CHAPTER 1
FROM 'SURFACE TO STORE' – AN OVERVIEW OF THE CASSEM PROJECT

Martin Smith*,
*British Geological Survey, Murchison House,
West Mains Road, Edinburgh EH9 3LA*

David Campbell,
*Scottish Power, Longannet Power Station,
Kincardine-on-Forth, by Alloa,
Clackmannanshire FK10 4AA*

Stuart Haszeldine,
Debbie Polson,
*School of Geosciences, Grant Institute,
University of Edinburgh, West Mains Road,
Edinburgh EH9 2JT*

Adrian Todd,
Heriot-Watt University, Edinburgh EH14 4AS

**Corresponding Author*

1.1 INTRODUCTION

Carbon capture and storage (CCS) brings new entrants to subsurface exploration and reservoir engineering who require very high levels of confidence in the technology, in the geological analysis and in understanding the risks before committing large sums of capital to high-cost drilling operations.

Many of the subsurface techniques used for hydrocarbon exploration are capable of translation to CCS activities. Unfamiliarity may, however, lead new entrants to openly question their applicability in order to transform their current understanding to a level where large capital investment can be organisationally justified. For example, some may make the erroneous assumption that a good CO_2 subsurface store should resemble the pressure vessel type of containment that is prevalent with surface installations. Basic concepts such as utilising the rock structure and mineralogy to control fluid flow and securing the CO_2 by residual trapping (between the rock grains) or by dissolution, as a superior storage mechanism, are counter intuitive and challenging to communicate effectively.

To achieve success and reliable operation in CO_2 emission reduction for coal- and gas-burning electricity power generation, all elements of the CCS chain have to function. In 2008 the CO2 Aquifer Storage Site Evaluation and Monitoring project (CASSEM) was one of the first UK based projects to attempt integration and full-chain connectivity from, capture and transport to injection, storage and monitoring. Its research is aimed at development of workflows that describe a CCS entry path for a target audience of potential new entrants, i.e. power utilities, engineering sector and government.

In contrast to other studies, the CASSEM project has applied the specification of the full CCS chain, using two exemplar sites (coal-fired power plants) with contrasting geological conditions in the subsurface, to tailor storage site selection and analysis.

Centred on the Ferrybridge Power Station in Yorkshire (Figure 1.1), a ‘simple’ site underlain by a thick, uniform sandstone with diverse legacy information available was sought onshore in the English Midlands. The offshore extension of this (Bunter) sandstone has been highlighted as a large potential aquifer store for CO_2 captured from power plants in eastern and South East England.

A ‘complex’ site was sought offshore of eastern Scotland, centred on the Longannet Power Station on the Firth of Forth near Edinburgh (Figure 1.2). This site was intended to confront the difficulties of investigating subsea structures with sparse legacy and incomplete information from hydrocarbon investigations. The selected site is a faulted and folded geological structure and the issues of seismic reflection surveys, detection of faults and fractures, and quality of the target reservoir, are similar to those which challenge offshore hydrocarbon exploration beneath the North Sea.

To complement the published research that arose from the CASSEM project (see bibliography of outputs) this book presents an overview of the results as multi-authored papers.

Figure 1.1 Ferrybridge Power Station, Yorkshire ©webbaviation

Figure 1.2 Image courtesy of Scottish Power. Longannet coal fired power plant, Firth of Forth

1.2 BACKGROUND

Global perspectives

CCS requires the modification, upscaling and operationalisation of several existing technologies. The challenge for industries and government is to link these in a business which is credible, reliable, safe, trustworthy, profitable and can competitively attract commercial investment. CCS has emerged from a 1990s concept to become, in 2011, a rapidly growing suite of desk studies, pilot investigations and global test sites and plants.

There are numerous CCS-related activities around the world (see http://www.geos.ed.ac.uk/ccsmap), but to date, there are still only four commercial CCS projects operating globally (Figure 1.3). The first capture of CO_2 for storage was at the Sleipner field, offshore of Norway, which utilises amines to separate natural 9% CO_2 from condensate oil. Two drivers for this project were the $50 per tonne tax on offshore emissions and the required quality of saleable hydrocarbon. Since October 1996, Statoil has been injecting 1 Mt CO_2/year into the Utsira saline aquifer (Statoil, 2010). This project has proved that it is possible to inject CO_2 into a high-porosity deep reservoir.

