

# THE ROLE OF NORTH SEA IN ACHIEVING NET-ZERO: ASSESSING THE FEASIBILITY OF LARGE-SCALE CO<sub>2</sub> STORAGE IN SALINE AQUIFERS

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# IMPERIAL



## Abstract

As global efforts intensify to combat climate change, carbon capture and storage (CCS) has emerged as a critical solution, particularly for decarbonising industrial sectors. Among CCS options, geological storage in deep saline aquifers offers significant long-term potential due to their vast capacity and widespread availability. The North Sea has been identified as one of the most promising regions in Europe for CO<sub>2</sub> sequestration, offering favourable geological formations and access to existing offshore infrastructure. With the UK targeting net-zero greenhouse gas emissions by 2050 and an estimated 78 Gt of CO<sub>2</sub> storage capacity in its offshore sedimentary basins, effective utilisation of the North Sea saline aquifers could play a key role in meeting national and regional climate goals. This study evaluates the feasibility of large-scale CO<sub>2</sub> storage in North Sea saline aquifers, focusing on site suitability, infrastructure readiness, regulatory frameworks, and sustainability. Using geological data and spatial mapping, the research identifies viable storage sites, assesses the potential for repurposing oil and gas infrastructure, and examines policy and economic conditions for deployment. The study also evaluates the potential climate impact and alignment with the UN Sustainable Development Goals (SDGs). The findings aim to support the development of the North Sea as a strategic hub for carbon storage in the UK.

## 1. Introduction

The utilization of renewable energy sources has increased substantially over time. Nevertheless, projections indicate that fossil-based fuels—coal, natural gas, and oil—will continue to supply approximately 78% of global energy demand by 2040, based on extrapolations from recent atmospheric CO<sub>2</sub> concentration trends (Figure 1). Carbon dioxide (CO<sub>2</sub>) is a major greenhouse gas (GHG) contributing to the warming of Earth's atmosphere. The combustion of fossil fuels releases CO<sub>2</sub>, which accumulates in the atmosphere and drives global warming, sea-level rise, and a range of environmental, health, and economic challenges. Reducing CO<sub>2</sub> emissions from fossil fuel consumption is therefore essential to mitigating these impacts and fostering a more sustainable and resilient future that addresses both environmental and societal concerns (Izadpanahi, Blunt et al. 2024)

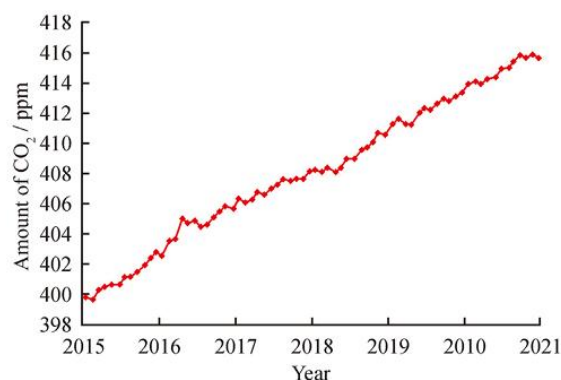


Figure 1. Trend of Atmospheric CO<sub>2</sub> Concentration

As global efforts to combat climate change intensify, carbon capture and storage (CCS) has emerged as a vital mitigation strategy, particularly for hard-to-abate sectors such as heavy industry and power generation. Currently, the primary types of geological formations suitable for CO<sub>2</sub> sequestration include saline aquifers, depleted oil and gas reservoirs, and coal seams. With the exception of saline aquifers, these storage options generally exhibit limited CO<sub>2</sub> storage capacity, involve relatively immature technologies, and require additional CO<sub>2</sub> separation and reinjection processes. In contrast, saline aquifers—widely distributed in sedimentary basins—offer significant advantages, including stable long-term storage, high reservoir porosity and permeability, and large potential capacity, as illustrated schematically in Figure 2. Consequently, CO<sub>2</sub> storage in saline aquifers is considered the most technically feasible and promising approach for large-scale carbon sequestration (Luo, Li et al. 2022)

CCS is increasingly recognised as a critical mechanism for achieving international climate objectives, including those articulated in the Paris Agreement and the United Nations Sustainable Development Goals (SDGs)—particularly SDG 13, which calls for urgent action to combat climate change and its impacts. Within this global context, the North Sea region has emerged as one of the most promising areas in Europe for large-scale CO<sub>2</sub> storage. The region benefits from a well-characterised geological framework, numerous deep saline aquifers, and extensive data derived from decades of hydrocarbon exploration. Moreover, its existing offshore infrastructure offers substantial potential for repurposing to support CCS deployment. Leveraging these assets positions the North Sea as a strategic hub for carbon storage, advancing both national and

regional decarbonisation targets. The United Kingdom (UK), for instance, has established a legally binding target to achieve net-zero greenhouse gas emissions by 2050, in line with its broader climate leadership ambitions. The UK Government's Net Zero Strategy and its support for emerging CCS clusters—such as the *East Coast Cluster* and *Acorn*—further underscore the growing policy commitment to large-scale CCS implementation.

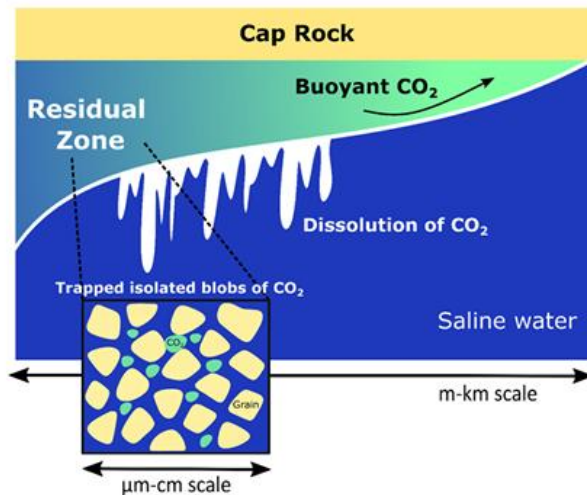


Figure 2. Schematic of a CO<sub>2</sub> plume after injection into a saline formation. The CO<sub>2</sub> plume moves upward due to buoyancy (shown in green). A fraction of CO<sub>2</sub> dissolves (shown in white) into the resident fluid (brine). At the tail of the plume, where brine displaces CO<sub>2</sub>, residual trapping of CO<sub>2</sub> occurs.

Geological assessments estimate that the UK possesses over 78 gigatonnes (Gt) of potential CO<sub>2</sub> storage capacity within offshore saline aquifers and depleted hydrocarbon reservoirs—a volume more than sufficient to accommodate the nation's projected carbon storage requirements for the coming decades. Within this context, the North Sea saline aquifers represent a cornerstone of the UK's net-zero pathway, offering potential benefits that extend beyond national borders by supporting wider European decarbonisation efforts. The principal saline aquifer locations along the UK continental shelf of the North Sea are shown in Figure 3 (Gammer, 2016). Effective utilisation of this storage capacity could also accelerate progress toward related SDGs, including SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation and Infrastructure).

