What do we need to know to safely store CO_2 beneath our shelf seas?

1st March 2024
Stakeholder workshop report

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The Agile Initiative, which launched in February 2022, is an Oxford University research programme that aims to revolutionise how world-class, high-impact research supports policymaking. Based at the Oxford Martin School with a major £10 million grant from the Natural Environment Research Council and led by Professor Nathalie Seddon, fast-paced solution-focused ‘Sprints’ respond to specific social and environmental policy questions identified in partnership with policymakers and key stakeholders across the UK. In these Sprints, interdisciplinary research teams drawn from across the University of Oxford work with key stakeholders within 12 months to feed evidence into the policy cycle in real-time. The Agile Initiative has ambitions to reshape how academic institutions value interdisciplinary collaborations and outputs beyond publishing papers, thereby catalysing a lasting culture shift for researchers and funders alike. The Agile Initiative reflects Oxford University’s commitment to net zero carbon emissions and net biodiversity gain and is part of an increasing community of projects and institutes at the University focused on the world’s most urgent environmental challenges.

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Remarks

This work was supported by the Natural Environment Research Council (NERC) grant number NE/W004976/1 as part of the Agile Initiative at the Oxford Martin School. This report was prepared by Agile Initiative Sprint 5 researchers, and led by Millicent Sutton, with Anna Rufas and Mike Kendall. We would like to express our thanks to the Oxford Martin School’s Agile engine room team.

Contents

Executive summary

This report summarises the content and discussion of an Agile Initiative workshop held at the University of Oxford on March 1st 2024, discussing "what do we need to know to safely store CO_2 in our UK continental shelf seas?" The workshop revolved around five themes.

1. Reservoir seal mechanisms.
2. Induced seismicity.
3. Long-term ecosystem monitoring using satellites.
4. Blue carbon disturbance.
5. UK regulation and legislation of CO_2 storage.

Carbon Capture and Storage (CCS) with permanent GCS is essential to achieving net zero emissions at the lowest cost in the UK. Recent IPCC integrated assessment models suggest that, in the absence of wide-scale behaviour change, it is increasingly unlikely that the $1.5\,°C$ target will be reached without GCS (Rogelj et al., 2018), further emphasising the importance of CCS globally and in the UK (Climate Change Committee, 2020). There is a need for evidence-based policy and regulation to align energy and climate policy, and scale up the UK storage industry to contribute to the volume of required CO_2 removals. This report describes the GCS research conducted by the University of Oxford, and the stakeholder feedback collected during the workshop. Discussion sessions focused on the consequences of the research on policy, investment, and future direction of CCS policy and legislation. Our research engages with some of the current questions and regulatory challenges, and we hope this may enable some evidence-led discussion of GCS policy-making. It also highlights some research gaps and opportunities for future investigation.

Research team

WP	Name	Affiliation	Email
1	Joe Cartwright	Dept. Earth Sciences	joe.cartwright@earth.ox.ac.uk
1	Jimmy Moneron	Dept. Earth Sciences	jimmy.moneron@earth.ox.ac.uk
2	Mike Kendall	Dept. Earth Sciences	mike.kendall@earth.ox.ac.uk
2	Tom Ketletty	Dept. Earth Sciences	tom.kettlety@earth.ox.ac.uk
2	Joseph Asplet	Dept. Earth Sciences	joseph.asplet@earth.ox.ac.uk
3	Heather Bouman	Dept. Earth Sciences	heather.bouman@earth.ox.ac.uk
3	Anna Rufas	Dept. Earth Sciences	anna.rufasblanco@earth.ox.ac.uk
4	Ros Rickaby	Dept. Earth Sciences	rosalind.rickaby@earth.ox.ac.uk
4	Malini Kallingal	Dept. Earth Sciences	malini.kallingal@earth.ox.ac.uk
5	Millicent Sutton	Dept. Geography, Oxford Net Zero	millicent.sutton@ouce.ox.ac.uk
5	Martje Köppen	Sustainable Law Programme	martje.koppen@law.ox.ac.uk
5	Hasan Muslemani	Smith School	hasan.muselmani@smithschool.ox.ac.uk
5	Steve Smith	Smith School	steve.smith@smithschool.ox.ac.uk
5	Myles Allen	Oxford Net Zero, Dept. Physics	myles.allen@ouce.ox.ac.uk

List of abbreviations, acronyms and symbols

BGS British Geological Survey

CCS Carbon capture and storage

CEFAS Centre for Environment, Fisheries and Aquaculture Science

CO_2 Carbon dioxide

DAC Direct air capture

DSNZ Department of Energy Security and Net Zero

EBA Ecological baseline assessment

EIA Environmental impact assessment

EOR Environmental outcome report

ESA European Space Agency

GCS Geological carbon dioxide storage

IPCC Intergovernmental Panel on Climate Change

NERC Natural Environment Research Council

MMV Measurement, monitoring and verification

Mt Megaton (10^{12} g)

ONZ Oxford Net Zero

PIC Particulate inorganic carbon

POC Particulate organic carbon

TC Total carbon

WP Work package

1 Introduction

Geologic carbon dioxide (CO_2) storage (GCS) is central to achieving net zero emissions at the lowest cost (IPCC, 2023). The global importance of carbon capture and storage (CCS) further emphasises the urgency of progressing CCS plans in the UK (Climate Change Committee, 2020). It is estimated that the UK will need to capture, remove and store 75–180 Mt of CO_2 from fossil fuel sources by 2050, with GCS coupled with bioenergy power generation and direct air capture (DAC) serving as key methods of carbon removal (Climate Change Committee, 2020, Fig. 2.14). This is highly ambitious, especially as there is currently no GCS operating in the UK. False starts over the past two decades have led to the UK with less progress than countries such as Canada, USA and Norway. Nevertheless, the UK has suitable geology, the necessary infrastructure and the industrial skills base to achieve the government's target.

