EUROPEAN COMMISSION
DG RESEARCH

SEVENTH FRAMEWORK PROGRAMME
THEME 5 - Energy
ENERGY.2010.5.2-1: CCS - storage site characterisation

Collaborative Project– GA No. 256705

SiteChar

Characterisation of European CO_2 storage

Deliverable N° D2.4
Best practices and Guidelines developed from the SiteChar project

Deliverable No.	SiteChar D2.4	
Deliverable Title	Characterisation of storage sites: Best practices and Guidelines developed from the SiteChar project	
Nature	Report	
Dissemination level	Public	
Lead Beneficiary	IFPEN	
Written By	F. Delprat-Jannaud (IFPEN), J. Pearce (BGS), M. Akhurst (BGS) and C. Nielsen (GEUS) *With supporting contributions from all of the SiteChar project*	
Due date	31/12/13	**Delivered on 27 December 2013**

Content

Executive Summary

The development of ‘dry-run’ storage permit applications within SiteChar at two credible CO_2 storage sites allowed development of effective approaches to site characterisation, which will enable robust and defensible permit applications to be developed by operators. The review of these applications and the lessons learnt will help regulatory authorities to identify the necessary levels of evidence required to assess the safety, containment and storage capacity of putative sites. This report presents the SiteChar recommendations which will enable operators to directly address key issues for cost efficient and effective storage permit applications.

Focused and risk-based site characterisation. The research conducted in SiteChar confirms that successful storage operations require site characterisation activities that are fit-for-purpose and focused on reducing uncertainty and risk for the specific site and specific CO_2 storage project. This requires the Competent Authority and operator to share a common understanding of the site and the storage project. SiteChar recommends that site characterisation should be driven by risk and uncertainty assessment, aiming to anticipate, reduce and mitigate risks and identify objectives for subsequent storage performance monitoring.

Storage complex definition. Practical approaches to defining the storage complex are required and have been developed within SiteChar.

EC Storage Directive improvements. Recommendations are made to improve and clarify the EC Storage Directive on a number of topics including the benefits of establishing permit performance conditions, the circumstances under which permits might be revised, the role of Competent Authorities in evaluating the potential impacts of storage projects on other future uses of the underground and the challenges of planning all details of the operation prior to final investment decisions and subsequent site testing.

Demonstrating permanent safe storage. Firstly, establishing agreement during the permit process of the level of evidence required to demonstrate permanent safe containment will be a significant aspect of site characterisation activities. In addition to successfully obtaining a permit to store, this agreement will also enable the transfer of the site to the State at the end of the project. This transfer will be planned from the beginning and prepared for throughout the CCS project. Both operators and Competent Authorities will need certainty on the metrics by which the site performance will be assessed and by which safe, permanent containment will be demonstrated. Secondly, managing uncertainty and conveying the level of confidence accurately without undermining the safety case require further attention. All predictions of site performance will carry a level of confidence and uncertainty. It will be important for Competent Authorities and operators to agree on the levels of acceptable uncertainty. Operators will need to develop a plan for uncertainty reduction during the process of operating the site, supported by an adequate baseline site characterisation and an appropriate program of site monitoring. Definition of acceptance criteria is the key to determine the level of required evidence to gain a storage permit, allowing both operator and regulator to demonstrate safe performance, both during the operational and closure phases and providing a basis for the design of the geological monitoring program and the corrective measures plan.

Recommendations for authorities. Governments set national policies and local authorities may contribute to their implementation through local policy development and the planning process. CO_2 storage projects could therefore form a component of the discussions about the approaches to sustainable energy supply as well as use of the subsurface. Furthermore, assessing interactions with other users is a key consideration for regulators but this might be challenging for operators since such an assessment requires an overview of relevant future uses of the underground. Management of the pore space is also a strategic issue that requires both operators and relevant authorities to consider the efficient use of the pore space in the selection and operation of sites.