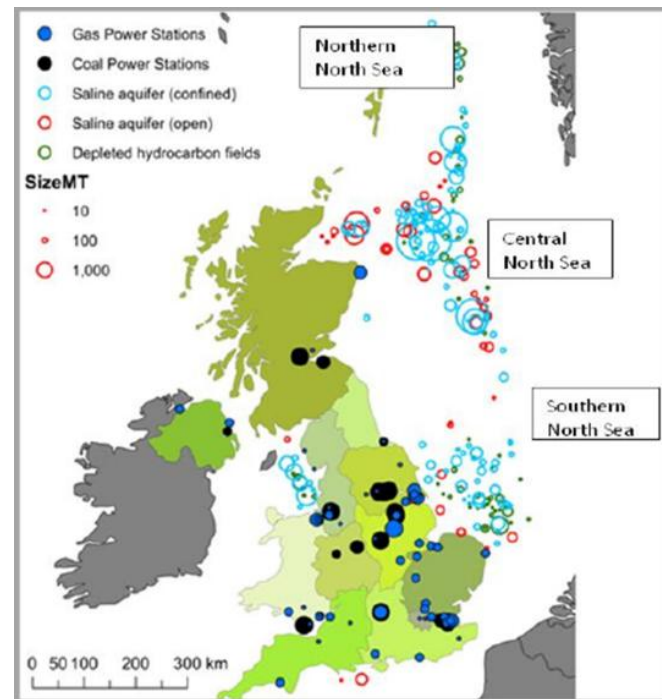


Figure 3. Distribution of the UK's CO<sub>2</sub> Storage Appraisal (UKSAP) sites and major emitters (Gammer, D., 2016)

This study aims to assess the feasibility of large-scale CO<sub>2</sub> storage in North Sea saline aquifers, with particular focus on geological suitability, infrastructure readiness, policy context, economic viability, and sustainability.

The specific objectives are to:

- 1) Evaluate the geological suitability of major saline aquifers in the North Sea;
- 2) Estimate storage capacity using established volumetric methodologies;
- 3) Assess the potential to repurpose existing offshore oil and gas infrastructure;
- 4) Analyse the regulatory and economic feasibility of large-scale deployment; and
- 5) Quantify the potential climate benefits and evaluate alignment with the United Nations Sustainable Development Goals.

This integrative assessment contributes to the ongoing European discourse on how best to mobilise the North Sea's unique geological and infrastructural resources in pursuit of climate neutrality.

## 2. Methodology

### 2.1 Research Design and Approach

This research is designed to evaluate the feasibility of large-scale CO<sub>2</sub> storage in North Sea saline aquifers, with the overarching aim of assessing the region's potential to contribute to national and European net-zero emissions goals. The central research question guiding this study is:

*“To what extent can North Sea saline aquifers serve as viable and sustainable reservoirs for large-scale CO<sub>2</sub> storage, considering geological suitability, infrastructure readiness, regulatory frameworks, economic viability, and alignment with climate policy objectives?”*

This question reflects the study's interdisciplinary nature, recognising that the success of CCS initiatives depends not only on geological feasibility but also on technical, economic, and policy conditions. To address this complex challenge, the research employs a multidisciplinary feasibility framework that integrates both quantitative and qualitative analyses across four main dimensions: geological assessment, infrastructure evaluation, policy and economic analysis, and sustainability assessment, as shown in Figure 4.

The research design follows an integrative, mixed-methods approach, combining technical data analysis with policy and economic evaluation. The geological component involves quantitative assessment of aquifer properties—such as porosity, permeability, pressure, and caprock integrity—to determine CO<sub>2</sub> storage potential using volumetric estimation techniques. This is complemented by an infrastructure assessment examining the adaptability of existing oil and gas infrastructure (pipelines, wells, and platforms) for CO<sub>2</sub> transportation and injection.

The policy and economic dimensions employ a qualitative–quantitative analytical approach, drawing upon legislative documents, industry reports, and cost model data to identify key regulatory enablers and financial constraints. A sustainability alignment analysis integrates these findings with the United Nations Sustainable Development Goals (SDGs) and EU climate neutrality objectives, providing a holistic understanding of how technical feasibility interacts with socio-economic and environmental considerations. (Uliasz-Misiak and Misiak 2024)

By integrating these analytical streams, the research adopts a systems-level perspective that captures the interconnected factors influencing CCS deployment. This approach enables the study to identify optimal geological sites, infrastructure reuse opportunities, and policy interventions that could facilitate cost-effective and sustainable CO<sub>2</sub> storage. The research approach is both exploratory and evaluative: exploratory in mapping the potential of saline aquifers within the North Sea Basin, and evaluative in assessing their readiness for implementation within existing economic and policy contexts. Through this design, the study aims to generate evidence-based insights that inform national CCS strategy development and support the wider European transition toward a low-carbon energy system.

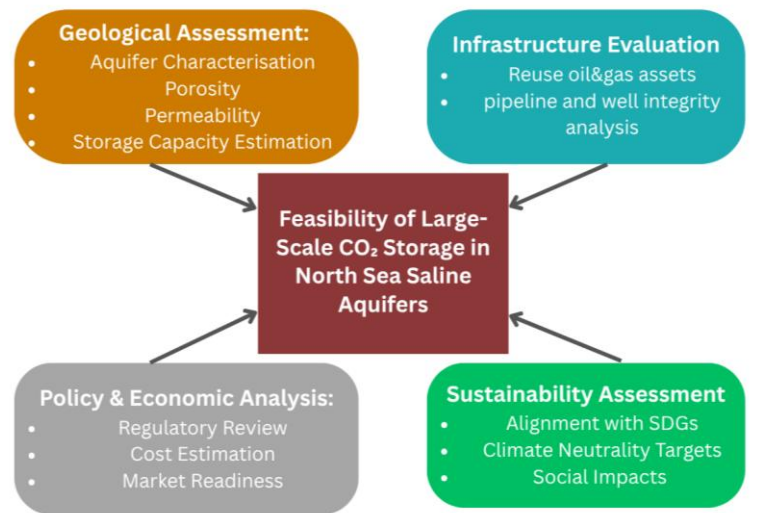


Figure 4. Integrated Feasibility Framework Output (Opportunities, challenges and policy recommendations for large-scale CO<sub>2</sub> storage)

## 2.2 Data Collection Methods

This study draws upon a combination of geological, technical, economic, and policy datasets to evaluate the feasibility of CO<sub>2</sub> storage in North Sea saline aquifers, with a particular emphasis on the United Kingdom sector. Data collection was guided by the need to ensure both spatial relevance and methodological consistency, integrating multiple open-access and institutional data sources.

### A) Geological Data

Geological data underpin the assessment of aquifer suitability and storage capacity. Key datasets were obtained from the British Geological Survey (BGS), which provides comprehensive subsurface geological and hydrocarbon records for the UK Continental Shelf. Supplementary data were accessed through the North Sea Transition Authority (NSTA) and published seismic survey interpretations, enabling detailed stratigraphic and structural mapping of potential storage formations. Well log data and core sample records were reviewed to quantify key reservoir parameters such as porosity, permeability, net-to-gross ratio, depth, and caprock thickness. Where applicable, data from the Norwegian Petroleum Directorate (NPD) were incorporated to provide regional geological context and to facilitate comparative analysis with the Norwegian sector of the North Sea, which hosts several operational CCS projects. These datasets collectively enabled the

identification of prospective saline aquifers and depleted hydrocarbon fields suitable for CO<sub>2</sub> storage in the UK offshore region.