A group of researchers from the University of Oxford assembled a diverse group of stakeholders to discuss the challenges, opportunities and wider research questions associated with GCS in offshore UK waters. The workshop was held on March 1st 2024, at the Oxford Martin School. Chatham House rules were observed, where comments from participants were not attributed to any individual or organisation. The workshop focused on the specific question: "What do we need to know to safely store CO_2 beneath our shelf seas?" Oxford researchers presented recent work, with a particular focus on the Endurance GCS site, located in the southern North Sea (Figure 1).

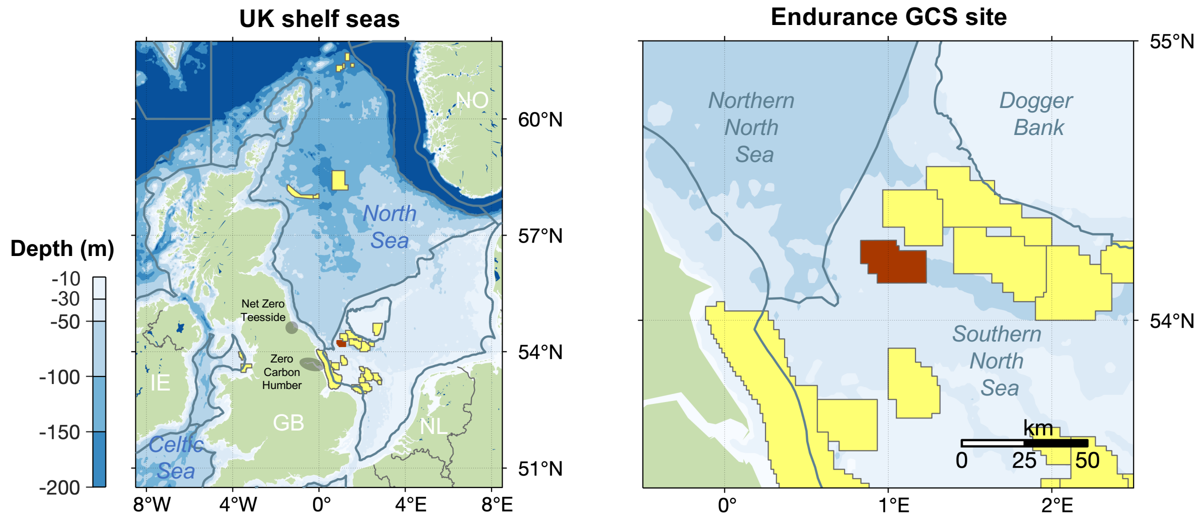

Figure 1. Map displaying licensed offshore capture and geological CO_2 storage (GCS) sites by the UK government as of spring 2024 (yellow), alongside the Endurance GCS site (brown). Additionally, it features the Teesside and the Humber industrial hubs for CO_2 capture, transport and storage at the Endurance. Grey lines delineate the OSPAR offshore regions and subregions.

This workshop is part of the Agile Initiative, a programme funded by the Natural Environment Research Council (NERC). It aims to deliver timely, policy-oriented research that focuses on the adaptation to climate change and the net zero transition.

The overarching aim of Agile is to transform how research responds to the needs of policymakers on critical environmental issues. To accomplish this, research is delivered in fast-paced sprints, typically lasting one year. In what is the fifth sprint, we are addressing challenges and risks associated with offshore GCS, aiming to deliver new research and integrate existing knowledge from across research and policy areas, identifying gaps and areas requiring further research. Our sprint concludes in June 2024.

Over 60 people attended the workshop, representing a wide range of stakeholders from industry to regulators. These stakeholders provided a diverse range of expertise, with the Oxford-led research only addressing a small part of the wider challenge of GCS implementation and monitoring. The duration of the research sprints naturally limits the scope of the research. The input and feedback from workshop participants will guide the work undertaken for the remainder of the sprint.

1.1 Aims of the workshop

Our workshop, designed to facilitate interdisciplinary discussion, had these four aims.

1. To present an overview of the research being done in the Agile sprint.
2. To enable networking and build future collaborations.
3. To identify gaps and research challenges.
4. To refine areas for further research.

In this report, we have tried to capture the feedback, outstanding questions and recommendations that represent the outcomes of the workshop. Audience polling, via online survey platform Mentimeter, was used to capture participant feedback. At the outset of the workshop, we asked participants to submit short answers to the question “What is the biggest barrier to offshore CO_2 storage in the UK?” (Figure 2). There were 75 responses to this prompt, with the most popular response being “cost” followed by “business models”, “economics”, “regulation” and “uncertainty”.

