

Progressing Scotland's CO₂ storage opportunities

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Location of study area showing national sectors of the North Sea





Foreword

The findings of this report and the requirement to accelerate the delivery of actions and investments in CO₂ capture and storage are now critically important. With the recognition that rapid man-made climate change is the greatest environmental challenge facing us today, this report identifies pathways to strategic deployment of Carbon Capture and Storage (CCS). Scotland's distinct research strengths, industrial profile and natural assets, such as our key saline aquifer resource, offer a realistic opportunity to position us as international leaders in tackling the climate change challenge. This is also coupled with our ability to produce high value skills, technological innovation and develop best practice in public engagement and understanding of CCS; therefore, this is a time to act and be well informed by this report.

The need to evolve further our generation and energy source mix is essential for a low carbon future. This is reinforced by the legislation and objectives laid out in the Scottish Energy Bill, the Scottish Climate Change Bill and the Scottish Government Low Carbon Economy Strategy which has a reduction of greenhouse gas emissions by 80% by 2050 as a central driver. Scotland can rise to these challenges and be at the forefront of building a sustainable low carbon economy and in generating energy efficiently, sustainably and in environmentally neutral ways.

As we seek to develop new low carbon solutions, create a new industry and maximise related Scottish economic value, it is fully acknowledged that CCS technologies are a rapidly developing area. Scotland is on track to become the first full-chain demonstrator in Europe linking CO₂ emissions from a coal-fired power station to storage in a deep saline aquifer in the North Sea. We are leaders in CCS research and, with our ambitious government targets, we are in the vanguard of international activity in this field.

Scottish Carbon Capture and Storage (SCCS), one of the largest UK groupings of academia and industry carrying out leading research on CCS, will become an international asset. Alongside the Energy Technology Partnership (ETP), covering all of our Universities' key energy research strengths, SCCS is already showing its capability to connect research, development, demonstration and deployment of CCS technologies and solutions.

I commend this report and see it as major step forward in realising Scotland's potential to create national partnerships between academia, industry and our policy makers as well as establishing international leadership in the creation of solutions to the global challenge of climate change.

Professor Jim McDonald

Co-Chair, Scottish Energy Advisory Board

Sleipner Field CO₂ injection project, Norwegian North Sea.
Photograph: Dag Myrestrand/Statoil.





Executive summary

Carbon capture, transport and storage (CCS) is a rapidly growing industry that offers both environmental benefits and substantial business, employment and research opportunities for Scotland and the UK. In 2009¹ the report *Opportunities for CO₂ storage around Scotland* identified the size of these opportunities and key initiatives that need to be acted upon to move CCS forward in Scotland. Government, industry and stakeholder organisations joined with Scottish Carbon Capture and Storage (SCCS) researchers in this *Scottish Carbon Capture and Storage Development Study* to progress some of the actions needed to inform the deployment of the entire CCS chain in Scotland and the UK. The study presents new insights on:

- A path to CCS, defining the activities and timescales to meet national and international ambitions for deployment of CCS and reduction of greenhouse gas emissions;
- Scotland's CO₂ storage assets, refining the estimated large-scale carbon dioxide (CO₂) storage capacity in North Sea sandstones;
- Skills and capacity needs for the future global CCS industry and how to realise opportunities it presents for UK economic development;
- Public communication and engagement on CCS.

A Path to Deployable CCS technologies was explored and mapped out by the study members in July 2009, prior to the commencement of the study. The path presents their view of the timescales and activities needed to implement CCS in Scotland which, adopted together with other low-carbon technologies, will contribute to the national target of 80% reduction of greenhouse gas emissions by 2050. This path has been adopted by the Scottish Government and Scottish Enterprise and has informed their document 'Carbon Capture and Storage—a Roadmap for Scotland' in 2010.²

Refining Scotland's CO₂ storage assets and assessing environmental impact

Suitable sites for long-term geological storage of CO₂ are most likely to be found in depleted oil and gas field reservoirs or in similar sandstones containing salt water ('saline aquifers'). Although it is likely that depleted gas fields will receive CO₂ from the first phase of demonstration CCS projects, Scotland's large North Sea saline aquifers appear to offer substantially greater total capacity for long-term storage. To refine the estimated CO₂ storage capacity a more detailed evaluation was undertaken of one of the ten saline aquifer sandstones shortlisted in the 2009¹ report. A review of world-wide CCS research and pilot projects was undertaken and provided a benchmark against which all of the candidate North Sea sandstones compared very favourably. Three areas of the North Sea were examined as potentially suitable for further investigation: the Moray Firth; the Central North Sea; and the Forth Approaches Basin. The Captain Sandstone beneath the Moray Firth was selected for detailed investigation as it is close to onshore CO₂ sources, existing offshore pipelines and data for the entire sandstone could be both acquired and interpreted within study resources. A 3D computer model of the subsurface geology was constructed and populated with characteristics of the sandstone available from oil and gas exploration data. The overall performance of the Captain Sandstone as a potential CO₂ store was tested by computer simulations of CO₂ injection and prediction of the position of the CO₂ after thousands of years.

Site investigations for a future CO₂ store will be needed to inform exploration licence, storage permit and environmental consent applications. An overview of the present day biological and sea-bed conditions for the Captain Sandstone study area from existing data was undertaken, to provide a baseline of observations, and environmental legislation relevant to a future CCS project was reviewed.

Skills and capacity building

An appropriately skilled and trained workforce, in addition to that already engaged in the engineering and offshore industries, will be an essential component of the new CCS industry in the UK. Study members contributed data on skill types and staff numbers for future CCS jobs. Prospective employment in Scotland and the UK, based on International Energy Agency projections of CCS projects worldwide, was presented to the Scottish Government and educators in September 2010 to inform future training needs.

Public communication and engagement for CCS projects in Scotland

Public support is essential to realise the environmental and economic benefits of CCS. To inform developers of future CCS projects in Scotland key points were drawn from a review of previous practice on public engagement worldwide. The study provides tools for the design of an engagement strategy at the level of individual CCS projects.

¹ www.erp.ac.uk/sccs

² www.scotland.gov.uk/Publications/2010/03/18094835/0

The key conclusions of the study are:

- 1. Scotland's potential for a North Sea carbon storage industry is endorsed.** Research by scientists, regulators, and industry stakeholders has moved CCS forward in Scotland by taking initiatives identified in the 2009 report *Opportunities for CO₂ storage around Scotland*.
- 2. The European significance of Scotland's CO₂ storage resource, estimated in a basin-wide assessment in 2009, is supported by more detailed evaluation of the Captain Sandstone, which has shown its estimated storage capacity is at least as large as previously calculated.**
- 3. The Captain Sandstone alone could provide a feasible secure store able to hold 15 to 100 years of CO₂ output from Scotland's existing industrial point sources.** The storage capacity of the Captain Sandstone is estimated to be more than 360 million tonnes of CO₂, even when applying the most stringent, geologically least favourable conditions. There is potential for an additional 1200 million tonnes storage capacity with significant investment. Simulated injection of 15 million tonnes of CO₂ a year for a period of 30 years and its movement for 5000 years into the future showed that all of the injected CO₂ was contained within the eastern part of the sandstone at depths greater than 800m below sea level.
- 4. Offshore carbon storage can be implemented in accordance with existing environmental legislation.** Available ground condition and environmental information indicates there are no obvious obstacles to CO₂ storage in the Captain Sandstone study area. Further data and monitoring will be needed prior to implementation of any future CO₂ storage site.
- 5. CCS could create 13 000 jobs in Scotland (and 14 000 elsewhere in the UK) by 2020, and increase in the following years, with a demand for a wide range of professional and craft skills.** Some of these jobs will be filled by skilled personnel transferring from other industries (e.g. oil and gas). However, the total workforce required will have to be maintained and augmented by newly trained personnel; additional training requirements must be recognised early to allow timely investment in suitable training programmes.
- 6. The UK plc share of the worldwide CCS business is potentially worth more than £10 billion per year from around 2025, with the added value in the UK worth between £5 billion and £9.5 billion per year.** Gaining the maximum benefit depends on UK companies winning domestic and export projects and government support for a steady roll-out programme of CCS projects.
- 7. There are best practice approaches to engaging the public and this study provides the tools to design and implement an effective engagement strategy. Public support will be essential if the environmental and economic benefits of CCS are to be realised. It is clear from experience in Europe and worldwide that project developers must win public trust.** The careful design of an effective, structured strategy for engagement and communication will be a vital element in the implementation of CCS. This will include early engagement with the public and stakeholders. Offshore Scotland, this is likely to include groups with fishing interests, marine conservation and protection, the Crown Estate, shipping and sailing interests, as well as the oil and gas industry.



Next steps along the path to CCS in Scotland

Concerted and co-ordinated activities by government, regulators, industry and academia in the two years since publication of the *Opportunities for CO₂ storage around Scotland* report have contributed to the establishment and growth of a CCS industry in Scotland and the UK. Progress along the path for the deployment of CCS in Scotland has been enabled by:

- The UK Government's support for a programme of up to four CCS demonstration projects
- Streamlining of the regulatory requirements by a Scottish Government CCS test exercise^{3,4}
- Industry investment in CCS pilot projects
- Research into the capture, transport and storage of CO₂ by academia and industry

However, the rate of progress needed for the implementation of commercial-scale CCS projects by 2015 has not been as rapid as envisaged in 2009. To meet the ambitious targets for CO₂ emissions reduction by CCS additional funding support will be required.

1. Further assessment and appraisal of the Captain Sandstone as a CO₂ store is justified by the encouraging research results from this study. Detailed information of the character of the sandstone and its performance, acquired during oil and gas exploration and production, should be used to test the assumptions used in this study. Additional investigation should cover:

- Further characterisation and definition of the extent of the sandstone, the nature of its boundaries and its ultimate storage capacity
- Whether or not there is flow along or across the mapped faults and the resulting implications for the quantity and rate of CO₂ injected
- The internal properties of the sandstone and their effect on the movement of the stored CO₂

2. The integrity of the rocks that seal the Captain Sandstone store must be demonstrated to the full satisfaction of regulators for a site to obtain a CO₂ storage permit.

3. To fully realise the European-scale storage potential outlined in the Opportunities for CO₂ storage around Scotland report, additional North Sea sandstones should be investigated alongside further detailed evaluation of the Captain Sandstone.

4. Further analysis of skills needs in the CCS industry is required and a review with government and its training agencies of actions is needed to identify additional skills requirements to maximise the economic benefit to Scotland and the UK.

5. The tools provided in this study should be used to design and implement a strategy for early public engagement and communication of CCS with the public and stakeholders in Scotland.

³www.scotland.gov.uk/Resource/Doc/917/0105308.doc

⁴www.geos.ed.ac.uk/sccs/regulatory-test-toolkit/



1. Introduction

Background

International and national ambitions to reduce the emission of greenhouse gases and their impact on climate change are expressed as targets of percentage reduction by specified dates. In March 2007, EU leaders committed Europe to develop an energy-efficient, low carbon economy by setting a series of climate and energy targets to be met by 2020. These targets included a commitment to reduce overall EU greenhouse gas emissions by at least 20% below 1990 levels; in the UK this target has been set even higher at 34% by 2020. Scotland is committed to an 80% reduction by 2050. The International Energy Agency (IEA) considers that Carbon Capture, Transport and Storage (CCS) is an integral part of the balanced portfolio required to meet these global emissions reduction and climate change targets at the lowest possible cost. To achieve these targets will require the implementation of an ambitious international programme of CCS projects (Table 1, see also Figure 30, p 45). Scotland, UK and European Union ambitions are for CCS to be available as a low carbon deployment option for power generation and major industrial plants by 2020, via a programme of commercial-scale demonstration projects.

Table 1. Ambitions for projected CCS deployment

The role of CCS in climate change mitigation in Scotland

CO₂ from fossil fuel-fired electricity generation accounts for approximately 35% of total UK and 41% of Scotland's CO₂ emissions. To achieve CO₂ emission reduction targets, CCS at fossil fuel-fired electricity plant will be essential to complement other low-carbon technologies and emissions-reduction strategies.

International Energy Agency (IEA) (www.iea.org/papers/2009/CCS_Roadmap.pdf)	Forecast that Europe (including the UK) will have in the order of 500 CCS projects by 2050
G8 countries	20 CCS projects committed by 2010 and operational by 2020
EU demonstration programme	10–12 commercial-scale demonstration projects operational by 2015
Scottish Government	CCS demonstrated in Scotland by 2020

What is CCS?

Naturally occurring carbon dioxide (CO₂) and its secure geological storage is demonstrated where it has been trapped for millions of years in oil and gas fields. For CCS the CO₂ generated by industrial activities is captured at the plant, transported by pipeline and injected into deeply buried rocks (Figure 1, p 2). The CO₂ displaces salt water, oil or gas, already present in microscopic pores within the rock. Proposed sites must be investigated and evaluated, to demonstrate that they are suitable for secure storage for thousands of years, before a permit will be awarded to begin test injection. Activities to monitor the proposed storage site during injection and after injection has ceased must also meet the requirements of regulators. CCS is an active field of research and development and a growing industry worldwide. The interpretations and analyses presented here were undertaken by researchers with decades of experience in these fields of expertise. Further research needs identified during the study are outlined in **Next steps along the path to CCS in Scotland** (p VII).

Opportunities for CO₂ storage around Scotland

In 2008 the Scottish Government and industry joined with Scottish Carbon Capture and Storage (SCCS) researchers to assess options for CCS in Scotland. The *Opportunities for CO₂ storage around Scotland report* (www.erp.ac.uk/sccs), hereafter referred to as the *Opportunities Report*, was published in May 2009. It quantified the annual CO₂ output from Scotland's three largest power stations as approximately 18 million tonnes in 2006, approximately 41 % of Scotland's total carbon emissions. The report also identified sites offshore Scotland with the potential for geological storage of CO₂. Options for a network to transport the CO₂ from industrial sources to offshore stores were presented, the economics, business risks and models and funding options for future CCS businesses were also reviewed.

In the *Opportunities Report* Scotland's offshore CO₂ storage capacity was estimated to be of European significance, 4600 to 46000 million tonnes, by calculation at a basin-wide scale. This provided an estimate of the capacity of potential storage sites but noted that further study was needed to determine what amount is likely to be available in practice.

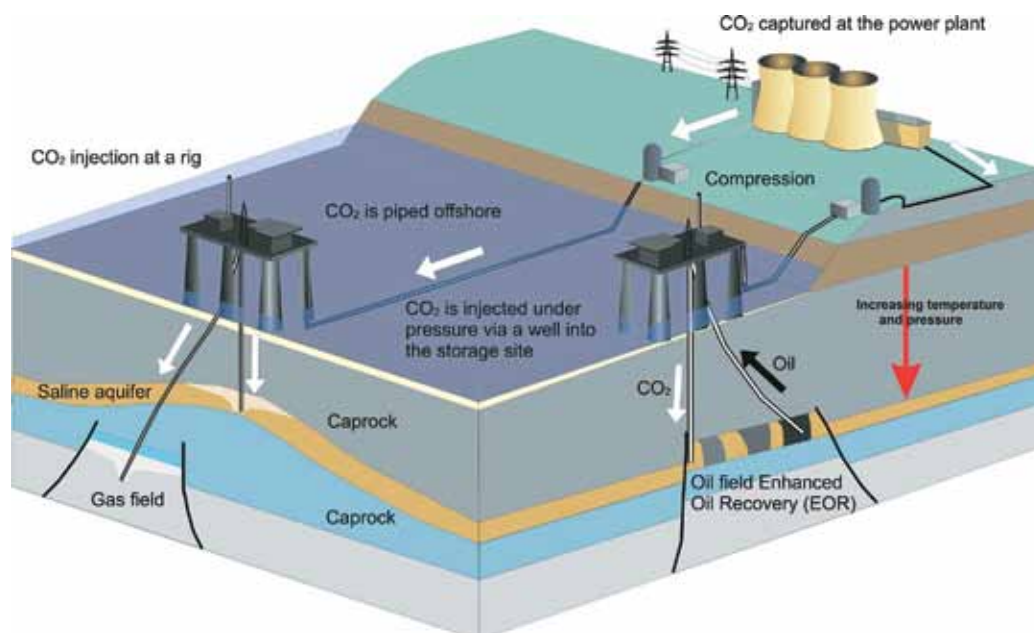
In July 2009, consortium members defined a **path to deployable CCS technologies** (see p4) that could be used in clarifying objectives for the deployment of CCS in Scotland. The path lays out the members' views of the activities and timescales to meet national and international ambitions for deployment of CCS and reduction of greenhouse gas emissions.

The Scottish CCTS Development Study

In August 2009 a second consortium of Scottish Government, industry and SCCS researchers established the Scottish Carbon Capture Transport and Storage Development Study to progress and map out further steps toward the deployment of CCS in Scotland. Study members' expertise spans activities in CCS and the work undertaken was informed by their knowledge. The investigations, based on the path to deployable CCS technologies and findings of the *Opportunities Report*, were regarded as essential to inform successful deployment of the entire CCS chain in Scotland.

This report presents a summary of the research results, to inform government, regulators, commercial organisations with operational interests and the public about deployment of CCS in Scotland.

Figure 1 Schematic diagram showing elements of CCS infrastructure and relationship with geological structure





Study objectives were to:

- Refine the estimated CO₂ storage capacity of one of the ten saline aquifer sandstones shortlisted in the 2009 report
- Provide estimates of skill types and staff numbers staff needed for the future CCS industry and underpinning research and development
- Inform developers of future CCS projects in Scotland of a strategy and tools to engage with the public and interested parties (stakeholders)

In the *Opportunities Report* the potential CO₂ storage capacity of Scotland's North Sea sandstones was assessed on a basin-wide scale and presented as a range of values. **Refining Scotland's CO₂ storage assets and assessing environmental impact** (see p 10) moves to a site characterisation appraisal of one sandstone using data and methods familiar to oil and gas exploration and follows internationally recognised CCS best practice.

The assessment of **skills and capacity building** (see p 45) needed for the future CCS industry was facilitated by Skills Development Scotland with input from members of this study and the Industry and Power Association. The findings were presented to the Scottish Government and educators in September 2010 to inform future training needs.

Although it is a new industry, research and pilot projects worldwide are increasing understanding of CCS. **Towards a public communication and engagement strategy for CCS projects in Scotland** (see p 52) draws on previous experience elsewhere to inform the lay person and prospective developer of CCS in Scotland and provides a toolkit for the design of an engagement strategy.

Study scope

Study investigations were selected as of benefit to the overall implementation of a CCS industry in Scotland and not specific to a future single CCS project. They were all undertaken within the study budget of £290 000, commenced August 2009 and completed by December 2010. This study used information from oil and gas exploration that could be made available within the study budget. There is other data that is more detailed and acquired more recently than that used here that was too costly or commercial in confidence. The acquisition of seismic surveys and the drilling of boreholes, costing millions of pounds, are clearly beyond resources available to the project.

2. The path to deployable CCS technologies

In July 2009, the consortium members compiled their views on the activities required to meet targets for the deployment of CCS and the dates at which they need to be attained, based on a timetable for the projected growth of CCS in the European Union, UK and Scotland (Table 2). The results were presented as a **path to deployable CCS technologies**. (www.geos.ed.ac.uk/sccs/regional-study/deployableCCStechology.pdf).

As well as guiding the work for this study, the path was adopted by the Scottish Government and Scottish Enterprise and informed their document *Carbon Capture and Storage—a Roadmap for Scotland* in March 2010. (www.scotland.gov.uk/Publications/2010/03/18094835/0).

Study member's evaluation of requirements for CCS deployment by 2020

In Scotland there is already a strong synergy between the ambitions of government and the needs of industry and academia to achieve implementation of CCS (Table 3). Deployment of CCS in Scotland requires integration of industry sectors. Study members recognised the wider challenges for the establishment of a viable CCS business environment to include:

- The development of business models and cross-disciplinary timelines for the CCS chain which is bringing together the diverse CO₂ source, transportation and storage industries
- The development and proving of the required interactions between these industries with their very different business models
- Attractive economic conditions which provide sufficient potential returns to allow the risk to be taken and the investment made by each party in the supply chain
- The establishment of a new CO₂ transport industry required to connect the existing capture (electricity companies) and storage (oil and gas companies) industries via an appropriate combination of regulation, free market drivers and government incentives



Table 2. Timetable used by study members, in July 2009, for projected implementation of CCS in the European Union, UK and Scotland to contribute to greenhouse gas emission reduction targets.

2009 (at start of study)	2015–2020	Required by 2020	2020	2020–2030	2030
Fledgling industry	<p>European Union 30 Mt per year CO₂ stored European Union–10 to 12 demonstration projects</p> <p>UK Up to 4 CCS demonstration projects</p> <p>Scotland 1 or more CCS demonstration project</p>	<p>Need large scale proven aquifer storage capacity</p> <p>Need an established financial funding method for CCS deployment</p>	<p>European Union 150 Mt CO₂ cumulatively stored</p> <p>European Union and UK CCS deployment commencing</p>	CCS roll out	<p>CCS the norm for large industrial plant</p> <p>European Union Capacity to store thousands of Mt CO₂</p> <p>UK Capacity to store thousands of Mt CO₂</p>

Table 3. Synergy between organisations in Scotland for CCS

Scottish and UK governments and their agencies	Contribution to meeting climate change emissions reduction targets, secure low carbon energy supply at affordable prices
	A largely decarbonised electricity generation sector by 2030
	Demonstrate CCS on a Scottish power station by 2020
Industry	Establish a strong energy and CCS industry to maximise economic benefit and employment opportunities
	Reliable technologies and strong industrial support capable of delivering CCS to meet ambitious programmes for the power industry
	Power plant and CCS suppliers and consultancies need references for their goods and services
	Adequate supply of skilled workers to allow businesses to achieve their ambitions across the capture, transport and storage chain
Academia and research base	Continuity and diversification of the oil and gas business in Scotland as a world player
	Clear direction and funding support to maximise future benefit for the country

For CCS to be available as a low carbon deployment option in Scotland by 2020 the study members considered the following were essential requirements:

- Proving of the technology via an initial round of commercial-scale demonstration projects operational by 2015, with a second round to follow soon afterwards to give confidence in the scaling-up from demonstration projects
- A CO₂ transport network
- Proven large-scale storage capacity, including a methodology and guidelines for geological storage site assessment;
- Research and development activities to improve technologies for capture, transport and storage of CO₂
- An engaged stakeholder community—study members noted the importance of engagement with the public and interested parties
- Industry capacity and skills development built up to staff the anticipated CCS projects
- Establishment of a viable CCS business environment
- An appropriate regulatory regime understood by CCS developers and the timely availability of such a regime to match the requirements of demonstration projects and CCS deployment

This is a high-level perspective, it presents an overview to identify what will be needed and when. The detailed integration of engineered capture at power or industrial plant, the technology of compression and transport by pipeline, injection and monitoring of CO₂ deep beneath the sea bed were considered beyond the remit of the study.

Four of the requirements were selected for more detailed consideration and activities were identified and presented against a timeline for each of the selected requirements as well as comments on objectives and learning from new and previous experience. These are to:

- Deliver commercial-scale CCS demonstration projects by 2015 (Figure 2)
- Prove the large-scale CO₂ storage capacity in North Sea sandstones by 2020 (Figure 3)
- Provide the underpinning research and development by and for UK economic development (Figure 4)
- Provide both the skills and staff numbers (capacity) needed for the future CCS industry (Figure 4)

The timelines were used to guide the choice of objectives for the study.