Foreword

SiteChar is a FP7 project funded by the EC, industry and national governments for the period from January 2011 to December 2013. SiteChar is dedicated to the development of a methodology for the assessment of potential storage sites and the preparation of storage permit applications, presented as a workflow incorporating technical and economic data, as well as assessing public awareness of CCS at two sites. SiteChar investigates the conditions under which European industry, regulators and other stakeholders might deploy geological storage on an industrial scale to reduce CO_2 emissions.

This report consolidates the key findings of the application of the SiteChar project in terms of guidelines for the preparation (for operators' point of view) and review (for regulators' point of view) of a storage permit. It is one of the three SiteChar public reports that summarise the outcomes of the project:

- D1.4 – Site characterisation workflow (Neele *et al*., 2013a);
- D2.1 - Characterisation of storage sites: Synthesis and lessons learned from the application of the SiteChar workflow (Delprat-Jannaud *et al*., 2013);
- D2.4 - Characterisation of storage sites: Best practices and Guidelines developed from the SiteChar project (this report);

to which the reader is invited to refer for complementary information about SiteChar outcomes (reports available at *www.sitechar-co2.eu*).

List of contributors

Coordinated by IFP Energies nouvelles, the project brings together additional sixteen partners from research, industry and a regulator, as well as the consultancy sector, from ten EU countries: AGH, ECN, Enel, GEUS, GFZ, IMPERIAL, BGS, OGS, PGNiG, Statoil, TNO, SINTEF-PR, UniRoma1-CERI, UfU, Vattenfall and the Scottish Government.

AGH: Lukasz Klimkowski, Stanislaw Nagy, Bartosz Papiernik

ECN: Suzanne Brunsting, Jessanne Mastop

Enel: Silvana Iacobellis, Monia Politi

GEUS: Peter Frykman, Carsten Nielsen

GFZ: Thomas Kempka, Juliane Kummerov

IFPEN: Axelle Baroni, Samir Békri, Dan Bossie-Codreanu, Florence Delprat-Jannaud, Brigitte Doligez, Audrey Estublier, Jean-François Gruson, Emmanuelle Hutin, Jean-Claude Lecomte, Stéphane Renard, Sylvain Serbutoviez, Olivier Vincké

Imperial: Sevket Durucan, Anna Korre, Ji-Quan Shi, Amer Syed

BGS: Maxine Akhurst, Eileen Callaghan, Sarah Hannis, Sandy Henderson, Ken Hitchen, Tim Kearsey, Gary Kirby, David Long, Mike McCormac, Jonathan Pearce, Martyn Quinn

OGS: Edy Forlin, Davide Gei, Barbara Merson, Sergio Persoglia, Valentina Volpi

PGNiG: Marcin Mazurowski

Scottish Government: Fiona Hepplewhite, Stuart McKay, Stephen Martin, Howard Steele, Linsey Wilson

SINTEF-PR: Per Bergmo, Ane Lothe, Etor Querendez, Joachim Rinna

Statoil: Bjorn Berger

TNO: Rob Arts, Christian Bos, Marielle Koenen, Daniel Loeve, Filip Neele, Manuel Nepveu, Bogdan Orlic, Maarten Pluymaekers, Ton Wildenborg, Philippe Steeghs, Merel Schelland, Daniela Sijacic, Tim Tambach, Jens Wollenweber

UfU: Marta Kaiser, René Zimmer

UniRoma1-CERI: Stanley Beaubien, Salvatore Lombardi

Vattenfall: Finn Dalhoff

Acknowledgment

The authors thank the SiteChar Advisory Panel on regulation: Stephen J Cawley (BP), Franz May (BGR), Greg Leamon (Geoscience Australia), Fernando Recreo (Cuiden), Steve Tantala (RET, Australia), Owain Tucker (Shell).

The authors also thank Hallvard Høydalsvik, Eirik Harding Hansen (Gassnova), Pascal Cessat and Natalia Quisel (Veolia Environnement) for fruitful discussions.