Figure 2. Word cloud showing responses to the prompt “What is the biggest barrier to offshore CO_2 storage in the UK?”. The size of each word indicates the number of responses. The modal response was “cost”, with 12 out of 75 responses. Created from a Mentimeter poll run during the workshop.

1.2 Scientific work structure

This Agile sprint is being delivered in five work packages (WPs).

WP1 Seal bypass mechanisms for CO_2 storage. **Jimmy Moneron** and **Joe Cartwright**.

WP2 Monitoring induced seismicity associated with CO_2 injection and storage. **Joseph Asplet**, **Tom Ketletty**, and **Mike Kendall**.

WP3 Ecological baseline assessment for the Endurance storage site using satellite remote sensing data of phytoplankton. **Anna Rufas** and **Heather Bouman**.

WP4 An evaluation of blue carbon in shelf seas and potential risks due to leakage. **Malini Kallingal** and **Ros Rickaby**.

WP5 The legal and regulatory framework underpinning the industry of CO_2 storage in offshore geologic systems. **Millicent Sutton**, **Martje Köppen**, **Hasan Muslemani**, and **Steve Smith**.

With the WPs over halfway complete, a summary of the research in-progress was presented at the workshop by the five postdoctoral researchers working on each WP. A copy of the presentations delivered for each WP during the workshop can be accessed through the Agile Initiative Sprint 5 site, at this link here. These short talks were followed by several discussion sessions. These primarily acted as a means of stakeholder feedback, posing questions and surveying responses.

This report is structured with summaries of each WP presentation (Section 2), followed by concluding remarks and key takeaways from the workshop discussion sessions (Section 3), concluding with follow-up steps (Section 4).

2 Work package summaries

2.1 WP1 – Leakage risk assessment

2.1.1 Scope and key questions

This WP uses seismic imaging data to analyse faults located above salt layers, and investigate the potential risk factors associated with CO_2 storage. In the southern North Sea basin, where the Endurance storage reservoir is located (in the Bunter sandstone), there are thick layers of salts and shales (known as "evaporites") both above and below the storage reservoir. The main rock units above Endurance acts as the primary and secondary seals or cap rocks, and the layers below (known as the Zechstein salts) are the seals for the extensive gas fields in the region. In the North Sea, natural methane seepage events have occurred throughout geological time (Römer et al., 2021), with gas escaping up though the Zechstein salts and into the overlying rock layers. Consequently, as with any proposed storage site, a thorough leakage risk assessment needs to be conducted for GCS development in the region. This research builds on the extensive risk assessment already done at the Endurance site.

Williams et al., 2014 identified that faults over thick salt layers are a key hazard associated with CO_2 storage in the North Sea's targeted reservoirs (i.e., the Bunter sandstone). These faults could serve as "seal bypass systems" (Cartwright et al., 2007). Notably, many of these faults "die out" within the Zechstein salt layer, beneath the Bunter sandstone, highlighting the need for investigation into this formation.

2.1.2 New research

Using three-dimensional visualisation techniques, combined with interpretation of numerous pre-existing drilled boreholes, we have examined the internal composition of the Zechstein salt formation. This analysis led to the mapping of potassium salts (K-salts), known for their greater mobility or malleability compared to surrounding layers. In UK GCS-licensed areas, these K-salts are typically situated in the uppermost layers of the Zechstein, exhibiting considerable variability in thickness. Notably, over salt domes, the K-salt layer reaches its maximum thickness. These areas of greater thickness are naturally regions with enhanced leakage risk due to the presence of faults that are generated by the K-salt's slow deformation over geological time. Whilst these K-salt and faults are generally lie beneath storage units in the southern North Sea, understanding their behaviour gives greater insight into the dynamics of sealing rocks, particularly salts, and informs leakage risk assessment methods.

2.1.3 Current unknowns

In light of the preliminary results, further characterisation of the Zechstein salt in the North Sea is recommended, with a focus on addressing several key questions.

- Are faults within the top seal the main potential leakage pathways?
- Has the importance of the fault shape within the Zechstein layer been considered in assessing potential leaks for fault systems situated above extensive salt layers?
- Do regions with thicker K-salt layers in the uppermost Zechstein exhibit contrasting structural styles with those salt domes for which K-salts show no such thickening?
- Is there a discernible relationship between faulting over the salt and the distribution of potassium salt (or other intrasalt/subsalt) layers?

Answering these questions will provide meaningful insights into the potential risks associated with GCS and inform strategies for mitigating leakage hazards in the North Sea basin. Our work will augment the analysis already done on the Endurance site.

2.1.4 Discussion points with stakeholders

- **Better risk quantification**. Understanding the likelihood of occurrence was one of the main questions from stakeholders. Is there a way to predict leakage more accurately, and what are the chances of leakage?
- **What defines a leak/leakage rate?** Is any volume of CO_2 deemed a leak, or is there a specific threshold? When does leakage become a concern? Many stakeholders posed related queries, such as the acceptable level of leakage and whether there exists a standardised definition for post-injection CO_2 leakage.
- **Time scales of potential leakage**. Do we know how long it would take for CO_2 to reach the surface? Do we know how long it would take for a CO_2 reservoir to deplete after leakage?
- **Leakage routes in the strata**. Do we have a proper understanding of gas "migration" routes from the reservoir to the surface? Can there be lateral migration through continuous strata and vertical migration through faults?
- **Risk of legacy wells**. Can legacy wells be considered as seal bypass systems? Can abandoned wells be preferential pathways for gas escape?