Figure 2 Activities and timeline for implementation of commercial-scale CCS demonstration projects by 2015 (redrawn from presentation prepared in June 2009)

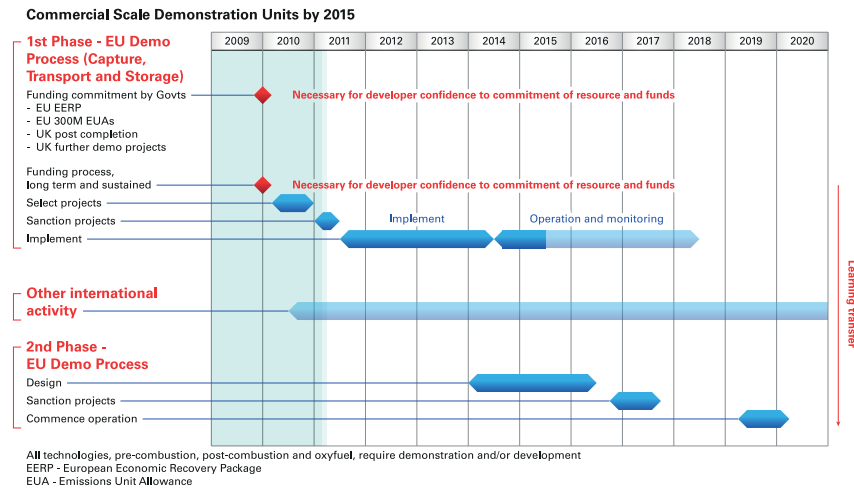


Figure 3 Activities and timeline for proving large-scale CO₂ storage capacity by 2020 (redrawn from presentation prepared in June 2009)

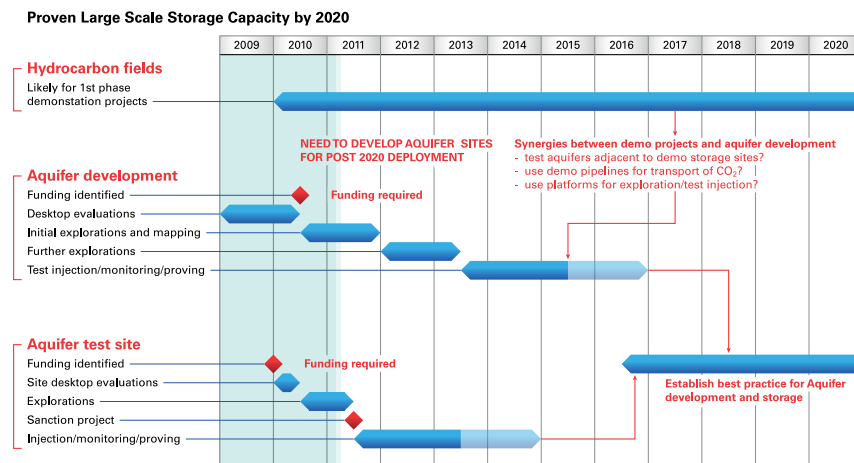
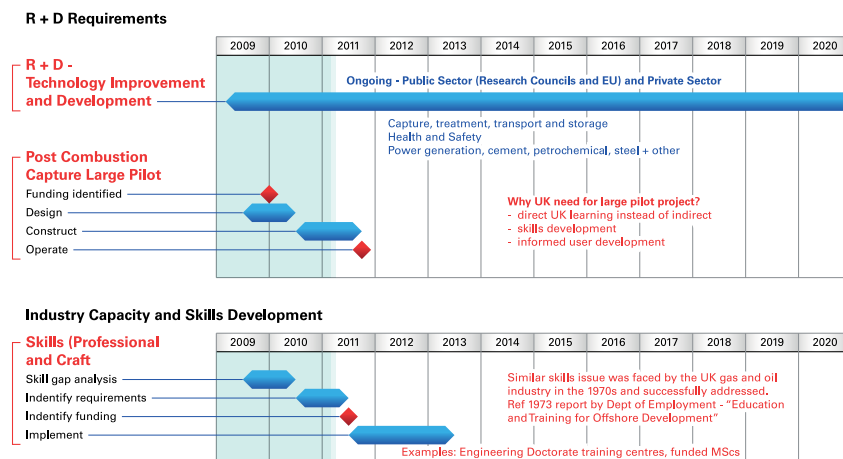


Figure 4 Timeline for research and development and industrial capacity and skills development needs to meet the requirements of CCS deployment (redrawn from presentation prepared in June 2009)



Progress along the path to deployable CCS technologies in Scotland

In the twenty months since presentation of the path in July 2009, concerted, co-ordinated and independent activities by government, regulators, industry and academia have contributed to the establishment and growth of a CCS industry in Scotland and the UK.

Work resulting from, or in parallel with, this study:

- The path was adopted by the Scottish Government and Scottish Enterprise and informed their document Carbon Capture and Storage—a Roadmap for Scotland in March 2010 (www.scotland.gov.uk/Publications/2010/03/18094835/0)
- Working with the UK Government and regulators, the Scottish Government undertook a CCS regulatory test exercise in August 2010 to ensure an appropriate consenting and regulatory framework for CCS (www.scotland.gov.uk/Resource/Doc/917/0105308.doc), a requirement of both the path and the roadmap. Learning from the test exercise has enabled SCCS to present a CCS Regulation Toolkit (www.sccs.org.uk/regulatory-test-toolkit/) to inform regulators worldwide
- SCCS researchers were actively involved in CASSEM (CO₂ Aquifer Storage Site Evaluation and Monitoring), a £2.5 million, three-year, research council funded project, which brought together industries from along the CCS development chain, to develop methodologies, work-flows and insights, essential for the successful identification and evaluation of safe and effective CO₂ storage in saline aquifers. The project, with outcomes relevant to new entrants to CCS, had a key focus on the analysis of sub-surface stores, uncertainty and risk analysis, preparing a full costing model and the public perception of CCS. Its results were presented in Edinburgh in September 2010 (www.cassem.net)

Scotland and UK initiatives and opportunities:

- Post-combustion CO₂ capture pilot plant has been tested.
- Support from the UK government for the implementation of CCS has extended from a single demonstrator to four projects, which may include gas-fired power generation. Substantial effort is being made by industry stakeholders to win funding to implement one or more of these projects in Scotland
- Three bids have been made for Scotland, out of nine in the UK, for European Union funding for the financing of commercial demonstration projects that aim at the environmentally safe capture and geological storage of CO₂ (www.ner300.com). Other European research funding has been won to further investigate large-scale storage and licensing of CO₂ offshore Scotland, supported by Scottish Government and regulators
- Initial proposals for funding were included in Government's Electricity Market Reform Consultation document, which closed for consultation in March 2011



Within the present study:

- Detailed evaluation of one of the ten North Sea saline aquifer sandstones identified as having potential for CO₂ storage in the Opportunities Report has confirmed its calculated storage capacity to be at the upper end of the range of previously estimated values. Thus, the encouraging findings reinforce the estimated European-scale significance of Scotland's North Sea CO₂ storage resource and justify/lend support to further research
- By evaluating the requirements for a single CCS project and scaling these up to meet the predicted growth of CCS projects globally, the study has been able to assess the skills-needs, employment possibilities and potential economic benefits arising from a major global programme of CCS on fossil-fuelled power plants
- Factors that should be taken into account in the design of an effective engagement strategy for a project to deploy CCS offshore Scotland have been identified following a review of approaches taken to the communication of CCS deployment worldwide. A toolkit has been provided for the design of such a strategy

Considerable progress has been made along the path for the deployment of CCS in Scotland. However, it can also be seen that the rate of progress has not been as rapid as envisaged in 2009, in particular that needed for the implementation of commercial-scale CCS projects by 2015 (Figure 2, p 7).

As a result of this study, a number of next steps along the path to CCS in Scotland are proposed; these should be implemented in parallel with a wider review of progress along the path in order to further inform the deployment of CCS in Scotland.

3. Refining Scotland's CO₂ storage assets and assessing environmental impact

3.1 Geological storage of CO₂

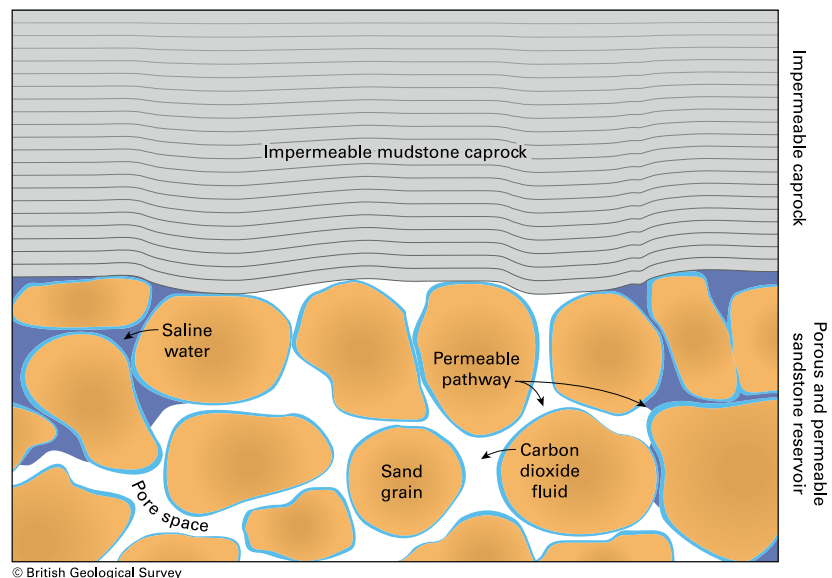
The basin-scale assessment of potential CO₂ storage sites carried out in 2009 and described in the *Opportunities Report*, estimated that offshore Scotland has an extremely large potential CO₂ storage resource in geological reservoirs containing oil, gas or saline water. Although it is likely that depleted gas fields will receive CO₂ from the first phase of demonstration CCS projects, it is Scotland's large North Sea saline aquifers that appear to offer substantially greater total capacity for long-term geological storage of CO₂, potentially providing a capability to permanently store at least 200 years of Scotland's current industrial CO₂ output. However, in comparison with oil and gas fields, the extent and properties of the North Sea saline aquifers are poorly known. The 2009 study provided a listing of potential storage sites but not absolute capacities and recommended more focussed studies to fully scope the saline aquifer storage potential (Figure 5).

In order to refine the estimated CO₂ storage capacity, this study has carried out a more detailed, site characterisation of one of the ten saline aquifer sandstones shortlisted in the *Opportunities Report*. One sandstone was selected for detailed investigation as it is close to onshore CO₂ sources, is in an area containing existing offshore pipelines and data for the entire sandstone could be both acquired and interpreted within study resources. A 3D computer model of the subsurface geology was constructed and populated with characteristics of the sandstone using information available from oil and gas exploration. This model was then used in computer simulations

to test the overall performance of the sandstone as a potential CO₂ store by numerical modelling of CO₂ injection and prediction of the position of the CO₂ after thousands of years. A review of world-wide CCS research and pilot projects was undertaken and provided a benchmark against which all of the candidate North Sea sandstones compared very favourably.

A geological structure used for a particular purpose (whether to extract oil or gas, water or coal or as a storage site for gases, liquids or solids) must be managed to take account of the particular and unique characteristics of each site. For a CO₂ store, environmental safety—in other words, the ability of the store to retain the injected CO₂—is of key importance. Management of a CO₂ storage site therefore requires a detailed and constantly updated view of the geology of the store and the migration of the CO₂ through it.

Figure 6 Schematic diagram illustrating porosity and permeability within a sandstone and overlying caprock





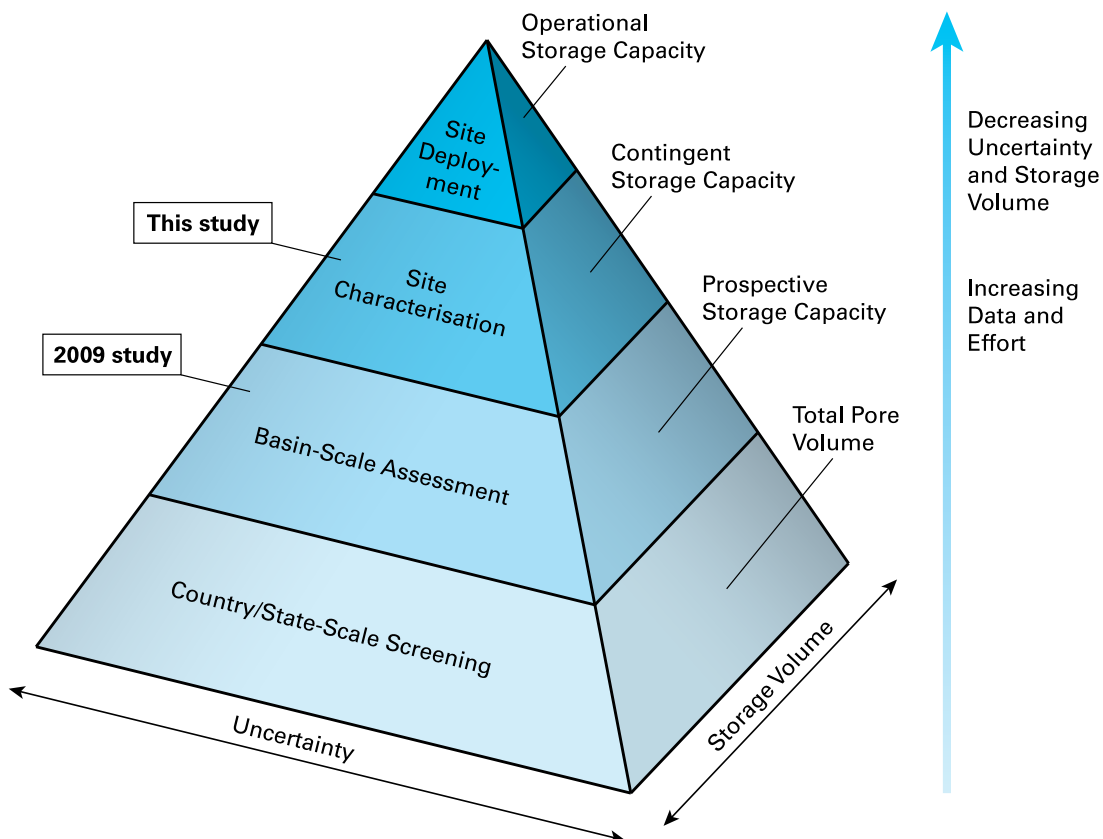
Storage capacity and suitability

The CO₂ storage capacity depends upon several factors. The **total volume of the storage reservoir** is relatively straightforward to determine, provided appropriate data is available. At a microscopic scale, reservoir rocks (for example, sandstones) contain spaces (between sand grains) within which fluids—hydrocarbons (oil, gas or gas condensate) or saline water—can be stored, or through which fluids can pass (Figure 6). The proportion of the total volume available for fluids is its 'porosity', and the ease with which fluids can pass through rock is described by its 'permeability'.

These fluids are all pressurised to a certain degree and must be displaced to allow storage space for CO₂; injection will cause further pressurisation. This places significant limits on the amount of CO₂ that can be stored, since excessive pressure may ultimately cause fracturing of the caprock. Thus, it is important to distinguish whether a reservoir is in 'open' pressure communication with surrounding rocks or whether it is 'closed'. CO₂ injected into 'open' reservoirs is accommodated by lateral displacement of the existing fluids, and gives rise to minimal, local changes in pressure. The storage capacity of 'open' saline aquifers is limited by how well the CO₂ displaces the saline water, the proportion of the saline aquifer that is structurally closed (trapping the CO₂) and the amount of CO₂ retained during migration. For 'closed' saline aquifers pressure will be the significant limiting factor. However, water production wells can be used to reduce the pressure and increase CO₂ storage capacity to similar levels as if the boundaries are open.

Open reservoirs offer better potential for CO₂ storage.

Figure 5 Storage pyramid illustrating different stages in CO₂ storage capacity assessment. This study has taken the assessment to the site characterisation stage for one North Sea saline aquifer, the Captain Sandstone (adapted from CSLF 2007 Storage Pyramid modified 2008 CO₂CRC Storage Capacity Estimation)



3.2 Selection of an example commercial-scale CO₂ store for Scotland

Benchmarking of worldwide CO₂ projects—context for site selection in Scotland

In order to provide a benchmark for the assessment of a North Sea sandstone as a geological CO₂ store, the study reviewed the ongoing work worldwide on practical injections of CO₂ as research tests for storage projects (www.sccs.org.uk). Injection projects for CO₂ have been underway for several years, and have become more numerous, with a trend to gradual size increase. The study examined twenty current or completed projects that are particularly important to the development of the injection technology into saline aquifers (Figure 7 and Table 4). They range from demonstration and small-scale technical development or testing sites to large industrial-scale CO₂ injection projects. The large projects, indicated in dark grey in Table 4, have industrial feasibility; the smaller ones were included as examples of technical development or of testing the injectivity into a given rock formation. The study reviewed aquifer characteristics, pressure issues, project costs, transport and monitoring for each of the projects.

Figure 7 Location of worldwide CCS projects reviewed in the study and listed in Table 4

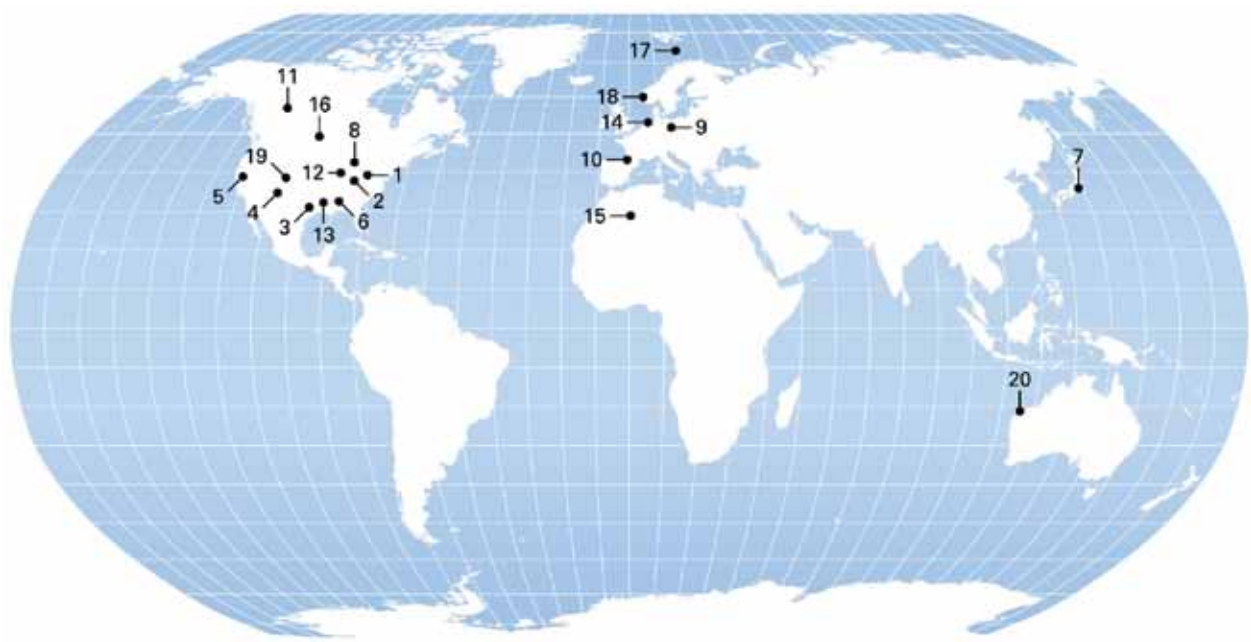




Table 4. Worldwide CCS projects; projects with industrial feasibility shown in dark grey

Project	Porosity of store rock (%)	Permeability of store rock (milliDarcies)	Store type	Estimated CO ₂ storage capacity (tonnes)	Summary of project progress and results
1 R.E. Burger, Ohio, USA	3.2	0.08	Onshore saline aquifer	0	Test injection showed rock porosity and permeability was too low
2 East Bend, Kentucky, USA	12	200	Onshore saline aquifer	1000 t	Successful injection of industrial CO ₂ in 2008
3 Frio Texas, USA	30	1500	Onshore saline aquifer	1600 t	First test injection in 2004 upon which further development of CCTS in the USA was based
4 Cholla, Arizona, USA	15	0	Onshore saline aquifer	1800 t	Cancelled injection rate was too low
5 Rosetta, California, USA			Onshore saline aquifer	2000 t	Cancelled for organisational reasons, no injection undertaken
6 Escatawpa, Mississippi, USA	21	1180	Onshore saline aquifer	2750 t	Injection successfully undertaken and monitored
7 Nagaoka, Niigata, Japan	22.5	6	Onshore saline aquifer	10 400 t	Injection and CO ₂ storage successful. Injection has ceased, monitoring continues
8 Gaylord, Michigan, USA	12.5	22.4	Onshore saline aquifer	60 000 t	CO ₂ from gas plant modelled, injected 2008–2009 and store monitored since 2008
9 Ketzin, Germany	23	750	Onshore saline aquifer	60 000 t	CO ₂ from gas plant modelled, injected 2008–2009 and store monitored since 2008
10 Lacq, France	3	23	Onshore depleted gas fields	150 000 t	Injection of CO ₂ from industrial source and storage, commenced 2010
11 Zama, Alberta, Canada	26	413	Onshore oilfield	250 000 t	CO ₂ from gas plant injected and monitored since 2006
12 Decatur, Illinois, USA	15	225	Onshore saline aquifer	1 000 000 t	CO ₂ from industrial source to commence injection in 2010
13 Cranfield, USA	20	1000	Onshore saline aquifer	2.1 Mt	Natural source, CO ₂ injected and monitored since 2008
14 K12-B, Netherlands	15	20	Offshore gas field	8 Mt	CO ₂ from gas field reinjected since 2004
15 In Salah, Algeria	17	5	Onshore saline aquifer	17 Mt	CO ₂ from gas fields injected since 2004. Monitoring for CO ₂ migration and leakage
16 Weyburn, Canada	26	15	Onshore oilfield	20 Mt	CO ₂ from industrial source injected since 2000 to enhance oil recovery. Prediction, monitoring and risk assessment of the storage site
17 Snøhvit, Norway	13	450	Offshore, saline aquifer	23 Mt	CO ₂ extracted from gas field production is transported back offshore via a 153 km pipeline and injected since April 2008. Monitoring for CO ₂ migration
18 Sleipner, Norway	37	5000	Offshore, saline aquifer	25 Mt	CO ₂ from gas field injected since 1996. Monitoring for CO ₂ migration and leakage
19 Rangely, Colorado, USA	12	8	Onshore oilfield	26 Mt	CO ₂ from gas plant injected since 1986 to enhance oil recovery. Monitoring for CO ₂ migration and leakage
20 Gorgon, Australia	20	25	Offshore saline aquifer	129 Mt	Project under construction. Injection planned to start 2014 for 40 years

Selecting a sandstone for site characterisation

The *Opportunities Report* identified ten saline aquifers that met best practice or minimum requirements for the storage of CO₂ (Table 5). The porosity, permeability and calculated storage capacity of the saline aquifers compare very favourably with other CCTS projects worldwide (Table 4, p 13). Each with estimated storage capacities of more than 50Mt, they offer some potential as large CO₂ stores and their general areal extents are shown in Figure 8.

