the atmosphere in production. It is currently the largest CO_2 injection project in the world and the first CCUS project in ultra-deep water (2010). By 2022 40.8 million tonnes of CO_2 have been injected. The target for 2025 is the reinjection of 80 million tonnes of CO_2 in CCUS -EOR projects. Possible future includes a CCUS Hub – with emitters from power plants, refineries, ethanol production and steel and cement works.

Pelican Project, Australia | Jane Burton, Victoria State Government

The Pelican Project is jointly funded by the Victoria State Government and the Commonwealth Government since 2010. Funding of A$200 million to date includes Pelican 2D seismic and wells and the completion of lots of studies. The storage capacity of Pelican is 6Mtpa, with the injection of 168MT over 30 years. Modelling of the site has been independently reviewed by several external bodies including CSIRO and BGS. There are three stages: onshore and offshore transport and storage. At the Pelican site, the offshore development comprises 2 drill centres, 4-6 subsea injection wells, monitoring wells, and a 60 km pipeline. There are two permitted sites, the Pelican and Kookaburra site (the latter is not worked as much –but is a world-class petroleum site). Technical studies are required to reduce containment risk. Community outreach has been a feature since the start, with pop-up sessions and school programs for kids. Key activities aim to reach FID in 2024.

Timor Leste | Francelino Antonio Xavier, ANPM

The Bayu-Undan (BU) field is a gas condensate field located offshore Timor-Leste in water depths of 80-100m. It is currently operated by SANTOS LTD and started production in 2004. It was discovered in 1995 and the expected end-of-life is 2023. Other potential storage nearby are depleted oil fields and prospective storage resources across the Timor Leste offshore area.

The scope of the BU-CCS project is to re-purpose existing production facilities with modifications for CO_2 storage, generate revenue for the Government of Timor Leste, create job opportunities for the people of Timor Leste and support global CO_2 reduction and climate change mitigation. Timor Leste contributes almost 0% of the total global emissions.

The project is currently ongoing a storage assessment with SANTOS, preliminary results suggest a storage capacity of >200MT of CO_2. There is a proven reservoir seal and high injectivity potential. There is also an ongoing assessment of the integrity of existing facilities (wells, platforms, and pipelines) and developments with a CO_2 source in South Korea (transport via vessels or pipelines). Ongoing engagement with IFC is to fully assess the project and relevant legal and regulatory frameworks. The expected start-up injection was initially planned to be in 2025 to align with the expected end-of-field life in 2022, but that has been postponed as the field is producing for longer than initially expected.

BU storage potentially provides the highest CO_2 injection capacity in the world, assessment is ongoing to verify and certify the storage, including MMV. The government of Timor Leste is committed to establishing the CCUS legal and regulatory frameworks in the next 5 years to support CCS operation in Timor Leste.

Discussion

Q1: How far along is the Northern Lights pipeline of customers?

The Northern Lights currently have four customers, two in Langship (Heidelberg cement, Norway, and the Fortum WtE plant) one will be ready for the initial start-up in 2024 and there are delays with the second. The other two are the Yara ammonia plant in the Netherlands and Orstad biomass in Denmark.

Q2: is the purity requirement for these four emitters (Northern Lights) the same?

A study on components was published in Phase 1 and has gone through further technical evaluation, the requirements will be published on our website when finalised.

Q3: What are the key risks you worry about (to all) is it supply, or injectivity?

Mostly aligning the revenue with the costs, and managing the delays of returns to investors. The UK approach is to sequence the storage sites and emitters together, one of the main risks for us is not storage. The key risk is how do you protect any part from becoming a stranded asset. That is what the UK government is trying to manage.

Q4: For the Prinos site in Greece, it's interesting to see cement works in Greece receiving Innovation Funding, is this a candidate for CO_2 source?

Yes, TITAN received innovation funding for a FEED study and is progressing rapidly with 3MT of emissions funded. We have not disclosed our commercial terms yet, so it will either go to us or the Ravenna Hub in Italy.

Q5: For Acorn we have had the track two announcement now. The sources have yet to be agreed by the government. Which are you anticipating will bid?

The main emitters expected are the St Fergus terminal, Peterhead power station, and central Scotland, using the feeder 10 pipeline transporting 6-10Mtpa from central Scotland.

Q6: For ITRI, exciting news about the injection test. What's the motivation for the monitoring well? Will you need a monitoring well in the future?

It is an important site for us. The site will be offshore. The monitoring well will include PT, VSP, DAS, and DTS. With DAS in the injection well too, if we want to see the plume then we need DAS DSP in the injection well as well. We have a future joint research project with Berkeley Lab to get help with the monitoring project.

Q7: there is a diversity of storage reservoirs. What are the drivers for choosing different storage reservoirs?

For Viking CCS the driver was the operating licences that were operated by partners and with their own infrastructure which have over 40 years of experience and production records plus proximity to emissions sources.

The Northern Lights storage was chosen by Gassnova (Norwegian Government) and it's a very nice reservoir. Many people ask 'why are you near the Troll field?' ultimately it was the best site that is close to facilities.

Tim Dixon at the close of the session summarised other offshore projects not represented.

1. Greensand (INEOS), Denmark
2. Bifrost, Denmark
3. L10, Netherlands
4. Poseidon, Norway
5. Polaris, Norway
6. Smeaheia, Luna, Trudvang, Poseidon, Havstjerne Norway
7. Woodside, Australia
8. Endurance Field, East Coast UK
9. Carbon-Zero (Cox Oil) Gulf of Mexico
10. Also, the longstanding offshore projects Sleipner, Snohvit, K12B and Tomakomai.

Session 3: Injection & Wells | Chair – Katherine Romanak

Managing our well stock | Owain Tucker, Shell & Nicola Clarke, IEAGHG

Nicola introduced the background to IEAGHG Risk Management Network and the most recent meeting in June at Heriot-Watt University on the topic 'Well integrity in a CCS project'

Owain went into further detail on wells and the importance of cementation and plug status. There are >8 million wells globally and knowledge about their status varies widely in digital and paper records. A 'no stone left unturned' approach is necessary to assess the impact of legacy wells on a potential storage prospect. A lot of work has been done on cement, and we have to realise that the subsurface is normally a stagnant system – so rates of alteration are limited by diffusion kinetics. A key message from the workshop was that 'alteration is not degradation': cement can be altered but is not necessarily degraded. If there is an existing flow path there will be a flow path for CO_2, conversely if there is not then it is all but impossible to create one.

It must be stressed that there is no capacity without containment according to SRMS (SPE Storage Resource Maturation System) so understanding the impact of wells on resource calculations is critical. Ways to unlock storage resource that has been impaired by legacy wells need to be researched, for example, quick cost-effective ways to remediate old wells. We also need research on natural wellbore closure. Nature can close wells up, for example in Brazil, drilling into salt (halite), if the well is left open (i.e. not cased) then the salt will flow and close the well very quickly.

Challenges for evaluating legacy well integrity include: there is no database of cement plug depths; cost and impact of remediation might be greater than the impact of a leak; quantifying potential leakage rates in old wells; data management; how we communicate risk with financers and insurers?

Recommendations: Cross-cutting meeting with insurers and financers, efforts to have 'best practice' examples, update capacity estimates, refocus on speciality cement (when it is beneficial and when is Portland cement better), and more case studies on existing leaky wells.

Q1: How much would it cost to assess an offshore site

The Captain Fairway (Acorn site) has 100 wells which took three FTE (full-time equivalent) staff 6 months to assess, so 18 months of effort. It's an interdisciplinary problem involving geologists, engineers, and drilling engineers. Do it simultaneously with assessing the caprock.

Q2: what happens when you intersect a well?

For migration-assisted storage, like at Quest in Alberta, Canada, the CO_2 is immobilised by capillary trapping and dissolution trapping. In a case such as this, a well (and a store) will end up with some carbonated water. When reusing an existing field, there will be free-phase CO_2 for millennia, so in this case, you could have flow to the surface. If this is uncontrolled it is termed a blowout.

Q3: Regarding well issues in the Petrel sub-basin – what are the well issues there?