2.2 WP2 – Characterising seismicity in the southern North Sea

2.2.1 Scope and key questions

Monitoring natural and induced earthquakes (or "seismicity") is important for the safe offshore storage of CO_2 in the UK. Various industries have injected fluids such as water, air, or CO_2 into geological formations deep underground (> 1 km) for many decades. It is known that fluid injection causes (or "induces") microseismicity –earthquakes typically too small ($M < 2$) to be felt at the surface– and can sometimes trigger larger fault reactivation. A notable example is the microseismic response observed during CO_2 injection at the In Salah project in Algeria (Stork et al., 2015). Fault reactivation could pose a risk to reservoir integrity, as the failure of the rock during the activation could create a permeable pathway allowing CO_2 to migrate out of the storage complex. However, it is possible that faulting could not create such pathways due to sealing mechanisms that can occur. This is area of significant uncertainty and active research. Any faulting or fracturing activity would generate microseismicity to some degree, bigger or smaller, which could be detected if sufficient monitoring is in place.

The UK continually experiences natural onshore microseismicity that is detected and reported by national seismic networks operated by the British Geological Survey (BGS). Microseismicity associated with industrial activities (or "induced microseismicity") has resulted in severe public backlashes and government interventions, and is thus a risk to project operations. Offshore CO_2 storage faces a similar risk to social licence to operate from seismicity, even if it poses little risk to CO_2 containment.

The BGS estimates that the UK national seismic network can reliably detect earthquakes with a local magnitude greater than 2-2.5 at the Endurance GCS site (Baptie, 2021). Although the region seldom experiences felt or large earthquakes, natural seismicity occurs. Establishing additional monitoring capabilities to reliably detect microseismicity is essential for distinguishing between natural and induced events near the Endurance. Any additional monitoring endeavour naturally will need to balance sensitivity and cost. In this work package, we are exploring the feasibility of using onshore seismic arrays in the UK to significantly improve the detection of microseismicity in a more cost effective manner than deploying sensors offshore. A similar deployment in Norway has shown that this approach has the potential to greatly improve the capability of an onshore network to detect offshore microseismicity (Zarifi et al., 2022). Onshore seismic arrays are relatively inexpensive compared to offshore monitoring options, and could form the backbone of a future enhanced monitoring network for the North Sea.

2.2.2 New research

In September 2023, we installed an array of eight Güralp Certimus broadband seismometers. The array is designed to focus signals on the frequency range we would expect for microseismic events. Consequentially, the deployment has a significantly smaller footprint than traditional seismic deployments, with all instruments contained within a circular area with a diameter of approximately 1 km.

We use a signal processing method know as beamforming (Rost & Thomas, 2002) to focus signals recorded by the array. This method, or similar array methods, is used commonly used by seismic observatories across the globe (Schweitzer et al., 2012). We have benchmarked our array against nearby BGS stations for an analogue earthquake which occurred near Quaking Houses, Durham. This earthquake is small, with a local magnitude (M_L) of 1.1, and is of a similar distance ($\sim$ 85 km), from the array as Endurance. Our array can clearly detect this event and the array analysis also yields the direction the signal came from. Back projecting the signal, using a simplistic method, yields a location within 5 km of the BGS reported location. We are conducting ongoing work to improve location accuracy, review other potential earthquakes in our data, and establish a near-real-time analysis framework.

2.2.3 Current unknowns

We are in the process of establishing the detection capability of the onshore array. The optimal long-term strategy for the region is still not clear. Other approaches, such as deploying ocean bottom seismometers or using fibre optic cables as distributed acoustic sensors may improve monitoring capability, but have higher associated costs. Seafloor deployments also face challenges in establishing real-time data acquisitions. The level of seismic monitoring required, and what methods used to meet that requirement, are yet to be established.

2.2.4 Discussion points with stakeholders

- **Monitoring levels**. What level of passive seismic monitoring is required? How will this change over the lifespan of a GCS project? Stakeholders agreed that comprehensive passive seismic monitoring is needed during injection. Onshore seismic arrays could constitute an important component of this monitoring framework. Baseline monitoring is desirable prior to injection, although the timescale needed for a full characterisation means that there will be some uncertainty in the natural rate of seismicity. The appropriate level of monitoring may vary depending on the location of different projects and as operations progress.
- **Location accuracy**. There will always be some uncertainty in an earthquake location. What level of uncertainty is acceptable to operators and to the regulator? The need to improve depth estimates for North Sea seismicity was highlighted during the discussion. This is an open area for future research.
- **Collaboration**. With the number of GCS licences being issued for the North Sea, there will be a natural overlap in passive seismic monitoring infrastructure. For example, the onshore seismic array we have deployed could be suitable to monitor Endurance and its neighbouring licence blocks. Pooling resources to monitor projects simultaneously across the North Sea could be beneficial for all operators. A poll of attendees indicated some appetite for collaboration and data-sharing between operators and public institutions, such as regulators and universities.
- **Responsibility for monitoring**. Who should be responsible for seismic monitoring? Should it be left to operators? Or should it be done by the regulator or the BGS? Is there a role for academic institutions? A poll of attendees was evenly split on whether operators or regulators should be responsible for passive seismic monitoring.
- **Public perception**. The public perception, and acceptance, of GCS projects are essential to their success. Several stakeholders raised if any potential seismic activity would be felt onshore. The BGS produce seismic hazard maps for the UK (e.g., Mosca et al., 2022) and these are being extended to cover offshore regions.