In this study, three areas—the Moray Firth; the Central North Sea; and the Forth Approaches Basin—were examined as potentially suitable for immediate further investigation based on the following criteria:

- Proximity to existing CO₂ sources (electrical generation and industrial sites)
- Access to existing oil and gas pipelines
- size and overlap, if any, between the different sandstone saline aquifers
- Presence of oil and gas fields and thus potential availability of data acquired during exploration and production
- Ability to define the nature of the aquifer from available data
- Access to data in terms of cost to the study

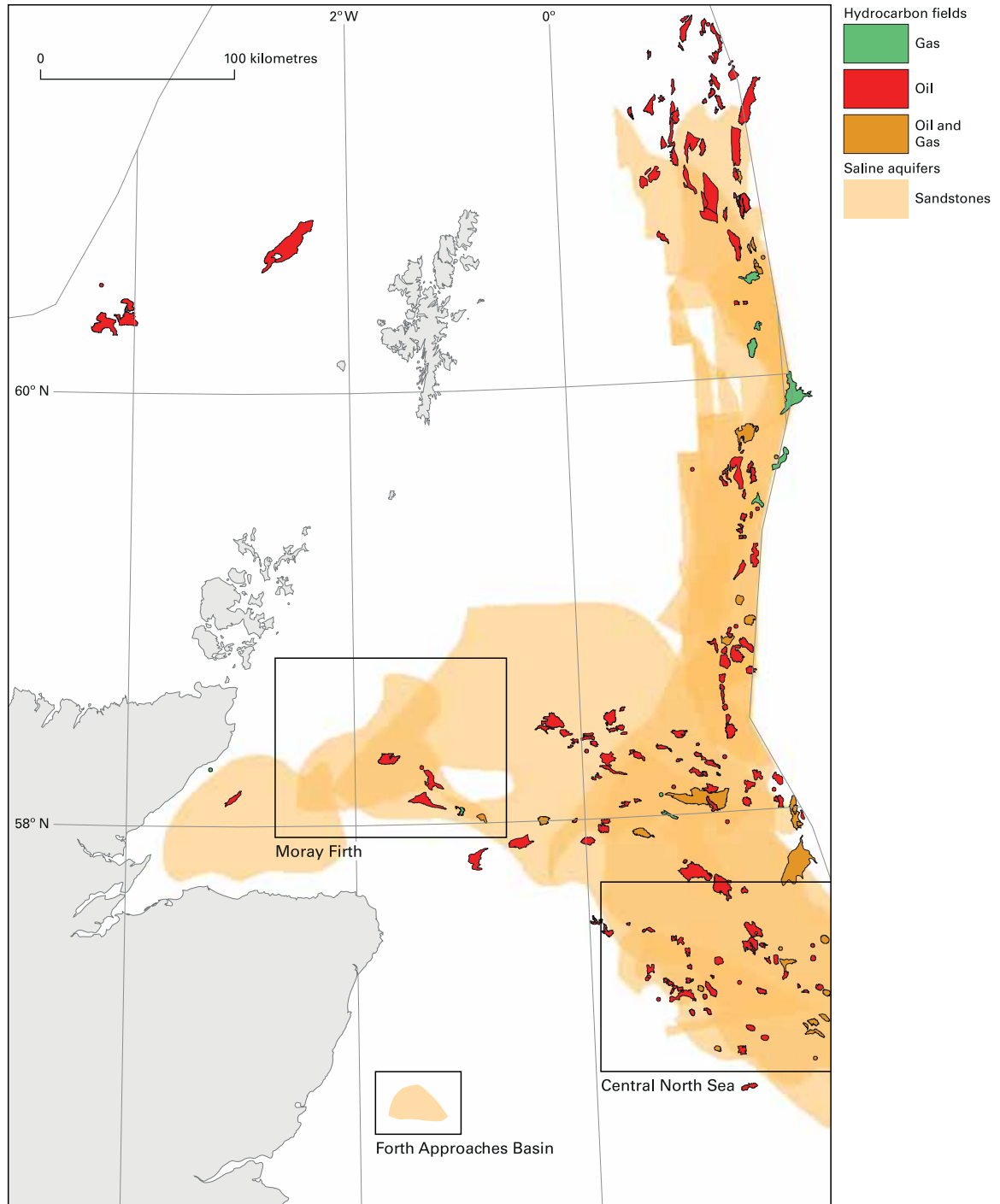
The Forth Approaches Basin area was considered, even though it does not contain one of the ten listed sandstones, as it is very close to onshore CO₂ sources, has a well-defined and constrained reservoir/seal combination and a relatively good seismic and well dataset.

Table 5. Summary of geotechnical screening criteria applied to saline aquifers

Reservoir Attribute	Best practice requirements	Minimum technical requirements
Depth	>1000m and <2500m	>800m and <1000m
Permeability	>500mD	>200mD and <500mD
Porosity	>20%	>10% and <20%



Figure 8 Extent of shortlisted saline aquifers, hydrocarbon fields and areas of investigation



The Captain Sandstone beneath the Moray Firth was selected for detailed investigation as it is close to onshore CO₂ sources, contains existing offshore pipelines and data for the entire sandstone could be both acquired and interpreted within study resources (Table 6).

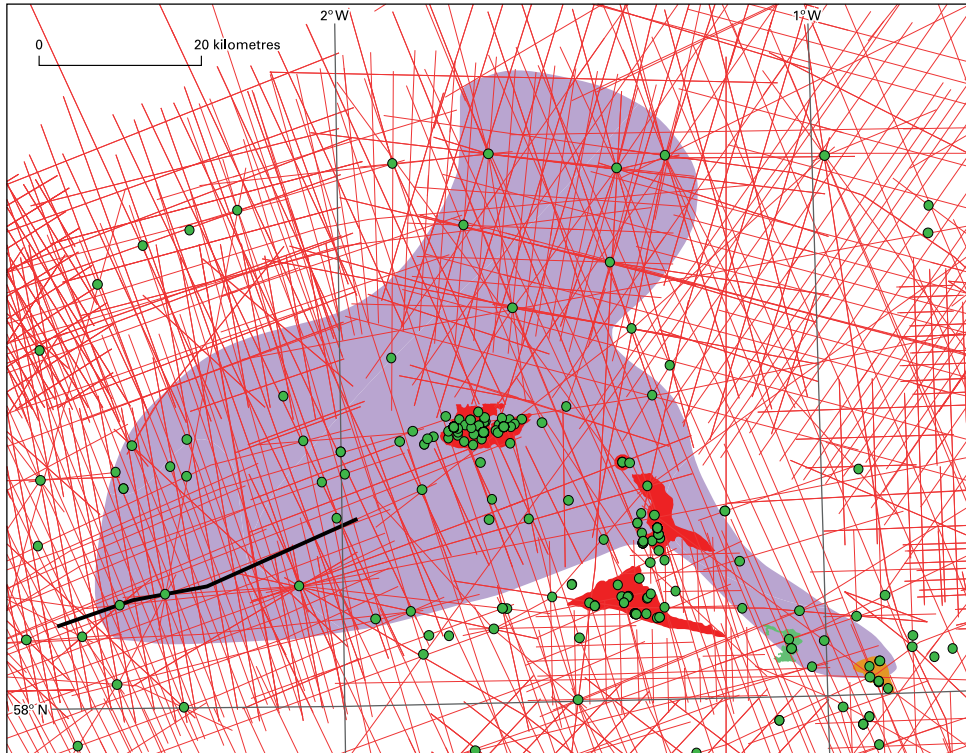
The Captain Sandstone is an extensive body of rock which also hosts several oil and gas fields, including the Captain Oil Field which is not part of this study. The Captain Sandstone continues beyond the mapped extent used for this study (see Figure 14, p21).

Table 6. Criteria applied to selection of saline aquifer sandstone for further study from the three chosen areas of the North Sea. Green–positive criteria indicator; Orange–neutral/average/uncertain criteria indicator; Red–negative criteria indicator

	Moray Firth	Central North Sea	Forth Approaches Basin
Proximity to existing CO ₂ sources	Closer to onshore CO ₂ sources than the Central North Sea area	Greater distance from onshore CO ₂ sources	Very close to onshore CO ₂ sources
Access to existing oil and gas pipelines	Crossed by several pipelines serving oil fields in the area and beyond	Crossed by pipelines serving the many oil and gas fields in the area	None in the area
Size and overlap, if any, between the different sandstone saline aquifers	Encompasses the entire captain sandstone and part of the Mey and Mains sandstones (Figure 8)	Contains the entire Tay Sandstone and parts of the overlapping Forties and Mey sandstones (Figure 8)	Includes an isolated occurrence of the Rotliegend Sandstone that has a slightly smaller storage capacity than 50 million tonnes
Size and overlap, if any, between the different sandstone saline aquifers	There are five oil and gas fields within the area, of which four derive some production from the Captain Sandstone. There are a total of 349 commercial wells within the study area, with more than half drilled in the hydrocarbon fields and the rest scattered over the study area, and a wealth of seismic survey data availability of a large amount of well data and reports associated with regional exploration and the oil and gas fields that produce from the Captain Sandstone	Availability of a large amount of well data and reports associated with regional exploration and the oil and gas fields (Figure 10) Good regional seismic survey data coverage	Relative sparseness of data (there are no oil or gas fields in the immediate locality) but has a well-defined and constrained reservoir/seal combination and a relatively good seismic and well dataset
Defining the nature of aquifer	Surfaces defining the top and base of the Captain Sandstone and any internal features, are unlikely to be resolvable on the seismic data	The Tay, Forties and Mey sandstone aquifers may be easier to map from seismic survey data than the Captain Sandstone	Uncertainty regarding the quality of the sandstone reservoir and its storage capacity.
Access to data in terms of cost to the study	Good quality regional seismic datasets available for licensing at a cost within study resources regional 2D seismic survey acquired since 1986 are plentiful and give good coverage of the Moray Firth area (Figure 9). From this dataset, seismic data of good quality and coverage could be made available within the resources of the study.	A large amount of regional 2D seismic survey data has been acquired since 1990 over the central north sea area. However, the cost of licensing the best seismic data coverage exceeds the study budget.	Has a well-defined and constrained reservoir/seal combination and a relatively good seismic and well dataset

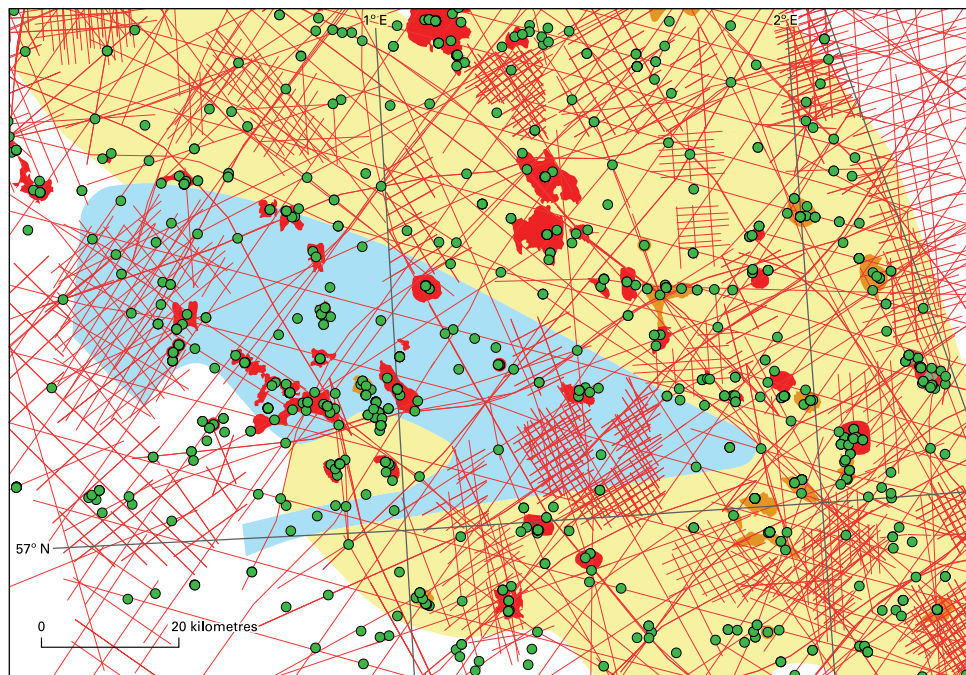


Figure 9 Moray Firth area showing regional seismic survey data (red lines), hydrocarbon fields (see Figure 8 for key), oil and gas wells (green dots). The extent of the Captain Sandstone, as mapped prior to the study, is shown in mauve



— Approximate location of seismic profile in Figure 13

Figure 10 Central North Sea area showing regional seismic survey data (red lines), hydrocarbon fields (see Figure 8 for key), oil and gas wells (green dots), the extent of Forties Sandstone (yellow) and Tay Sandstone (blue)



3.3 3D modelling and characterisation

A 3D model was constructed of 43 fault and six rock layer boundaries interpreted from the regional seismic surveys (acquired and licensed by Fugro and WesternGeco) and well data accessed, with permission, from the Common Data Access (CDA) database, additionally the study acknowledges the provision by Senergy of stratigraphic information from their Ternan Central North Sea Study. Four key surfaces (shown on Figure 11) imaged by the seismic data (Figure 13, p21) were chosen to form the framework for the 3D model. Seismic profiles were displayed and interpreted in two-way-travel-time (TWTT) and the resulting surfaces and associated faults were converted to depth in metres below mean sea level (Figures 12 and 13).

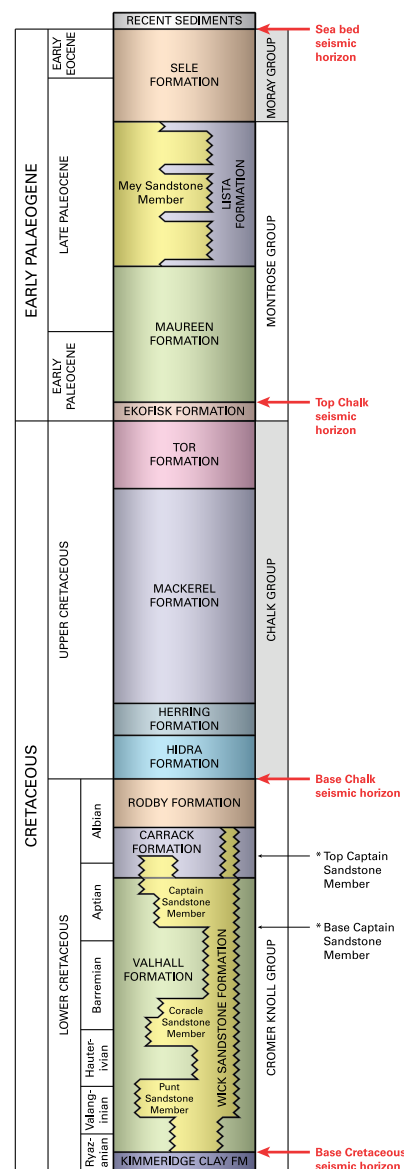
The subsurface rocks in the study area are divided by faults into basins and sub-basins with intervening ridges (or highs) and platforms (Figure 12). Not all faults cut through every surface defining the 3D model. Some were active only before the Captain Sandstone was deposited and terminate at or beneath this aquifer. Other faults have moved more recently and extend upwards through the Captain Sandstone and a proportion of these have been mapped to extend through the entire section to the sea bed (indicated in blue in Figure 12).

Within and around the study area, the strata are inclined toward the east, and as a result, progressively older rocks crop out at the sea bed towards the west (Figure 13, p21).

The rock sequence present within the 3D model is summarised in Figure 11. The four key surfaces, Sea Bed, Top Chalk, Base Chalk and Base Cretaceous subdivide the rock succession into three parts. The Lower Cretaceous sequence consists of sandstone and mudstone layers and includes the Captain Sandstone saline aquifer reservoir. The base of the Lower Cretaceous surface defines the base of the 3D model. The Lower Cretaceous is overlain by a succession of predominantly chalky limestone of the Chalk Group with occasional thin mudstone layers. The base of this succession, the Base Chalk surface, is close to the top of the Captain Sandstone reservoir (Figure 11). The Chalk is no longer present in the western part of the study area due to uplift and erosion following its original deposition. It thickens eastwards to 500m in the West Halibut Basin. The Top Chalk surface is itself overlain by a succession of interbedded sandstone, siltstone and mudstone. Again, due to post-depositional erosion, this interval is absent in the west of the study area but reaches a maximum thickness of about 1700m in the West Halibut Basin. The Sea Bed surface defines the top of the 3D model.

The Captain Sandstone is the youngest of a number of sandstone units of Lower Cretaceous age (yellow on Figure 11). The sand was sourced from the East Shetland Platform (Figure 12) and deposited south of the Wick Fault by submarine currents. The most detailed information on the Captain Sandstone comes from the Captain Oil Field in the centre of the study area (Figure 12), where an upper and a lower sandstone are distinguished, separated by the Mid Captain Shale. Well data shows that this shale is not mapped over the entire areal extent of the Captain Sandstone and, consequently, is unlikely to be a continuous barrier to migration of CO₂. Surfaces defining the top and base of the Captain Sandstone and the Mid Captain Shale were interpolated from well data and by reference to the overlying Base Chalk surface.

Figure 11 Sedimentary rock succession present within the study area. Key surfaces in the 3D geological model are arrowed (*surfaces defining the top and base of the Captain Sandstone were interpolated from well data and by reference to the overlying Base Chalk surface)

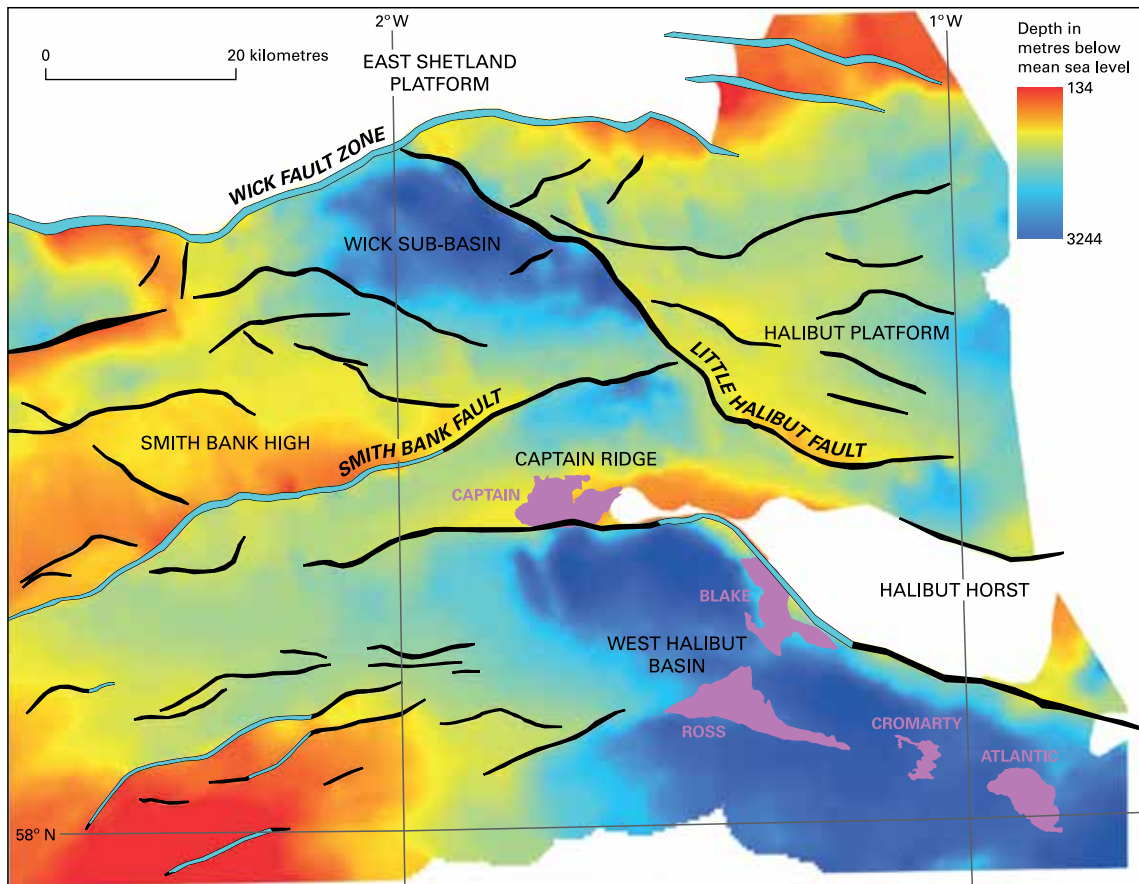




In general, the caprock to the Captain Sandstone reservoir is Lower Cretaceous mudstone of the Rodby and Carrack formations that vary in thickness over the study area (Figure 11). However, in places these Lower Cretaceous mudstones are absent and Upper Cretaceous chalky limestones of the Chalk Group rest directly on, and are a caprock to, the Captain Sandstone.

The Captain Sandstone and surrounding rocks crop out at sea bed in the west of the area and delineation of this western boundary of the potential CO₂ store is an important part of the 3D model. Well data constrain the western boundaries of each of the 3D model surfaces but are not sufficiently numerous to map in detail the subcrop at sea bed. Seismic interpretation was used to further constrain the surfaces, but this method was not successful everywhere because of 'multiple' reflections from the sea bed which interfere with 'primary' reflections from the boundaries of interest (see Figure 13).

Figure 12 Faults, basins, ridges and platforms within the Moray Firth at the deepest mapped surface of the 3D geological model (base Cretaceous surface). Faults that extend through overlying rocks to the sea bed and indicate potential leakage points for CO₂ are coloured blue



Populating the 3D model

The following characteristics of the strata between the modelled surfaces were collated and used to populate the model, in order to inform the numerical simulation of CO₂ injection:

- Porosity (see Figure 6, p10)
- Vertical and horizontal permeability (a measure of the communication or connectivity between the pore spaces)
- Proportion of sandstone to overall thickness (net to gross) for
 - Undivided Captain Sandstone
 - Upper Captain Sandstone
 - Lower Captain Sandstone
- Compressibility
- Salinity
- Pressure
- Temperature

The data was collated from oil and gas wells. The type and amount of data retrieved depended on what was available, the relevance of the data collected and reports for each well. Compressibility and salinity information were only rarely available. 'Net to gross' was estimated from composite geophysical logs. Maps showing 'net to gross' information for the total Captain Sandstone reservoir and its upper and lower divisions were produced using information collected from the well database, combined with published information on the Captain Field. This allows the volume of the potential storage reservoir to be calculated from the total volume of rock, and combined with porosity, gives the available fluid space.

The properties of the Captain Sandstone vary both vertically and laterally. The Mid Captain Shale is potentially a barrier to the flow of CO₂. Two versions of the geological model were constructed to take account of the uncertainty on the extent and possible influence of the shale. In the first, the Mid Captain Shale was assumed to be continuous across the total extent of the Captain Sandstone. In the second, the shale was restricted to an area defined by its observed presence in wells.