If you drill through a water-bearing formation, is there a risk to the environment? In this case, you have drilled a water well. If you drill through gas – yes there is a risk of flow to the surface. Operators plugged the gas bearing interval, and then set a shallow plug to stop the water flow. This shallow plug would not stop CO_2 from the Elang and Plover. They were responsible operators working according to their regulator-approved plans, but neither they nor the regulator were thinking about pumping in CO_2.

Capacity/pressure space – Gulf of Mexico | Alex Bump, University of Texas

The Gulf of Mexico contains over 1 million wells and the states of Texas and Louisiana lead the US in emissions and have a proven hydrocarbon system. This presents both a huge need for emissions reduction and a huge potential in available storage resources. The State waters have 30GT of 'static storage capacity' and the Texas coastal Miocene system has about 125Gt. However, the calculation of static capacity depends on the assumption that there are open boundaries in the reservoir. Faults will form barriers and compartmentalise the reservoir. There is an increasing number of large-scale proposed storage projects. Each will create pressure boundaries for each other, and leads us to question 'what happens if we pressure these up? what if you pressured it all up? what capacity do you get?'. By running calculations using the same grids, porosity, allowable pressure change, and total compressibility, these result in a reduction in capacity from 125Gt to ˜12Gt, that is roughly 0.4% storage efficiency instead of 4%. At present, some operators are working on 40%. This is achievable in only one or both of two ways—you either produce water or you swipe pressure space from your neighbours.

How do you reconcile competing uses? Screening in the Gulf starts with the well map, and identifying where are the gaps? Wells are not evenly distributed, they are generally associated with structural closures. Injection down-dip in the gaps between wells offers the chance to avoid them. The pressure footprint of injection is defined in law by the Area of Review (AoR)—the region of pressure elevation sufficient to lift dense injection zone brines up to the lowest freshwater via a hypothetical open wellbore. Three examples of injection into a typical Gulf Coast reservoir were presented with a 400km^2 area, closed boundaries, 25% porosity, and 100mD permeability. We'll inject 1MTPA for 20 years at 2.5km depth and look at the resulting AoR. A. if you only have 100m reservoir thickness, you will raise pressure enough that the AoR covers the entire 400 km^2. B. If you add more reservoirs, such that the net thickness is 400m, you can reduce the AoR to a small circle ~5km in diameter. C. But if someone else comes along and adds another, identical project anywhere in the same compartment, the combined effect is to pressure up the whole thing. Fringe pressures from the 2 projects add to push you over the edge. No one is thinking about this—projects are being considered only in isolation, so far as I know. There are broader implications for regulation, these include project spacing and the value of land. The big lever is water production—if you can produce water, you can balance injection and withdrawal and manage pressure. But then you need to do something with the water, which carries its challenges. Without water production, you achieve these high storage efficiencies only by swiping pressure space from your neighbours. This is something to consider, do we let market forces decide? i.e. first man to the post, this has implications on land value, project leasing, and regulatory spacing. The current regulations all focus on pore space, but the key measure is pressure space.

Comment 1: we have been thinking about it in Northern Lights, what will happen if we are all injecting at the same time? How do you calculate?

The work will be published and Alex is happy to share.

Comment 2: we (BOEM) are also indeed thinking about this in the US OCS (outer continental shelf) – thanks for the work

Q1: pressure limitation is a concern for saline formations with closed boundaries? What about open boundaries – is it ok if wells are spaced? What about depleted fields -ok?

Depleted fields are pressure-depleted because they are closed boundaries. Basins have edges, even in open boundaries you are dependent on compressibility etc. Every reservoir is closed at some scale.

Time and quantities matter—the greater the volume and the faster the injection, the more likely you are to see closed boundaries

Q2: if two operators are injecting, the first 'wins'. What's the best way to get the most amount stored, from the state perspective?

Incentivising projects, best assigning their own compartment. The goal is to get as much CO_2 as you can in the ground, you probably need more wells to evenly distribute. The bottom line is for everyone to be aware of the potential problem, to model multiple projects together, and then monitor and update plans as they inject.

Interactive session, Key aspects to planning a CO_2 storage site | Alex Bump

Alex asked participants to write down their primary concerns in six categories: geological properties; pressure barriers; infrastructure; permitting; public outreach; other. All comments from the in-person and online participants can now be viewed here.

Session 4: Legal, Regulatory & Accounting | Chair- Paulo Seabra

Delivering Carbon Storage on the UK Continental Shelf – The NSTA's role in regulating and stewarding activity at pace and scale | Matthew Farris, North Sea Transition Authority

The North Sea Transition Authority (NSTA) are the UK's licensing and permitting authority for offshore carbon storage on the UK Continental Shelf. The NSTA's role is regulating, licensing, permitting and stewarding activity effectively to enable the North Sea energy transition. UK Government targets require pace and scale to deliver four CCUS clusters by 2030, with 20-30 MtCO2/year 'Capacity'. Further projects are needed to meet targets thereafter.

As of August 2023, the NSTA was;

- Stewarding 6 carbon storage licences across 3 projects.
- Had awarded 5 carbon storage licences and extended duration of two carbon storage licences.
- Was running the UK's first ever carbon storage licensing round in which 21 licences are offered for award covering ~12,000km2, (these have since all been awarded).

There is an expectation that licenses will be competing for pressure space, and need to make sure they work together and with other marine users. NSTA will steward this the same way they steward area plans. The time required to meet targets is a challenge; it typically takes 6-9 months to receive applications, 2-4 years to characterise a site, 2 years for Assess-Define including 6-9 months to process a permit application, so between 5 and 8 years before a Carbon Storage Permit is awarded. For many new licences, this puts the development and first injection beyond 2030.

NSTA has published guidance on Applications for a Carbon Storage Permit and will publish further detailed guidance on deliverables/expectations.

The high-level regulatory map is very complex, NSTA has good engagement with other regulatory stakeholders such as The Crown Estate/Crown Estate Scotland, OPRED and DESNZ and as part of the NSTA-led Energy Integration Project has mapped out key consenting and regulatory steps. Specific areas of licence management and leases are being addressed including consents and operational activities. When the full potential of the basin is better understood, then stakeholders can have a coordinated approach, and deliver results quicker, also reducing co-location issues. NSTA has several current co-location initiatives they are working on.

ISO Update: WG3-27914 | Simon O'Brien, Shell

ISO standards are voluntary, revisable and developed based on a community consensus and do not take precedence over law. The standard is initially written by a Technical Committee comprised of subject matter experts, approved by participating member countries and revised/updated every 5 years. They are primarily used by private stakeholders; although governments may choose to adopt the standards. There are many goals and benefits to using standards such as promoting knowledge transfer, enabling economic growth and public acceptance.

ISO/TC 265 – Carbon Capture, Transportation, and Geological Storage. ISO International Technical Committee for Standardization in Carbon Capture and Storage was established in 2012. The purpose is to promote environmentally safe and long-term containment of carbon dioxide in a way that minimizes risks to the environment and human health. 25 Participating "P" members are obligated to vote on all questions and 17 Observing "O" members who can submit comments and attend meetings. The general principles of these standards are technology neutrality, regulatory neutrality and complementing other standards. TC 265 has published several standards;

- ISO 27913 – Pipeline transport of CO_2
- ISO 27914 – Geological Storage of CO_2
- ISO 27916 – Storage of CO_2 using enhanced oil recovery
- ISO 27917 – Vocabulary for cross-cutting terms
- ISO 27919-1 – Performance evaluation methods for post-combustion capture integrated with power plant
- ISO 27919-2 – Evaluation procedure to assure and maintain stable performance of post-combustion capture plant integrated with a power plant.

Standards can be used by regulators as 'optional' references for performance-based frameworks.. For example; USA - ISO 27916 standard is referenced in the 45Q application by the Internal Revenue Service; Norway referenced the standards in their guidelines (not regulations), they indicated that ISO 27914 should be used for assessing well barriers; Canada isbuilding regulations that align with the standards. In the EU – the taxonomy aligns.