2.3 WP3 – Ecological baseline assessment for the Endurance

2.3.1 Scope and key questions

WP3 focuses on establishing an ecological baseline assessment (EBA) for the Endurance GCS site using satellite remote-sensing data of marine phytoplankton. Phytoplankton, photosynthetic aquatic microorganisms that are the primordial carriers of carbon in the ecosystem, are vital in assessing the net-zero (carbon) efficiency of GCS technologies, holding a central position in our EBA. A baseline assessment provides insights into the reference conditions of the marine ecosystem before any human intervention –with the potential for disturbance– occurs. An EBA involves analysing the long-term trend of key ecosystem indicators, like phytoplankton, which are sensitive to environmental changes like ocean acidification, eutrophication, and warming. Those factors contribute to shifts in plankton dynamics and stocks, making changes in phytoplankton an effective early-warning signals of ecological disturbances (Blackford et al., 2021; Global Climate Observing System, 2024). Understanding long-term trend deviations and attributing them to specific factors is crucial for identifying anomalies, such as accidental GCS leakage. Despite the likelihood of CO_2 leakage, or it extending to the seafloor, being low, understand its impacts and means of measuring them is vital to monitoring plans for GCS operations.

2.3.2 New research

We use satellite remote-sensing technology to retrieve phytoplankton data, a method that is currently not used in the extant EBA for the Endurance (British Petroleum, 2023). Unlike conventional *in situ* shipboard sampling, satellites offer a lower labour-intensive solution, and have been providing data daily since the 1990s over broad spatial scales. This makes them a cost-effective tool for ecosystem monitoring. Satellite-based monitoring can be used in a wide variety of applications, such as detecting harmful algal blooms that affect fish populations (International Ocean Colour Coordinating Group, 2021), identifying methane leakages from oil and gas operations (Tollefson, 2024), or assessing the eutrophication of waters following illegal wastewater discharge into the oceans (Van Der Zande et al., 2019).

Our assessment footprint spans 100 x 100 km^2 centred around the Endurance site. The validation of satellite data relies on *in situ* oceanographic datasets from the UK environment agency CEFAS (Centre for Environment, Fisheries and Aquaculture Science), incorporating one-off sampling points in the North Sea (cruise data) and time-series stations (SmartBuoy systems). Notably, our EBA includes the calculation of water column ("blue") carbon stocks, a crucial variable omitted in the existing EBA for Endurance, which predominantly focuses on biodiversity metrics and sedimentary blue carbon. The calculated temporal evolution of water column carbon stocks, derived from a European Space Agency (ESA) satellite-based product of phytoplankton productivity (Kulk et al., 2021), highlights the importance of the timing of human-induced alterations, with different months of the year carrying a varying amount of water-column carbon at risk of disturbance if leakage to seafloor were to occur.

2.3.3 Current unknowns

- Identifying the ecosystem factors governing phytoplankton long-term trends, which we address by building a correlation matrix mapping the metrics of phytoplankton dynamics (so-called "bloom phenology" metrics) to presumed environmental controls (biological, biogeochemical and physical drivers, as well as climate indices).
- Assessing the risks faced by mixed-layer phytoplankton communities in the event of CO_2 or brine leakage.
- Exploring the potential contribution of new satellites (e.g., NASA's PACE mission or MethaneSAT), which have a higher spectral resolution, in creating novel metrics for ecosystem response and recovery in case of leakage.

2.3.4 Discussion points with stakeholders

- **Data transparency**. We aim to integrate the collated datasets into a public data repository, disclosing data origins and collection methods. The use of freely available satellite data reinforces the concept of data transparency, fundamental for accountability and for public perception of GCS.
- **GCS storage capacity vs disruption**. Does a GCS project have the capacity to store more carbon than it could disrupt from the ecosystem in the unlikely event of a leak? Is that risk level acceptable?
- **Satellite signal sensitivity to leakage**. Can leakage of CO_2 or brine induce a discernible anomaly in the satellite signal? As no leaks have ever been detected during any CO_2 storage operations, there is a lack of underlying data to test this question. However natural analogues could be used, like natural CO_2 seeps, to understand satellite signal sensitivity.
- **Distinguishing leakage signal from climate change disturbances**. Can we reliably separate a signal resulting from leakage from one due to climate change?

Stakeholders also raised additional points about the marine environment. However, many fall under the purview of a Measurement, Monitoring and Verification (MMV) assessment, rather than an ecological baseline assessment, which was not within the scope of WP3. They should, however, be taken into account in the future.