Figure 13 Seismic profile showing reflectors which define the key model surfaces (vertical exaggeration approximately X8). Approximate location of the profile is shown in Figure 9

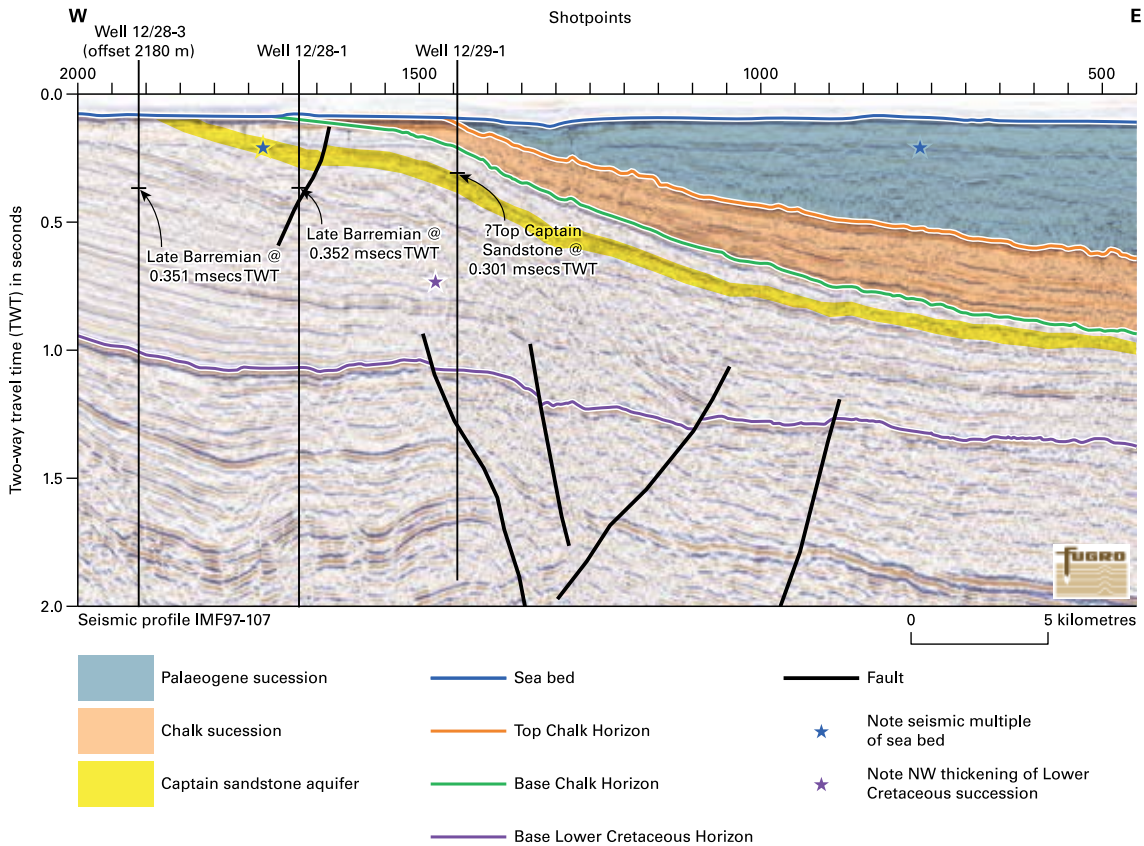
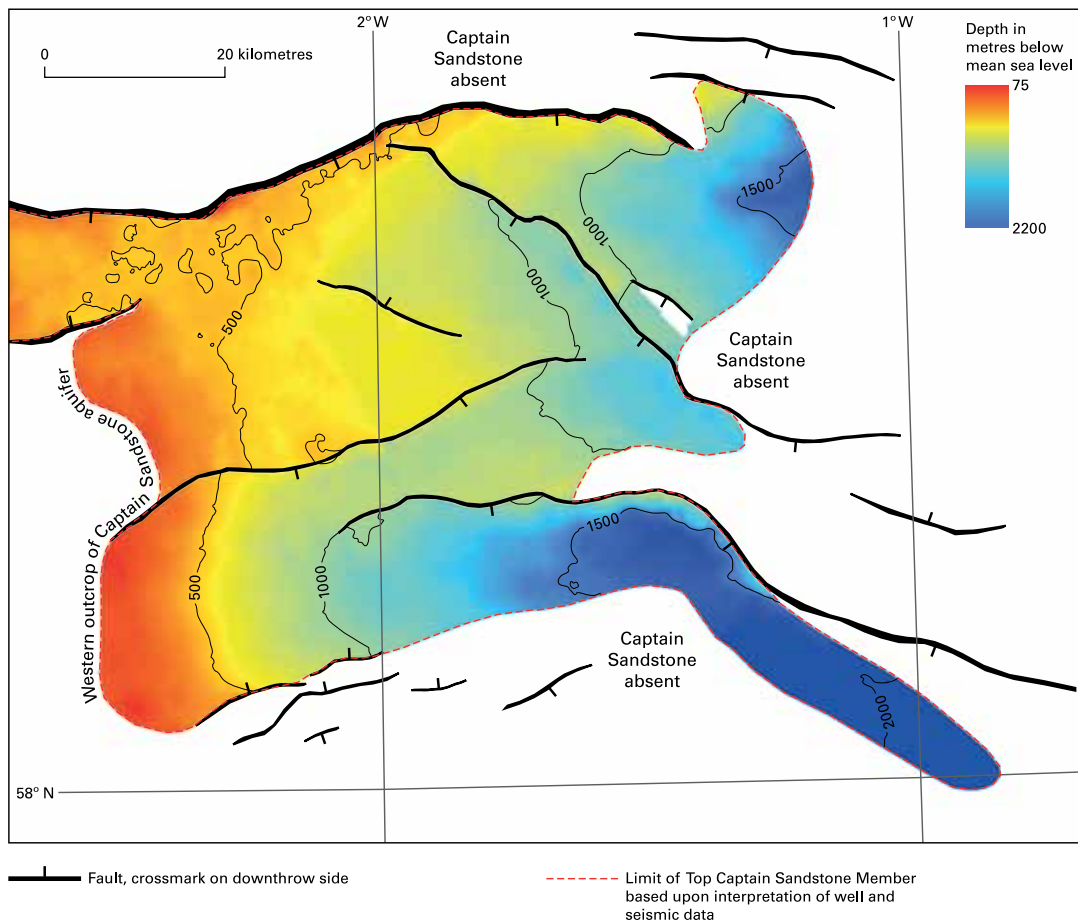


Figure 14 Depth to the Top Captain Sandstone surface



3.4 Investigating dynamic storage capacity and CO₂ injection

The volume of CO₂ that can be stored in the Captain Sandstone (storage capacity) was investigated by dynamic numerical simulations of CO₂ injection. These simulations are used to calculate the amount of injected CO₂, the best position for the injection wells, and the movement of CO₂. From these calculations the pressures changes and the position of the CO₂ after thousands of years can be estimated. The accuracy of the calculations depends on the quality of the information used; the better the quality of the input data, the more accurate the prediction.

CO₂ storage and monitoring

As well as providing improved calculations of estimated storage capacity, an important objective of the numerical simulations was to predict how to avoid flow of the injected CO₂ toward potential leakage points (Figure 15), these include:

- Faults at or close to the sea bed—a small proportion of the faults cutting the Captain Sandstone appear to extend to sea bed (Figure 12, p 19)
- The Captain Sandstone where it shallows and is expected to crop out at the sea bed along its western margin
- Vertical diffusion where the mudstone seal rocks are thin or absent and sealing relies solely on the overlying Chalk

The migration of injected CO₂ towards existing oil and gas fields was also a determining factor. Five fields operate within the Captain Sandstone area. The Captain, Blake, Cromarty and Atlantic fields produce oil and gas from the Captain Sandstone itself. In addition the Ross field produces from older rocks beneath the Captain Sandstone. Calculations were performed to investigate the impact of CO₂ injection on the pressures in these existing oil and gas fields and also the option to increase storage capacity and stay within accepted pressure limits by extraction of water from the Captain Sandstone using production wells.

Migration of CO₂ out of the confines of the Captain Sandstone may also occur via abandoned oil and gas well sites—although the majority of commercial wells are concentrated within the oil and gas fields, exploration wells are distributed over the extent of the Captain Sandstone. Mitigation to avoid such potential leakage points will be by inclusion of the position of abandoned wells as a component of the safety management of a potential CO₂ store.



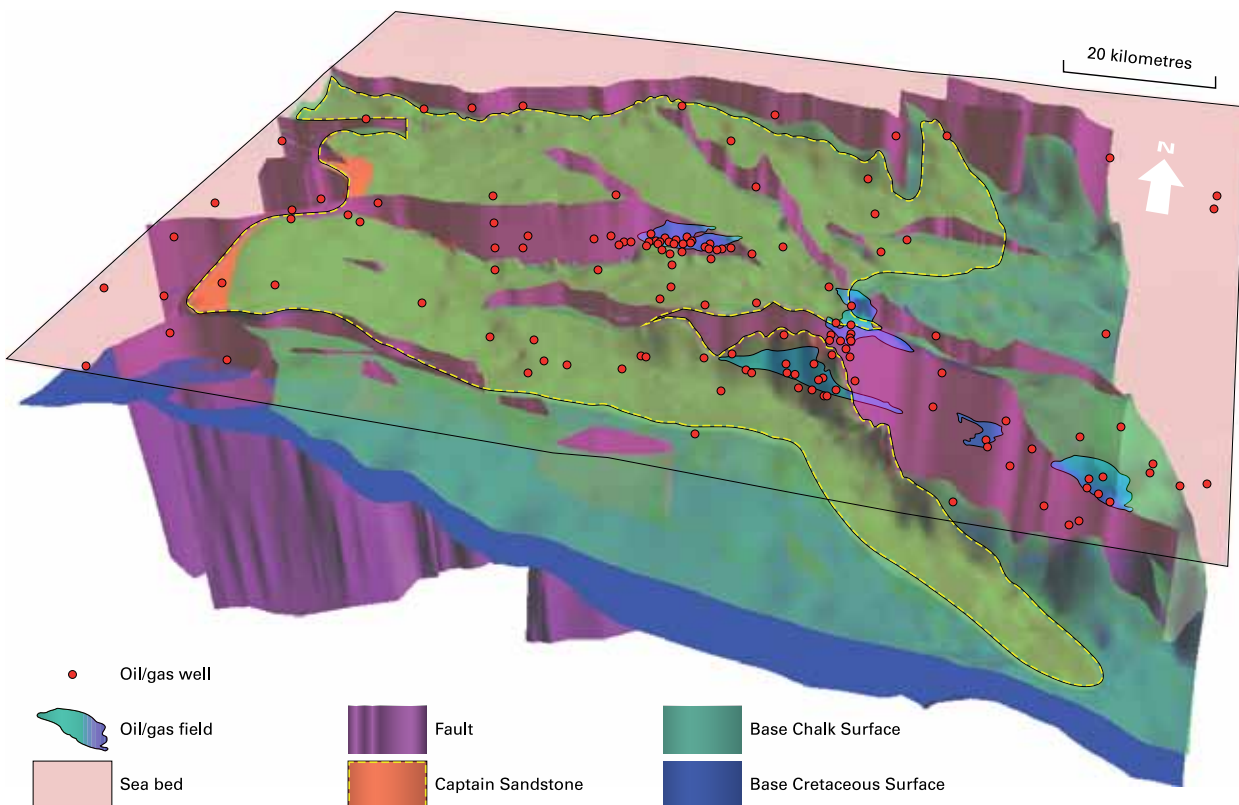
Dynamic modelling calculations

The 3D geological model described above and shown in Figure 15 was imported into Petrel software (Figure 16, p25), to generate a numerical model. A numerical simulation of CO₂ injection was run, using ECLIPSE software, to calculate the CO₂ storage capacity and examine pressure changes caused by CO₂ injection. Many simulations were run to investigate the effect of factors such as the injection rate, well placement, uncertainty in the geological model and flow conditions across the sandstone boundaries*.

First, the overall migration of CO₂ and the pressure response over the entire Captain Sandstone was studied by the calculated injection of 15 million tonnes CO₂ per year at selected locations. Secondly, the specific pressure response in individual wells was calculated, since it is essential that the calculated pressure changes are within accepted engineering limits. The injection rate for the second set of calculations was restricted to a maximum of 2.5 million tonnes CO₂ per year for each of a possible 15 well locations considered.

* Schlumberger are thanked for the use of Petrel and ECLIPSE 300 CO2STORE in this research

Figure 15 3D view of Captain Sandstone. The base Chalk surface is shown transparent, so that the extent of the Captain Sandstone can be seen beneath it



Porosity and permeability values used in the calculations

Ranges of porosity and permeability values used for the modelled rock layers in both sets of calculations are shown in Table 7. The ratio of vertical to horizontal permeability (K_v per K_h) is usually much less than one because rocks are layered. Well core measurements demonstrate the ratio is close to 1.0 in the Captain Sandstone, so in this study K_v per K_h is set to 1.0 for sandstone and 0.1 for all other rock types. The thickness and the proportion that is sandstone (Net to Gross) was taken from maps described above (see **Populating the 3D model**, p20).

Table 7. Range of porosity and permeability values used in the calculations for each of the rock layers

Rock layer	Porosity (%)			Horizontal Permeability (milliDarcy)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Rocks above the Chalk seal rocks	1	10	5	0.0001	0.01	0.001
Chalk seal rocks	1	10	5	0.0001	0.01	0.001
Mudstone seal rocks	1	10	5	0.0001	0.01	0.001
Upper Captain Sandstone	20	40	30	100	10000	2000
Mid Captain Shale	1	10	5	0.0001	0.01	0.001
Lower Captain Sandstone	20	40	30	100	10000	2000
Lower Cretaceous rocks	1	10	5	0.0001	0.01	0.001

Limitations of the calculations

The accuracy of these calculations depends on the quality of the data available. In particular:

1. The assumptions made about the sandstone boundary conditions, as either open or closed to fluid flow, are key factors that would affect the CO_2 storage capacity. Particular attention was focussed on the western boundary (where the sandstone may crop out at the sea bed), and the south eastern boundary (where the Captain Sandstone may directly overlie sandstones further to the east)
2. The extent of the Mid Captain Shale is unknown (see 'Populating the 3D model'), so two scenarios were calculated: Mid Captain Shale across the full extent of the sandstone; and shale only where it is observed in wells
3. Whether or not there is fluid flow along or across faults (Figure 17) which would affect lateral migration of CO_2

Because of these uncertainties, it is essential to consider pilot CO_2 injection to test and refine the calculation before full implementation of a CCS project.



Figure 16 3D static geological model in Petrel software (units are metres)

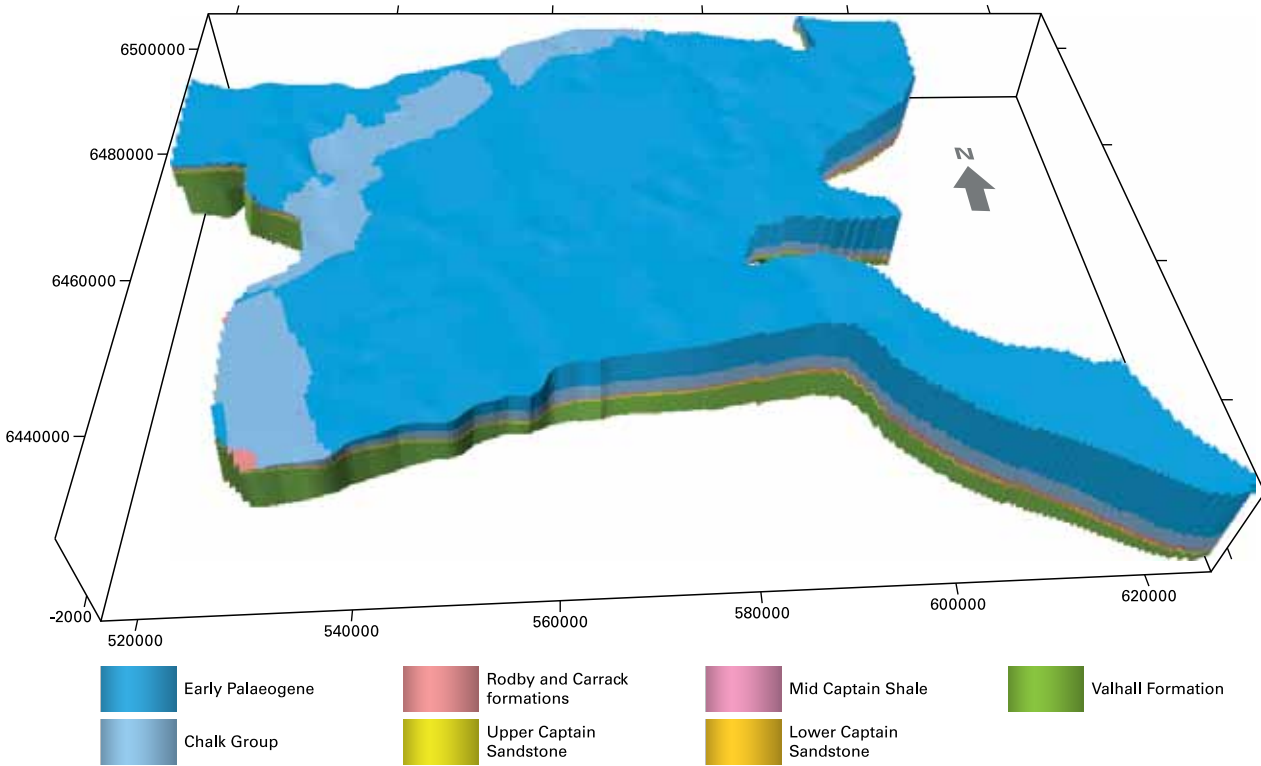
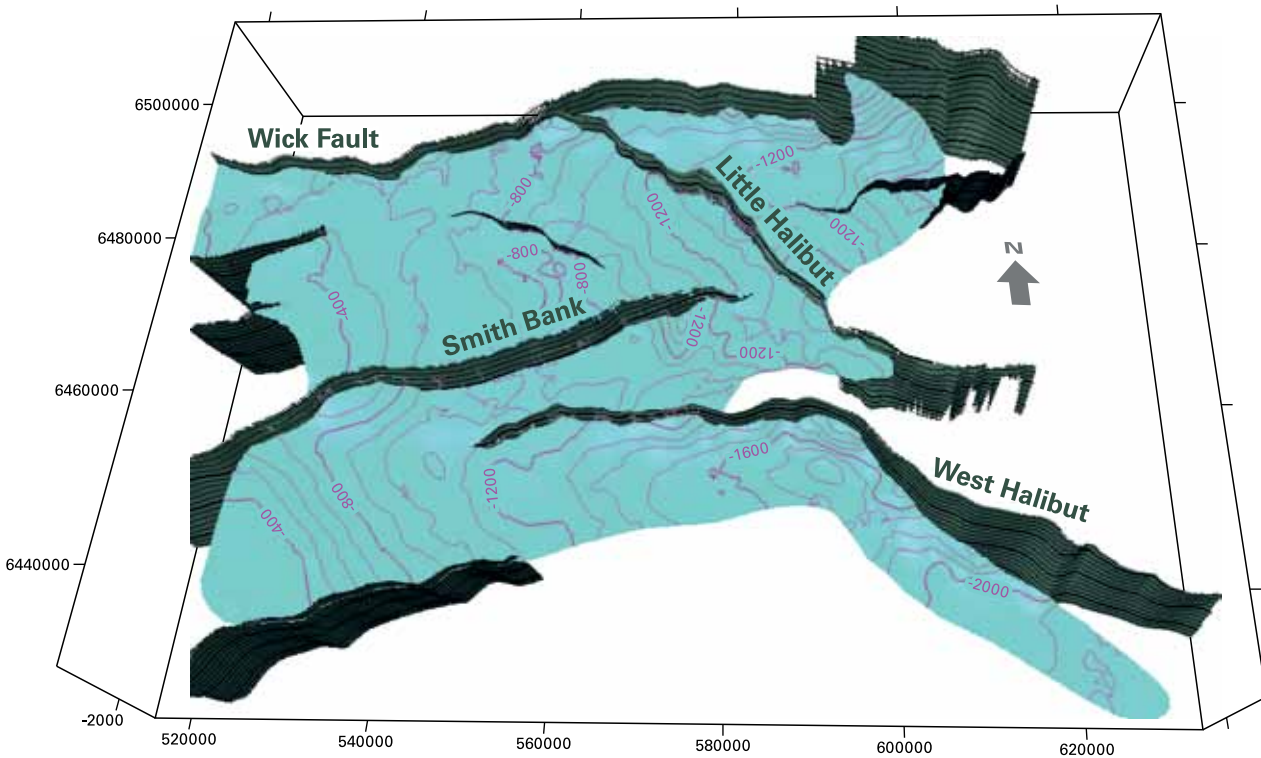


Figure 17 Location of main faults in Petrel 3D geological model and contours of the depth to the top of the Captain Sandstone (in metres below mean sea level)



1) Overall CO₂ migration and pressure response calculations

Migration of CO₂ injected at 12 selected locations, at a rate of up to 15 Mt CO₂ per year for a period of 30 years was calculated and the results are shown in Figure 18 (it is not envisaged that this amount would be injected through a single well). Factors considered when selecting the injection sites include:

- Retaining the CO₂ at depths greater than 800 m below sea level
- Avoiding significant localised increases in pressure
- Avoiding oil and gas fields

Figure 19 illustrates the distribution of CO₂ from 1 to 5000 years after commencement of injection, calculated assuming a target injection rate of 15Mt CO₂ per year at injection location I1. CO₂ is predicted to reach the top of the sandstone after five years of injection and stops moving along the seal surface after about 1000 years. It is clear that CO₂ is contained within the sandstone and injection at location I1 will not lead to CO₂ migration to the western boundary of the sandstone. Injection at a rate of 15 Mt per year for 30 years at any of the other 11 locations led to similar results.

From this modelling it is concluded that, due to the large lateral extent of the Captain Sandstone, injection can be managed to ensure that CO₂ does not migrate to the western boundary of the sandstone where it crops out at the sea bed.

2) Pressure response to CO₂ injection calculated in individual wells

The pressure changes in response to the injection of CO₂ were calculated for each individual injection well. A low side case was defined, assuming restricted conditions, as shown in Table 8. The assumed values were relaxed in subsequent calculations to identify how sensitive the results are to variations in these parameters. The constraint for all of the numerical simulations is that the maximum pressure in the injection wells must not exceed accepted engineering limits.

Using combinations of the low side restricted case and relaxed parameters; differing scenarios were defined and calculated (Table 8). The scenarios are numbered and described in Table 9, p28.