Capture at industrial scale has been operated since 15 September 2000 by the Dakota Gasification Company at the Great Plains Synfuels Plant near Beulah, North Dakota. In 2010, about 3 Mt CO_2 per year is captured using methanol and transported 325 km by pipeline for use in enhanced oil recovery by miscible flooding in the Weyburn and Midale fields in Saskatchewan (Dakota Gas, 2010). This project has proved that it is possible to transport and inject compressed CO_2 in a 24/7 operation linked to a commercial chemical plant.

In July 2004 the In Salah onshore gas field in Algeria began to capture 5.5% CO_2 from natural gas, to achieve saleable pipeline quality. Like Sleipner, this field uses activated methyldiethanolamine capture, but differs in that injection is into the same reservoir from which the gas is extracted. In 2010, about 1.2 Mt CO_2/year was being emplaced through three horizontal boreholes, and this has become the most closely monitored and scientifically investigated CO_2 storage in the world (In Salah, 2010). This project has proved that it is possible to inject into a poor-quality storage reservoir and has developed monitoring techniques for onshore applications.

In April 2008 the Snøhvit field, producing liquefied natural gas offshore of Barents Norway, began injecting 700,000 Mt CO_2/year. This 5–8% CO_2 is separated from the hydrocarbons by processing onshore and returned by a dedicated 7-inch pipe to be reinjected into the Tubåen saline aquifer via a remotely operated seabed installation. The saline aquifer lies 2,500 m beneath the seabed and beneath the reservoirs at Snøhvit containing commercial gas (Statoil, 2010).

Finally, since 2007 the US Department of Energy has funded about 12 small-scale pilot injection projects (US DoE, 2010), and the results of about 20 significant injection tests have become available (SCCS, 2010-03).

In summary, three of the major commercial projects and numerous test sites currently exploit saline aquifers for CO_2 storage and demonstrate the importance of being able to identify, understand, develop and predict how these stores will perform.

UK perspectives

The CASSEM project was conceived in December 2005 at a time when several events had combined to bring CCS closer to reality. These events included the seminal 'wedges' publication of global

CO_2 reduction, prominently featuring CCS, by the Carbon Mitigation Initiative at Princeton (Pacala and Socolow, 2004); the 2005 proposition by BP and Scottish and Southern Energy to develop CO_2 capture at the Peterhead power plant in North East Scotland and link that to storage in a depleted North Sea oilfield; the G8 Article 14 statement on CCS at the 2005 Gleneagles meeting: 'We will work to accelerate the development and commercialisation of Carbon Capture and Storage technology.' (G8 Gleneagles, 2005) and the 2005 UK House of Commons Science and Technology Committee investigation of CCS (House of Commons, 2006).