- **Ecosystem monitoring responsibility and duration**. Who will fund both long- and short-term ecosystem monitoring? What is the optimal duration for post-closure monitoring?
- **Environmental risk magnitude during different GCS phases**. What is the level of risk posed to the environment during various phases of GCS operations (during injection, during dismantling and post-closure)?
- **Impact threshold of leakage on ecosystem**. What is the required flux of leakage for it to impact the ecosystem and become visible in the satellite signal?

- **Manifestation of leakage effects on ecosystem**. In what form will the leakage manifest its effects on the ecosystem, particularly in terms of biological responses?
- **Ecosystem response time and recovery time to leakage**. How long does it take for the ecosystem to sense leakage? How quickly will ecosystems recover?
- **CO_2 dissolution and dispersion**. What proportion of leaked CO_2 at the seabed will reach the surface ocean ecosystem before dissolution and dispersion by currents?
- **Brine leakage monitoring and environmental impact**. How can we monitor the leakage of brine? What are the environmental repercussions of brine leakage, considering factors like ionic imbalance and the presence of metals?

2.4 WP4 – Sedimentary blue carbon

2.4.1 Scope and key questions

WP4 focuses on quantifying the sedimentary blue carbon across the Endurance GCS site, and potential risks due to CO_2 leakage. Sedimentary blue carbon refers to the carbon that is stored within coastal and marine sedimentary environments, primarily in the form of organic matter derived from marine plants and animals (Fest et al., 2022). This carbon can be stored for long periods, sometimes thousands to millions of years, in sediments beneath the ocean floor or within coastal wetlands. Termed "blue" carbon, it underscores the significance of coastal ecosystems, such as mangroves, salt marshes, and seagrasses, in sequestering CO_2 from the atmosphere and storing it in their biomass and associated sediments. If leakage were to occur from GCS reservoirs, the CO_2 may be a threat to sedimentary blue carbon ecosystems. Quantifying the effect of leakage on sedimentary blue carbon has, to our knowledge, not been assessed especially for the North Sea sediments. Therefore, assessing the amount of blue carbon stored in sediments is a crucial first step in quantifying the value of so-called ecosystem services to carbon storage.

2.4.2 New research

For the first time in the North Sea, estimates of maximum sedimentary blue carbon have been calculated using compiled data of total carbon (TC), particulate organic carbon (POC), and particulate inorganic carbon (PIC) in sediments obtained from the BGS sample repository (Smeaton et al., 2021). These samples are from a range of location around the North Sea and near the Endurance licence block. We have also estimated the rate of carbon loss in the sediments through CO_2 bubbling experiments under laboratory conditions.

These samples were analysed for the percentage of inorganic and organic carbon through elemental analysis. The rate of loss in sediment carbon contents was analysed by bubbling CO_2 through these sediment samples. The experiments revealed a decline of about 75% in TC when the sediments were bubbled with CO_2 for approximately 5 days. However, the maximum loss for PIC and POC remained constant throughout the experiment. Our bubbling experiments indicate that inorganic carbon is most likely to dissolve within the sediments, while the loss of organic carbon appears minimal.

2.4.3 Current unknowns

The question arises: what proportion of the more vulnerable PIC located in the North Sea sediments is actually at risk from a leakage event? Integrating TC across the surface sediments to a depth of about 10 m, we determine roughly 1470 Mt of TC is present, with 92% being PIC and 8% POC. However, the risk of loss of PIC only exists during a leakage event, which would most likely be isolated to a small spatial footprint. To approximate this scenario, we can consider the dimensions of pockmarks – areas of where natural gas seepage has occurred over geological time, where disturbed sediments are observable on reflection seismic images of the subsurface – to estimate the sediment volume that could be considered "at risk". Calculation of carbon at risk from one leakage event (e.g., one pockmark of 50 m radius and 10 m depth) reveals a TC estimate of around 0.82 Mt, with 8% of PIC and 7% of POC at risk of loss.

Furthermore, our bubbling experiments revealed that the pH decreased from 8.81 to 5.95 within half an hour of CO_2 bubbling (as expected for the acidification of seawater with pure CO_2). However, by the end of the experiment, the pH increased to 6.05 due to the dissolution of carbonate minerals present in the sediments, which add alkalinity. This suggests that in the unlikely event of a leakage, some of the leaked CO_2 is neutralised by the release of alkalinity, which aids in storing the carbon from the sediments as dissolved inorganic carbon in the ocean. Based on these results, it can be inferred that POC-rich sites have a lower risk of blue carbon loss from a leakage event, but lack neutralisation potential for CO_2 leakage, whereas PIC-rich sites have a higher risk of blue carbon loss but some neutralisation potential. It is uncertain if this neutralisation potential is sufficient to wholly mitigate the effects of a CO_2 leak, and this is an area of ongoing research.

2.4.4 Discussion points with stakeholders

- **Quantifying blue carbon considering leakage factor**. How can we accurately quantify blue carbon considering the potential leakage rate across the entire site?
- **Heatmap for PIC and POC**. Create a heatmap illustrating the distribution of PIC and POC across the Endurance site.
- **Definition of leakage**. What constitutes "leakage", and how might it impact surface sediments?
- **Carbon loss from infrastructure deployment**. How might carbon loss occur due to disturbance of sediments during the deployment of infrastructure for GCS?
- **Detection of leakage events**. How quickly could a leakage event be detected through carbon loss from shallow sediments?