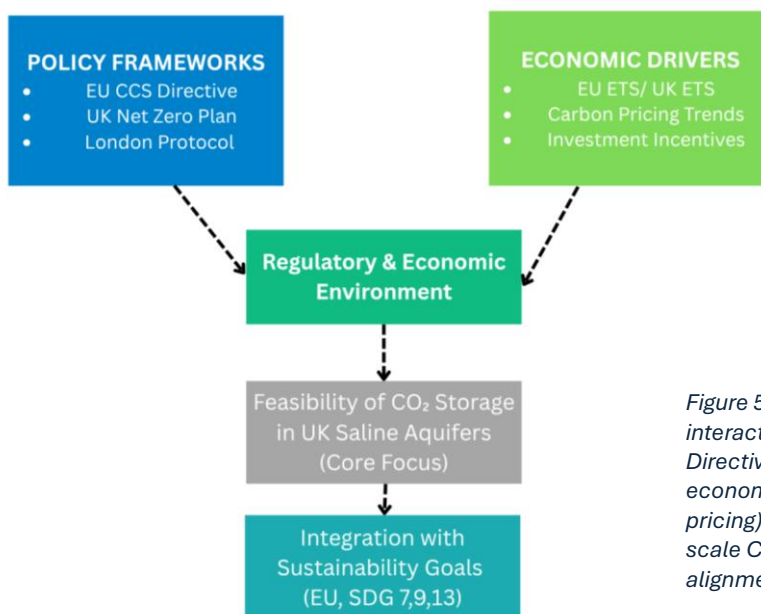
### ***B) Infrastructure Data***

Infrastructure data were compiled to evaluate the feasibility of repurposing existing oil and gas assets for CO<sub>2</sub> transport and injection. Information was obtained from NSTA, UK Oil and Gas Authority (OGA) archives, and decommissioning reports from offshore operators. These sources provided insight into the location, condition, and specifications of wells, platforms, and subsea pipeline networks. Additionally, pipeline network maps and infrastructure datasets were used to assess proximity to major emission clusters, particularly those along the UK East Coast (e.g., Teesside and Humber regions), which are central to ongoing CCS development plans.

### ***C) Economic and Policy Data***

Economic and regulatory data were collected to evaluate policy readiness, cost structures, and investment incentives associated with CCS deployment in the UK and wider European context. Key legislative documents include the European Union Carbon Capture and Storage Directive (2009/31/EC), the UK Net Zero Strategy, and amendments to the International Maritime Organization's (IMO) London Protocol, which governs transboundary CO<sub>2</sub> transport and storage.

Economic indicators and carbon market data were derived from the EU Emissions Trading System (ETS) and the UK ETS, enabling comparative assessment of carbon price trends and their implications for project viability (Figure 5). Additional reference was made to industry feasibility reports, academic literature, and governmental white papers to contextualize regulatory developments and policy mechanisms supporting CCS expansion in the UK.



*Figure 5. Conceptual Schematic showing the interaction between regulatory frameworks (EU CCS Directive, UK Net Zero Strategy, London Protocol) and economic mechanisms (EU ETS, UK ETS, carbon pricing) that collectively shape the feasibility of large-scale CO<sub>2</sub> storage in UK saline aquifers and their alignment with broader sustainability goals*

#### D) **Case Study Data**

To supplement primary datasets, case studies of operational CCS projects—including Sleipner, Snøhvit, and Northern Lights in the Norwegian North Sea—were reviewed to benchmark technical performance and identify best practices applicable to the UK context (Uliasz-Misiak and Misiak 2024). These case studies provided valuable empirical insights into injection strategies, monitoring and verification protocols, and long-term storage integrity, serving as analogues for assessing UK project feasibility.

Collectively, these diverse data sources establish a robust empirical foundation for evaluating the geological, technical, and regulatory feasibility of CO<sub>2</sub> storage in UK saline aquifers (Figure 6). The integration of multi-source datasets ensures a comprehensive and contextually grounded analysis of the North Sea’s potential as a strategic carbon storage hub.

#### Key Datasets Used in This Study

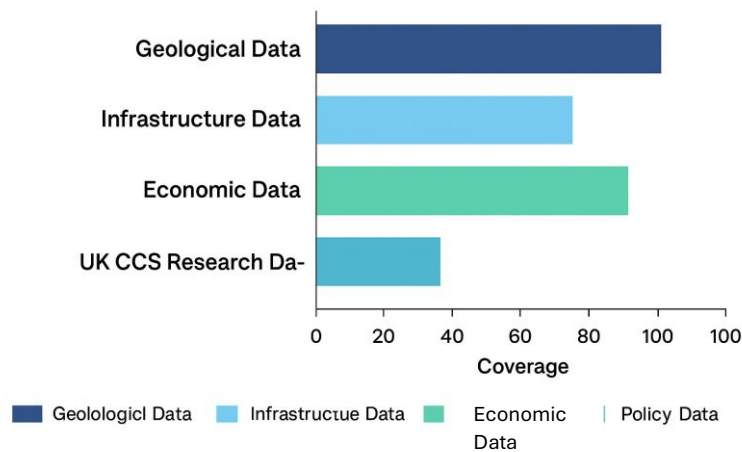


Figure 6. Key geological, infrastructure, economic, and policy datasets used in this study, illustrating their thematic coverage and spatial or temporal extent across the UK North Sea. Data compiled from BGS (2024), NSTA (2024), UK CCS Research Database and EU and UK ETS carbon price archives

#### 2.3 Site Selection Criteria

The selection of suitable saline aquifers for CO<sub>2</sub> storage in the North Sea was conducted using a set of technical and locational criteria aimed at ensuring storage efficiency, injectivity, and long-term containment security. Candidate sites were screened according to the following parameters:

1. **Depth:** Only aquifers deeper than 800 meters were considered to ensure that CO<sub>2</sub> would exist in a dense, supercritical state (Izadpanahi, Blunt et al. 2024), thereby increasing storage efficiency and reducing buoyancy-related leakage risks.
2. **Reservoir Quality:** Aquifers with porosity greater than 20% and permeability exceeding 100 millidarcies (mD) (Worden 2024) were prioritized to ensure sufficient pore volume and injectivity for CO<sub>2</sub> storage operations.
3. **Seal Integrity:** Preference was given to aquifers overlain by thick, laterally continuous caprocks with minimal faulting. Impermeable seals, such as shale or evaporites, were considered ideal for long-term containment.
4. **Aquifer Thickness:** Only formations with a thickness exceeding 50 meters were selected to provide adequate storage capacity.

5. **Proximity to CO<sub>2</sub> Sources and Infrastructure:** Candidate sites were evaluated based on their distance from major industrial CO<sub>2</sub> emission clusters and existing offshore infrastructure, to minimize transportation costs and facilitate practical implementation.

This multi-criteria screening approach enabled the identification of optimal storage sites by balancing geological suitability with logistical feasibility. The workflow for site screening and selection is illustrated in Figure 7, following a decision funnel approach (Baig, Fentaw et al. 2025)