Revising of the ISO 27914 standard for CO_2 Geological Storage is in progress as the original standard was published in 2017. The purpose of the standard is to promote commercial, safe, long-term containment of Carbon Dioxide in a way that minimizes risk to the environment, natural resources and human health. This covers management systems, site screening, selection and characterisation, risk management, well infrastructure, injection operations, monitoring and verification, quantification and verification (new scope added in 2022) and site closure. Ideally, it will be ready in late 2024.

Transport of CO_2 for Offshore Storage under the London Protocol | Tim Dixon, IEAGHG

The London Convention and London Protocol are marine treaties – global agreements regulating the disposal of wastes and other matters at sea. The London Convention was established in 1972 (82 countries) and the London Protocol in 1996 (53 countries as of October 2019). The London Protocol prohibits the dumping of all wastes with some exceptions depending on material and access to waste disposal. Initially, the London Protocol prohibited some CCS project configurations, so in 2006 some amendments have been adopted to allow CCS. CO_2-specific guidelines were published in 2007, to guide assessment, permitting, monitoring and risk management - effectively an environmental impact assessment process.

London Protocol Article 6 prohibits transboundary transport of CO_2 for geological storage. Norway proposed an amendment in 2009 to allow the export of CO_2 provided there has been an agreement or arrangement between the countries concerned. But up until October 2019, there was still an export ban in place as not enough parties had accepted this amendment for it to come into force.

In October 2019 the Netherlands and Norway proposed to LP14 meeting at IMO in London a "Provisional Application" of the export amendment. This was successfully adopted on 11 October 2019. CO_2 export is now allowed for offshore storage. The guidance documents have been updated. The exporting country characterises the CO_2 stream and the receiving country characterises the storage site. Declarations of provisional application have been received by IMO from the Netherlands, Denmark, Korea, Belgium, and Sweden as of April 2023. Denmark-Belgium has done the first export for the Greensands test injection.

Implications of the Net Zero Industry Act for CO_2 storage development in the EU | Toby Lockwood, CATF

The Net Zero Industry Act (NZIA) has implications for storage. CATF (a philanthropic organisation of 160 global staff) works in the EU, and they have looked at coordinated infrastructure build-out and enduring 'beyond demonstration' policy, highlighting both storage and funding gaps. They have campaigned for the inclusion of CO_2 storage in the TEN-E regulation and non-pipeline transportation in TEN-T. CATF is tracking over 100 projects, largely storage in the North Sea. The past year has seen a big increase in North Sea exploration licences. There are lots of capture projects but few storage projects in Europe, so the Net Zero Industry Act has set bold targets of 50Mt target for storage capacity in the EU, with the obligation on Member States to share storage data and declare CCS plans and needs. There is an obligation for oil & gas companies to share data and develop storage capacity. Using the CATF cost tool to estimate costs we see that storage is feasible and that the oil & gas sector has the resources and expertise to scale up rapidly. 350MT CO_2 will be estimated to be transported in 2050 and two scenarios were presented, one with export to large storage options, and one with domestic onshore storage options. It was suggested to create a Capture and Storage Platform, with a CO_2 matching platform for emitters and storage options.

Recent Advancements in the Carbon Capture and Storage (CCS) Regulatory Framework in Brazil: Progress and Prospects | Isabela Morbach, CCS Brazil

There is a growing market for CCS in Brazil, with ~200 $MtCO_2$/y identified potential for CO_2 capture, and ~40MTPA identified potential for Bioenergy with Carbon Capture and Storage (BECCS). Sources of interest for BECCS are concentrated in the south of Brazil – where ethanol production is located. A map of storage opportunities was presented, spread across Brazil with a range of aquifers. No numbers are yet available on storage resources – there is a paucity of seismic data. There are currently 4 planned projects, but government regulations do not currently allow CO_2 storage although legislation is in progress. The proposal is similar to other regulatory frameworks, EOR is already permitted in Brazil. The system deals with the long-term liability and permanent transfer of responsibility to the state. The bill is now awaiting approval.

Session 5: Interaction with other users of the seabed | Chair- Lizzie Whiteley

The competition for offshore real estate: Windfarms and Hybrid Uses | John Underhill, University of Aberdeen

Co-location issues are increasingly prevalent in the North Sea. For example, bp-led Endurance, a Track 1 carbon store, initially overlapped with the Orsted operated Hornsea windfarm which is the largest offshore fixed installation in Europe. Although this specific issue has now been resolved by changing the location of the wind farm, the issue has not gone away and affects many areas.

Conflict for space matters because it impacts monitoring, risk, insurance and indemnity. We have different regulatory bodies for different sectors. How do we decide what sector has primacy? Could it affect the UK's ability to meet Net Zero targets? Underhill et al (2022)[1]

Another example is the Pickerill Field, a Rotliegend sub-salt field with potentially a large capacity for CCS as 440 Bcf is produced in total[2]. A wind farm (Outer Dowsing) has been proposed to go over it. The top structure map shows the production revenue fence – and declares the totality of production but the field is compartmentalised and there are three separate "mini" Pickerills which make up the opportunity. A similar compartmentalisation affects the Inde and Viking Fields, something that has led the Victor field to progress in the Viking CCS permit.

Composite Common Risk Segment (CRS) Mapping can be used to produce traffic light-coded maps, to help identify where the best areas for CCS are. Red – run out of seal or reservoir with high risk, orange – medium risk, and green – low risk. Then overlay the wind farms and marine conservation areas as they must also be considered. We must understand how many stakeholders are in the game.

The main conclusion is that it's getting mighty crowded! Can we find a way for wind farms and carbon stores to co-locate e.g., through novel MMV strategies? There are lots of competing stakeholders and regulators in the mix. What has primacy when there is overlap? Unless we get it sorted out, we could be imposing barriers to meeting targets. Is there a need for an overarching Net Zero Regulatory Body to referee and adjudicate when conflicts arise to ensure UK Net Zero plc makes the best and most informed choices?

Q1: legacy wells are not plotted, what happens if you have to bring rigs back in to remediate a well?

Yes, one rogue well is a red flag for a site, and you need to remediate it and be able to get there. There has been little to no discussion about how you make a pathway to get there.

Q2 Who will take the responsibility here? Crown Estate or Wind Farm operators?

It's really new territory. I don't think the wind farms know that this is an issue. If something leaks after 31 years, who is responsible for the leakage? Many issues here are to be resolved.

Q3: Who is regulating the outcrop of Bunter on the seafloor under the wind farm area, what comes out? Who is responsible? Outside of the licence area. We do have to have those conversations now. Do fear ambition is not going to be met by the reality.

Wind developers in a different time scale, different pace to the CCS, and there is potential for a lot of wind farms.

The Acorn project has partial overlap with wind farms in the Outer Moray Firth (Marram Wind), as do some sites in the East Irish Sea.

Q4: PilotStrategy Portugal, will be similar to our case. Wind farms are more attractive than CCS in Portugal. Do you see any positive synergies can we learn?

[1] Underhill, J.R., de Jonge-Anderson, I., Hollinsworth, A.D. and Fyfe, L.C., 2023. Use of exploration methods to repurpose and extend the life of a super basin as a carbon storage hub for the energy transition. *AAPG Bulletin*, *107*(8), pp.1419-1474.

[2] De Jonge-Anderson, I., and J. R. Underhill, 2022, Use of subsurface geology in assessing the optimal co-location of CO2 storage and wind energy sites: Earth Science, Systems and Society, v. 2, 10055, 20 p., doi:10.3389/esss. 2022.10055.

Oil and gas production are generating more electricity offshore to reduce dependence on onshore power generation. Much more dialogue is needed to get an understanding of the issue. Crown Estate and NSTA have opportunities.

There was a report commissioned by Crown Estate and NSTA, a couple of years ago. With workshops looking at juxtaposition, and actions to start an overarching body.

The last wind licence round (UK) had no bidders, suffering from strong financial headwinds, labour costs and raw materials. This buys a little bit of time to get it right.'. The price for wind is too low. There are lots of issues with wind that are on everyone's radar.