Figure 18 Contour map of depth to top of the Captain Sandstone, in metres below mean sea level, with positions of selected injection locations (I1 to I12)

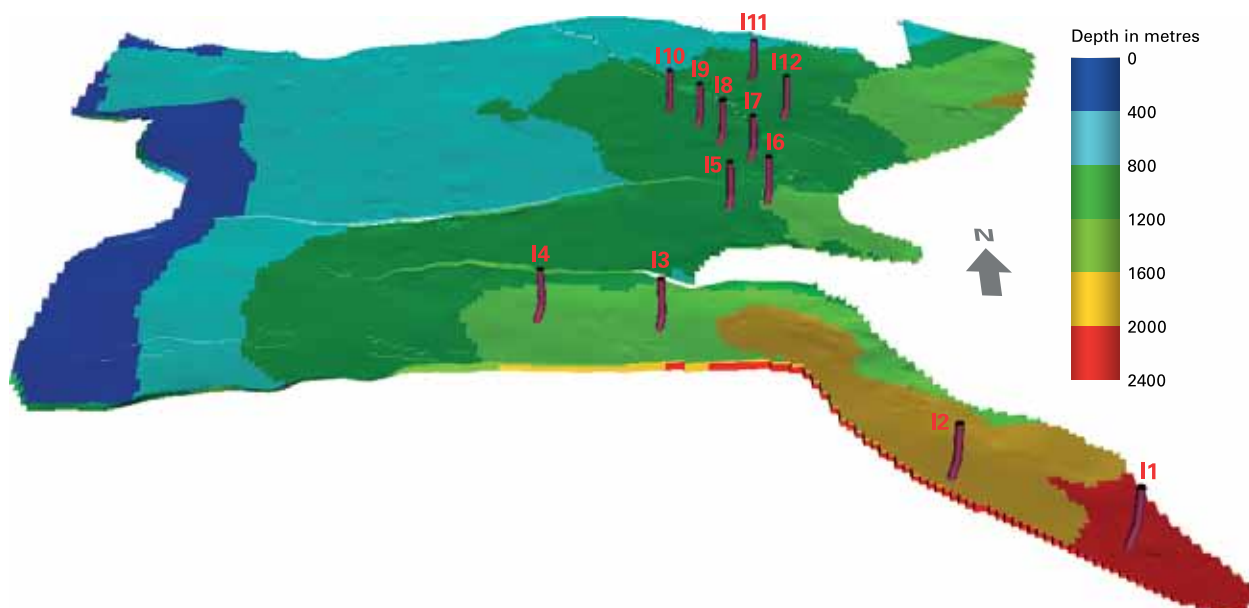




Figure 19 CO₂ distribution at the top of the Captain Sandstone over time for injection location I1

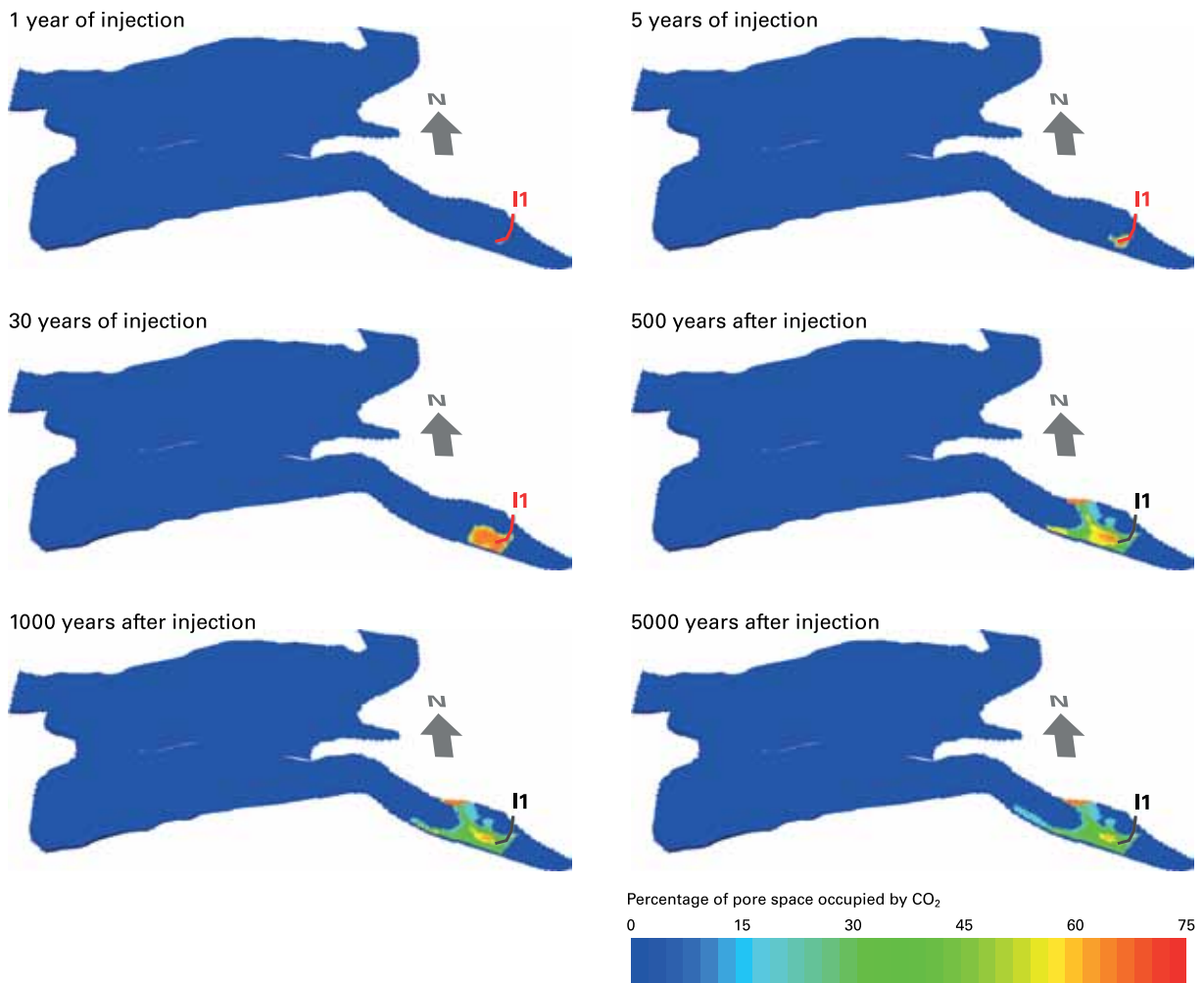


Table 8. Low side 'restricted' and high side 'relaxed' parameters and sensitivity variations to test assumptions made for the Captain Sandstone pressure constraints

Sensitivity variation	Low Side Case 'Restricted'	High Side Case 'Relaxed'
Faults within sandstone either sealing or not sealing	Sealing	Not sealing
Pore compressibility	7x10 ⁻⁵ 1/bar	14x10 ⁻⁵ 1/bar
Extent of Mid Captain Shale	Extensive and continuous	Only where observed in wells
Maximum allowed injection pressure	1.3 x starting pressure	1.5 x starting pressure
Sandstone boundary conditions	All boundaries closed to flow	Western sandstone boundary (at sea bed) open to flow Western sandstone boundary (at sea bed) open to flow Basal sandstone boundary open to flow Upper sandstone boundary open to flow
Permeability of overlying rock	Impermeable	Permeable
Permeability of overlying rock	Impermeable	Permeable
Permeability of overlying rock	None	12

In all these calculations 12 injection wells were set to a target injection rate of 2.5 Mt CO₂ per year and allowed to continue injecting for up to 100 years, leading to a potential cumulative storage capacity of 3000 Mt CO₂. However, during the calculated injection period the pressure increased, and the injection capacity of the 12 wells progressively decreased due to the cumulative effect of all the wells injecting at once. After 10 years the injection rates in all wells were less than 2.5 Mt per year, and after 50 years only the deepest well could maintain injection.

This leads to the conclusion that a storage site even as large as the Captain Sandstone must be considered as a single continuous unit because of the degree of pressure communication across the entire system. The total volume of CO₂ stored in this low side scenario is 358 Mt (Table 9).

The cumulative volume of CO₂ injected from all 12 injection wells for selected scenarios over the 100 year period of injection was calculated. The CO₂ stored in each of the modelled scenarios is given in Table 9, and illustrated graphically in Figure 20. The nature of the boundaries—whether they are open to flow or not—is the most important parameter in these calculations. In all cases with one or more open boundaries, there is still injection capacity at the end of the 100-year period. If closed boundaries are assumed, injection can only be maintained for up to 30 years, with a consequential reduction in storage capacity. This is due to the build up in pressure that occurs in a closed system. However, water production wells can be used to reduce the pressure and increase CO₂ storage capacity to similar levels as if the boundaries are open.

Table 9. Calculated scenarios and their storage capacity, storage efficiency and likely period of operation

Scenario number	Scenario description	CO ₂ storage capacity	Storage efficiency	Likely effective operational period [†]
		(million tonnes)	% of total pore volume	Years
1	Low side 'restricted' calculation	358	0.601	15–25
2	Low side 'restricted' calculation but with a higher pore compressibility value	532	0.661	20–30
3	Low side 'restricted' calculation but with non-sealing faults	362	0.606	15–25
4	Low side 'restricted' calculation but with a greater maximum injection pressure	607	0.989	20–30
5	Low side 'restricted' calculation but with Mid Captain shale only where observed in wells	546	0.576	20–30
6	Low side 'restricted' calculation but with Mid Captain shale only where observed in wells and a higher maximum injection pressure	814	0.856	25–30
7	Low side 'restricted' calculation but with western sandstone boundary (at sea bed) open to flow	1558	1.654	100
8	Low side 'restricted' calculation but with western and south eastern sandstone boundaries open to flow	1620	1.720	100
9	Low side 'restricted' calculation but with western, south eastern and basal sandstone boundaries open to flow	1660	1.762	100
10	Low side 'restricted' calculation but with western, south eastern, basal and upper sandstone boundaries open to flow	1655	1.757	100
11	Low side 'restricted' calculation but with 12 water production wells	1668	2.075	100

[†] The duration of the operational period will be influenced by the number of injection wells.



Figure 20 Storage capacity of 'relaxed' scenarios as a percentage relative to the low side 'restricted' scenario (see Tables 8 and 9). Note that the operational period required to inject the given storage capacity will depend on the number of wells used

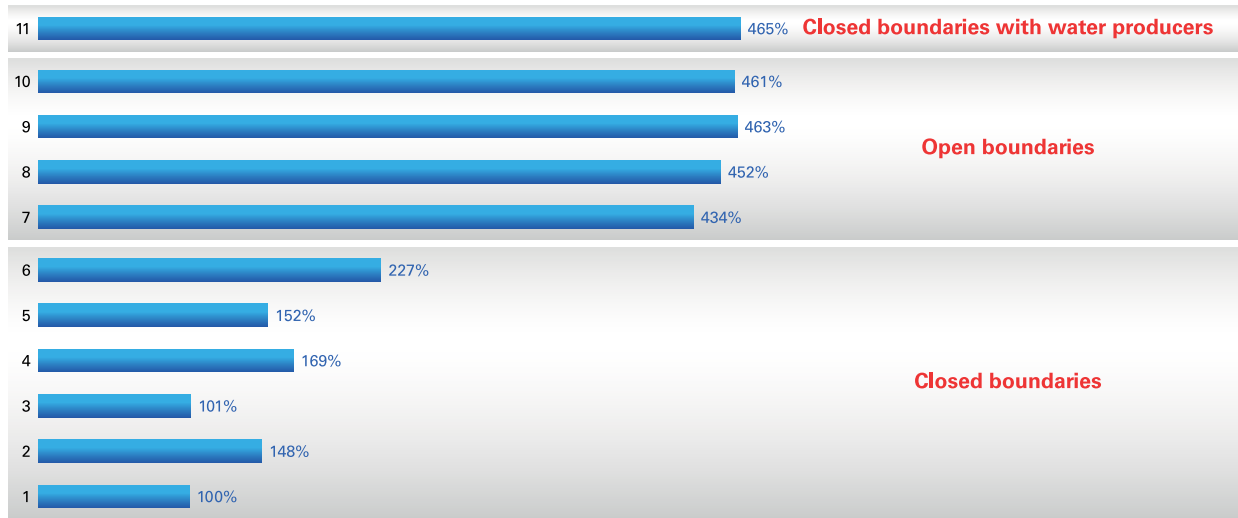
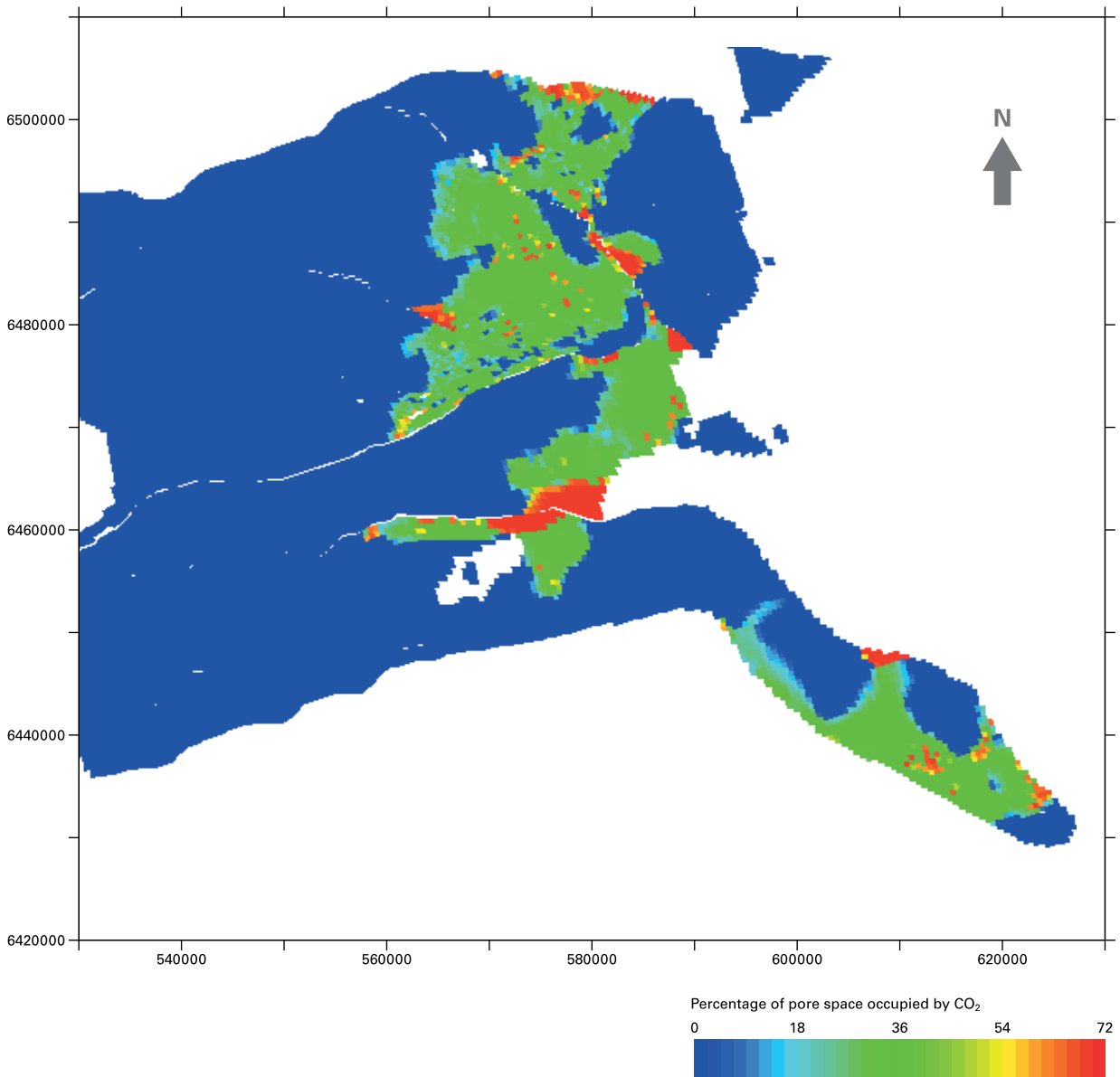


Figure 21 Distribution of CO₂ after 100 years of injection (Scenario 7 of Table 9) and 900 years of and of CO₂ migration



Calculated migration of CO₂ by fine-scale modelling

Fine-scale modelling of the zones where predicted CO₂ migration takes place was also carried out. By describing the sandstone with a higher resolution model it is possible to more realistically predict the flow of CO₂ through the rock layers. An example is shown in [Figure 21](#). In this case, CO₂ was injected for 100 years, and then a further 900 years of CO₂ migration was calculated. At the end of this period all the injected CO₂ was contained within the Captain Sandstone at depths greater than 800m below sea level.

Captain Sandstone characterisation and investigation of dynamic storage capacity and CO₂ injection—key conclusions

The Captain Sandstone is known with greatest confidence around the associated oil and gas fields. Away from the fields there is uncertainty around many of the characteristics of the sandstone. To demonstrate the sensitivity of the estimated storage capacity and pressure to variations in these uncertain characteristics, a wide range of calculations has been performed.

- The porosity, permeability and calculated storage capacity of the Captain Sandstone compares very favourably with other CCS projects worldwide ([Table 4, p 13](#)).
- The Captain Sandstone has significant potential CO₂ storage capacity. Even with the most restricted conditions with all boundaries closed to flow the probable storage capacity is calculated to be about 358 million tonnes, giving a storage efficiency of 0.6% of pore volume with an expected operating life-span of at least 15–25 years. The expected reduction in calculated storage capacity normally associated with increased data and research effort ([as illustrated in Figure 5, p 11](#)) was not found.
- If 15 million tonnes of CO₂ is injected per year at any one of 12 selected injection locations, it will be contained at depths greater than 800m below the sea bed.
- The possible storage capacity of the Captain Sandstone may be at least four times greater if the aquifer boundaries are open. This increase would be a result of displacement of salt water, and not CO₂.
- The storage capacity of the Captain Sandstone with the western boundary open to flow is calculated to be 1558 million tonnes CO₂.
- The storage capacity if the sandstone is closed to flow may be increased from 358 to 1668 million tonnes CO₂ by significant additional investment in 15 to 20 water production wells with maximum water production rates of 4000 m³ per day.
- There is about a 10% increase in CO₂ storage capacity if the over- and underlying rocks are permeable (even with very low permeability values).
- Initial results suggest that if CO₂ injector wells are positioned at least 10 km away from oil and gas fields and potential leaking faults, CO₂ may not reach the fields or potential leak points within 300 years, but further investigation is required. CO₂ migrated to the top of the sandstone after five years of injection and movement of CO₂ beneath the overlying caprocks stopped about 1000 years after injection had ceased.



- Injection of 2.5 million tonnes CO₂ per year in one well has an impact on the pressure throughout the entire Captain Sandstone, and thus interference between different injection locations must be considered.
- Further assessment and appraisal of the Captain Sandstone as a potential CO₂ store is justified. In particular, to examine and test the assumptions used in this study and their impact on store operation and capacity by:
 - Investigation of the nature of the sandstone boundaries and so the magnitude of the probable additional storage capacity
 - Flow along or across the mapped faults and the implications to the amount and rate of CO₂ injected and any compartmentalisation of the sandstone resulting in early shut down of injection wells
 - The presence of less permeable or more permeable layers within the sandstone and their effect on the injection rate and movement of the stored CO₂
 - Study of the caprocks sufficient to demonstrate to regulators the integrity of a CO₂ storage site in the Captain sandstone including the character of the caprocks, variation in the thickness and type of caprocks, effects of pressure and temperature changes associated with CO₂ injection or oil and gas production, any interaction between the rocks and injected CO₂, and the likelihood and impact of abandoned oil and gas wells, the presence and character of faults that intersect the caprocks and may extend to the sea bed and any evidence of natural fluid movement below sea bed.

3.5 Legislative, ground condition and environmental considerations

Compliance with environmental legislation and the assessment of potential impacts of a CCS project are prerequisites for CCS activities. Shallow ground conditions around the UK, the physical character of the sea-bed surface and underlying sediment, marine organisms and marine environment, are generally well known from survey data and monitoring activities. The North Sea is especially well understood as a result of the many site investigations and environmental impact assessments that have been undertaken for exploration and production of oil and gas. The study reviewed the environmental legislation relevant to a carbon capture and storage (CCS) project in the study area. Available environmental information was reviewed and assessed as a first step in establishing an initial environmental baseline to inform an appraisal of suitability for geological storage of CO₂ in the Moray Firth study area and identify any known environmental issues relevant to the development of any future carbon dioxide store.

Carbon capture and storage (CCS) legislation review

The EU CCS Directive (2009/31/EC) on the geological storage of carbon dioxide establishes a legal framework for the environmentally safe geological storage of CO₂ and lays down requirements covering the entire lifetime of a CO₂ storage site. The Directive applies to geological storage of CO₂ within the territory of the Member States, their exclusive economic zones and on their continental shelves. It stipulates that geological storage of CO₂ will not be possible without an appropriate permit.

The UK Energy Act 2008 applies to geological storage of CO₂ both onshore (a decision has been taken not to allow CO₂ storage onshore) and offshore which comprise:

- Internal waters adjacent to Scotland
- The territorial sea adjacent to Scotland (up to 12 nautical miles out to sea)
- The UK offshore area (between 12 and 200 nautical miles out to sea), designated as a Gas Importation and Storage Zone (GISZ)

The Energy Act 2008 established a legislative basis in the UK for permitting the offshore storage of carbon dioxide. Under the Energy Act 2008, the Scottish Ministers are the licensing authority for the purpose of granting licences for exploration and for carbon storage under the territorial sea adjacent to Scotland. If a storage area is partly under the Scottish territorial sea and partly in other UK territorial waters or in a Gas Importation and Storage Zone, the licensing authority may be the Scottish Ministers or the Secretary of State. Marine Scotland will act as the Regulatory authority for this licensing regime in Scotland.

It is assumed that most (if not all) of the proposed CCS activities within the study area will occur outwith the Scottish territorial sea. The licensing authority for a development would therefore be Department of Energy and Climate Change (DECC). However, the western boundary of the wider study area falls within or close to 12 nautical miles of the shore.



Environmental legislation framework

The UK government has sought to exploit the existing legislative framework covering the offshore oil and gas industry as a basis for the control of offshore CCS operations by modifying certain key pieces of legislation (Table 10). This will enable offshore CCS developers to work under a well-established and clearly understood permitting regime.

In addition, use of the sea bed in the area of interest requires permission from the Crown Estate. This permission is given in the form of a 'Crown lease', which includes either a lease for activities in the UK territorial sea or an authorisation for CCS activities within the GISZ. The provisions of a Crown lease may determine the site location and the period for which a licence is granted.

In Scotland, any land-side infrastructure such as pipelines or onshore facilities will be likely to fall under the Pipelines Act 1962, Pipeline Safety Regulations 1996 and Town and Country Planning (Scotland) Act 1997.

Table 10 Energy Act 2008 (Consequential Modifications) (Offshore Environmental Protection) Order 2010

**Applies the offshore oil and gas environmental regime to gas unloading and storage and CO₂ storage.
Main regulations covered are:**

- Environmental impact Assessment Regulations (EIA Regulations)
- Offshore Habitats Regulations (Habitat Regulations)
- Offshore Marine Conservation Regulations (OMR Regulations)
- Offshore Combustion Installations Regulations
- Greenhouse Gases Emissions Trading Scheme Regulations
- Offshore Chemical Regulations (OCR Regulations)
- Oil Pollution Prevention and Control Regulations (OPPC Regulations)
- Emergency Pollution Control Regulations (EPC Regulations)
- Merchant Shipping Regulations (Oil Pollution Preparedness, Response & Cooperation Convention) Regulations (OPRC Regulations).

Geographical restrictions apply in relation to some regulations in Welsh and Scottish territorial waters.

Sea bed and shallow subsurface ground conditions

The nature of the sea bed and shallow subsurface needs to be determined because:

- Natural features of the sea–bed surface may affect decisions on the positioning of the CO₂ injection wells and infrastructure
- Movement of sediment over the sea-bed surface may affect the monitoring of gas in the store and identification of any leakage pathways
- The sea bed is an important location in the exchange of liquids and gases and evidence of natural events, such as natural gas seeps, should not be misinterpreted as leakage of CO₂ from a geological storage site
- The nature of the sea bed influences the marine ecology (and consequently factors such as designated conservation areas and preferred regions for commercial fishing) and surface sediments influence the types of biological communities present in or on the sea bed
- Existing cable, pipeline, well or other infrastructure may present potential obstructions to the installation of any facilities for CO₂ injection, storage or monitoring

In the study area, bedrock is overlain by glacial and marine sediments, predominantly muds and sands, deposited during the Quaternary (the last 2.5 million years). These are more than 100m thick in the east, thinning and becoming locally absent towards the west (Figure 22). The sedimentary sequence has been subdivided and mapped in detail in the eastern part of the study area during systematic surveys, but is less well known in the west. The character of the various mapped units reflects the recent glacial history of ice sheet advance and retreat.