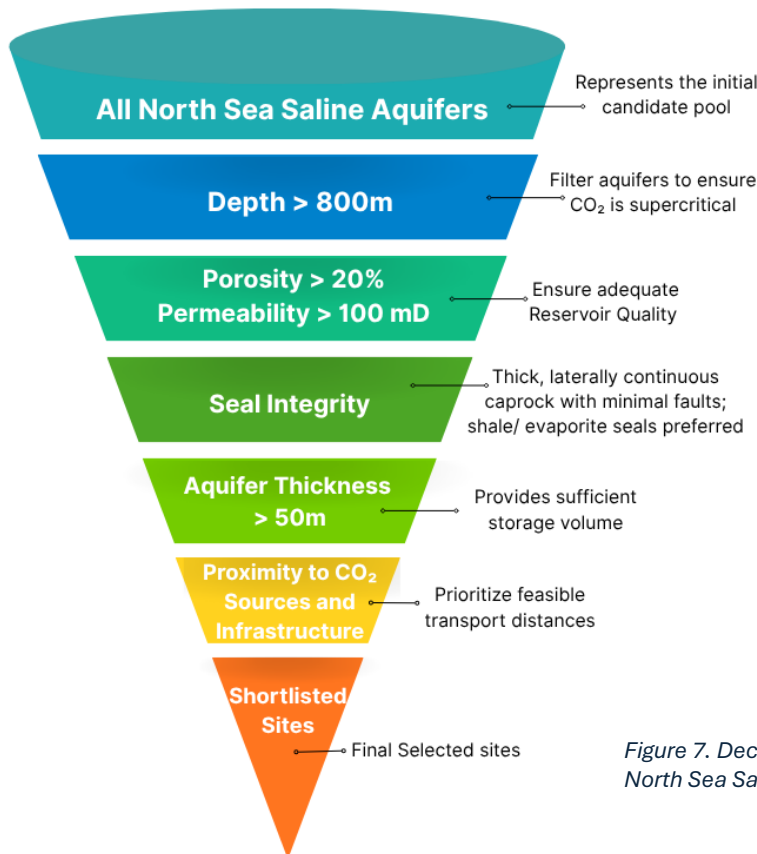


Figure 7. Decision Funnel for Screening and Selecting North Sea Saline Aquifers for CO<sub>2</sub> Storage

## 2.4 Storage Capacity Estimation

The volumetric storage capacity of saline aquifers was estimated using the standard equation:

$$M_{CO_2} = A \times h \times \phi \times S_{CO_2} \times \rho_{CO_2}$$

Where

A = area of the aquifer (m<sup>2</sup>)

h = aquifer thickness (m)

φ = porosity (fraction)

S<sub>CO<sub>2</sub></sub> = storage efficiency factor (typically 0.02 - 0.06 for saline aquifers)

ρ<sub>CO<sub>2</sub></sub> = density of CO<sub>2</sub> under reservoir conditions (typically 600-800kg/m<sup>3</sup> at depths > 800 m)

This approach provides an initial estimate of the CO<sub>2</sub> mass that can be safely stored in a given aquifer, taking into account reservoir geometry, rock properties, and CO<sub>2</sub> behaviour under in-situ conditions. (Ringrose, Furre et al. 2021)

## Storage Mechanisms

CO<sub>2</sub> is retained in saline aquifers through multiple physical and chemical processes, which act over different timescales and contribute to increasing storage security:

### 1. Physical Trapping

- **Structural/Stratigraphic Trapping:** CO<sub>2</sub> is held in discrete accumulations by buoyancy forces (generated by density differences between injected supercritical CO<sub>2</sub> and brine) beneath impermeable caprocks. Some important storage sites considered suitable for this are anticlinal traps, fault traps, lithological and unconformity traps.

**Residual (Capillary) Trapping:** As CO<sub>2</sub> migrates, portions become immobilized in the pore space due to hysteresis in relative permeability. It is achieved through the snap-off effect caused by the capillary force and wettability in the pores of the brine aquifer, which causes CO<sub>2</sub> belonging to the non-wetting phase to be truncated and sequestered in the porous medium as a stationary phase (Tillero 2024)

### 2. Chemical Trapping

- **Solubility Trapping:** CO<sub>2</sub> dissolves into the formation water, slightly increasing its density and inducing density-driven convection. The effect is reduced in highly saline aquifers. (Chen, Yu et al. 2023)
- **Mineral Trapping:** Over long periods, dissolved CO<sub>2</sub> can react with divalent cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Fe<sup>2+</sup>) to form stable carbonate minerals. The extent is limited by the availability of reactive metals.

The relative importance of each mechanism evolves over time, with structural trapping dominating initially and residual, solubility, and mineral trapping becoming increasingly significant in the long term storage security, consistent with the IPCC (2005) guidelines (Figure 8) (Worden 2024)

## 2.5 Risk and Policy Analysis

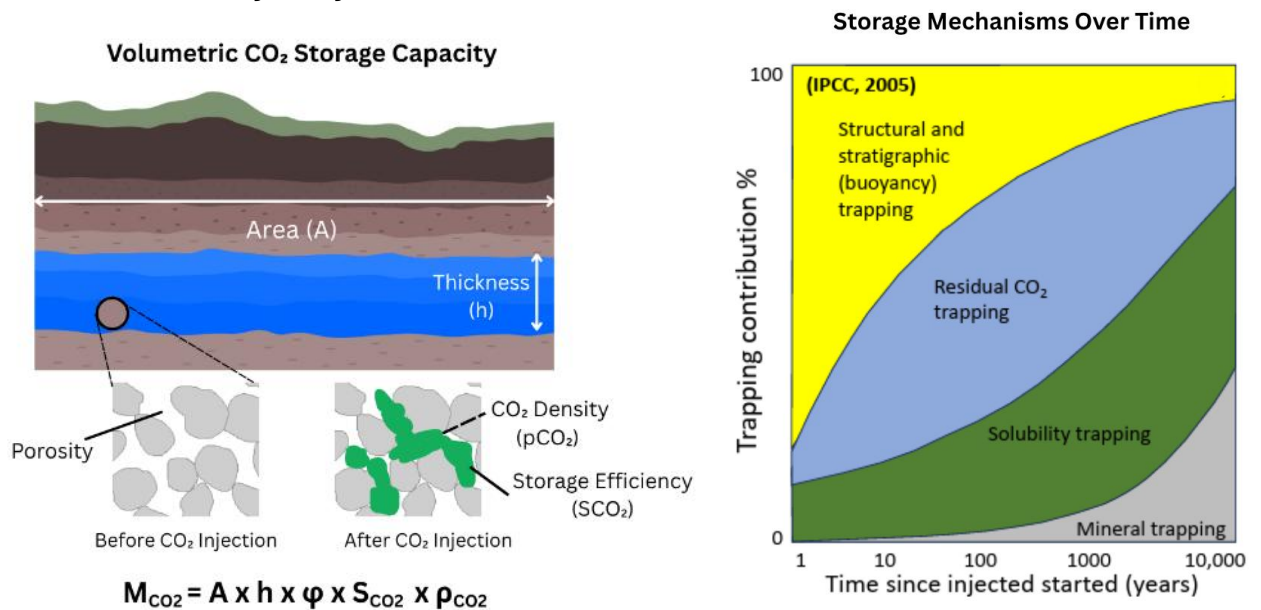


Figure 8. Illustration of volumetric CO<sub>2</sub> Storage capacity estimation in a saline aquifer (left) and the evolution of dominant storage mechanisms over time (right)

### *Risk Assessment Framework*

The evaluation of risks associated with CO<sub>2</sub> storage in saline aquifers was conducted using a structured probability-consequence matrix, a widely adopted methodology in geotechnical risk management. This approach facilitates the systematic identification, assessment, and prioritization of potential hazards, enabling the development of targeted mitigation strategies.

Risk Categories Assessed:

1. Geological Risks
  - CO<sub>2</sub> Leakage: Potential migration of CO<sub>2</sub> through faults, fractures, or abandoned wells, compromising storage integrity.
  - Caprock Integrity: Assessment of the seal's ability to prevent upward migration of CO<sub>2</sub>.
2. Operational Risks
  - Induced Seismicity: Seismic events triggered by changes in subsurface pressure during CO<sub>2</sub> injection.
  - Injection Failures: Operational issues such as equipment malfunctions or well integrity breaches.
3. Financial Risks
  - Investment Uncertainty: Fluctuations in carbon pricing and potential liabilities affecting project viability.
  - Cost Overruns: Unanticipated expenses arising from geological uncertainties or regulatory changes.
4. Societal Risks
  - Public Acceptance: Community concerns regarding safety and environmental impacts.
  - Reputational Risks: Potential damage to stakeholders' public image due to perceived environmental hazards.