The role of CCS in an integrated energy system at the North Sea | Joris Koornneef, TNO

The North Sea is home to many different sectors, and we need to fully unlock the potential here while respecting the carrying capacity of nature and society. The North Sea Energy (NSE) Program has almost 40 partners from industry, science, research institutes and NGOs. The consortium aims to identify, assess and progress offshore synergies between CO_2, Hydrogen, Natural Gas and Electricity transition at the North Sea. In the NSE program, we look for synergies between offshore sectors, also concerning other transitions (food, nature) and users at the North Sea. Within the energy sector, CCS is a key pillar.

We currently focus on establishing spatial-specific development plans for areas where these energy functions coincide; e.g. Energy Hubs. A roadmap for the North Sea is missing. This means there is no guiding document for offshore commodities on how space will be divided between different users of the sea. Looking at the coming decades (up to 2050) we see a decline in natural gas, and huge growth in offshore wind, and other offshore renewables e.g. solar; green hydrogen (transport renewable energy as molecules to shore), blue hydrogen, and CO_2 stored. However, targets for the development of these four energy commodities are not equally stated by the North Sea countries. This gap needs to be filled.

In our scenario, we envision a peak of the CO_2 storage sector for 2050 with 170 Mt of CO_2 stored on an annual basis. To visualise the spatial transition we have developed the North Sea Energy Atlas online, which endeavours to publish as much spatial information on offshore energy as possible including spatial conflicts.

Doing a deep dive into one of the development areas (we dubbed this Hub West) in the western part of the Southern North Sea, between the UK and the Netherlands. we are developing future pathways to show synergy and spatial challenges between wind, gas, CCS and other users and aim to avoid competing use of space.

For example, the Dutch Lagelander wind area was originally a candidate area for the Offshore wind Roadmap until 2030/2031, but there are spatial conflicts due to oil and gas platforms and safety areas for helicopter landings. This reduces the area for the wind developer and has a negative impact on the business case for developing offshore wind in that area. Also, it is an area of high relevance for CO_2 transport and storage (e.g. Aramis CCS) and should possibly be open for seismic surveys in that respect. The wind area has therefore not been selected to be developed in the short term.

In the NSE program, we are also studying the synergy between offshore blue and green hydrogen. Together they could form a strong supply mix to kickstart the hydrogen economy and provide a stable and secure hydrogen supply. This also includes blue hydrogen being produced from natural gas. Competition could then exist between blue and green in the re-use of wells, subsurface reservoirs and pipelines (H_2 transport and storage & natural gas & CO_2) with time being a very important factor that determines the availability of existing infrastructure for transition developments.

Regarding climate and nature, CCS has clear climate benefits but also needs to avoid negative (local) environmental effects. It all demands a coherent strategic and long-term plan; CCS is crucial for the North Sea but is intertwined with the wider energy system and other transitions at sea.

Q1: Do we rely on politicians to agree or does money talk?

It starts with understanding each other better, we need to talk about what the potential conflicts and synergies are. We need to think outside of the sector or even national boundaries, thinking about the options and what synergies there are to be explored. Make it part of the wider North Sea strategy for CCS and then trickle this down to individual licence applications. There are smart solutions possible when working intensively together.

Q2 What are the monitoring challenges?

There are challenges of shooting 4D seismic in wind areas so depending on the project specifics it is needed to also look for other ways to do MMV in that context, and then ensure that the competent authority and windfarms are on board with these monitoring technologies. This discussion is needed soon and at a fast pace to limit any spatial conflicts in the future.

DAY 2

Session 6: Transport & Infrastructure | Chair – Owain Tucker

Development and operation of CCS pipeline network | Stefan Belfroid, TNO

Two CCS developments in the Dutch North Sea will start soon, Porthos and Aramis. They are different types of networks: one a single source-single pipeline single store and the other a backbone network with multiple hubs with different owners and spokes to different storage options. What is the best operating pressure, how do you control the pressures and flow rates, and what happens with extensions to new hubs?

Network behaviour is controlled by well pressure or reservoir conditions. Well injections are governed by: erosion/vibration; downhole temperature (hydrate prevention, fault activation); downhole pressure (reservoir pressure drop); and wellhead temperature (e.g. two-phase flow, SSSV, freezing annulus fluids). A well has a minimum and maximum flow; very low flow can sometimes be present in certain regions. The operational range is restricted by the wellhead temperature. The operational range is very sensitive to the manifold temperature and reservoir injectivity. The ways to extend the operational envelope include injection in the gas phase; increasing the manifold temperature; designing well completion such that wellhead pressure is high enough; and downhole chokes. However, there is never a single solution.

In this study, we designed a simple network, with a 100 km backbone, and four hubs with 3,3,1,4 wells. The trunkline has a minimum operation pressure, at the hubs there is a pressure control to keep pipelines at a minimum pressure. At hub level, there is a desire for flow control which will determine the final flow distribution. Regarding operating pressure, the minimum pressure is determined by the worst well in the system. Depending on the composition and temperature, the pressure can be reduced without too much temperature cost. In case of contaminants larger temperature drops are possible. There is an economic incentive to be at minimum pressure. Is it advantageous to run at higher pressures than minimum? In terms of the dynamic response: the pipeline must be able to handle fluctuations. Pipelines are in the liquid phase. The response depends on well locations. Higher operation pressure allows for better control.

The performance of a network depends on the wells. Wells performance changes through time as the reservoir pressures change with injection. It is critical to calculate the pressure and flow rates in the network for a complete injection period.

Conclusions: CCS network operations can be complex. Pipelines operate in the liquid phase, meaning that the operating pressure is sensitive to dynamics. Minimum pressure, to ensure single operation. The maximum operating pressure is determined by the worst injection wells. Therefore, coordination between hubs might be beneficial.

CO_2 Shipping Developments | Ajay Edakkara, Shell

Shell has a long history of shipping and maritime operations, with a huge shipping arm of 450 maritime professionals around the globe. Some of the liquid CO_2 shipping backgrounds and challenges were presented. We are used to the transport of food-grade CO_2. For Northern Lights, the ships are under construction with a 7400 tonnes capacity. These are medium-pressure ships (around 15 bar). There are also low-pressure, lower-temperature, options on the drawing board (6.5-9.5 bar). There is the potential for dry ice at low pressure, and Shell is looking at how to manage that. Owing to the density of CO_2 being higher than LNG, it results in ships being longer, broader and deeper than LNG carriers. Larger ships will generally mean low-pressure (tanks can be lower unladen weight). Larger ships are required for economies of scale. Emitters generally have limited or no knowledge of shipping/terminal/jetty interface requirements. Ajay presented the designs for the medium pressure 7500 tonne ships, and early-stage designs for inland waterways (barges), and larger low-pressure vessels with capacity up to 70,000m^3. Standardisation comes from using ISO and Society of Gas Tankers and Terminal Operations (SIGTTO), all under the IMO (International Maritime Organisation). Classification societies include e.g. DNV, NGO, OCIMF, ISO, SIGTTO. SIGTTO is progressing with guidance documents to provide guidance on safe transport of CO_2 etc. including terminals. ISO technical reports on purely shipping are designed to give a good insight for emitters and policymakers.

Qualitative Well Integrity Risk Assessment for Carbon Storage in the Gulf of Mexico Depleted Fields | Brigitte Petras, Battelle

The scope of the work is safe CO_2 storage in offshore reservoirs by developing qualitative risk assessment for ranking wellbore integrity for potential CO_2 storage applications from well records in depleted fields. Wellbore cement integrity is important, followed by casing integrity. We have identified stoppers e.g. leakage pathways and different cements, the leakage pathways could be from multiple cement defects. Well integrity analyses has a focus on cement integrity at caprock and cement plugs. In looking at offshore well leakage impacts, studies show that CO_2 disperses and dissolves quickly but could have an impact on certain habitats and could affect existing infrastructure based on the depth of water. In a GoMCARB study at >50m depth CO_2 attenuates in water, at 10 m water depth with a large-scale blowout underway, hazardous CO_2 concentrations extend to hundreds of meters from the emissions source. In the ECO2 EU Project they studied natural and artificial CO_2 seeps in the North Sea and the Mediterranean.