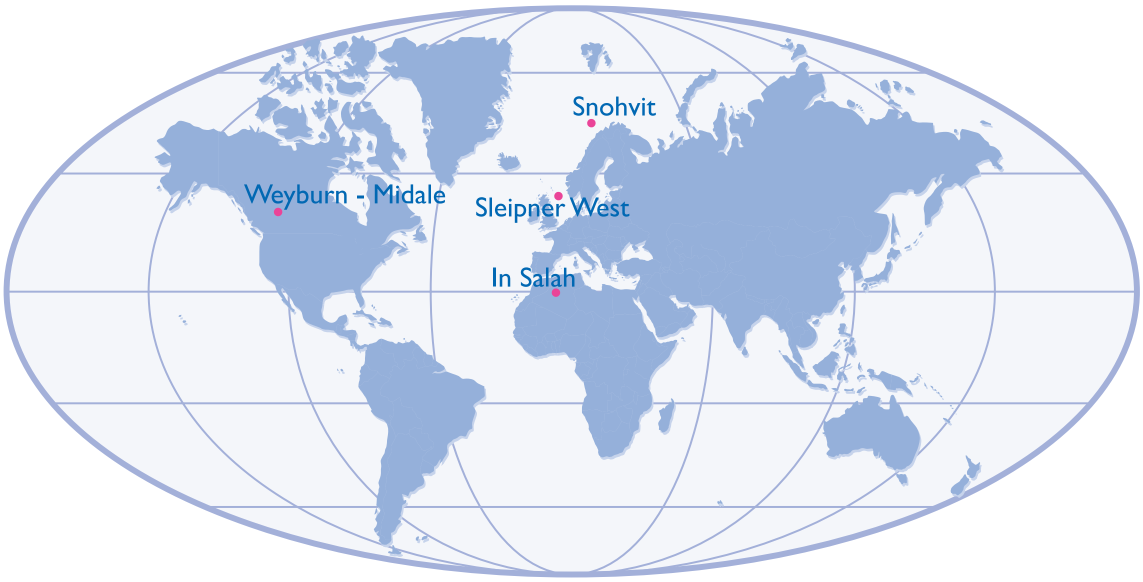

Figure 1.3 Map showing location of key commercial projects for CO_2 transport and storage. Map after www.geos.ed.ac.uk/ccsmap

In 2005 the UK government Department of Trade and Industry (DTI) produced the first formal Carbon Abatement Technology (CAT) strategy (DTI, 2005). It clearly stated that CCS would be vital to any decarbonisation of fossil-fuelled electricity generation in the UK.

By early 2006 these concepts crystallised and gained momentum in response to a funding call from the UK Department of Trade and Industry Technology Programme, as part of Low Carbon Technologies. At this time, working on the storage of CO_2 was uncommon. As a result, the process of garnering interest and financial support from business and industry (a requirement of many funding streams) was very challenging. Most large commercial companies were unconvinced that CCS would be necessary, or would even become mandatory. In 2006 the UK government published its Energy Review, which identified a clear role for CCS and was followed by the Energy White Paper in 2007. In 2007 the UK government also launched its competition for full-chain CCS demonstration.

These activities have incentivised the post-2008 landscape for UK CCS research funding. New opportunities were released by the Technology Strategy Board (TSB), the Research Councils Energy Programme (RCUK, 2010) and by the creation of the Energy Technologies Institute (ETI) and the Environmental Transformation Fund (ETF).

UK work on regulation and licensing has also proceeded apace. The UK government has made compulsory a 'capture-ready' specification for all new gas-fired and coal-fired power plant. This has been further augmented by a compulsory operation of CCS on at least 300 MW of any new coal-fired power plant. A funding mechanism, the UK electricity levy, was introduced in 2010 to enable the number of CCS demonstration plants to be increased from one in 2014 to a minimum of four within an undefined period around 2016. In 2011 this levy was cancelled and will being replaced by a premium price tariff for decarbonised electricity. There is active discussion of introducing an emissions performance standard, on new coal plant and on new gas plant.

The Committee on Climate Change has recommended a significantly more stringent CO_2 reduction target of at least 80% less than 1990 emissions by 2030. As part of this, the UK has an explicit vision that the electricity supply will be decarbonised to about 10% of its current emissions by 2030 (an average 500 g CO_2/kWh to less than 100 g CO_2/kWh; with coal plant reducing from 800 g CO_2/kWh to around 50 g CO_2/kWh). This will require CCS to work effectively. The economic climate has, however, become more challenging. Construction of a large coal power plant is a major undertaking for any utility; with the addition of CCS adding significantly to the capital cost. Government assistance is needed in a closely competitive 'free-market' economy like the UK.

In summary, CASSEM was conceived in a period when CCS was a 'proposition for visionaries'. It has now developed into a mainstream government and industry policy; if a CCS researcher had been incommunicado during the lifetime of the project, they would return now to an unrecognisable world of CCS policy and funding.

1.3 THE CASSEM PROJECT

Capture is essentially a process engineering activity where the effectiveness of the CO_2 removal from the flue gases is predictable in relation to proven capture technology and the sizes and operating conditions of the ancillary plant involved. Similarly, a pipeline transport solution is predictable in relation to the application of known engineering methods.

By contrast, the storage element, of injecting and storing CO_2 into subsurface water or oil-bearing structures, is fundamentally much less certain in the prediction of behaviour. It requires integration and understanding of the geological framework with the multiphase flow behaviour in the pore space of the reservoir rock over a large area (typically tens of km^2). Unlike a pipeline, to simply calculate capacity and flow determination in this pore space is a major technical challenge. Multiple natural processes are in operation, some poorly understood and quantified. Timescales of prediction are not minutes and hours, as familiar to power plant engineers, but tens of thousands of years into the future.