Each risk was evaluated based on its likelihood of occurrence and potential impact, categorizing them into low, medium, or high-risk levels (Figure 9) ([Uliasz-Misiak and Misiak 2024](#)).

### *Policy and Regulatory Framework*

The regulatory landscape for CO<sub>2</sub> storage is shaped by both European Union directives and international agreements:

- EU CCS Directive (2009/31/EC): Establishes requirements for site selection, storage permits, monitoring, and post-closure responsibilities, ensuring the safe and effective implementation of CCS projects
- London Protocol Amendments (2006): Permit the cross-border transport and sub-seabed storage of CO<sub>2</sub>, facilitating multinational CCS projects under stringent environmental safeguards
- National Regulatory Frameworks: Country-specific regulations that address local geological conditions, permitting processes, and liability regimes, ensuring compliance with both EU directives and international agreements.

These policies collectively provide a robust framework for managing risks associated with CO<sub>2</sub> storage, balancing environmental protection with the facilitation of climate change mitigation efforts. (Baig, Fentaw et al. 2025)

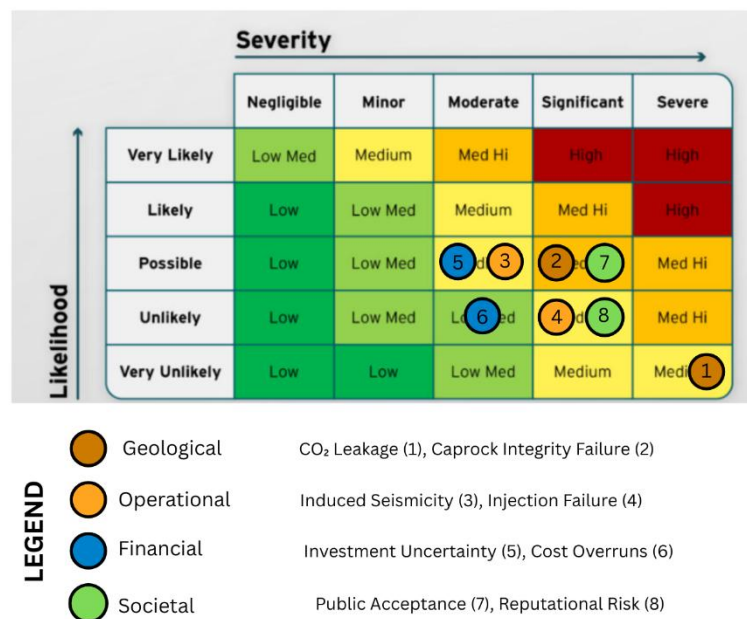


Figure 9. Risk Interaction Matrix for CO<sub>2</sub> Storage in Saline Aquifers. This matrix illustrates the assessed probability and consequence of various geological, operational, financial, and societal risks, aiding in the prioritization of mitigation strategies.

### 3. Results

#### 3.1 Geological Storage Potential

The geological analysis highlights several offshore saline aquifers in the UK sector of the North Sea as highly prospective targets for large-scale CO<sub>2</sub> storage. Among these, the Bunter Sandstone and Captain Sandstone formations emerge as particularly promising based on their depth, porosity, caprock integrity, and proximity to major emission sources and infrastructure.

The Bunter Sandstone, located beneath the southern North Sea, covers an area of approximately 20,000 km<sup>2</sup>, with average porosities of 20–22 % and a depth range of 1500–2000 m (Rigby and Alsayah 2024). Its estimated CO<sub>2</sub> storage capacity is 200–500 Mt, supported by very good sealing properties and its proximity to key UK industrial clusters such as Teesside and Humber. This strategic location aligns the Bunter Sandstone with national decarbonisation initiatives such as the Zero Carbon Humber and Net Zero Teesside projects.

The Captain Sandstone in the UK central North Sea is another high-priority candidate, lying at depths of 1000–1500 m with porosities of 20–25 %. The formation benefits from a tight shale caprock, ensuring excellent seal integrity. Its estimated capacity ranges from 100–300 Mt, and its proximity to the St Fergus Gas Terminal enhances its potential for early deployment. It is a designated target for the Acorn CCS Project, which aims to establish one of the UK’s first operational CO<sub>2</sub> storage hubs. Although not in the UK, the Utsira Formation in Norway remains an important benchmark in the North Sea basin. Covering more than 26,000 km<sup>2</sup> with porosities of 30–40 % and thicknesses up to 250 m,

it has demonstrated secure CO<sub>2</sub> storage for over two decades through the Sleipner CO<sub>2</sub> Storage Project. The operational experience from Utsira provides a robust analogue for UK formations, particularly in understanding plume migration, monitoring, and risk mitigation. Additional formations such as the Skagerrak Formation and Central Graben Formation offer further multi-gigatonne capacity within the broader North Sea basin. While these are strategically located to serve emission sources in neighbouring countries, their geological characteristics also reinforce the region’s overall suitability for basin-scale CO<sub>2</sub> storage as shown in the table below (Table 1).

Table 1. Suitability of Major Saline Aquifers for Basin-scale CCS

Site / Formation	Country	Depth (m)	Porosity (%)	Caprock Integrity	Estimated Capacity (Mt CO <sub>2</sub> )	Infrastructure Proximity
<b>Captain Sandstone</b>	UK	1000–1500	20–25	High (tight shale sealing)	100–300	High (near St Fergus Terminal)
<b>Bunter Sandstone</b>	UK	1500–2000	20–22	Very good	200–500	High (Endurance platform area)
<b>Utsira Formation</b>	Norway	800–1000	30–40	Excellent	>10,000	Existing CCS infrastructure (Sleipner)
<b>Skagerrak Formation</b>	Norway	1200–1800	25–30	Very good	Multi-Gt	Medium
<b>Central Graben Formation</b>	Norway	1500–2500	20–28	Good	Multi-Gt	Medium

The results indicate that the UK possesses significant CO<sub>2</sub> storage potential within its offshore saline aquifers, particularly in formations proximal to industrial clusters, which reduces transportation costs and infrastructure requirements. The geological characteristics — notably high porosity, suitable depth intervals, and strong caprock integrity — align well with international best practice standards for secure long-term CO<sub>2</sub> storage. A key finding is the clear relationship between increasing depth and storage capacity across these formations (Figure 10). Deeper reservoirs generally offer higher pressure regimes and larger available pore volume, though they also present engineering and monitoring challenges that must be carefully addressed during project design.

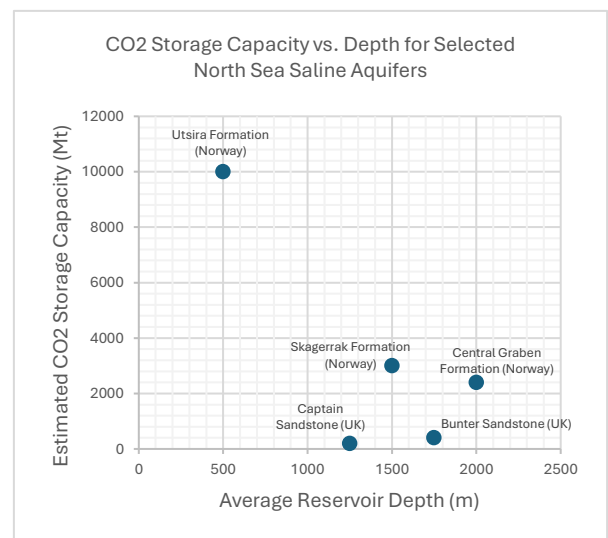


Figure 10. Relationship between estimated CO<sub>2</sub> storage capacity and average reservoir depth for selected aquifers.