The sea bed slopes gently towards the east from about 50m water depth in the west to more than 140m in the north–east. The shallowest waters (approximately 33m deep) are over sand banks. During the last 2.5 million years there have been episodes of severe erosion by ice, rapid changes in sea level and very high rates of sediment accumulation. Near the western limit of the Captain Sandstone the bedrock surface was eroded into hollows up to 75m deep; changes in ice flow direction created a very complex pattern of buried and open channels (Figure 23). Two groups of deep open channels are interpreted to have formed beneath the last ice sheet, eroded by ice or fast-flowing water. East–west oriented channels south of the Captain Sandstone outline include the Southern Trench which is around 25km in length, 2km wide and locally over 220m deep. A series of north–south orientated channels cuts across the centre of the Captain Sandstone area. The largest is around 25km long and approximately 140m deep at its deepest point (Figure 23). Open channels create an uneven relief for the positioning of sea-bed equipment. A bathymetric survey that images the sea bed at a very high resolution, with pixels 1m or less across, would inform the investigation of a potential CO₂ storage site.



Figure 22 Generalised thickness of Quaternary glacial and marine sediments above rockhead in the Moray Firth in metres. Dashed outline shows approximate position of study area

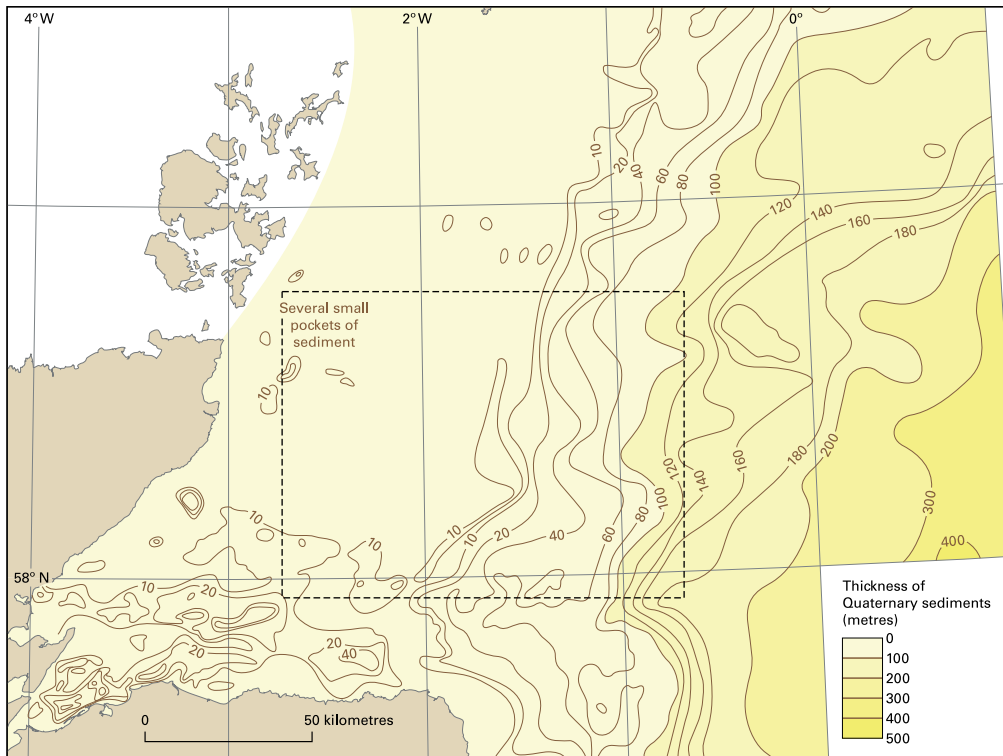
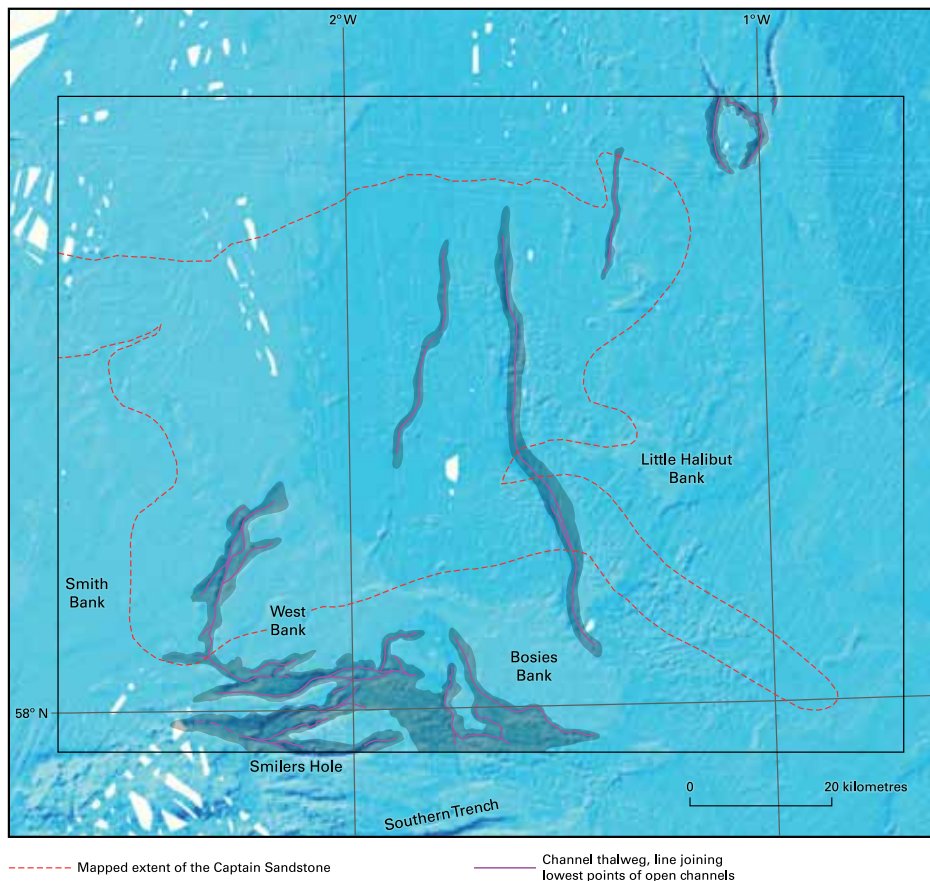


Figure 23 Image of sea-floor topography for the study area, generated by the Olex system



Erosional channels were also formed during previous glaciations and were subsequently infilled. These buried, infilled channels may provide a pathway for migrating shallow CO₂ and their possible presence increases the area that must be monitored if a geological storage site is established. During this study several such buried channels were identified and mapped. Further detailed mapping of these features will be required if this area is to be used as a CO₂ storage site.

Sea-bed sediments

Sediment distribution in the Moray Firth reflects both the glacial history of the area and the present-day flow of water currents. In general, sea-bed sediment becomes progressively finer with distance from the coast, and coarser sediments found in the west where water depth is less than 100m. Sampling has shown that very soft sediments predominate in the north-eastern part of the area. Long-term placement of any heavy monitoring equipment will need to be designed to be suitable for the sea floor.

The north-western part of the study area is dominated by biogenic deposits, specifically calcareous shells transported from the sea floor around Orkney. There are also small areas of outcropping rock in this region (Figure 24).

Features on the sea-bed surface

In the north-west corner of the study area the currents are strong enough to create migrating sediment dunes and banks. Evidence of any CO₂ leaks here might be obscured by sediment movement but these areas lie west of the extent of the Captain Sandstone. In the north-west part of the area there are several low north-east-trending linear ridges of sediment or moraines, deposited as the last ice sheet melted.

Pockmarks—relict features caused by fluid escape at the sea bed during ice sheet melting or by leaking natural gas—have been identified in the Witch Ground and Forth formations in the east of the Captain Sandstone area. These shallow depressions in the sea floor (Figure 25) form most readily in soft mud and their size decreases with increasing coarseness of the surface sediment. The area of their occurrence will need to be evaluated together with information on their age, density and supported habitats in order to satisfy conservation criteria and to ensure that the natural occurrence of such features is not confused with the escape of CO₂ from a storage site.

Seismic profiles reveal the presence of natural shallow gas by acoustic blanking (where reflectors on the profiles are obscured due to the presence of trapped gas), columnar disturbance of acoustic reflectors and pockmarks, both buried and at the sea bed (Figure 25). All are evidence of natural fluid movement in the shallower sediments.



Figure 24 Map of sea-bed sediments

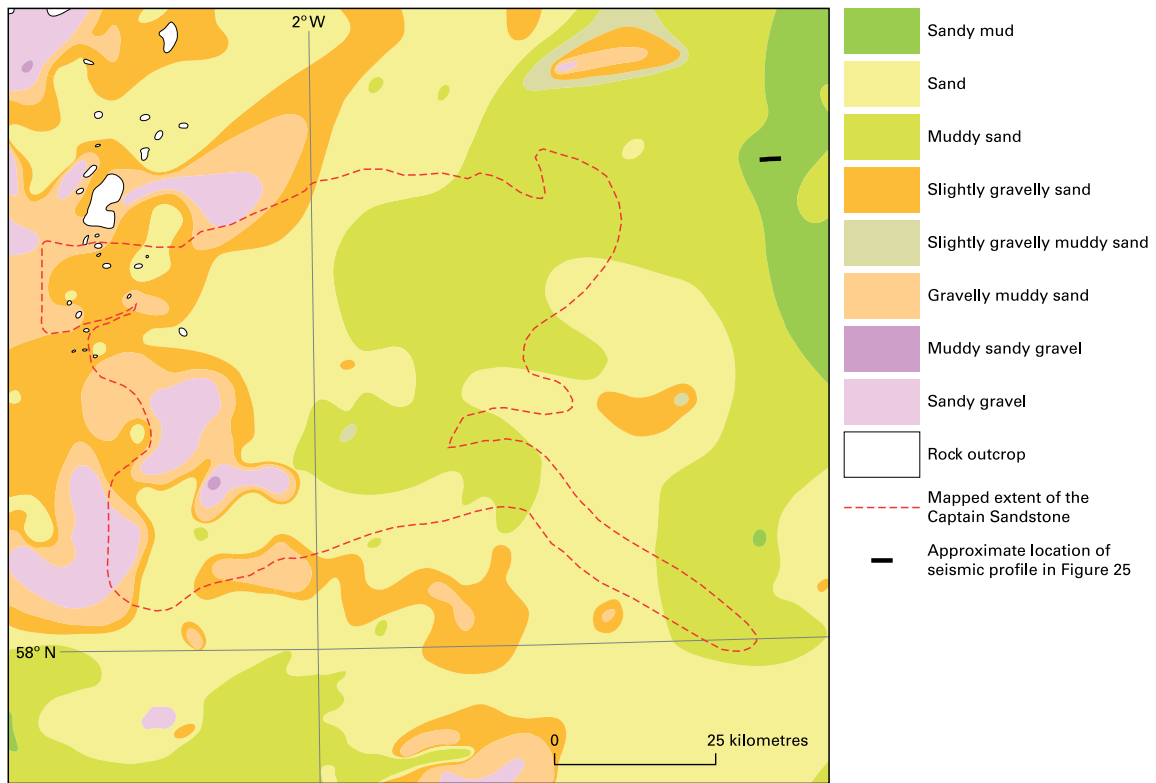
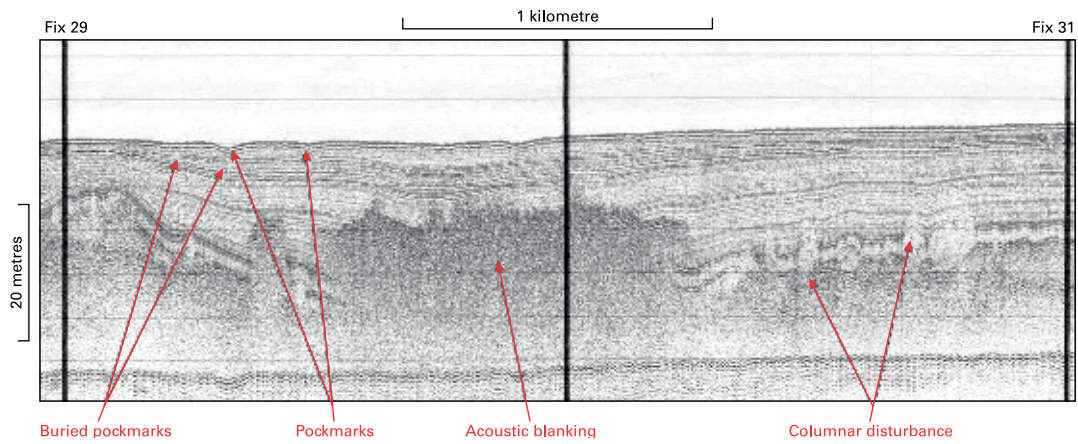


Figure 25 Seismic survey profile from 1979 showing gas features. Approximate location of the profile is shown in Figure 24



Environmental impacts of CCS project operations

Most of the environmental impacts of CCS project operations (Table 11) are expected to be very similar to those of oil and gas operations, which have taken place in the North Sea for decades and are well understood, well legislated and well managed. Their residual impacts are generally considered to be minimal and thus should provide no obstacle to carbon storage development. Research into the potential environmental impacts of CCS including the effects of CO₂ leakage and exposure has been limited. Studies relating to the sequestration of anthropogenic CO₂ in the deep ocean and increased oceanic absorption of atmospheric CO₂ have led to a clearer understanding of the impacts of increased carbon dioxide on marine organisms. Although these do not specifically relate to the impacts of CO₂ leakage from CCS operations, this research can be used to draw broad conclusions about the potential impacts on marine organisms in such an event, but the extent to which these would apply to a proposed CCS project should be treated with caution.

Biological conditions

Water depth, temperature and currents, sea bed sediment type and wind affect the biological conditions in the Captain Sandstone study area. Current flow in the area is complex due to the interaction of a number of different water masses (Figure 26). The main influence on currents in the Moray Firth is the North British Coastal Current. In the western part of the study area, this water mass joins with local, coastal currents to form a weak, clockwise circulation around the Moray Firth. Deeper water (greater than 100m) in the east of the study area is influenced by mixed (coastal and oceanic) waters which are brought into the North Sea by the Fair Isle current. Cold Atlantic bottom water creates a density gradient which steers the current along the 100m depth contour in the northern North Sea, passing through the study area. This current acts as a boundary, generally keeping the waters of the Moray Firth distinct from the offshore waters of the northern North Sea.

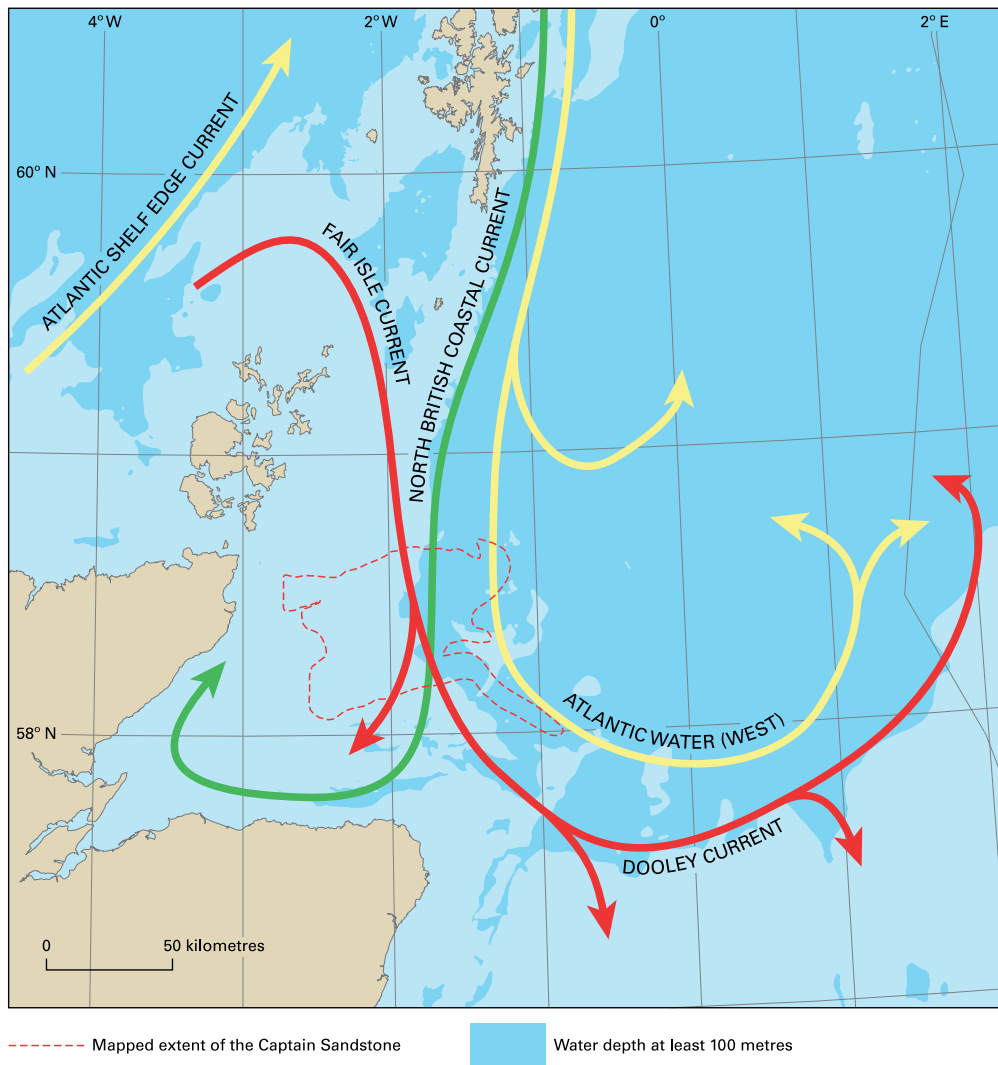
In general, the main influences on benthic communities, animals and plants that live in or on the sea bed, are water depth and sediment type. It is likely that the benthic community present in the shallow, sandy sea bed in the western part of the study area will vary significantly from that present in the deeper, muddy sediments of the east. It would be expected that benthic communities found in the study area would match species compositions previously identified for similar areas of the northern North Sea and Moray Firth. Communities present within pockmarks may differ from surrounding areas, depending on the sediment types present. The northern North Sea does not support particularly large or diverse populations of marine mammals. However, a population of resident bottlenose dolphins is found in the inner Moray Firth, to the west of the Captain Sandstone area. In addition, the Moray Firth region is internationally important for seabirds, with a number of species present in numbers equalling or exceeding 1% of their European population.



Table 11. Potential environmental impacts of CCS project operations

Drilling and long-term operations	Accidental events
Disturbance to the sea bed by placement of feet or anchors and chains (depending on drilling rig type) causing loss of benthic communities and re-suspension of sea bed sediment	Fuel oil spills
Disturbance to other users by excluding them from part of the sea and regulated by The Coast Protection Act 1949 (Energy Act 2008 from April 2011)	Exposure of marine organisms to CO ₂ from a ruptured pipeline, loss of well control, or CO ₂ migration to the sea bed surface over time
Discharge of formation water and drill cuttings to sea, and underwater noise generation	
Emission of CO ₂ generated by fuel consumption	

Figure 26 Current circulation in the northern North Sea



Planktonic, sea-bed and pockmark communities

- Plankton, plant-like and animal species that drift with the ocean currents, are a critical component of the marine ecosystem and are expected to be a mixture of oceanic and neritic (shallow water) planktonic species.
- Benthic communities, animals and plants that live in (infauna) or on (epifauna) the seabed.
- West of 100m water depth contour: sands and sandy gravel, areas of muddy gravel. Infauna: echinoderms, bivalve molluscs and polychaetes. Epifauna: echinoderms, hermit crabs.
- East of 100m contour: finer sands, sandy mud. Infauna: polychaetes, amphipod crustaceans. Epifauna: hermit crabs, shrimp, molluscs, echinoderms.
- Pockmarks: the presence of carbonate structures associated with these may result in a richer and more diverse epifauna. Species include bivalves, anemones, buccinid gastropods and pogonophoran worms.

Fish and shellfish (Figure 27)

- Commercially, the most important fish are haddock, whiting, monkfish, cod, herring, and Norway pout; the shellfish Nephrops (Norway lobster) and scallops.
- Spawning grounds: cod, herring, lemon sole, Nephrops, Norway pout, sandeel, sprat and whiting. Spawning areas are not rigidly fixed, changing with the prevailing environmental conditions and time of year.
- Nursery grounds: lemon sole, Nephrops, sandeels, whiting, Norway pout, sprat, haddock and saithe. Nursery grounds are present all year round.

Marine mammals

- Year round inhabitants: minke whales, white-beaked dolphins, harbour porpoise.
- In the inner Moray Firth: bottlenose dolphins.
- Occasional visitors: long-finned pilot whale and killer whale; common, Atlantic white-sided and Risso's dolphin.
- Seals: both grey and common seals.

Seabirds

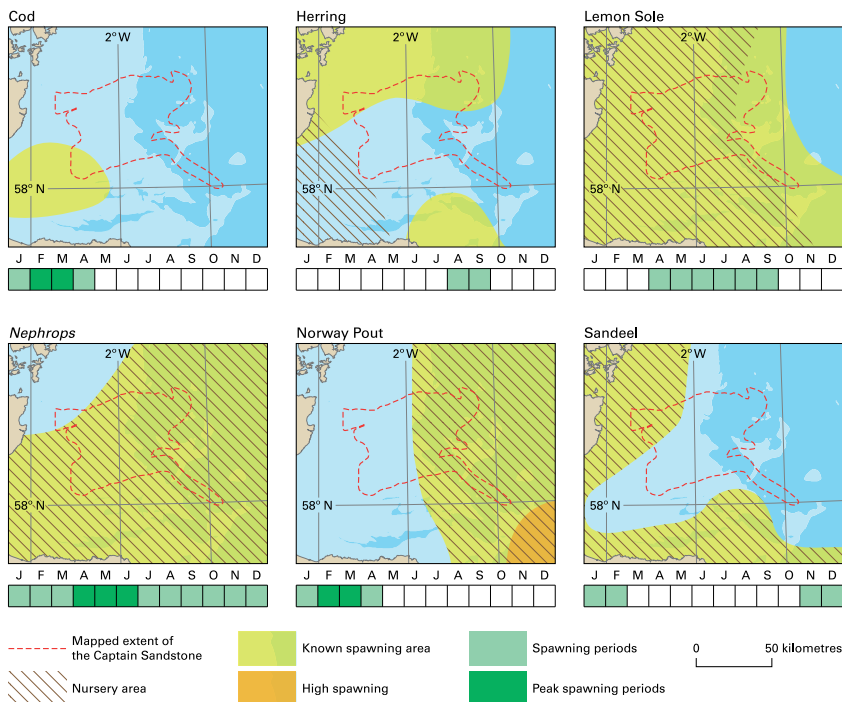
- The Moray Firth region is internationally important for seabirds including fulmars, gannets and auks.
- During the breeding season (March to June) the highest densities of birds are found close to the coastal breeding sites (especially East Caithness cliffs, Troup Head and Lion's Head and the Orkney Islands). Vulnerability to surface pollution varies throughout the year and generally decreases with distance from shore.