These guidelines have benefited from informal discussions with an number of regulators who are thanked, amongst those Jonathan Thomas and Paul Batty (DECC Energy Development Unit, UK) and Lionel Perrette (French Ministry of Environment and Sustainable Development and Energy).

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 256705 as well as Enel, Gassnova, PGNiG, Statoil, the Scottish Government, Vattenfall and Veolia Environnement. They are gratefully acknowledged.

Reference

This report should be cited as:

Delprat-Jannaud F., Pearce J.M., Akhurst M. and Nielsen C., 2013. Characterisation of storage sites: Best practices and Guidelines developed from the SiteChar project. SiteChar Report D2.4. 85 pages.

1 Introduction

1.1 Context

The IPPC (2013) confirms “warming of the climate system is unequivocal, and since the 1950’s, many of the observed changes are unprecedented over decades to millennia”. CO_2 concentrations have actually increased by 40% since pre-industrial times, primarily from fossil fuels combustion. Today fossil fuels still supply 80% of global energy consumed and are expected to remain dominant in the fuel mix for decades. Therefore, if unabated, CO_2 emissions will continue to rise (by 3.2% from 2010 to 2011, IEA, 2012) likely exceeding the 2°C mean global temperature rise for the 21st century which is widely expected to lead to prejudicial environmental damage. Limiting the average global temperature increase to 2°C will require the deployment of a coherent portfolio of low-carbon technologies, among which “CCS will be a critical component in a portfolio of low–carbon energy technologies if governments undertake ambitious measures to combat climate change” (IEA, 2013). This position is recognised worldwide, in particular in Europe where “in the transition to a fully low-carbon economy, the Carbon Capture and Storage (CCS) technology is one of the key ways to reconcile the rising demand for fossil fuels with the need to reduce greenhouse gas emissions. Globally CCS is likely to be a necessity in order to keep the average global temperature rise below 2 degrees” (COM, 2013).

CCS is a well-understood technology that has been developed and used for decades. In particular, in the last decade, research performed by industries, universities and research centres in Europe and worldwide in laboratories, natural CO_2 reservoirs and pilot sites, has demonstrated that geological storage of CO_2 is a viable and secure technology provided rigorous site selection and operations are undertaken. In August 2013, the Global CCS Institute identified sixty-five integrated CCS projects around the world among which twelve are currently operational large-scale CCS projects which prevent 25 million tonnes of CO_2 per year from reaching the atmosphere (GCCSI, 2013). However, the development of CCS projects has been slower than expected due to the costs for capturing CO_2 at large industrial sources and the lack of public acceptance of storage in deep geological formations. In this context, developing robust approaches to CO_2 storage site characterisation is crucial.

In addition, legal and regulatory frameworks are essential to ensure that CO_2 geological storage is safe and effective, that natural resources are effectively used and that storage sites and the accompanying risks are appropriately managed. In 2009, the European Commission (EC) provided a legal framework for CO_2 capture, transport and storage, with the development of the EC Storage Directive which was required to be transposed by Member States by June 2011 (EC, 2009). The EC has also issued four guidance documents to support coherent implementation of the EC Storage Directive across the EU Member States (EC, 2011). The first guidance document outlines a CO_2 storage life-cycle risk management framework, whereas the other three address issues such as the characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures, criteria for transfer of responsibility to the Member State, and financial security. Even if the formal transposition deadline of June 2011 was missed by all but one, in June 2013 all Member States except one have notified the EC of their transposition measures; the EC is in the process of verifying the conformity of these measures. The EC Storage Directive requires potential operators to apply for a storage permit. The application is required to demonstrate that the site design and operation will lead to safe and permanent containment.

To date only one permit application has been submitted, which was on behalf of the ROAD project in the Netherlands, which is one of the more advanced demonstration projects in Europe. It might take a number of years before full permit applications are made in many Member States.