### 3.2 Infrastructure Repurposing Potential

The North Sea region offers one of the most advanced offshore infrastructure networks globally, built over five decades of hydrocarbon exploration and production. This legacy infrastructure presents a strategic opportunity to accelerate CO<sub>2</sub> transport and storage deployment while reducing overall project costs.

The analysis reveals that the UK’s offshore pipeline system—spanning more than 7,000 km—is particularly suited for CO<sub>2</sub> transport repurposing, especially in corridors originally designed for dry natural gas. Preliminary estimates indicate that reusing existing pipelines, platforms, and terminals could reduce capital expenditure by 20–40 % compared to developing entirely new transport networks. This cost advantage, combined with reduced permitting and construction timelines, makes infrastructure repurposing a critical enabler for near-term CCS deployment in the UK sector of the North Sea. (Ringrose, Furre et al. 2021)

Decommissioning data from the NSTA and the BGS show that numerous offshore platforms nearing the end of their production life could be retrofitted into CO<sub>2</sub> injection hubs. Notable examples include installations in the Goldeneye Field and the St Fergus Gas Terminal region in northeast Scotland, both of which have existing compressor and well access infrastructure. By converting these assets, decommissioning costs can be offset while providing immediate operational support for carbon storage projects such as Acorn CCS and the East Coast Cluster.

Experience from projects such as Northern Lights in Norway demonstrates the feasibility of integrating dedicated CO<sub>2</sub> transport systems with repurposed assets to create multi-user storage networks. These developments underline the potential for cross-border coordination, allowing the North Sea to emerge as a shared European CO<sub>2</sub> storage basin (Figure 11)

The assessment of key infrastructure elements is summarised in Table 2, which highlights their relative feasibility for reuse and the associated technical and operational considerations

Table 2. Feasibility and Considerations for Repurposing Existing Offshore Infrastructure for CO<sub>2</sub> Transport and Storage

Infrastructure Element	Feasibility for Reuse	Considerations
Offshore Platforms	High	Existing structures (e.g., Goldeneye, St Fergus) can house compressors and injection equipment.
Subsea Pipelines	High (if dry gas design)	Must assess steel grade, corrosion resistance, and CO <sub>2</sub> phase (supercritical).
Wellbores (abandoned)	Medium–Low	Cement/casing integrity must be evaluated; old wells may act as leakage paths.
CO <sub>2</sub> Injection Wells (new)	Required	New wells with corrosion-resistant steel and cement for dedicated injection.
Compression Facilities	High	May be upgraded from gas processing sites. Power demand and location matter.
Monitoring Infrastructure	Medium–High	Seismic arrays, pressure gauges, and remote sensing must be added or adapted.

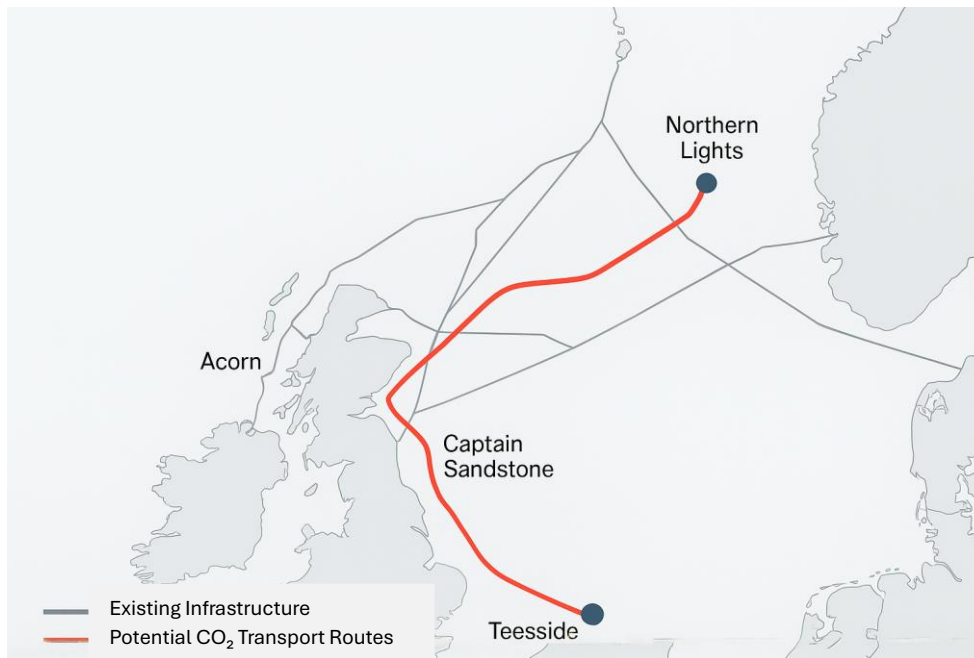


Figure 11. Map showing existing offshore infrastructure and potential CO<sub>2</sub> Transport routes linking key UK Saline aquifer storage sites (Captain and Bunter Sandstone Formations) with major CCS hubs (Acorn and Teesside). (NSTA, 2020)

### 3.3 Policy and Economic Feasibility

The regulatory framework (EU CCS Directive 2009/31/EC and London Protocol amendments) provides the necessary legal scaffolding for offshore storage. Still, national transpositions and ratification differences across North Sea states create practical uncertainty for cross-border hubs. This regulatory heterogeneity links directly to the high financial risks identified in §2.5: stricter national liability and financial-assurance rules reduce societal/reputational risk but increase upfront capital requirements and insurance costs.

#### **Site-level cost evidence**

Representative, site-level and project examples from the North Sea indicate that storage costs vary substantially with geology, monitoring expectation, and infrastructure needs:

1. Utsira / Sleipner (Norway) — operating experience from Sleipner reports low incremental injection costs relative to capture; historical project reporting indicates injection costs on the order of ~\$17/tCO<sub>2</sub> (illustrative unit for injection operations). Sleipner demonstrates long-term operational feasibility and large capacity potential in the Utsira formation
2. Captain Sandstone (UK) — appraisal documentation (DECC / UKERC technical report) estimated capital investment at £152M (PV10, 2015), equating to roughly £2.5 per tonne of modelled stored CO<sub>2</sub> in that appraisal scenario — a useful historical benchmark for storage CAPEX per tonne when scale and lifetime are considered.
3. Bunter Sandstone (Southern North Sea) — capacity and dynamic behaviour are well documented in regional reservoir studies; few open-literature site-specific unit cost publications exist, so Bunter cost assumptions should be aligned with regional integrated T+S benchmarks and sensitivity ranges derived below (Tillero 2024)

Regional and literature synthesis suggest integrated transport + storage (T+S) costs for North Sea saline aquifers typically fall in the €10–40/tCO<sub>2</sub> band, depending on distance to hub, monitoring stringency and whether hub economies of scale are realised. This is consistent with broader European/IEA/industry cost ranges.