Effects of CO₂ exposure on marine organisms

There are two primary biological impacts resulting from the leakage of CO₂ in the marine environment. These are the direct toxic effects of CO₂, resulting in an abnormally high level of carbon dioxide in the blood (hypercapnia), and the indirect effect of reduced pH (increased acidification) as a result of the reaction of CO₂ with the surrounding seawater. In general, the magnitude of any environmental impact from a CO₂ leak will depend on the duration of exposure and level of pH change. Although data sources are limited, it is apparent that accidental CO₂ leakage presents could potentially impact upon a wide range of marine fauna. The extent of any such impacts from a leakage in the study area would depend largely on the extent and duration of the leakage, the behaviour of the CO₂ in the environment and the susceptibility of the organisms within the area. It is expected that, due to their largely sedentary nature, benthic communities, including the larvae and eggs of certain fish species may be most vulnerable to CO₂ exposure. There is evidence that a CO₂ less sensitive to CO₂ than invertebrates and the limited research available also suggests that the direct toxic effects of CO₂ are of greater significance to increased juvenile fish and egg mortality than increased ambient acidity. In the event of a localised CO₂ leak, it is probable that any fish will be able to avoid the impacted area, by swimming away from it. Spawning grounds for several species of fish are located within the study area (Figure 27). The majority of fish species release their eggs directly into the water column, which then spread out over a wide area. Increased CO₂ levels from a point source would therefore be unlikely to affect a significant proportion of any population. Sandeels, herring and Nephrops spawn directly onto the seabed however, and so could be expected to have a greater potential to be affected by any unexpected CO₂ releases. Nonetheless, as any of the effects described above would be expected to be limited to a very small area, it seems unlikely that a significant part of the population of these species would be affected by such a release.

Figure 27 Important fish spawning and nursery grounds in the vicinity of the study area



Conservation and protected areas

Habitats and species of importance at a European level are protected via the designation of Special Areas of Conservation (SACs), under the Habitats Directive, and Special Protection Areas (SPAs) under the EC Birds Directive (Figure 28). The Moray Firth SAC protecting the resident bottlenose dolphin population lies 60 km west of the Captain Sandstone. The nearest land masses to the study area, the Aberdeenshire and Caithness coastlines, and the Orkney Islands, contain numerous internationally designated coastal conservation sites. However, none of these extend into the study area and are unlikely to be affected by any CCS operations.

The faunal communities present at pockmarks within the study area have not yet been established. However, it may be noted that these pockmarks are smaller than those upon which protection as SACs has previously been conferred—for example, at the nearby Witch Ground. There is currently no evidence that they are actively seeping gas.

Other users of the sea

The area lies on the western edge of an area of intensive oil and gas activity. Existing oil field infrastructure could come to obstruct the installation of facilities for injection, storage or monitoring (Figure 29). The extent of the Captain Sandstone lies to the east and away from a wind farm licence area and a telecommunications cable lies along its western margin. Factors that may affect deployment of CCS include:

- Infrastructure and sea-bed obstructions
 - Pipelines, cables and well heads
 - Renewables—wind turbines and their attendant infrastructure. Note that foundation designs for offshore wind turbines are predominantly piled structures thereby creating potential pathways to the sea bed for gas that has migrated to the near sea-bed sequence
- Vessel traffic
 - Moderate shipping traffic
 - Fisheries: mixed demersal fishery; pelagic fishery; shellfish fisheries
- Military activity



Figure 28 Conservation and protected areas

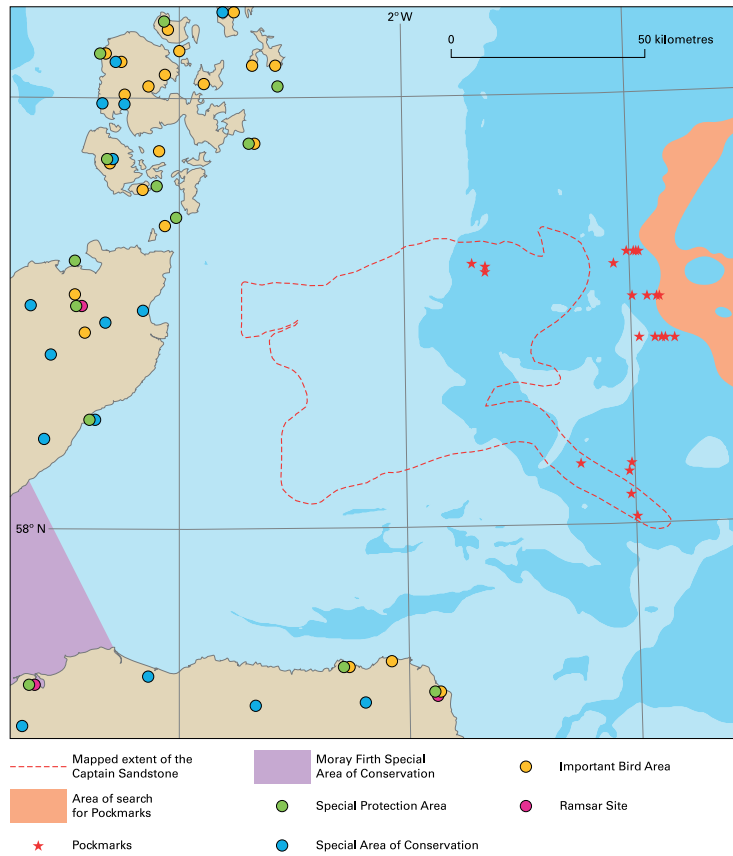
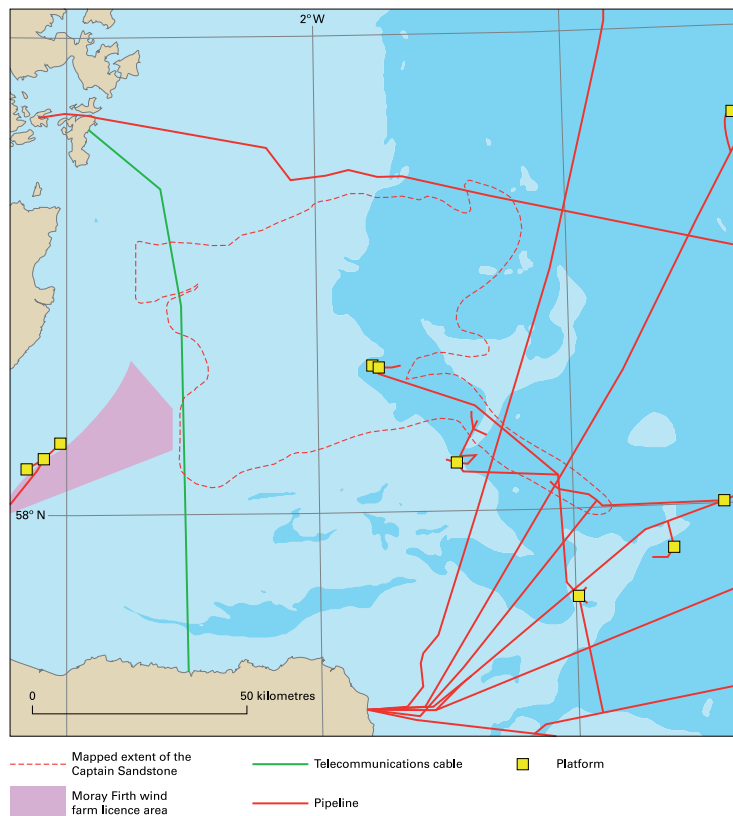


Figure 29 Sea-bed infrastructure



**Legislative, ground condition and environmental considerations—
key conclusions**

- A CCS development in the study area in the northern North Sea would be subject to a range of legislative controls. Permitting for offshore CCS activities would be regulated via the Energy Act 2008 and the Storage of Carbon Dioxide (licensing etc) Regulations 2010. Due to technical similarities in the activities involved, such a development would also be subject to regulations which control oil and gas activities in the North Sea.
- Site investigations for a CO₂ storage site will need to map the sea bed, shallow subsurface ground conditions and biological conditions to an extent sufficient to satisfy licence, storage permit and environmental regulations for approval by the relevant authority.
- Prior to injection of CO₂, any occurrences of gas blanking and the presence of pockmarks should be mapped in detail to determine the distribution of pre-existing features due to natural gas accumulations and escape, and any biological communities associated with them.
- Expected environmental impacts from CCS operations are also very similar to those of oil and gas operations. The physical presence of the rigs, vessels and installations; discharges of drill cuttings, drilling fluids and cement; aquifer water discharges; underwater noise generation; and, atmospheric emissions may all cause environmental impacts. However, similar impacts are caused routinely by the oil and gas industry in the North Sea, and elsewhere in the world, and these impacts are well understood, well legislated and well managed, whereby their residual impacts are generally considered to be minimal.
- Although data sources are limited, it is apparent that accidental CO₂ leakage presents could potentially impact upon a wide range of marine fauna. The extent of any such impacts from a leakage in the study area would depend largely on the extent and duration of the leakage, the behaviour of the CO₂ in the environment and the susceptibility of the organisms within the area. It is expected that, due to their largely sedentary nature, benthic communities, including the larvae and eggs of certain fish species may be most vulnerable to CO₂ exposure. Any acute effects are expected to be very localised.
- No environmental 'show stoppers' for CCS have been identified in the Captain Sandstone study area.



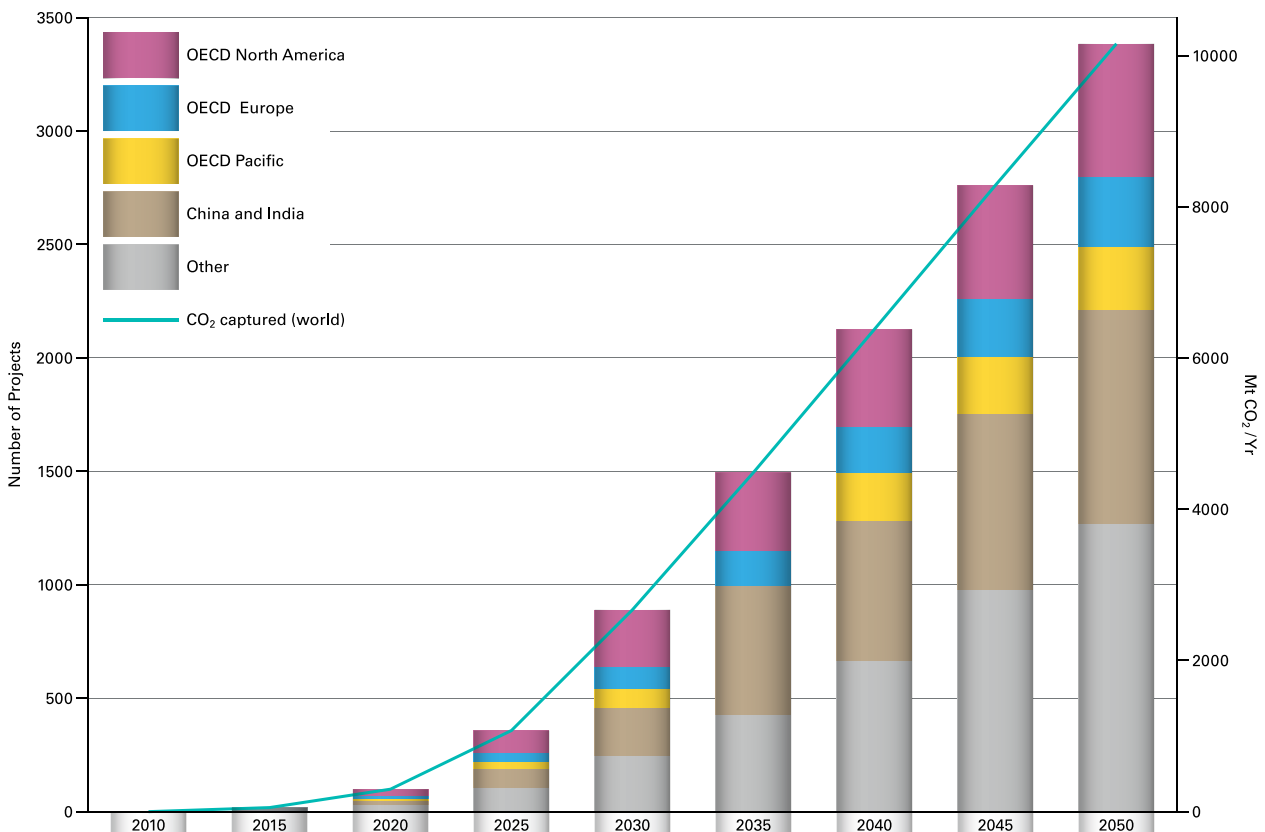
4. Skills And Capacity Building

The deployment of CCS technology will require a high level and breadth of technical expertise, including scientists, engineers, technicians and craftspeople. A good understanding of these requirements is essential in order for industry and policy makers in Scotland to be prepared to take up opportunities in CCS.

The International Energy Agency (IEA) CCS Technology Roadmap (www.iea.org/papers/2009/CCS_Roadmap.pdf) anticipates that Europe, including the UK, will host a large number of CCS projects—around 500 by 2050 (Figure 30). Additionally, the future CCS industry offers UK companies the opportunity for worldwide export of their products and skills. The scale of this opportunity is huge and based on experience in offshore oil and gas and power plant exports it would be realistic to target a 10% global market share or more. By evaluating the requirements for a single CCS project and scaling these up to meet the predicted growth of CCS projects globally, the study has assessed the skills—needs, employment possibilities and potential economic benefits arising from a major global programme of CCS on fossil—fuelled power plants.

The model here assumes each project will be coal fired, as coal—fired power stations are seen as a prime candidate for CCS as they emit the highest level of CO₂ per MWh. However, it should be kept in mind that gas—fired power plants will also require CCS to meet climate targets and the effect it would have on the results. The projected economic benefit and jobs would be reduced commensurately with the share between coal and gas, since the carbon dioxide per MWh is roughly halved for gas—fired power plants with CCS.

Figure 30 IEA CCS project forecast
(adapted from IEA Clean Coal Centre)



The study developed a roll-out programme based on the needs of the UK and on the IEA forecast to meet CO₂ emission reduction targets (Figure 30). The three phases of the programme are split as follows:

- Phase 1—the early demonstration projects starting 2011 to 2013
- Phase 2—the ‘second tranche’ required by 2020
- Phase 3—the ‘commercialisation phase’ post 2020

Figure 31 and Table 12 indicate how CCS projects are likely to develop by phase and by region. For projects occurring in the UK it is assumed that UK companies and organisations which have centred their CCS business in the UK (collectively referred to as ‘UK plc’) will secure all key contracts, while for overseas projects they will achieve a 10% share of the global market. The estimates of the number of projects that might be won have been divided into projects won in the UK and projects won overseas. Progressing through the phases, the number of projects increases, highlighting the scale of the opportunity open to industry.

The figures calculated are not specific to Scotland but represent opportunities for UK industry as a whole. Scottish industry and universities are well placed to secure a large share of these opportunities, if the UK becomes involved early and progresses to be a centre of excellence and a world leader in CCS.

Table 12. Numbers of CCS projects by phase and region

	UK	Worldwide, excluding UK	Total by Phase
Phase 1 (2011–13)	4	2	6
Phase 2 (2014–17)	10	8	18
Phase 3 (2018–50)	98	250	348
Total by Region	112	260	372

Figure 31 UK share of anticipated future CCS projects

A. UK CSS rollout



B. Worldwide CSS rollout





Using data made available by companies active in the power generation, CO₂ capture and storage industries, a template model was developed in eight main work packages from initial project development to project operations (see Table 13).

In collaboration with the supply chain, all of the individual software and hardware costs, which make up each work package, were assessed and a costing developed for each line item. Each line item in the model was then assessed on its percentage level of manpower and materials content. The manpower cost of each task was then calculated based on the hourly rate for the direct labour carrying out the task on each. Man-years were then further broken down into the level of input required by each profession (by degree subject) and craft to complete the task.

Calculations were based on a 'bottom-up' assessment based on a single full chain CCS project (a 400MWe supercritical coal-fired power plant with post-combustion carbon capture, pipeline transport and storage in a depleted hydrocarbon field offshore) combined with a roll-out programme through to 2050. The rollout programme is based on the IEA projections for CCS to meet climate change targets and an assumption that the UK industry will achieve a 10% share of the global carbon capture market.

Table 13. 2030 job breakdown by work package

Work Package	Number of UK Jobs
Project Development and Front End Engineering and Design (FEED) Study	563
Civils	9,860
Boiler	12,409
Turbine and Generator	310
Carbon Capture	7,325
CO ₂ Transport	1,605
CO ₂ Storage	2,635
Operations	34,307
Total	69,014

Detailed costs were derived for each year of a project, assuming a six-year build programme, together with a breakdown into the level of input required by each profession and craft to complete the task. It was then estimated whether the project would lead to added value and employment in the UK. The calculated job numbers were assessed for their likely location and assigned to one of three categories:

- Likely jobs in the UK—these include design, engineering, project management, and for UK projects only, construction and operations
- Possible jobs in the UK—these include manufacture of plant and equipment that might otherwise be imported
- Probable jobs outside the UK—these include overseas construction and operations and imported materials

The completed project template was combined with the anticipated roll-out programme of CCS projects to calculate the overall economic opportunity and employment prospects for the UK share of global CCS projects from 2011 to 2050.

The total capital expenditure (CAPEX) required for anticipated CCS projects rises rapidly from 2011 to 2020 (Figure 32). The investment rate of just over £14 billion per annum attained in 2020 continues for ten years to 2030 as the UK completes its total programme. Investment then continues at around £11 billion per year until 2050. Capital expenditure on CCS for likely jobs in the UK rises to a maximum of around £5 billion per year in 2020, which is maintained until 2030 and then decreases to an average of over £2 billion per year until 2050.

Figure 32 Capital expenditure required for the roll-out of CCS projects 2011 to 2050

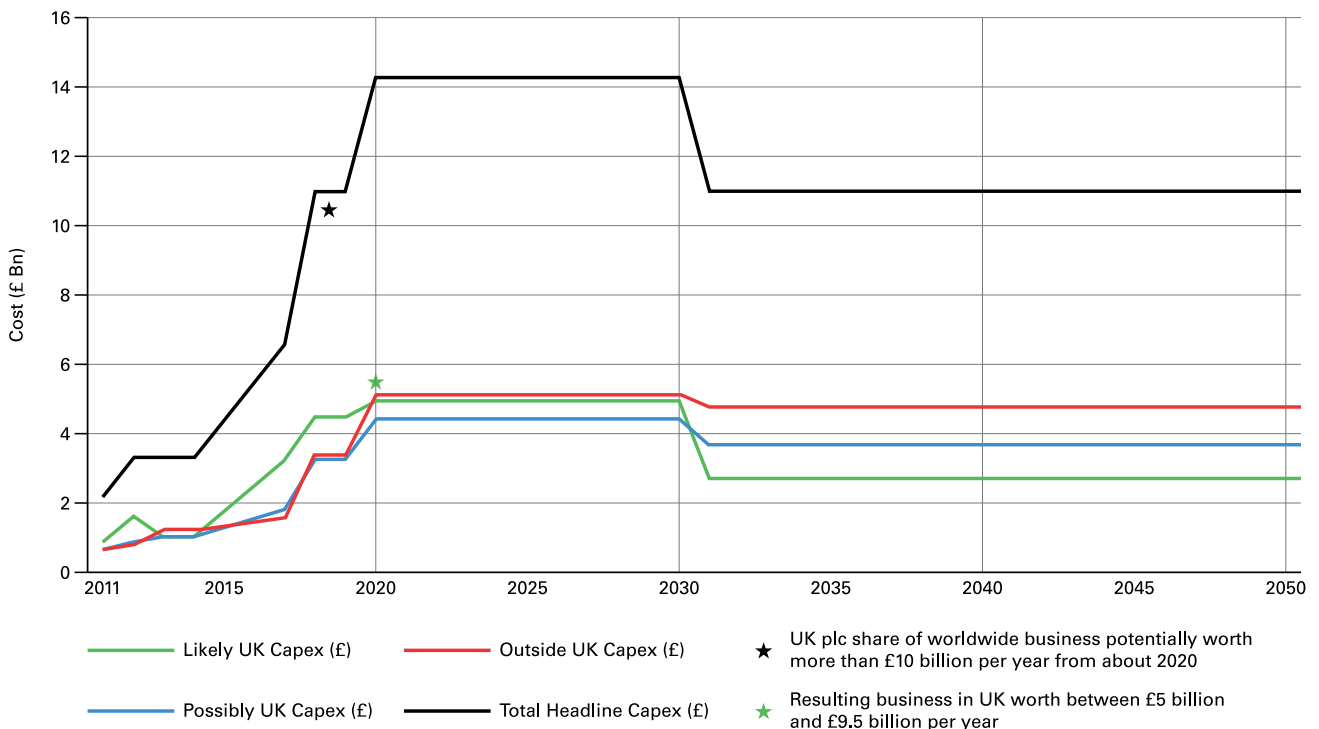
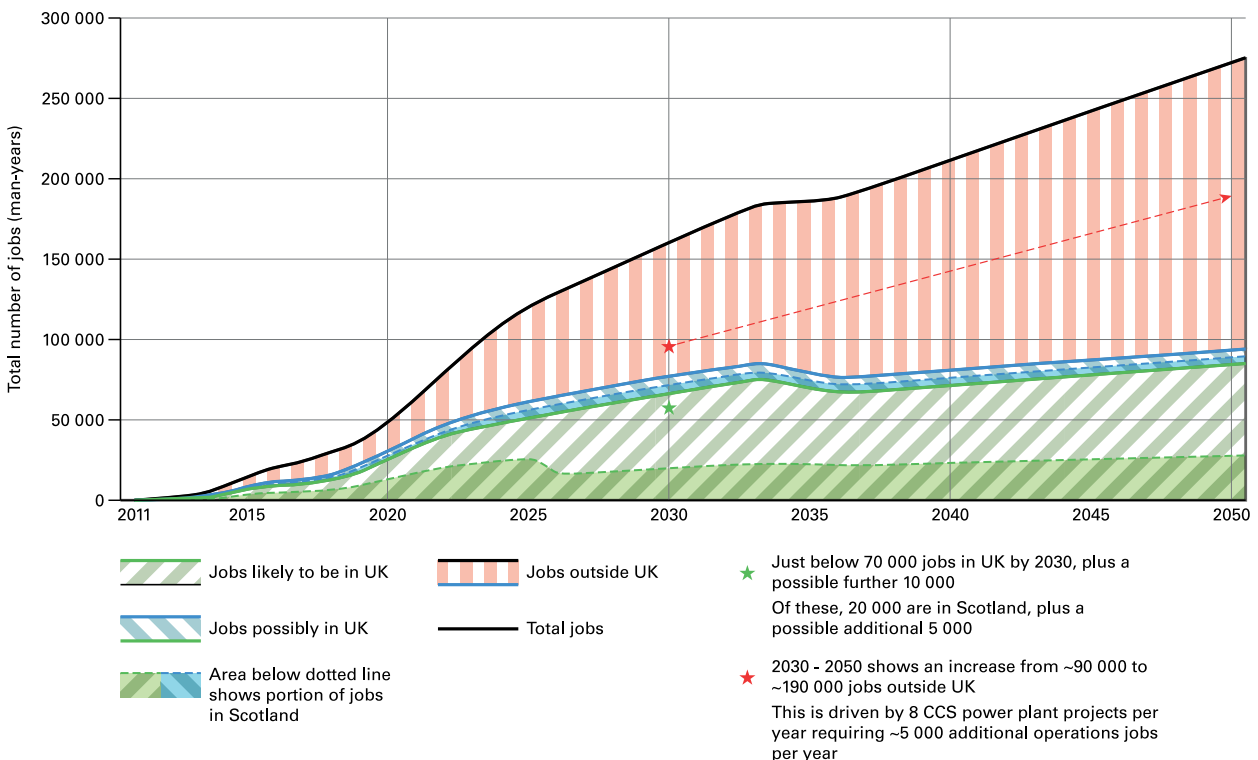




Figure 33 highlights the job prospects open to the UK, and specifically Scotland, in CCS. The proportion of jobs in Scotland was worked out by estimating what percentage of the UK jobs that would be expected to be based in Scotland for each work package. The UK share of a worldwide CCS business could create 27 000 jobs in the UK from 2020 (green line in Figure 33), 13 000 of these estimated to be in Scotland. The jobs in the UK increase steadily from 2011 to 2018 and then more rapidly year on year reaching 70 000 jobs by 2030, of which 20 000 could be in Scotland. By 2030 there are a further 10 000 CCS jobs that could be located in the UK, of which 5000 are estimated to be in Scotland. The increasing trend continues to 2050 at which point it is forecast that Scotland could host nearly 30 000 of the 85 000 jobs likely to be located in the UK plus just under half of the further 9000 jobs that may be located in the UK.