CASSEM is a predominantly desk-based study and design, involving laboratory modelling, experimentation and a social-science field study.

Over three years the CASSEM project has adopted a 'learning-by-doing approach' and evolved to derive a series of activity workflows and insights into the methods and techniques that will reduce uncertainty in the early stage (pre-drilling) characterisation of a CO_2 store in a saline aquifer (Figure 1.4). The project has not aimed to determine the eligibility of either site for a storage licence or permit.

The scope of the project includes five key elements (Figure 1.5):

- **Surface facilities:** focuses on handling and transport. These activities, researched mainly by the industrial partners, are described in Chapter 2.

- **The CO_2 store:** which provides an outline methodology for solving CO_2 storage via a series of process-orientated workflows covering geological modelling, reservoir simulation, monitoring and the assessment of uncertainty and risk. These activities, covered by the academic and research partners, are described in chapters 3, 4 and 5 and 7 and summarised in Figure 1.5.

- **Risk and uncertainty:** a basic understanding of uncertainty analysis and risk, covered by the academic partners, is presented in Chapter 6.

Injection strategies as an example of risk mitigation are described in Chapter 7.

The economics of CO_2: a transparent and accessible whole-chain analysis tool, developed by the industry partners, is presented in Chapter 8

Public perception: this comprises an early test and review of the public understanding of CCS in the regions of the exemplar sites. The work was completed by the Tyndall Centre, University of Manchester, and is presented in Chapter 9.

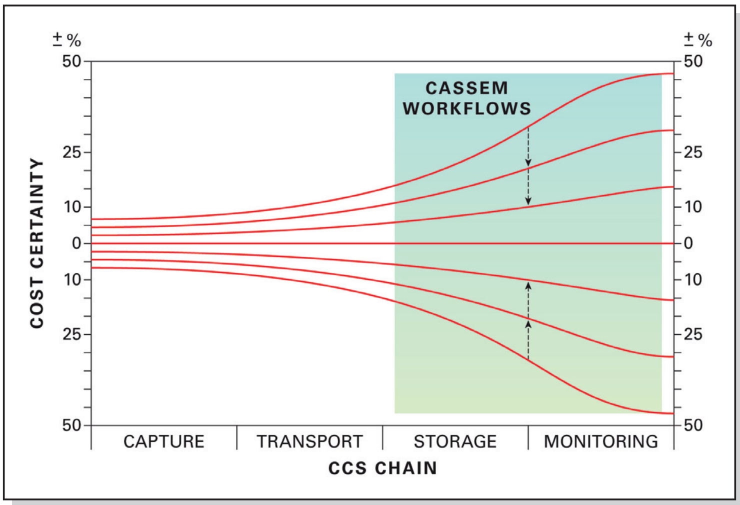

Figure 1.4 Graph of CCS chain versus cost certainty. Shaded area highlights main CASSEM project activities aimed at reducing uncertainty

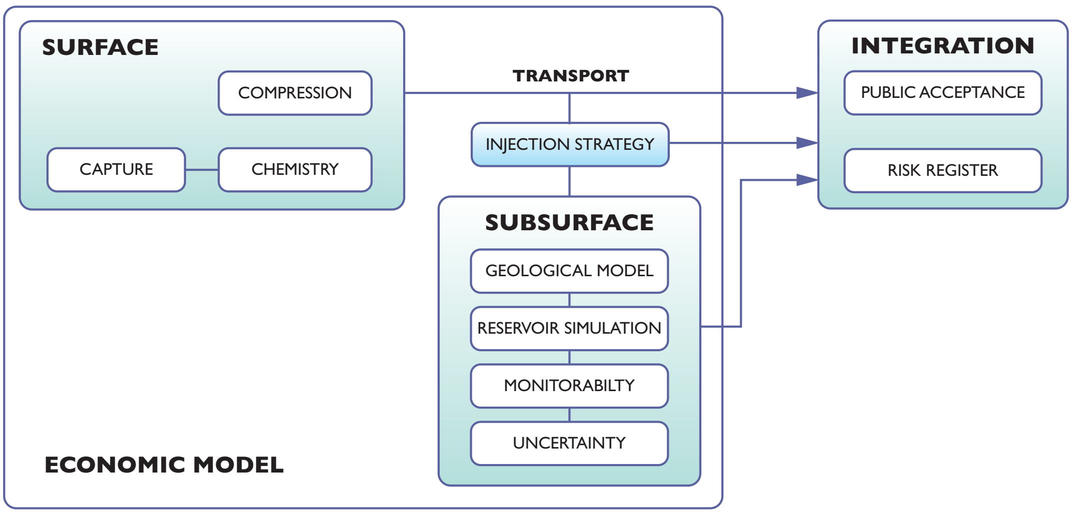

Figure 1.5 The CASSEM view of the CCS chain and connections between surface and subsurface.