1.2 Objectives of the SiteChar project

Objectives of the SiteChar project

The objective of the FP7 SiteChar project is to facilitate the implementation of CO_2 storage in Europe by integrating, improving, extending and testing standard site characterisation workflows, and by establishing the feasibility of CO_2 storage on representative potential CO_2 storage complexes suitable for development in the near term. For this purpose, SiteChar has developed 'dry run' permit applications for two technically credible storage options to assess the permitting process, albeit within the resource limitations that a research-scale project imposes.

Overview of SiteChar

SiteChar has examined the entire site characterisation chain which includes demonstrating that sites investigated for CO_2 storage have sufficient capacity to accept the expected CO_2 volumes, sufficient injectivity to receive the expected rate of supplied CO_2 and appropriate containment to store the injected CO_2 for the period of time required by the regulatory authority, so as not to pose unacceptable risks to the environment, human health or other uses of the subsurface.

The SiteChar research focused on five potential European storage sites, representative of a range of geological contexts, as test sites for the site characterisation workflow: a North Sea multi-store site offshore Scotland, an onshore aquifer in Denmark, an onshore gas field in Poland, an offshore aquifer in Norway, and an aquifer in the Southern Adriatic Sea (Figure 1.1). At the Danish and Scottish sites, the studies have developed 'dry-run' storage permit applications which have been evaluated by a group of independent experts. The studies conducted at the other sites focused on specific barriers related to the site characterisation methodology. The synthesis of these site applications is presented in SiteChar D2.1 (Delprat-Jannaud *et al*., 2013).

Development of internal 'dry-run' storage permit applications, tested by relevant regulatory authorities was a key innovation of the SiteChar project. This iterative process helped to refine the storage site characterisation workflow and identify gaps in site-specific characterisation needed to secure storage permits under the EC Storage Directive, as implemented in host Member States.

In addition to technical issues, SiteChar has considered the important aspect of the public awareness and public opinions of these new technologies. Site-specific public engagement activities were conducted at the onshore Polish site and the offshore Scottish site.

The SiteChar workflow for site characterisation

The SiteChar workflow for CO_2 storage site characterisation (SiteChar D1.4, Neele *et al*., 2013) provides a description of all the elements of a site characterisation study, as well as guidance on these issues, to streamline the site characterisation process, and to make sure that the output covers the aspects mentioned in the EC Storage Directive (EC, 2009). Characterisation of a site relies on the following steps that are performed in 'roughly' the following order:

1) Data acquisition and quick analysis;
2) Qualitative and quantitative risk assessment;
3) Geological assessment;
4) Hydrodynamic behaviour;
5) Geomechanical assessment;
6) Geochemical assessment;
7) Migration path analysis;
8) Well integrity analysis;

9) Monitoring, mitigation and remediation planning.

Step 2, qualitative and quantitative risk assessment, is to be conducted iteratively throughout the site characterisation phase of a project, taking results from the other steps as appropriate. Step 3 would be performed prior to Steps 4 through 9. There should be close working and iterative discussions between experts involved in Steps 3, 4 and 5. Steps 6, 7 and 8 could largely be performed in parallel. Step 9 requires availability of at least first results from all technical evaluations in Steps 2 to 8. It is important to note here that the above ordering is not prescriptive. In addition to these technical steps, following steps should be performed in parallel to the characterisation:

10) Social acceptability analysis;

11) Economic assessment.

These steps are described in Neele *et al*. (2013) and illustrated on specific sites in Delprat-Jannaud *et al*. (2013).

The SiteChar sites characterisation

The SiteChar portfolio (Figure 1.1) includes five European storage sites, representative of a range of geological storage types comprising depleted oil and gas reservoirs and deep saline aquifers, in both offshore and offshore contexts, with different regulatory requirements, *etc.* This portfolio provides the opportunity to examine the entire site characterisation process, from the initial feasibility studies through to the final stage of application for a storage permit, on the basis of criteria defined by the relevant European legislation, *i.e.,* including estimations of storage capacities of aquifers at basin or reservoir scale, predictions of plume migration, evaluation of injection scenarios, risk assessment, development of the site monitoring plans, technical and economic analyses (assessment of all the costs related to storage) and public engagement activities.