The general methodology is as follows: data collection of case studies – rank risk likelihood – rank severity of impact – well integrity risk scores. The required data includes geologic data - well ID and location data, such as the geographic locations of wells (longitude and latitude) and well records. Collecting the data is not simple. The well integrity risk assessment workflow is risk= likelihood * impact. The objective is to rank well attributes for leakage risk. The overall leakage risk can be estimated afterwards. Three impact categories were used: environmental; water depth; and proximity to existing infrastructure/transit. In summary, legacy wells are a potential leakage that have to be considered when scoping out carbon storage reservoirs. Qualitative risk assessment is a systematic high-level scoping tool to start this process and identify low and critical risk wells, and where additional information is needed to assess risk. More detailed studies can be done, including geology. In this project missing data was a key issue.

Practical Approaches to CO_2 Subsurface Storage Risk Assessment | Sheryl Hurst, Risktec

Successful risk management requires two main aspects. A structured approach includes identification, analysis (how likely) and evaluation (can we live with it). Secondly, an appropriate and proportionate approach, asks what is acceptable to intolerable, and evaluates complexity. The approach is outlined as follows: risk identification – qualitative risk analysis – risk evaluation. Early stages are different from late stages. Risks include scoping the assessment of loss of containment, injectivity, capacity, induced seismicity, effects on environment, health, reputation and finances. Structured qualitative approaches include: potential applications; scenario identification and ranking; review and communication of risks. Considerations are: uncertainty, what are the differences with the oil industry? Can we accept the risk? Risk scenarios involves risk identification and ranking with structured brainstorming e.g. geological leakage pathways. Create a risk assessment matrix with uncertainty and acceptability. Risk analysis and evaluation, asks: what controls exist? how good are the controls? what is known/unknown? what uncertainties exist? what more could we do? Problems could include that the comparison is not possible. Advantages include that it is easy to communicate with people. The example given is a populated bowtie, which draws your attention to the gaps and is easy to communicate. For a quantitative assessment, and only move to quantitative if you can't live with the level of risk e.g. wells, for each barrier give an estimation of permeability and probability of failure; estimation of leakage rate; event tree analysis of each leak path; and the summation of results.

In summary, a structured risk assessment approach is required. There are many different stakeholders. The most appropriate tools/techniques depend on the level of risk, the complexity/uncertainty, the available information, and the end use/ audience for the assessment. Bowties provide an easily understood representation of how risks are managed as they are applicable at all stages, the detail can be varied to aid communication to specific groups, and they can accommodate uncertainty. Quantitative approaches can be used, where there is a scarcity of data they are indicative only and comparative rather than absolute, as they infer a degree of accuracy.

Comment from the chair –it's getting the right level of communication for the right people. Scale the communication to the audience.

Discussion

Q1: for Brigitte on micro annuli.

This is more detailed than we have covered in our survey. There are other clues you could look at, it's a complex question.

Q2: what is the viability of transport in the gas phase in the offshore?

Unlikely, due to compression.

Q3: How likely is shipping in the outer continental shelf?

Yes, there is potential to use it in conjunction, no reason why not. Difficult to give firm options. Challenging permitting, with pipelines and stakeholder management.

Q4: On managing the value chain. Regarding CO_2 purities, capture on power plants might give 95% purity. Should impurities be managed at emitters or a central hub? Does Shell have any solutions?

The question is the level of impurities, not the purity of CO_2, even at 99%, what is in the impurities is the key. Should be at the capture plants. We can't have it on the ships. In Asia Pacific the travel time is 5-15 days. The capture plant has to get rid of the impurities. IMO standards state that you are not allowed to vent (on ships) due to safety

You could strip out at the final leg. The question is what do you do with what you strip out? You end up with another conditioning unit.

Q5: regarding shipping, how far are we in using the ship to take LNG to one country and return with CO_2 back or is that a non-starter.?

It is going to be a very expensive option, due to pressure. If you combine it, it is possible but at what cost? CO_2 will be the determining factor and not carrying enough LNG to be cost-effective. The commercial case is not attractive.

Comment – if three or more side-tracks are considered high risk, most wells in the GOM would be high risk.

This would be good for quick screening.

Comment from Stefan – the thing I want to stress, is an operational issue – expect some competition between hub owners. It can be detrimental to other users. Injectivity is very sensitive to temperature effects, even between the seasons. The difference in temp and pressure, 5 degrees C vs 15 degrees (sea temperature) the velocities change, 100 km pipeline in winter arrives at ambient temperatures but in summer it does not. 2 degrees, could be a dramatic change in density/pressure.

We see this at Quest. There is better injectivity in winter than in summer by about 10-15%.

(Battelle) On well integrity, as we look at more permitting we are getting more questions on specific wells and we hope to present more on that next year.

Q6: are ships designed for rivers?

Barges are designed for rivers, but the quantities are limited on those., Mississippi has restrictions and its own criteria e.g. depth of the channel and CO_2 barges will be deeper. We have looked at that – lower capacities and won't necessarily be cost-competitive against pipelines.

Q7: regarding the re-use of pipelines.

It can be useful between platforms. Acorn is going to re-use the pipeline, need to check corrosion, ran a pig through to check if it is still there and the corrosion status, and to check if it can take CO_2. What are the original specifications? It's the coatings on the inside and outside that matter. Many onshore pipelines can only take the gas phase. The alternative is to add lots of booster stations along the way.

Q8: for Ajay, on the slide of three ships there is CO_2 capture on the ship on top of the image, is this happening?

We are working on the design, it is a base case for the large ships but not for the Northern Lights project where the vessels are smaller so have less space for capture equipment.

Session 7: Stakeholder Engagement | Chair – Tim Dixon

Stakeholder views on offshore monitoring in the Gulf of Mexico | Katherine Romanak, University of Texas at Austin

The Gulf of Mexico region has many sources of CO_2 that could be stored in nearby large underground reservoirs. However, to implement CCS projects, we need to understand the interplay between societal, legal, regulatory, and technical factors. The legal and regulatory aspects are designed to protect the public and allow them to comment on the projects. The technical and societal aspects are more complex and involve stakeholder interactions, especially with the storage process. We need to address two main issues: how to provide assurance, understanding, and acceptance of CCS to the public, and how to communicate the technical details to a non-scientific public.

One of the technical issues is how to explain how the CO_2 is stored, how long it will stay there, and what are the geologic mechanisms that ensure its safety. One of the socio-emotional issues is how to overcome the negative perceptions and the lack of trust in the industry that some people may have. These issues affect the acceptance of CCS, which is critical for the success of the projects. As CCS is growing and more projects are being developed, more people are facing the possibility of having CCS facilities near their homes. For many, this is the first time they have heard of CCS. Moreover, we need to consider the concepts of environmental justice and responsible research and innovation, which are gaining traction in society. Therefore, we need to shape our outreach in the Gulf of Mexico in a way that we can learn from the important societal conditions and provide greater insight into how to create successful outreach for the projects.

One of the research questions we asked was: what are the roles of technology and society in reassuring the public about CCS? We want to know which factors are more likely to garner public support for CCS and which factors are more likely to assure the public that CCS is safe. We also want to know if the stakeholders would be willing to participate in the monitoring of the CO_2 storage. We need to balance the stakeholders' assurance with the cost-effectiveness of the monitoring. We compare two types of monitoring techniques: complex monitoring which uses complex algorithms to determine thresholds, and simple monitoring which uses simple data reduction with clear graphical thresholds. Monitoring is tricky because it can provide security, but it can also raise doubts (for example, if people think that extensive monitoring means that CCS is dangerous or if less extensive monitoring makes people think that the project is not rigorous enough with safety).