1.4 SURFACE: FACILITIES AND TRANSPORT

Aspects of surface handling and transportation in a CCS scheme are considered in Chapter 2. The main industrial partners to the project (Scottish Power and Scottish and Southern Energy) provided summary data and know-how for the two exemplar sites used in the CASSEM project.

In terms of implementation, it is assumed that the source of the CO_2 feeding into the project will be a high-efficiency coal-fired power plant with a unit size of 800 MW. The capture plant would be post-combustion, using solvents (amines) to chemically absorb the CO_2 from the flue gas.

A 75 km radius limit was placed on a store site, which meant that predominantly onshore pipelines would be investigated as the transport option. This work, completed by AMEC, essentially tested the UK regulations and design practices, as applied to CO_2 pipelines, by examining the options and executing a high-level routing study. The exercise clearly demonstrated that both sites had various route options and that transportation by pipeline was achievable within current guidance and regulations.

1.5 TARGETING UNCERTAINTY: STORAGE AND MONITORABILITY

One of the key challenges in a CCS scheme is to address the inherent uncertainty surrounding the geological store. Data on the storage formation will always be comparatively sparse compared to the capture and transport components, thus making it the largest source of uncertainty in any CCS project. This is increasingly recognised as a major challenge to the regulatory process. The CASSEM project has therefore sought to target the reduction of uncertainty in the characterisation of a subsurface store. Our approach allows early application of low-cost methods to assess basic storage site requirements so that deficient candidate stores are rejected with minimum effort. Tracking the magnitude of key uncertainties throughout the CCS chain ensures that they lie within acceptable bounds when investment decisions have to be made.

Based on experiences gained during the project, we have developed a series of linked workflows that address the application of geological and petrophysical data to the modelling, interpretation and prediction of CO_2 behaviour when injected into a saline aquifer (Figure 1.6).

In Chapters 3 and 4 these workflows are described and illustrated with worked examples from the exemplar sites. The workflows, essentially iterative cycles of data assessment, encompass a range of activities, including site selection, geology and geomechanics of the aquifer formation and cap rock, followed by geochemistry and flow simulations of CO_2 under various injection scenarios, and then some consideration of geophysical techniques for monitorability (Chapter 5).

In both the geological modelling and reservoir simulation activities, model development is characterised by increasing levels of complexity, data analysis and cost. These levels are separated by gates at which an evaluation can be performed to make an informed decision on whether to invest further in data collection and refinement, forward data and results to other activities, or place the developing model on hold, in order to progress other models or sites being investigated in parallel.

Monitoring the physical properties of CO_2 in a subsurface store is another of the key challenges facing the nascent CO_2 storage industry. Monitoring is dependent upon the specific characteristics of the geology and the phase conditions of the injected CO_2; both will vary from site to site. The geophysical work undertaken within the CASSEM project is currently ongoing. For this publication we present preliminary findings (Chapter 5) which address our understanding of 'monitorability' and test the application of different geophysical techniques to the CASSEM sites.