**Revenue context and sensitivity**

Observed EU ETS prices have been volatile but are materially above typical storage costs: EU allowance prices in 2025 are in the €60–80/t window (recent datapoints ≈ €76–78/t). UK traded carbon value scenarios published for modelling provide low/central/high pathways to 2050 that the government uses for appraisal. Under a midcase carbon price of ~ €70–80/t and T+S cost of ~ €20–30/t, the implied margin (~ €40–60/t) is sufficient to cover capture and O&M for many industrial sources; however, sensitivity testing shows margins compress quickly if carbon prices fall or if site costs exceed the midcase (Figure 12)

**Policy implications linked to risk matrix**

Because financial and societal risks are tightly coupled (see Section 2.5), scaling CCS in the North Sea depends on three policy elements:

1. Long-term revenue certainty (CfDs, carbon price floors or guaranteed offtake),
2. Harmonised liability/permit rules across North Sea states to enable cross-border hubs
3. Targeted de-risking mechanisms for first-mover projects (grants, PPP structures or limited state assumption of long-tail monitoring liability).

With those enablers, hub deployment can realise 15–25% per-tonne cost reductions via economies of scale, improving resilience to price shocks

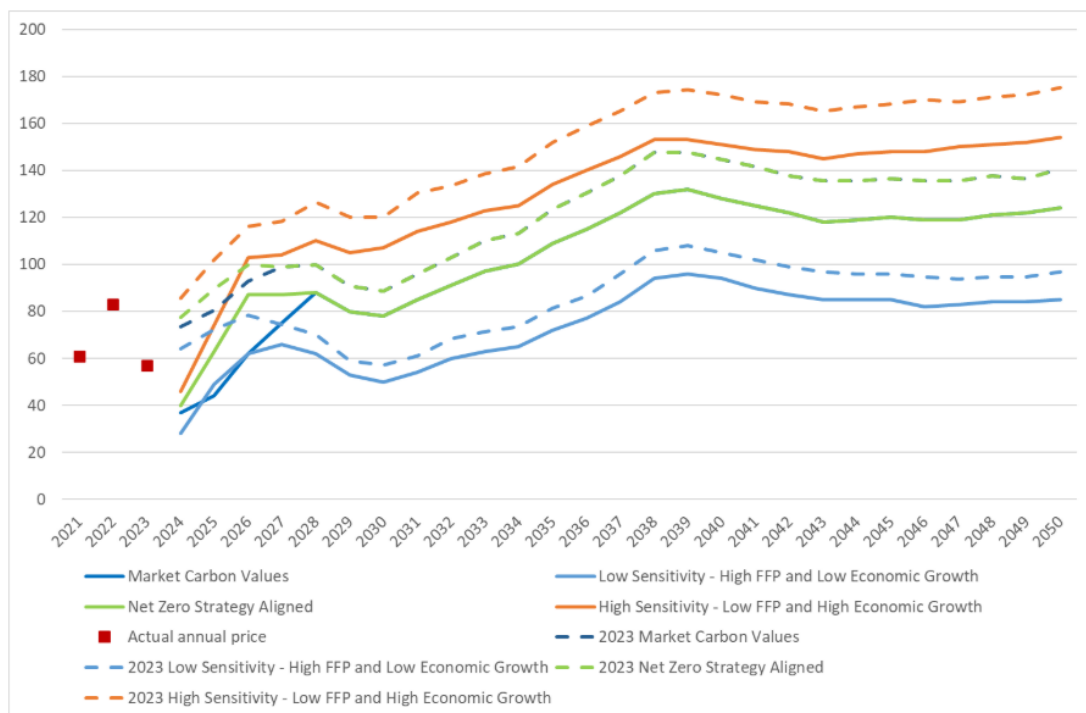


Figure 12. Historical and Projected Carbon Prices in the EU ETS and UK ETS / Traded Carbon Values (€/tCO<sub>2</sub>) based on GOV.UK (2024)

### 3.4 Risk Assessment

The probability–consequence matrix (Figure 9; Section 2.5) highlights distinct risk profiles across geological, operational, financial, and societal domains for CO<sub>2</sub> storage in North Sea saline aquifers. The overall findings indicate that geological containment risks are low in likelihood but potentially severe in consequence, while financial and societal uncertainties remain the principal challenges to project feasibility. The risk factors are listed in Table 3 and correspond primarily to geological and operational categories as defined in Section 2.5

#### Geological Risks

The risk matrix classifies CO<sub>2</sub> leakage and caprock integrity risks as very unlikely to possible, but significant to severe in consequence. Extensive geological characterisation of the Bunter, Captain, and Utsira formations indicates robust sealing capacity and sufficient structural closure (IEAGHG, 2019).

The Sleipner project in the Utsira Formation, operating since 1996, provides over two decades of monitored data confirming long-term containment with no detectable leakage to the seabed (MIT CCS, 2023). Time-lapse seismic surveys demonstrate that plume migration remains confined within predicted reservoir boundaries, supporting the low-probability, moderate-consequence classification adopted in the risk matrix.

Table 3. Geological and Operational Risk Factors with their possibility and impact severity

Risk Factor	Leakage Pathway	Likelihood	Impact	Notes / Rationale
<b>Fault Reactivation</b>	Faults/fractures near the injection	Medium	High	Depends on tectonic setting and injection pressure; risk increases with poorly mapped faults.
<b>Abandoned Wells</b>	Legacy wellbores	High	Medium	Many old wells in North Sea may not be properly sealed; cement degradation is a concern.
<b>Caprock Failure</b>	Caprock breach	Low	High	Rare if caprock is intact; proper site selection minimizes risk.
<b>Pressure Buildup</b>	Over pressurization	Medium	Medium	Can reduce injectivity or compromise caprock; requires pressure monitoring and brine production.
<b>Lateral Migration</b>	CO <sub>2</sub> movement beyond the structural trap	Low	Medium	Depends on reservoir boundaries and caprock continuity.
<b>Well Integrity (new)</b>	CO <sub>2</sub> injection wells	Low–Medium	Medium	Depends on cement/casing design and operational monitoring.

#### Operational Risks

Induced seismicity and well integrity were assessed as *moderate but manageable*. While injection-related microseismic events have been observed in some pilot projects globally, no significant events have been recorded at North Sea storage sites. Figure 13. Below highlights

some of these operational risks like induced seismicity and injection failure (Worden 2024) Real-time seismic and pressure monitoring, adaptive injection control, and pre-injection site screening substantially mitigate these risks (IEAGHG, 2019). The application of closed-loop reservoir management systems—where injection rates are continuously adjusted based on downhole pressure feedback—has proven effective at Sleipner and Snøhvit. No significant seismic events have been recorded at Sleipner or UKCS pilot sites, confirming the “moderate but manageable” assessment.

### Financial Risks

Financial and liability-related risks are the highest residual category. Uncertainty persists around long-term liability transfer, post-closure financial security, and carbon price volatility. Under the EU CCS Directive, site operators remain responsible until a competent authority formally accepts transfer—typically after 20–30 years of post-closure monitoring (EU Directive 2009/31/EC; DESNZ, 2024). Experience from commercial appraisals (e.g. the Captain site feasibility study) shows that uncertainty in carbon price trajectories and decommissioning liabilities can raise the weighted cost of capital by 2–3 percentage points (UKERC, 2015). These risks justify the *high-impact, medium-probability* placement on the matrix and underline the need for robust financial-assurance instruments and policy clarity (see Section 3.3).

### Societal Risks

Public acceptance and reputational risks remain a critical variable. Surveys across the UK and Norway reveal mixed perceptions of CCS safety and necessity: while over 70 % of respondents recognise its potential role in decarbonisation, fewer than half express comfort with nearby offshore storage. Social licence is influenced more by trust in regulators and operators than by technical understanding. Public opposition can delay permitting or increase monitoring obligations, thereby reinforcing the link between societal and financial risk categories identified in Figure 9. Hence, transparent stakeholder engagement and consistent communication of monitoring results—such as the open Sleipner time-lapse data repository—are central to risk reduction.