The number of jobs highlights the employment prospects in CCS open to the UK and, specifically, Scotland. It is important to recognise that CCS jobs in the UK are spread across all of the job disciplines and work packages. The breakdown of jobs in 2030 further demonstrates the importance of all the work packages if the full economic value is to be realised in the UK (Table 13, p47).

Figure 33 Potential CCS job prospects open to the UK



The skills required to allow the UK to take advantage of and be a leader in CCS are presented by job discipline in Table 14, as are the number of jobs per year that will be required for the anticipated CCS projects from 2011 to 2020. Some of these jobs will be filled by skilled personnel transferring from other industries (e.g. oil and gas). However, the total workforce required will have to be maintained and augmented by newly trained personnel.

The training requirements are identified in Table 14 and the UK must recognise this early so as to invest in suitable CCS training programmes such as specialised post-graduate one year MSc courses in Carbon Capture and Storage, Power Plant Engineering (Carbon Capture modules) with specialist modules in Capture, Transport, Storage (offshore engineering) and Storage (geology). Further, there will be a demand for 2,000 apprentices per year across the UK.

The training needs have to be further analysed and it is recommended that the Skills Development Scotland access the skill requirement numbers against the normal output from the education system so as to identify additional skill requirements (by engineering profession and discipline) for the CCS roll-out programme.

Table 14. Forecast of annual skill requirements by discipline for 2011 to 2020

Discipline	Number of Jobs required each year to meet CCS Programme (Additionally)										Additional Training Requirements
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
Mechanical Engineering	188	448	477	938	1,503	2,155	2,890	3,700	4,772	6,388	Degree plus post-graduate training
Civil Engineering	32	72	67	355	878	923	739	1,075	1,640	2,239	Degree
Electrical Engineering	48	98	72	157	213	284	356	485	581	748	Degree plus post-graduate training
Process Engineering	62	133	113	199	267	347	442	600	717	896	Degree plus post-graduate training
Offshore Engineering	27	68	68	119	253	447	562	607	792	1,074	Degree plus post-graduate training
Geology	25	57	50	88	193	350	452	491	633	859	Degree plus post-graduate training
Crafts	0	0	37	1,624	4,744	5,767	5,492	6,633	10,040	14,487	Modern apprenticeships
Totals	382	876	884	3,480	8,051	10,273	10,933	13,591	19,175	26,691	



Skills and capacity building—key conclusions

- The deployment of CCS technology will require a high level and breadth of technical expertise, including scientists, engineers, technicians and craftspeople. A good understanding of these requirements is essential in order for industry and policy makers in Scotland to be prepared to take up opportunities in CCS.
- The UK has a solid base of knowledge and experience in CCS which provides an excellent foundation on which to build and to take 'first mover' advantage of the CCS opportunities in the UK and worldwide. Much of this knowledge and experience is based in Scotland.
- By evaluating the requirements for a single CCS project and scaling these up to meet the predicted growth of CCS projects globally, the study has been able to assess the skills—needs, employment possibilities and potential economic benefits arising from a major global programme of carbon capture and storage on fossil-fuelled power plants.
- The model assumes each project will be coal fired, but it is important to recognise gas-fired power plants with CCS and the effect it would have on the results. This means the projected economic benefit and jobs would be reduced commensurately with the share between coal and gas, since the CO₂ per MWh is roughly halved.
- The UK share of a worldwide CCS business could create 27 000 jobs in the UK from 2020 (13 000 of these estimated to be in Scotland), increasing to 70 000 by 2030 (20 000 of these estimated to be in Scotland). A further 10 000 jobs, half of which it is estimated could be in Scotland, could be attracted to the UK given government support.
- CCS jobs in the UK are spread across all of the job disciplines and work packages.
- The UK plc share of the worldwide CCS business is potentially worth more than £10–14 billion per year from around 2025, with the added value in the UK worth between £5 billion and £9.5 billion per year.
- Gaining the maximum benefit depends on UK companies winning domestic and export projects and government establishing a steady roll-out programme. The economic opportunities and jobs in the UK are critically dependent on the UK's demonstration programme of four projects and on UK companies winning a sizeable share of the early demonstration projects;
- Economic opportunities will be delayed and CO₂ emissions reduction targets will not be met if implementation of CCS projects is less rapid than forecast by the International Energy Agency.
- The model lists job numbers by engineering profession (by discipline) and craft. It is recommended that these numbers be assessed against the normal output from the education system to ascertain the additional skills required for the CCS roll-out programme. Training requirements must be recognised early so as to invest in suitable CCS training programmes.
- The next steps should include a review with government and its agencies of actions needed to maximise economic benefit.

5. Towards a public communication and engagement strategy for CCS projects in Scotland

Public support will be essential if the environmental and economic benefits of CCS are to be realised. In order to stimulate the design of effective engagement strategies between the public and proponents of CCS projects in Scotland, the study reviewed approaches to the communication of CCS deployment worldwide, from national to local project level. From this, it has identified factors that should be taken into account in the design of an effective engagement strategy for a project to deploy CCS offshore Scotland. A detailed report (www.sccs.org.uk/SCCTS_WP4_Final_Report.pdf), summarised here, outlines tools for the design of the strategy, describes different communication and engagement techniques, provides evidence for the various possible approaches and lists practical resources and materials already developed. The report does not adopt a prescriptive approach, but rather presents the information from which a developer can design a strategy appropriate to a particular locality and context.

Engagement is the process of having an informed, two-way discussion and interaction between the proponent (developer, government department, etc.) and an affected party (stakeholders, lay public, local community, etc.) of a proposed CCS development. If the reasons for a CCS project are sound, the plans carefully laid, and social conditions favourable, a good engagement strategy will greatly increase the chances of its public acceptance. Public perceptions and concerns for CCS projects entail not only factors relevant to any new infrastructure project but also those specific to CCS, such as the safety concerns arising from long-term storage. The careful design of an effective, structured strategy for engagement and communication between the public and proponents of CCS projects is, therefore, an essential element in the implementation of CCS in Scotland.

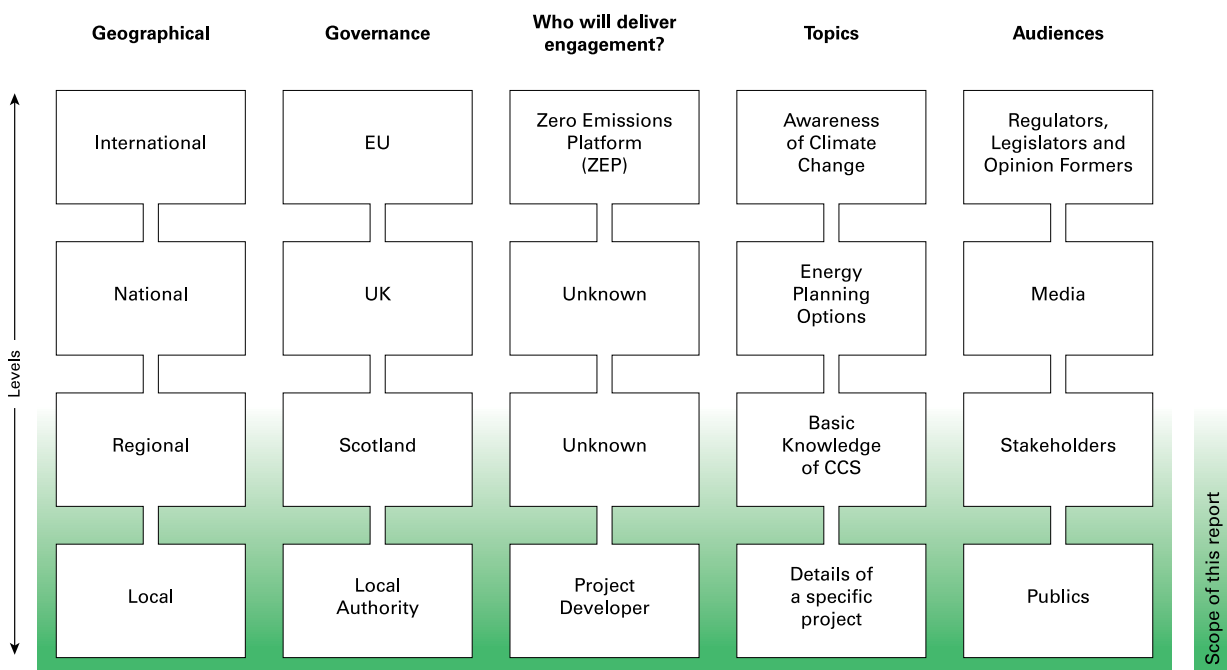
The goal is that the support of public and stakeholders for a project is built by providing opportunities for them to ask, and hear answers to, their questions, and to present input to decisions. The resulting sense of empowerment will build trust in the project; and through improved understanding of the wishes and concerns of public and stakeholders, will permit CCS developers to improve both the project itself and their engagement strategy.



Strategic thinking on engagement in the wider strategy of CCS deployment

Considering the scale of deployment envisaged by proponents, communication and engagement related to CCS has not moved as quickly as might be expected or as is desirable. Levels of knowledge and awareness of CCS technologies amongst the UK and Scottish public are presently very low. Bodies delivering engagement to the public and stakeholders operate on many levels—from international to local (Figure 34). Project developers can and do deliver engagement at local level, and the Zero Emissions Platform (ZEP) is committed to engagement at European level, but there is a gap at regional and national levels. No group has yet taken it upon itself to engage the general public in the UK, although some groups have stated intentions to do so or are beginning to bridge this gap. The UK Office of Carbon Capture and Storage, launched in March 2010, states that one of their main goals is ‘raising levels of understanding about CCS within governments, industry and the public’. The Carbon Capture and Storage Association (CCSA) have begun initial work on communication at the national level. The Scottish Government, following a stakeholder consultation informing the published roadmap, acknowledge that ‘governments will have a crucial role’ and advocate a coalition of government, non-governmental organisations, academia and industry to address public awareness issues. Note that stakeholder engagement does not necessarily lead to public acceptance. Stakeholder engagement and public engagement are distinct activities and should be treated as such.

Figure 34 Levels of various aspects relevant to CCS engagement

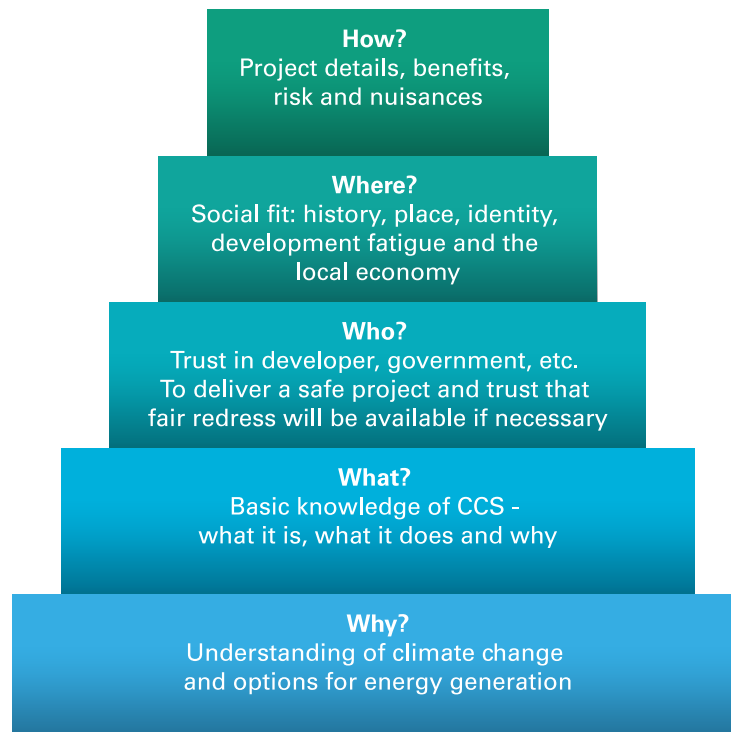


The study examined case studies of public perceptions of, and reactions to, CCS projects from around the world and drew upon insights gained from the wider literature on public engagement and responses to infrastructure developments. As a result, the study has recognised five major topics, which cover the key questions relating to CCS deployment, upon which to engage the public at the local to sub-national level (Figure 35). Not every step will be necessary for every stakeholder and some topics may be better delivered by groups other than project developers operating at the local scale.

Best practice on engagement worldwide has been established by the seven Regional Carbon Sequestration Partnerships (RCSPs) in the USA. These have generated a wealth of valuable experience. One of the key findings of the RCSPs is that public trust in the developer, regulators and government (at various levels) has been found to be more important than technical information on the project detail or risk assessment. To acquire this trust, developers must:

- Deliver truthful information and a safe project
- Operate a transparent and fair decision-making process
- Be accountable should things go wrong
- Treat the local public fairly in the distribution of economic benefits and any hazards

Figure 35 Key steps towards public acceptance of CCS projects





Tools for designing an engagement strategy

There are no 'right or wrong' answers with respect to what a proponent or developer should do vis-à-vis communication and engagement, but some approaches are more likely to lead to public acceptance than others. An engagement strategy should be specific to each context, suiting the project, its location, the developers' philosophy and possibly matched to local expectations. As with any relationship, public engagement cannot be delivered in one event, but must be built up over time and through many and repeated interactions. There are different types of engagement—for gathering data, for informing people, for persuading people, for eliciting opinions. There are different ways of making decisions when managing a project—with more or less public involvement, although the public generally respond better when they feel they have been given a say in outcomes affecting them.

Five elements of an engagement strategy are recognised (Table 15). They focus on engagement at the individual project level, and particularly on engaging with the local public. The elements may run concurrently and do not have to occur in a specific order; the order and number of iterations will depend upon context specific factors as well as the approach of the project developer.

Table 15. Elements of an engagement strategy

Philosophy	<ul style="list-style-type: none"> • The decision-making style adopted • Degree of public and stakeholder participation desired • Approach to Risk communication • Transparency • Willingness to modify philosophy depending upon stakeholder expectations
Project design	<ul style="list-style-type: none"> • Project vision • Location • Design • Alternatives considered • Justification—why in general and why this specific project? • Possibility to modify project design to accommodate stakeholder preferences
Early engagement	<ul style="list-style-type: none"> • Stakeholder mapping • Public mapping • Social analysis • Location analysis • Information gathering • Begin building trust • Use information to begin designing communication and engagement campaign
Engagement campaign	<ul style="list-style-type: none"> • Engagement with publics & stakeholders • Communication with publics, stakeholders & media • Responding to issues as they come up • Risk communication
Acceptance & maintenance	<ul style="list-style-type: none"> • 'Social permit' to operate • Regulatory permits in place • Local and national planning permissions • On-going engagement throughout construction and operation phases

Philosophy includes the various decisions to be made by the developer influencing the design of an engagement strategy. Making assumptions explicit can help in deciding what kind of engagement campaign is desired, and what is most suited to a particular project. Matching stakeholder and public expectations to the engagement campaign delivered is well worthwhile.

Project design includes all aspects of project design, from the initial justification for why the project is necessary and the developer's vision for what the project should be; to the location, the scale, the infrastructure, the benefits and the risk assessment; to the construction, operation, long-term monitoring and final decommissioning of the facility. Allowing the public to understand how the project has been designed and why it has been designed the way it has can increase acceptance, and if proactive and timely can increase levels of trust

Early engagement is the initial process of gathering the information useful at the design stage, including stakeholder and public identification and initial interactions; and beginning to understand the local context through the various research methods termed social characterisation. Its purpose is to understand and anticipate likely responses to a project, and possibly to modify project design. Scotland has a history of fossil fuel extraction from onshore coal fields and, more recently, from the North Sea. Where experiences have been good this could be built upon for CCS; but where experiences have been bad or are resented, CCS may not be popular. The developer is best placed to identify the key stakeholder groups with respect to a specific project. Offshore development entails its own distinctive stakeholder groups, well known to the oil and gas sectors. The key stakeholder groups for CCS offshore Scotland are likely to include fishing interests (commercial and recreational), marine conservation and protection, the Crown Estate, shipping and sailing interests, etc.

The engagement campaign encompasses all dialogue and information sharing between the developer and other parties, once a project has been announced publicly. In order to build support for projects, it is necessary for the public and stakeholders to know about the project. For stable long-term support, it may be necessary for them to understand the project and the motivations for it. Methods include focus groups, surveys, questionnaires, interviews, workshops, public meetings, exhibitions, citizen panels and juries, printed media, internet sites, press statements and newsletters. Engagement should begin as early as possible; be fitted to technical and regulatory stages; and should provide awareness of practical operations before they begin so that the local public are aware of what it is going on. Engagement and outreach should be integrated within normal project management.

Acceptance and maintenance include the various types of acceptance that need to be obtained. The social permit, the focus of this section, must be maintained; it can potentially be 'revoked' by new concerns which may be outside of the control of the developer. The best way to guard against this is to maintain high levels of trust and to manage an open, transparent and robust process of engagement and communication, and of course a good safety record. A distinctive feature of CCS is the long term nature of CO₂ monitoring requirements. Some kind of engagement work should be planned throughout the 30 year after-drilling time period during which the company is responsible before handing over to the government for long-term stewardship.



Communication is essential, although it is not enough on its own to satisfy most people. Issues identified during early engagement should help design communication materials and topics, and popular wider issues should be included even if they seem to be not directly relevant to the particular project. A neutral tone presenting factual information is generally preferred to self-promotion or a persuasive tone, and communication materials can lose their credibility if the developer is perceived as untrustworthy or dishonest. Organisations that have prepared outreach materials are listed in (Table 16). The materials range from technical reports and fact sheets to videos and animations.

Table 16. Organisations providing CCS outreach materials

Source
Zero Emissions Platform (ZEP) www.zeroemissionsplatform.eu/
CO₂ Capture Project (CCP) www.co2captureproject.org/
Bellona Foundation www.bellona.org/ccs/index_html www.youtube.com/watch?v=IH3hgqLM94U
Shell www.shell.com/home/content/innovation/people_planet/ccs/ccs_how_does_it_work/
CCSA www.ccsassociation.org.uk/index.htm
Statoil www.statoil.com/en/newsandmedia/multimedia/filmsandvideos/pages/default.aspx
Scottish Power www.scottishpower.com/carbon_capture_storage/default.asp www.scottishpowerccs.tv/
IEAGHG http://www.ieaghg.org/index.php?/20091218110/what-is-css.html
CO₂Net www.co2net.eu/public/downloads.asp
Masdar and Hydrogen Energy www.youtube.com/watch?v=ll0Dw3vfjZk&feature=related
UNEP http://www.unep.org/dec/docs/CCS_guide.pdf
CO₂CRC www.co2crc.com.au/
CCS Education Initiative www.ccs-education.net/index.html

**Towards a public communication and engagement strategy—
key conclusions**

- Public support will be essential if the environmental and economic benefits of CCS are to be realised.
- Public trust in project developers is key, especially when the type of project is unknown in the region.
- Public perceptions and concerns for CCS projects entail not only factors relevant to any new infrastructure project but also those specific to CCS, such as the safety concerns arising from long-term storage.
- The careful design of an effective, structured strategy for engagement and communication between an affected party (stakeholders, lay public, local community, etc.) and proponent (developers, government departments, etc.) of CCS projects is an essential element in the implementation of CCS in Scotland.
- Offshore development entails its own distinctive stakeholder groups, well known to the oil and gas sectors. This includes: fishing interests (commercial and recreational); marine conservation and protection; Crown Estate; shipping and sailing interests.
- The design of an engagement strategy needs to be appropriate to a particular locality and project context.
- The study provides tools for the design of an engagement strategy, describes different communication and engagement techniques, provides evidence for the various possible approaches and lists practical resources and materials already developed.
- Engagement and outreach should be integrated within normal project management. They should begin as early as possible; be fitted to technical and regulatory stages; and should provide awareness of practical operations before they begin so that the local public are aware of what it is going on.
- A distinctive feature of CCS is the long term nature of CO₂ monitoring requirements. Some kind of engagement work should be planned throughout the 30 year after-drilling time period during which the company is responsible before handing over to the government for long-term stewardship.



Concluding remarks

Greenhouse gas emissions and their impact on climate change are of great concern to mankind. The standard of living for human populations may increase with industrial development but this can be associated with increased emission of CO₂ and other greenhouse gases. Development and deployment of low-carbon technologies worldwide will contribute to reduced global CO₂ emissions. In Scotland, CCS at fossil fuel-fired electricity plant will be essential to complement other low-carbon technologies and emissions-reduction strategies.

Research and development in CCS is expanding rapidly throughout the world. In the two years since publication of the *Opportunities Report* in Scotland, research on combustion technology has continued, a post-combustion CO₂ capture pilot plant has been tested and substantial effort made to apply for funding of more than one demonstration CCS project to be based in Scotland.

The work presented here provides good evidence of the strong synergy between the ambitions of government, industry and academia to make Scotland and the UK world leaders in the CCS industry. Working together they have presented the requirements, activities and timelines for deployment of CCS as a normal low-carbon option for industrial plant by 2020. Streamlining of the regulatory regime was undertaken as a result of adoption by Scottish Government of the initial findings/preliminary output and undertaken in parallel with this study. Planning for the education and training of the CCS workforce was conducted and in conjunction with assessments of skills needs for other industries.

Detailed evaluation of one of the ten saline aquifer sandstones identified as having potential for CO₂ storage confirms its calculated storage capacity to be at the upper end of the previously estimated range in research presented here. Even by applying the most 'restricted' geological conditions it has the potential to hold at least 15 years and up to one hundred years of Scotland's industrial CO₂ output. These findings support the European-scale significance of Scotland's North Sea CO₂ storage resource. The expected reduction in calculated storage capacity normally associated with increased data and research effort was not found in the investigations presented here.

The UK and Scotland can reap the employment and business opportunities of a North Sea and global carbon storage industry by provision of a highly skilled and trained workforce by building on the knowledge and skills in the existing engineering and oil and gas industries. The high level and breadth of future expertise and staff numbers needed, 13000 in Scotland by 2020, to capitalise from the emerging carbon storage industry are evaluated and already have been presented to education and training organisations.

The public can be reassured of the protection of the environment and other uses of the sea over an offshore carbon store by legislation that has for decades regulated North Sea oil and gas activities. However, wider public support is essential for carbon storage to become an effective low-carbon technology. We will neither reach the targets for reduced greenhouse gas emissions nor achieve the projected employment and business development without public understanding of the overall benefits of carbon storage. Winning of public trust should follow a strategy of early communication and dialogue by project developers as outlined in this study.

Scotland can realise the environmental benefits and business opportunities of carbon storage. The research findings presented here illustrate the storage resource, skills, knowledge and innovative drive to implement CCS in Scotland. They provide a firm footing from which to take the next steps along the path to deployment of CCS in Scotland.



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