2.5 WP5 – Regulation and legislation of offshore CO_2 storage in the UK

2.5.1 Scope and key questions

This research stream focuses on mapping the UK regulation pertaining to offshore carbon storage licences, focusing specifically on the Endurance reservoir. We have created maps of the responsible regulators in the UK, and workflow diagrams for understanding the licensing and permitting processes for obtaining a carbon storage licence. This work package examines the applicable legislation and regulation, as well as recent legislative changes relating to the planning processes and environmental impact assessments (EIA). We follow the dynamic, fast-paced policy space in the UK to understand where policy is heading, and to understand governmental priorities in the attempt to scale up the industry. We research policy mechanisms in other jurisdictions, for example Norway and the USA, to understand their strengths and weaknesses, and where the UK could learn from their strengths.

2.5.2 New research

The regulatory environment (for example, the EU Revocation Act and Levelling-Up Act) is constantly changing and sometimes uncertain. Our interim findings identify some challenges in current regulations. The challenges we have identified are the following;

- Lack of provision for liabilities between licence blocks (oil-producing, carbon-storage).
- Lack of provision for cross-border reservoirs and liabilities between Norway-UK shared continental shelf.
- Lack of integrated marine planning across different marine uses, e.g., carbon storage, offshore renewable infrastructure, fishing, marine protected areas, deep-sea mining or shipping.
- Siloing of marine spatial planning from GCS considerations, with potential seabed licensing conflicts between offshore renewable infrastructure, seabed cables, fishing, trawling, deep-sea mining and GCS.
- Unclear post-closure monitoring obligations for GCS.
- Lack of provision for onshore storage in the UK following partial rescindment of the EU CCS Directive (2009).

2.5.3 Current unknowns

The regulatory environment for CO_2 capture, transport and GCS is evolving rapidly as the UK Department of Energy Security and Net-Zero (DESNZ) aims to create a full-scale industry by 2030 (DSNZ, 2023). The UK Government has recently passed legislation called the Levelling Up and Regeneration Act 2023, which attempts to streamline and reduce the bureaucracy of planning regulations for infrastructure projects (Rankl, 2023). However, this has created significant planning uncertainty because it alters EIAs to Environmental Outcome Reports (EOR), and consolidates ministerial power to make final decisions for an infrastructure project like GCS.

2.5.4 Discussion points with stakeholders

The consensus in the room coalesced around three key ideas. First, “one regulator to rule them all” would be unworkable. Second, attendees welcomed the shift away from storage capacity towards injection capacity. Third, attendees recognised the growing competition of jurisdictions for CCS (which is a known phenomenon in trust law).

The stakeholders seemed to identify the following challenges within regulation. First, stakeholders identified that there were not enough resources in the regulatory bodies to support the current system, let alone at the speed and size of scale-up required to meet 2050 Net-Zero targets. Many stakeholders, particularly representatives from oil majors, identified that there is a flight risk from companies to other jurisdictions if the UK regulatory environment is not enough of an enabler to the fully scaled industry. Interestingly, industry stakeholders identified that there is no mechanism for allowing companies to compensate for missing interim targets by using removals and counting these removals towards their interim targets. This is a data point which requires further corroboration from researchers.

Stakeholders considered the future-proofing of regulation to be an important question. Industrial stakeholders identified that robust, consistent policy, with adequate forward planning, was essential, and as of yet, unaddressed in the regulation. Analogies from separate sub-surface industries like hydraulic fracturing, or Enhanced Oil Recovery (EOR) were mooted as an indicator for assessing potential future risks.

The final question stakeholders required addressing, related to the social licence to operate, and how to communicate the risks associated with GCS to the public. Stakeholders viewed communication with the public as essential, but there was no consensus on methods or timing of communication.

3 Concluding remarks and takeaways

The 1st March workshop was held under Chatham House rules, which created honest, frank, forward-thinking conversations about the regulation and the science of offshore carbon storage in the UK. This would not have been possible without stakeholder engagement and interest, so, thank you.

The workshop highlighted the importance of knowledge-sharing, cross-sector collaboration, and interdisciplinary thinking to adequately address the significant challenges as the UK storage industry expands. The workshop highlighted the challenges of offshore GCS, rooted in concerns around cost, over-regulation, and sub-surface uncertainties. There was a shared recognition that the industry needs to be regulated carefully to build public trust, and social licence to operate. Also, regulation may be needed to ensure that the industry is used for removals, rather than solely mitigation reduction. Looking ahead to the UK's 7th Carbon Budget, there was recognition that we must consider the role that offshore carbon storage may play in the UK's Net Zero strategy, and the implications for the industrial scale-up.

The key takeaways from each WP discussion were as follows.

WP1: Leaky fault discussion

The constitution of a "leaky fault" is both a scientific and communication challenge. The issue is not necessarily identifying the faults, the issue is the behaviour of the fault in a leakage scenario. Any uncertainties regarding stress and pressure changes requires honest conversations about the range of subsurface uncertainty.

WP2: Passive seismicity discussion

There is concern about the public reaction to an induced seismicity event. There needs to be enough monitoring so regulators and operators can distinguish between natural baseline seismicity and microseismic events induced by GCS operations. More regulatory guidance may be required for monitoring requirements, risk attribution, and characterisation in particular reservoirs.