We conducted a survey with a sample of Americans who are over 18 years old and live in Texas, Louisiana, and Florida. We chose these sites because they are close to CCS facilities, both onshore and offshore. We sampled 997 subjects, 44% male and 56% female. We used a novel segmentation approach that divided the subjects into two groups: those with higher science orientation, who prefer complex messages and consume science media, and those with lower science orientation, who struggle with complex messages and consume little science media. Science orientation is quite critical for understanding and accepting CCS. We conducted a 2x2 experiment with four key variables: attitudes, perceived ease of use, confidence in doing the monitoring themselves, and support for CCS.

The results showed that for those with higher science orientation, social norms did not influence their opinions, as they could assess and understand the results themselves. For those with lower science orientation, social norms were the primary influential factor in their opinions. Simple monitoring was favoured by both groups, but for those with lower science orientation, it was only effective if it was delivered by a community member they knew and trusted.

Our conclusions and recommendations are: beliefs about CCS are different among people with higher science orientation and those with lower science orientation. For both groups, simple monitoring is preferred over complex monitoring. It is important to engage community leaders in stakeholder outreach, especially those with a higher science orientation. The public should not be treated as a single entity but as a diverse and heterogeneous group. Society must act to address the climate change challenge, and social science collaboration can help to achieve that.

Key determinants of public reactions to CCS in the UK: What shapes acceptance? | Darrick Evensen, University of Edinburgh

Currently, work is ongoing in scoping a CO_2 storage research facility in the UK[3]. This has a social science component to assess social attitudes to local hosting of major 'Net Zero' infrastructure and citizen science opportunities beyond CO_2 storage. We undertook a longitudinal sample that is trackable throughout time, this occurred in July 2023 with a YouGov survey in the UK, with a national sample of 4,109 and a localised sample in the Humber region (high industrial cluster) of ~1000 people. They watched a video about CCS at the beginning of the survey.

[3] A scoping study for a deep geological carbon dioxide storage research facility (British Geological Survey). https://www.bgs.ac.uk/download/a-scoping-study-for-a-deep-geological-carbon-dioxide-storage-research-facility/

40-50% had no knowledge of CCS at all. There was support for storage from different capture technologies but less for BECCS. Trust in institutions to help deliver CO_2 storage projects regarding competence and trustworthiness, the BGS and NERC scored highly whereas government and councils scored poorly, with industry in the mid-range. What are people going to do if something is built? 40-45% would offer support, ~30% would oppose (with 15% actively opposing) and 27% were indifferent. What would they do? contact local politicians, tell family and friends, use social media etc. Some predicators of active opposition include safety concerns, low trust, females, knowledge (more likely to be active – either for or against), and political party (high amongst greens and Brexit voters). In cases of active support, predicators include high trust, male and the desire to meet climate goals and reduce CO_2 emissions. The expectation is that both active support and opposition will grow as knowledge expands. Safety concerns and climate benefits are the most important associations. Trust is a powerful influence but can slowly be built.

Recommendations: More understanding of how people react to communication messages on concerns from trusted sources. Public perceptions of carbon storage monitoring: the majority do not know about organisations and monitoring. Recommendation: increase awareness of monitoring organisations, organisation independence, and safety assurances, via trusted sources.

Stakeholder Engagement and a Just Transition - What is required of CCS? | Tavis Potts, University of Aberdeen

The three pillars of a Just Transition need to work in partnership: jobs/skills, community revitalisation and empowerment. Jobs are incredibly important. CCS development is at an early stage and has the potential to contribute to employment growth and be part of the Net Zero portfolio. Substantial further work needs to be done on the community revitalisation linking CCS to local economies and infrastructure. Gaining a social licence is a critical step in CCS and without it can undermine support and slow future initiatives.

For a just transition the process should be fair, equal, inclusive, and open. The benefits need to be well distributed across society. Just transition and the context of CCUS includes Net Zero Jobs, skills and training means building and training the workforce. Community revitalisation includes community wealth building; and investing in communities (How does CCS contribute?). Participation, inclusion and empowerment: who is at the table with CCUS development (social licence). Jobs, skills and training – community revitalisation – and inclusion are all interlinked. Growth of UK CCUS exports could support £4.3 billion in GVA (gross value added) and 48,000 jobs per annum by 2050. Aberdeen city segregation shows that heritage from the oil industry development has resulted in clearly defined zones of wealth and deprivation. What can we learn from the oil and gas industry? Improve investments in communities and generate opportunities for men and women. In the case of Aberdeen the construction of a Net Zero industry park is planned on the greenspace of the Torry's community (an area of deprivation) but which could further strip away a valued resource from this community. A study on Understanding Social Values on Low Carbon Sub-surface Technologies in the UK and Australia by Aya EL Samad shows that people are more likely to give support to offshore CCS. Can we learn from the Wind farm industry?

DOE's Stakeholder Engagement Efforts in the Wake of the U.S. Bipartisan Infrastructure Law's $12 Billion Investment in Carbon Management | Mary-Ellen Kwong, US Department of Energy

Ms Kwong provided a general overview of the U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM)—highlighting in particular FECM's portfolio of CO2 geologic storage projects and the expected growth in U.S.-based CO2 storage wells in light of the Bipartisan Infrastructure Law's $12 billion investment in carbon management. Ms. Kwong highlighted that engagement with communities and stakeholders is critically important for carbon management to reach the deployment pace and scale needed to make a difference for climate and to maximize economic, environmental, and societal benefits for communities and other stakeholders. She highlighted FECM's recent on-the-ground engagements and some of the learnings from those. She also introduced DOE's Community Benefit Plan framework, which aims to ensure that projects that receive public funding—particularly from the Bipartisan Infrastructure Law and the Inflation Reduction Act—create tangible benefits for the communities and workers where the projects are located.

Discussion

Q1: how does this compare to wind – there are a lot of parallels.

Tavis: I hate 'consultations' – people feel talked at. Better to run assemblies, and ask what the people want. Part of the solution is giving communities the voice to shape what they want. Work extra hard with marginalized communities who don't take online surveys and are deeply affected by fuel poverty.

Q2: What makes this different? Where does all the wealth go? Central belt, London if you are lucky Glasgow. What is going to be different?

Tavis: 60 years of the impacts positive and negative of oil and gas industries. It provided good jobs, but also an impact in creating a fly-in and fly-out culture. The money went to the government, whereas Norway handled it differently. Aberdeen is calling itself the Net Zero capital but is facing the closure of libraries and swimming pools. We have to be brave about taxation. Who are the people in power? What has changed? Citizens and communities have a much louder voice, with more awareness, and more ways to voice themselves. They get a piece of this pie. CCS needs to think a bit better about partnering.

Q3: how do you identify community leaders?

Katherine: identify the high science-leaning people at local colleges, and they know their community – let them decide.

Q4: What is the role of media in communicating science to the public?

Derrick: how do people get their information (UK)? Hear from scientists, BGS, and trusted actors? They actually get it from the Daily Mail, and if lucky from broadsheet papers.

CATF ran a workshop on CSS for the media, it didn't get the attendance we would have hoped for, so we need to figure that out.

Katherine: people are searching for the answer. Go to the IPCC. That is the most rigorous piece of work. Media has lots of misinformation.

Q5: What % of people are swing voters for CCS? How much scope is there to change people's minds?

Derrick: lots of potential to educate as the knowledge is currently low.

Tavis: very busy space offshore, it used to be far away. From fishermen, who hold a lot of political clout to new industries, floating wind and new tech in the subsurface. It's a charged area. Marine planning strategies in Scotland, The National Marine Plan is currently in round two. There will have to be some zoning, which people don't like, both on a horizontal and vertical plane.

Q6: Do the public care?

Derrick: there are some Scottish-specific studies on the on and offshore, although there is not as much difference as you might think. Research in 2016 showed localised awareness where there was potential for CCS. The larger issue driving concern focussed on leakages, that CO_2 is not sequestered – than on carbon budgets. Denmark, however, sees a strong onshore offshore variance from the public.

Katherine: The offshore Gulf Coast has no drinking water or 'not in my backyard'. People may live in the onshore but they work and play in the offshore – so they care especially about natural beauty and ecosystems. Not necessarily less, but significantly different.