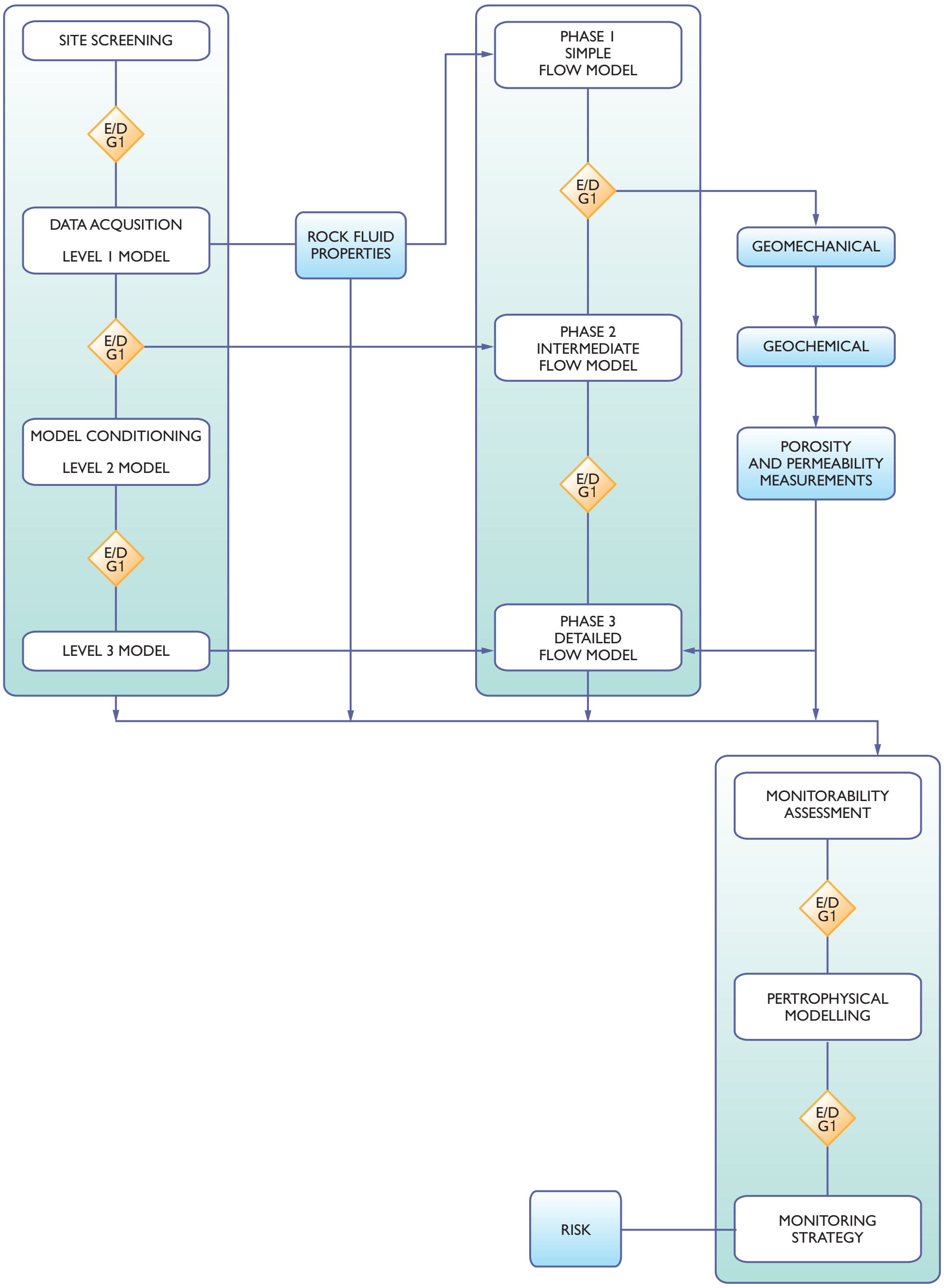

Figure 1.6 Simplified workflow model derived from the CASSEM project. Orange coloured diamonds represent evaluation-decision gates (E/D G1)

The inherent heterogeneity of the subsurface makes it impossible to know with 100% certainty whether a site will meet all the requirements for storage until long after injection of CO_2 has started. Thus, in Chapter 6, we focus our uncertainty analysis on the storage activity. The aim here is to investigate how we categorise a site as a good candidate site, in terms of capacity, security, injectivity and monitorability, within acceptable uncertainty bounds. Any measurement and modelling activity should be valued in the context of whether it will further reduce uncertainty on one of these key areas to the stage where a decision to accept or reject the site can be made. Combining these terms also highlights the tensions between the effects of different processes. For example, the dissolution of CO_2 in water is desirable from a security and capacity point of view, but will make it harder to monitor.

The criteria for site selection (Chapter 3) are therefore defined from the prior information regarding what makes a good storage site. These are global criteria, which provide an effective filter and do not, for example, take into account site-specific covariances. They ensure that likely sites potentially fall within acceptable storage uncertainty bounds.