The summary of the characterisation of the five sites and the key learning from site characterisation and storage permit applications are presented in Delprat-Jannaud *et al*. (2013).

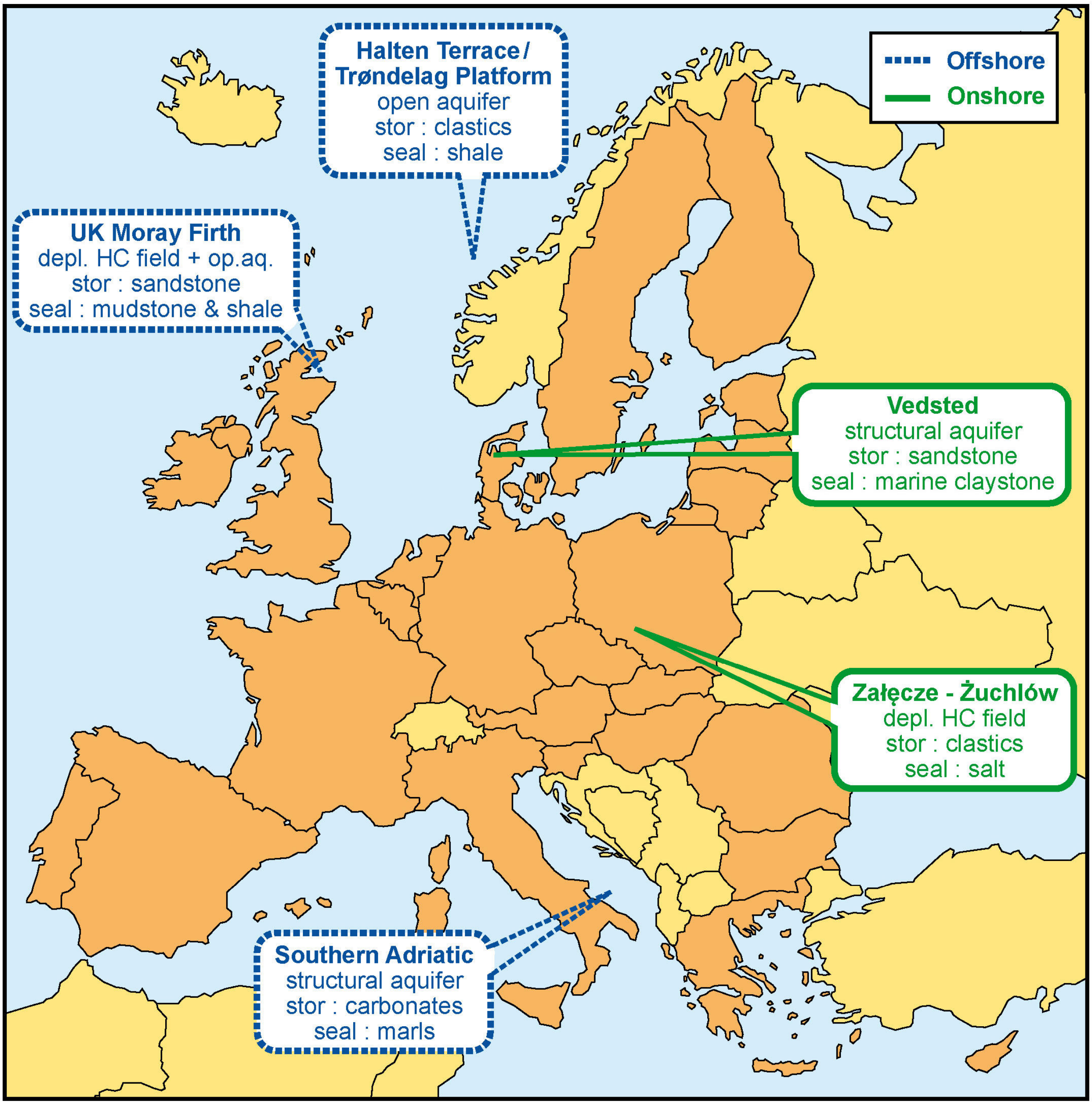


Figure 1.1. *The SiteChar portfolio.*

1.3 The SiteChar permitting process

Status of industry permitting activities in Europe

To date, as far as the authors are aware, only one storage permit has been submitted in Europe which is by the ROAD[1] project. ROAD plans to store CO_2 captured from the new 1,100 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the Rotterdam port. Storage will be in the P18A depleted gas reservoir under the North Sea. This gas reservoir is located 20 kilometres off the coast and is at a depth of 3,500 metres under the seabed. Capture rates will be around 1.1 Mt CO_2 per year from 2015. Development of the storage permit took approximately two years[1].

Other industrial consortia are undertaking detailed site characterisation in preparation for submitting permit applications but are not yet ready. Two sites are being investigated in the UK North Sea as part of the UK Government's Commercialisation program[2]: the Peterhead Project in Aberdeenshire in Scotland and the White Rose project in the southern North Sea. The Peterhead project is evaluating the storage potential of the depleted Goldeneye hydrocarbon field in the Outer Moray Firth, and the White Rose project is undertaking detailed site characterisation investigations, including drilling of an exploration well, in a structure in the Bunter Sandstone saline aquifer. It is believed that neither project has submitted a storage permit application at the time of writing. Other demonstration projects that are ongoing, such as at Sleipner and Snohvit, are operating under petroleum licences.

Completion and review of 'dry-run' permit applications within SiteChar

The SiteChar project has undertaken site characterisation activities at five sites that may provide credible options for future CO_2 storage. The sites were selected to represent different geological and storage solutions across Europe. Two of the sites, the depleted hydrocarbon Blake Field and Captain Sandstone multi-store site in the UK northern North Sea and the Vedsted aquifer site in onshore Denmark, were selected for detailed site characterisation to enable development of 'dry-run' storage permit applications. It should be noted that none of the sites investigated within SiteChar have to date been selected for CO_2 storage. The objective was