Catalina: Northern Lights project, interesting that people don't realise that risk is low, that leakage of CO_2 has less impact than leak of oil and gas. What is your opinion on induced seismicity, NL injection into virgin pressure space might cause seismicity. How to make people confident that we won't cause damage? A question that we have is, are we transparent about it? If we measure seismicity should we show the data to everyone? Are they going to get worried about it? Even though small events don't really mean anything. If they don't know it's happening, should they know even though?

Tavis: the public is not simple or homogenous, things always get out, don't try to hide anything, open is best. Direct. Proper engagement. Don't sanitise the process.

Katherine: A risk assessment tool will probably help. What's going to make a difference? We need protocols in place to respond to public concerns.

Derrick: In the case of fracking they used a traffic light system which was a disaster. Thresholds need a well-designed risk register.

Session 8: Monitoring | Chair – Simon O'Brien

Greensand Monitoring Research | Andreas Szabados, Wintershall DEA

This project is transforming mature oil reservoirs into CO_2 storage. Phase 1, a Danish licence was awarded in 2023 covering Siri Canyon and pilot injection in Nini West reservoir (2023). Phase 2, initiated in 2021 with a new consortium of 23 partners, focused on pilot injection in early 2023. This involved reservoir testing and included geochemistry, the steel impact for well design, and the development and testing of monitoring. Nini West field is a depleted reservoir (2003-2018) with one exploration well with sidetrack, a producer and sidetracked (inactive), and a water disposal well (active). On March 8, 2023, the first cross-border offshore CO_2 was transported and became Denmark's first CO_2 injection for storage. Transport was via ISO containers by ship, to an unmanned platform. Batches were injected into the reservoir several times. The actual injection period lasted 42 days and injected 4,100 tons instead of 10,000 tons. There were seven cycles of injection, with a water injection pre-test and post-test, then a step rate test at the start and end. They conducted a seismic baseline and 2 monitoring activities. They monitored the downhole injection pressures and temperatures and conducted dynamic modelling and history matching. The aim is to fill up the depleted reservoir. Think what the CO_2 plume looks like, the reservoir is 15 m thick. 100m radius plume is observed from the modelling. Injectivity performance was very stable throughout the 7 cycles. There are challenges to the CO_2 plume monitoring, 4D seismic is high cost and has an environmental impact. Frequent subsurface monitoring is needed. Decided on a focused seismic concept, required 3D full wave field analysis. Focused seismic is efficient in measuring the absence or presence of CO_2. The signal-to-noise ratio is key. With fluid substitution modelling, with synthetic gathers the CO_2 in water creates new peaks in the wavelets. 16 receiver and 7 source locations are planned.

DAS deployed at seabed for Passive Seismic Monitoring: Application to CO_2 Storage | Estelle Rebel, Total Energies

Conformance and containment risks include the presence of wells, the status of the caprock, and potential fault reactivation. Induced seismicity can be one sign of containment loss. At the Northern Lights project we have installed fibre optics, where we use the same cable as internet boxes, the cable turns into thousands of sensors. Measurements include temperature/pressure, acoustic vibrations, and strain. The pilot project at the Northern Lights is a proof of concept, using 90 km long telecom fibre installed for 9 months. The goal is to assess the sensitivity of fibre optic cables for earthquake monitoring and develop and industrialise real-time processing solutions. The cables registered more than 60 events, magnitude 1.3 at 10 km away. There is a reasonable sensitivity and overlap with OBN acquisition. There were 9 events at the same time as OBN and DAS. We are currently trying to develop an automatic workflow to detect earthquakes and isolate informative time windows. It can form part of the monitoring toolbox and can monitor seismicity and reduce microseismic acquisition cost, offers an offshore solution for passive monitoring, there is no equivalent today on the market. Future work needs to push further data analysis.

Acorn – Measurement, Monitoring and Verification (MMV) Planning | Gwilym Lynn, Shell

The Scottish Cluster uses the Captain store and is centred around the Goldeneye field with multiple CCS evaluations over the years, the latest of which is Acorn. Their MMV philosophy is:

1. Conformance, long term security of CO_2 storage.
2. Containment, evidence that it stays in the reservoir
3. To give confidence to stakeholders.

MMV aims to detect and alert and measure and is in all parts of the project lifecycle, from initial characterisation, suitability, and the establishment of baselines. We have legacy MMV on one of the most studied stores in Europe. Four wells have core, and gauges in the wells and data. First as Longannet and Peterhead CCS Projects, now Acorn. The platform has now been removed. STEMM-CCS project was planned and performed in the area. Models guide expected CO_2 behaviour and monitoring provides key inputs for calibration and provides updates to history matching and dynamic calibration. Regarding containment, the key risks are CO_2 leakage or brine leakage up a well. It's essential to have plumbing diagrams, where are the plugs? are they in the right place? Bowties, what are the options? Barriers on the left and right side of the top event. Every store is different, each store has its own containment risks and technology has detectability limits. There is a challenge with a slight overlap with floating windfarms especially challenging sailing seismic vessels through them, we need to coexist and figure that out. Focus on MMV on the seabed and shallow areas, geosphere and injection well. Regarding the injection well, is it in the right place and does it have the right cement jobs? The geosphere is a challenging area to access and image. To achieve success in a depleted field is challenging as you get a blank volume back, we've planned for a closure survey. A multibeam echo sounder, looking for bubbles, with side scan sonar. There are ongoing discussions and maturation as Acorn progresses through the permitting process and will continue to evolve.

The Northern Lights CO_2 transport and storage company: how we built a robust monitoring and response plan | Catalina Acuna, Northern Lights

The Northern Lights project is a CCS project that became a reality, from building ships to using a storage complex called Aurora. Aurora in a nutshell it is 100 km offshore, 2700 m deep, located on the flanks of the Troll field structure targeting the (deeper) Johanson Fm reservoir. The reservoir is a pre-rift, shallow marine Jurassic sandstone. The Drake Fm is the primary seal (thick package of deep water, organic-rich shales) and with a secondary seal at the BCU (Base of Cretaceous Unconformity). Two wells; one is the injector. Why do we monitor? Risks have been identified and studied through the work program both pre and post-FID. The remaining risks must be handled through a robust program and response plan. The main risk is the plume crossing the licence border (out of the storage complex). For example, a CO_2 plume that goes too fast. They have studied all potential risks and created risk mitigation. Even though a project is approved for development, it still needs a storage permit and injection permit. The authority also requires monitoring. Monitoring is vital in achieving the license to operate and the permit to inject. In building the seismic monitoring plan we used forward seismic simulations based on a selection of dynamic modelling scenarios outlining the variety of potential migration cases. Modelling is undertaken before and after- particularly focussed on the detectability of CO_2 in the seismic. The monitoring plan is based on the identified pathways/bowties and seeks to address the leakage paths as outlined in the CRA (containment risk assessment). There is a new dynamic model used to update seismic repeat survey planning (timing extent). 4D seismic baseline is primary monitoring. Seismic has both passive and active monitoring. Passive is continuous. Active monitoring is at a specific time, to monitor plume speed. The monitoring plan during injection comprises primary monitoring of seismic and in-well (pressures and temperatures with downwell gauges). Instrumentation for in-well planned monitoring covers injection pressure – continuous and reservoir pressure – and planned/regular fall-off testing. Triggered monitoring would be employed in case of non-conformance or non-containment, or indication of fracture development. Phase one will have four seismic repeats.

Discussion

Q1: After the initial measuring and calibration (Greensands), are there plans to monitor plume migration?

Andreas: There is a difference between the pilot and the actual injection. Spotlight seismic showcase. Trigger technology, it's about conformance. We want to implement spotlight seismic to our project. If we see migration it would trigger the use of 4D seismic. But the idea is not to use 4D if possible. We can increase the frequency of seismic monitoring, using spotlight techniques.

Q2: It took a while in Quest to get the injectivity we wanted early on. Will you be able to get the desired injectivity at Greensands?

We are happy that we can get the injectivity we want.

Q3: for Estelle, using onshore detection to monitor seismic events, where are you from auto-picking from the offshore?

Using fibre optics alone., we are close to automating that.