Initial data collection and first response tools (Chapter 3) are the start of making the uncertainty assessment site-specific at a relatively low cost. These assessments generally reflect uncoupled processes and therefore make simplifying assumptions. This stage is key to informing on likely coupled processes that need to be explored in the reservoir simulations. The decision to progress to further investment should reflect that uncertainties are being favourably reduced.

Reservoir simulations (Chapter 4) allow the exploration of coupled processes in a physical and stochastic modelling framework. They produce posterior distributions on capacity, security and injectivity, with regard to the parameter space explored. Users must bear in mind that if a key control has not been included, the uncertainty bounds will be biased. The choice to move to more complex reservoir simulations is motivated by the expected information gain by doing so and the ability for this information to further reduce uncertainty. The monitorability assessment (Chapter 5) overarches these activities and is informed at all stages. It is mostly constrained by the results of the simulations, but can feed back into choosing the best injection strategies.

Similarly, any storage site must meet some acceptable limit of risk. Risk is usually defined as a combination of the probability and impact of some event. For example, the probability that CO_2 will leak to the surface and the scale of the impact on the environment. Hence, in assessing a site, consideration must be given, not only to the probability that the site will fail to perform as predicted, but also to the impact of failure. Using a risk register to assess and rank areas of risk, high risk factors can be identified and addressed through mitigation activities. In the CASSEM project a 'Features, Events and Processes' (FEP) based register was used to identify key areas of risk for both sites. Uncertainty is an influential factor on risk, and hence reducing uncertainty may be an important mitigation activity. The CASSEM methodology uses a structured decision process that explicitly includes uncertainty and risk, to identify, rank and select project activities. This is demonstrated with the selection of data acquisition activities based on the risk assessment results and the most up-to-date understanding of uncertainty.

Midway through the project a risk assessment identified the highest FEPs for both sites (Chapter 6) and led to specific mitigation activities being incorporated into the project. These activities are identified as case studies and are presented in Chapters 2, 3, 4 and 5 and 6.

A further three high-level generic FEPs were considered for their potential significance to reducing uncertainty and improving investor confidence. These included alternative strategies for injection of CO_2, whole-chain cost analysis and public perception.

1.6 INJECTION STRATEGIES

Alternative engineering strategies involving surface mixing of supercritical CO_2 are discussed in Chapter 7. Although still at a theoretical stage, these strategies offer the potential to significantly mitigate risk during injection and to provide storage solutions that are thermodynamically and environmentally stable and permanent.

For example, if the CO_2 can be immobilised by mixing with brine to reduce buoyancy, then it may remain underground indefinitely, even if the integrity of the cap rock is breached, thus reducing monitoring costs and decreasing uncertainty. These benefits are offset by the additional cost and scale of surface mixing facilities.

1.7 COSTING OF THE CCS CHAIN

Financial viability is the greatest risk to CCS. In Chapter 8 a transparent and open-source full CCS costing model is explained. The model highlights the importance of the underlying assumptions to the output presented and of such models. For example, one of the biggest challenges in a step-by-step approach to analysis of a CCS scheme is the way the rest of the CO_2 chain will react to large changes in CO_2 flow rate. Thus, the quality requirements of the subsurface store cascade back through the CCS chain and require assessment of the key design parameters and design variables at each step. Building this into a costing model is challenging.

1.8 PUBLIC PERCEPTION

Finally, fundamental to the acceptance of potential CCS storage projects is the ability to support the scientific and technological assessments with effective communication of the opportunities and risks to the public and policy makers. As recent experience in Europe has shown, CCS implementation can be blocked by public resistance and therefore needs to be communicated in a clear and transparent manner to all stakeholders.

Chapter 9 explains a process of using citizen panels at the two exemplar sites to investigate understanding and views on CCS before and after engaging with project experts. After the process, concerns on CCS technology were significantly reduced. Storage and the potential for leakage were viewed as the greatest concern, but, engaging with the experts generated sufficient trust such that the risks could be accepted.

The greater public concerns were around the wider political, financial and governance aspects of CCS and, ultimately, on the appropriateness of CCS as a climate change mitigating technology. How could safe monitoring be ensured over hundreds of years? What are the costs and benefits of developing CCS and how could these be distributed in a fair manner? Therefore, in any CCS project, early engagement and implementation of an effective communication plan with local stakeholders should be viewed as an essential element in developing CCS technologies.