to identify effective approaches to site characterisation by developing 'dry-run' permit applications, and undertaking independent reviews of these applications, to enable robust and defensible permit applications to be developed by storage operators in the future. It is also hoped that relevant regulatory authorities would find the process useful in identifying the necessary levels of evidence required to assess the safety, the containment and the capacity of putative storage sites. The 'dry-run' process also allowed testing and refining of the SiteChar workflow for site characterisation.

Although this permit review was undertaken whilst maintaining some degree of independence from the permit development teams, a very close dialogue was maintained with each team during the development of their 'dry-run' permit applications. This was to support the permit development, ensuring it addressed, to the extent possible, the requirements of the EC Storage Directive and to provide advice on specific technical issues concerning the development of the evidence base to support the storage applications.

The review has compared the 'dry-run' applications against the requirements in the EC Storage Directive (EC, 2009), and the associated Guidance Documents (EC, 2011). In addition, for the UK site, the UK-specific guidance documents[3] produced by the UK Department of Energy and Climate Change were also used to assess the completeness and relevance of the evidence provided.

---

[1] http://cdn.globalccsinstitute.com/sites/default/files/publications/111356/case-study-road-storage-permit.pdf

[2] https://www.gov.uk/uk-carbon-capture-and-storage-government-funding-and-support

[3] Carbon Dioxide Storage Licence Application |Guidance, available at https://www.gov.uk/oil-and-gas-licensing-for-carbon-storage--3

Detailed reviews have been undertaken by the SiteChar Regulatory Advisory Board who has provided significant advice, as well as detailed reviews, throughout the process:

- Owain Tucker, General Manager CCS, Shell UK;
- Steven Cawley, Subsurface Resource and Projects Manager, BP UK;
- Franz May, Head of Unit Processes and technologies of CO_2 Storage, BGR Germany;
- Fernando Recreo-Jimenez, Safety and Performance Assessment Head of Unit CO_2 Geological Storage Programme, Cuiden;
- Steve Tantala, Manager, CO_2 Regulation Transport and Storage, Department of Resources, Environment and Tourism, Australia;
- Greg Leamonn, Senior Advisor Greenhouse Gas Advice, Department of Resources, Environment and Tourism, Australia.