Q4: for Estelle, we know the Oygarden fault system is active. How good is your Z detection, of the epicentre?

Estelle: that is why we need the P and S waves then we can estimate. Use onshore and the DAS then we can get better estimation.

Q5: for Estelle, if you are detecting smaller events can you estimate the magnitude?

We haven't started to work on that yet, but it may be possible to get something.

Q6: for Estelle, how can you tell the difference between natural and induced seismic events?

Depth is the main important parameter. 20 km deep, it's probably tectonic.

Q7: for Catalina, what are the requirements for post-closure monitoring? When might the plume extend to the Troll field?

The handover period is 20 years from now. There are many scenarios, we might have a plume going over the border at Troll – if we are in operations, we have to do a progressive baseline. The baseline now just goes over our licence. We might need to do a repeat seismic that covers the area outside of our complex. Then we either switch to the other well or start producing water.

Q8: for Catalina, what will control the speed of the plume movement?

The permeability and rock quality of formation and our ability to inject into different formations. The value of early seismic in 2027 will answer those questions.

Q9: with a smaller subset of monitoring technologies is there pushback from regulators to include more?

Northern Lights - they want more monitoring, we evaluated DAS on wells, but not the connectivity.

Greensands - we want to bring down environmental impact and cost, but not at the expense of quality.

Q10 can you comment on the frequency of seismic surveys, they are higher than oil and gas and have higher costs and environmental impact.

Northern Lights, difficult to offer sound rationale on only four surveys. We have to be careful, Sleipner was first, proposed seismic surveys every three years – they are oil and gas and can pay for it.

First projects are precedent settings for future projects and key learnings.

Q 11: any modelling on well-head blowouts?

The biggest risk is when the rig is getting set up.

What is the different between a CO_2 and gas blowout? It gets COLD. How should these things be controlled? Facilities, design, safety.

Session 9: Environmental Aspects | Chair – Nicola Clarke

Environmental monitoring strategies developed through controlled release experiments | Marius Dewar, PML

Dr Dewar introduced the QICS project offshore Scotland, with small-scale release experiments, with site-specific responses. There was some evidence of mobilisation of heavy metals, but within environmental thresholds and recovery within 3 weeks. They are moving towards models as release experiments are very expensive. When you fit models, e.g. impact area vs leakage rate it's a straight line relationship. Baselines were established through STEMM-CCS near Goldeneye. We know enough from experiments, observations and models to understand scales and impacts, and there are sufficient technologies and methodologies to enable effective monitoring.

Potential environmental impacts from offshore CO_2 storage in the UK | Paul Wood, Shell

We have ten years of looking at environmental impacts including seabed leakage. The Goldeneye site is at 150m water depth, the surface is muddy sand and homogenous. It has sparse megafauna dominated by sea pens, worms and starfish. A polychaete dominated benthic infaunal community with species typical of the Central North Sea including cetacean and fish species. There are scattered pockmarks but with no evidence of bacterial mats, active seeps or Methane Derived Authigenic Carbonate. We have gone through the process of Environmental Impact Assessments three times with Longannet, Peterhead and Acorn. The environmental impacts include localised temporary changes in water chemistry. CO_2 is most likely to dissolve within 1-3 m of release. Hydrogen ions make seawater more acidic. A decrease in carbonate ion availability affects marine fauna which require carbonate minerals to form shells or skeletons. Benthic and calcifying organisms are more sensitive. Impacts are likely to be of temporary and localised nature. Monitoring, Measurement and Verification require a focused plan, with technology and irregularity identification. The risk of leakage to the seabed is considered extremely low. The identification of an irregularity is key. ROV/AUV can look for bubble streams and bacterial mats which would trigger further surveys and risk assessments.

Considerations for new seismic data acquisition supporting CCS in the Gulf of Mexico | Katherine Romanak for Tip Meckel, University of Texas at Austin

One consideration for seismic surveys is the potential for negative impacts on cetaceans, such as whales and dolphins, that rely on sound for communication, navigation, and feeding. Therefore, it is important to address the regulatory and environmental issues related to seismic surveys in both state and federal waters. The federal government has established a task force to coordinate the permitting and licensing of offshore CCS projects, which will require new seismic activities. Additionally, the Marine Mammal Protection Act requires the monitoring of marine mammals for any changes in their behaviour due to seismic surveys. It is yet to be determined how the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) will incorporate these requirements into their regulations. Furthermore, any new survey acquisition will have to go through the National Environmental Policy Act (NEPA) process, which involves public participation and environmental impact assessment. To reduce the potential harm to cetaceans, some researchers are looking at modifying the seismic acquisition process by using higher frequency but not as loud sources, which may have less impact on marine mammals.

Environmental monitoring of offshore carbon storage – experience from ACT4storage and outlook for Smart AUVs | Ann Blomberg, NGI

Smart AUVs are flexible and can be fitted with lots of different sensor technologies. Financed by Gassnova and industry partners, we conducted a controlled release experiment in 60 m deep water.. Using multibeam, sonar (acoustic sensors), and HiSAS sonar, and using 3 types of moving platforms: ship, AUV, and glider. Obtaining 20 days of background data. CO_2 and O_2 show good correlations, and when you add CO_2 you can detect changes. The takeaway messages are gas bubbles are visible and up to 30-40 m above the seabed. pH sensor makes it well-suited for AUV. Gas exchange enables bubbles to exist long after their CO_2 content has dissolved. Smart AUVs are suitable for the detection and quantification of greenhouse gas seepage. They are looking to develop 'intelligent' monitoring, where if a leak is detected it can be stopped and investigate in depth. Further trials will occur in 2024 and 2025 at 400m out from the shore, and demonstrate automated response to CO_2 and CH_4 release.

Conclusions & Recommendations | Chair – Tim Dixon, Katherine Romanak, Nicola Clarke

Conclusions

- There is an encouraging number of projects in development, but there aren't enough projects in the pipeline to deliver deployment targets.
- Resource estimates are contingent upon well density and pressure space, and are easily exaggerated when these factors are not considered.
- Spatial resource allocation is strategic – collaboration is key.
- The time required to apply for licenses and permits needs to be accelerated. Governments need to offer and operators to request these more quickly. There is a need for clarity over the way that we license projects. The more we do it the shorter the duration will be. For example, positives in the way companies worked with UK NSTA to develop plans – modifying work programs and optimising shaved a year off.
- The Just Transition concept is being recognised by CCS projects.
- MMV plans are maturing and being approved by regulators, first projects set a precedent.
- Protocols for responding to stakeholders' concerns need to be established upfront before a project begins (there will be false accusations).
- Community benefits are key, even for the offshore.
- It is important to communicate risk in a way that is transparent e.g. for induced seismicity.
- The overall public has a very low knowledge and understanding of CCS.
- We currently have the technical tools to implement environmental monitoring, but the approach to this monitoring must consider the high risk of false positives for leakage due to natural environmental variability.
- Monitoring technologies are available now which raises the question of whether there will be a reduced need for R&D in new technologies.
- Basin-wide management with competing subsurface activities is an emerging topic.

Recommendations

- Develop/prove monitoring techniques for use in wind farms.
- Resource allocation is strategic – maximise opportunity.
- Know the local community and collaborate.
- Establish protocols for leakage attribution. Response protocols -need to be established upfront (there will be false accusations).
- Seek to gain clarity over the way that we license as more experience is gained.
- Improve public knowledge about CCS and understand how to positively engage the media.
- Need to ensure information on offshore storage is given to the Global South, especially countries with no hydrocarbon industry.
- Develop protocols for assessing and monitoring leaky wells.
- Develop carbon markets that apply both on and offshore.
- Develop ways to manage the 'commons' (pressure space) and determine who is responsible.

Closing remarks

Tim Dixon closed the meeting by thanking the Steering Committee, Aberdeen University for hosting (particularly Rachel Elliot and Clare Bond), and Storegga for their invitation, co-hosting and sponsorship. Tim invited anyone to get in touch if they would like to host the next offshore workshop.

Evaluating technology options to mitigate greenhouse gas emissions

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