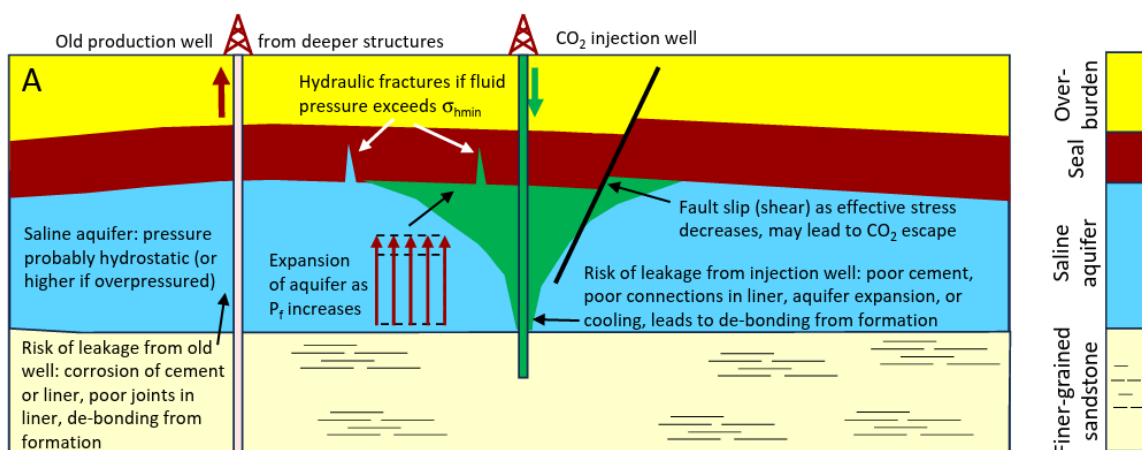


Figure 13. Factors influencing the risk of leakage in saline aquifers and depleted gas fields: green (down) arrow represents CO<sub>2</sub> injection, red arrows (up) represent the risk of fluid escape from old wells. (Worden 2024)

## Overall Risk Profile

Integrating the probability–consequence results across domains, the aggregate project risk level is moderate, with strong geological and operational control but continued exposure to financial and societal uncertainties. Long-term project viability therefore, depends chiefly on stable policy frameworks, clear liability transfer mechanisms, and sustained public trust—factors aligning with the recommendations derived from the policy and economic feasibility assessment (Section 3.3).

### 3.5 Climate and Sustainability Contributions

The deployment of CCS in North Sea saline aquifers offers substantial contributions to climate mitigation and broader sustainability objectives. Based on the results presented in Sections 3.1–3.4, saline aquifer reservoirs demonstrate high storage capacity, low leakage risk, and operational feasibility under current technological constraints, supporting their role as effective carbon sinks.

#### *Climate Mitigation Potential:*

Our feasibility assessment indicates that the selected aquifers can store CO<sub>2</sub> volumes on the order of 78 billion tonnes, which could significantly offset industrial and power-sector emissions in the North Sea region. Assuming a conservative annual injection scenario of 4 million tonnes per year, CCS operations in these formations could contribute to a reduction of 200–300 million tonnes of CO<sub>2</sub> per year. This aligns with IPCC projections for required negative emissions pathways to limit global warming to 1.5–2°C (IPCC, 2023). Furthermore, operational risk factors, summarized in Table 3, suggest that geological integrity and monitoring strategies are sufficient to mitigate leakage and long-term environmental hazards, preserving the climate benefits over the operational and post-closure phases. (Ringrose, Furre et al. 2021)

#### *Sustainability Implications:*

Beyond climate mitigation, CCS projects in the North Sea have wider sustainability co-benefits. Storage operations support several UN SDGs:

- 1) SDG 7 (Affordable and Clean Energy): Supports low-carbon energy transition while enabling continued fossil energy use.
- 2) SDG 9 (Industry, Innovation, and Infrastructure): Drives innovation in subsurface monitoring, injection optimization, and operational safety.
- 3) SDG 13 (Climate Action): Directly reduces greenhouse gas emissions, supporting national and global targets.
- 4) SDG 14 (Life Below Water): Effective site selection and monitoring help safeguard marine ecosystems.

Integrating CCS within regional energy infrastructure and climate policy frameworks enhances the sustainability profile of North Sea operations while supporting a just transition to low-carbon energy systems. Overall, the results indicate that CCS in North Sea saline aquifers is not only technically and economically feasible but also contributes meaningfully to climate mitigation and sustainability objectives. Future work should focus on long-term monitoring, ecosystem impact assessments, and integration with renewable energy strategies to maximize societal and environmental benefits.

## 4 Discussion

The findings reinforce the North Sea's role as Europe's leading carbon storage hub. Geological analysis confirms that saline aquifers, particularly the Utsira Formation and the Bunter Sandstone, provide sufficient capacity and containment integrity for multi-gigatonne storage. The operational track record of Sleipner, which has safely stored CO<sub>2</sub> for nearly three decades, provides strong empirical evidence that large-scale injection is both technically feasible and environmentally secure. Infrastructure repurposing emerges as a central enabler, offering cost savings while supporting the transition of offshore industries. Instead of incurring billions of euros in decommissioning liabilities, existing platforms and pipelines can be integrated into a CO<sub>2</sub> storage network, contributing to a just transition for workers and communities historically dependent on oil and gas.

Economically, CCS in the North Sea has reached a tipping point, with storage costs comfortably below prevailing carbon prices. However, investment risks remain high without stable policy frameworks. Governments will need to provide de-risking mechanisms to mobilize private capital, including guaranteed revenue streams and long-term liability management.

The primary challenge lies not in technical feasibility but in governance and public acceptance. Regulatory fragmentation across jurisdictions and uncertainty over liability transfer could delay projects. Public scepticism of CCS, often framed as prolonging fossil fuel use, must be addressed through transparent communication and demonstration of climate and sustainability benefits, as highlighted in Section 3.5. By explicitly linking CCS deployment to SDGs 7, 9, 13, and 14, stakeholders can appreciate both climate mitigation and broader societal contributions.

## 5 Conclusion and Further Research

This study demonstrates that the North Sea's saline aquifers are geologically, technically, and economically suitable for large-scale CO<sub>2</sub> storage. Key formations such as the Utsira Formation and the Bunter Sandstone possess multi-gigatonne storage potential, validated by pilot and commercial projects. The repurposing of existing infrastructure offers substantial cost reductions and accelerates deployment, while regulatory frameworks, though supportive, require further harmonization for cross-border projects. Economically, storage is viable under current carbon prices, and sustainability analysis confirms strong contributions to SDGs 7, 9, 13, and 14. The North Sea has the potential to transition from a hydrocarbon production zone to Europe's leading carbon storage hub, capable of sequestering 200–300 MtCO<sub>2</sub> annually by 2050. Realizing this potential will require coordinated governance, public-private investment, and societal engagement. If achieved, the North Sea could anchor Europe's pathway to net-zero while demonstrating how legacy hydrocarbon regions can be transformed into climate solutions that generate both environmental and socio-economic value.

Future research should advance geophysical and geochemical monitoring techniques to verify the long-term containment and structural integrity of CO<sub>2</sub> storage reservoirs. Further assessment of ecological and biogeochemical impacts from offshore storage is needed to safeguard marine systems and guide mitigation strategies. Integrated modelling of reservoir pressure dynamics, plume migration, and cross-border CO<sub>2</sub> transport will enhance regional coordination and storage efficiency. Strengthening transparent communication and stakeholder engagement remains essential for fostering public trust and ensuring the sustainable deployment of carbon storage technologies.

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