WP3: Environmental footprint of a leaky carbon storage reservoir discussion

There was concern about the horizontal and vertical spread in a leakage event scenario, and a lively discussion around monitoring phytoplankton using satellites as a proxy for assessing the environmental impacts of a leak from a GCS site. What would the response of the marine ecosystem look like in the event of an accidental leakage? What technologies do we need to deploy to monitor it and contain it? Again, further consideration by regulators may be required for nested scales of monitoring. We have lots of modelling data for the spatiotemporal traceability of a leakage, but less in situ monitoring data. Thus, emphasis needs to be placed on acquiring real-time *in situ* data.

WP4: Role of "blue" carbon discussion

This was a lively discussion around pockmarks and disturbance by subsurface projects to inorganic and organic carbon on the seabed. Blue carbon estimates are a reality check of how much carbon is present in the marine system, thus suggesting that it must be preserved and disturbance to it must be minimised. Should regulation be required to count total carbon within a licence block to ensure minimal disturbance?

WP5: Regulation as an enabler discussion

There was a general consensus that we need to speed up regulation and make it more streamlined to enable rapid scale-up of the storage industry. There was discussion of how regulations may balance with liabilities, and the creation of various systems, like low-regulation, high-liability versus high-regulation, low-liability.

Stakeholders

From our perspective, the key takeaways for each stakeholder group were the following:

- **Industry**. Research done in Universities can be used as an independent assessment of the safety of CCS, and how we scale up the industry to mitigate CO_2 emissions.
- **Civil society**. The risks of doing CCS versus the risks of not doing CCS need to be appraised, by an impartial organisation.
- **Project developers**. Subsurface planning is essential. A long-term monitoring framework for the sub-surface, and a mechanism for allocating sub-surface pore-space by sector, is needed.
- **Regulators**. There is a limited, but developing, understanding of questions regarding the allocation and interaction of subsurface pore space. In a UK context, a next logical step is to expand out to regulation of onshore as well as offshore storage, and include improved regulation of geothermal resource exploitation.

4 Follow-up steps

The discussions in this workshop will be used to produce a final technical report and will inform several scientific research papers, following useful insights and comments from stakeholders. We have already had many follow-up conversations, and we plan several further research projects, some inspired directly by discussions during the workshop.

The University of Oxford has an active carbon storage and net-zero research community, with multiple research institutes in the University, such as Oxford Net Zero (ONZ, https://netzeroclimate.org), several ongoing large research programmes, and other NERC funded-projects. Due to the short duration of this Agile Initiative research sprint, there are many follow up activities to the above research efforts that will be pursued in the future, particularly in how they intersect with other areas of research. We want to foster active collaboration with stakeholders to pursue this research, either within the above programmes or in entirely new research projects.

We recognise the importance of research into public perception and social license, net-zero governance, law, and economics. Further interaction with external industry bodies, government, and regulators is needed. Please do stay in contact with us; we welcome visits to Oxford, further collaborations, and research projects.

If these particular fields are of interest, please do not hesitate to contact the following researchers:

- Induced seismicity and geophysics (Mike Kendall, Tom Kettlety)
- Noble gas research (Chris Ballentine)
- Leakage mechanisms (Joe Cartwright)
- Ecosystem impact (Ros Rickaby, Heather Bouman, Michelle Jackson)
- Fluid-flow modelling (Chris MacMinn)
- Policy, law, governance, social license (Myles Allen, Steve Smith, Oxford Net Zero)

The workshop has sparked multiple avenues for future research. One example is the production of a set of “principles for geological CO_2 storage”. If you are interested in collaborating on this project, then please contact millicent.sutton@ouce.ox.ac.uk.

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Authors

Millicent Sutton
Research Associate, Oxford Net Zero

Anna Rufas
Postdoctoral Research Associate, Department of Earth Sciences

Joseph Asplet
Postdoctoral Research Associate, Department of Earth Sciences

Malini Kallingal
Postdoctoral Research Associate, Department of Earth Sciences

Jimmy Moneron
Postdoctoral Research Associate, Department of Earth Sciences

Joe Cartwright
Professor of Earth Sciences, Department of Earth Sciences

Tom Kettlety
Research Fellow, Department of Earth Sciences

Mike Kendall
Chair of Geophysics, Department of Earth Sciences

Heather Bouman
Professor of Biogeochemistry, Department of Earth Sciences

Ros Rickaby
Chair of Geology, Department of Earth Sciences

Myles Allen
Head of Atmospheric, Oceanic and Planetary Physics in the Department of Physics, and Professor of Geosystem Science in the School of Geography and the Environment

Steve Smith
Executive Director, Oxford Net Zero and CO2RE

For More Information

agile@oxformartin.ox.ac.uk

agile-initiative.ox.ac.uk

@oxmartinschool

Sprint Research Team:

https://www.agile-initiative.ox.ac.uk/sprints/what-do-we-need-to-know-to-safely-store-co2-beneath-our-shelf-seas/

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The Agile Initiative,
Oxford Martin School,
34 Broad Street,
Oxford, OX1 3BD, United Kingdom