Specific issues that have arisen during the storage permit developments have also greatly benefited from informal discussions with a number of regulators from the UK and France, for which the SiteChar team is very grateful.

In real projects, especially first-of-a-kind projects in CO_2 storage, no individual regulator could be expected to properly assess applications of this type without support from technical specialists, particularly in relation to the hydrodynamic modelling. The review process undertaken here took several weeks, excluding discussions undertaken prior to permit application submission. It would be expected that in a real application, this review process would take several months including support from technical experts as appropriate. The regulator is likely to request additional information to support or clarify the content of the application. There may be several iterations of the application submission and evaluation.

Specific topics were highlighted during discussions. They included:

- The challenges in defining the storage complex and the need to have an agreed approach between the operator and the Competent Authority to defining the storage complex. This was especially relevant where storage is being considered in saline aquifers in which pressure responses might be expected far beyond the extent of the injected CO_2 plume;
- The definition of the storage site performance and the benefits of using pre-defined permit performance conditions as qualitative and quantitative indicators of site performance;
- The potential for interactions to occur with other users of the subsurface;
- The need for pressure management through water production.

Glossary

Most terms used in this report have been used with the same meaning as defined by the relevant regulations. However three terms require further explanation:

- *Leakage* – here used in the definition used in the Emission Trading System, *i.e.,* CO_2 emitted to the atmosphere or seabed.
- *Closure* – this term is somewhat inconsistently used within the EC Storage Directive and Guidance Documents. Here, it is taken strictly as the point of end of injection. This requires terms such as post-closure period, post-transfer period and post-injection monitoring period to be used to describe other regulatory time periods.

- *Permit Performance Conditions* – conditions that are agreed between operator and Competent Authority to define the expected performance of the site. It is expected they will be a combination of qualitative and quantitative conditions. They are not formally required by the regulations governing CO_2 storage.
- *Project concept* – short summary of the objectives of the storage operation in terms of masses to be stored, capture, transport and storage infrastructure and overall relationships between storage operator and transport and capture operators.

1.4 Scope of the SiteChar best practices and guidelines

Reference to previous works

The SACS - Best practice for the storage of CO_2 in saline aquifers (Chadwick *et al*., 2008), referred to here as the SACS Best Practice Manual (BPM), provides a summary of data requirements for site characterisation:

The key datasets for a robust characterisation of reservoir and overburden are:

- A regular grid of 2D seismic data over sufficient area to characterise broad reservoir structure and extents;
- A high quality 3D seismic volume over the injection site and adjacent area, tuned if possible for satisfactory resolution of both reservoir and overburden;
- Sufficient well data to permit characterisation of reservoir and overburden properties.

The BPM provides a set of site slection criteria which are proposed for suitable geological storage sites (Table 1.1).

Table 1.1. *Site selection criteria from the Best Practice Manual (BPM).*

	Positive indicators	**Cautionary indicators**
RESERVOIR EFFICACY		
Static storage capacity	Estimated storage capacity much larger the total amount of CO_2 to be injected.	Estimated effective storage capacity similar to total amount of CO_2 to be injected.
Dynamic storage capacity	Predicted injection-induced pressures well below levels likely to induce geomechanical damage to reservoir or cap rock.	Injection-induced pressures approach geomechanical instability limits
Reservoir properties		
Depth	> 1000m < 2500m	< 800m > 2500m
Reservoir thickness (net)	> 50m	< 20m
Porosity	> 20%	< 10%
Permeability	> 500mD	< 200mD
Salinity	> 100 gl^{-1}	< 30gl^{-1}
Stratigraphy	Uniform	Complex lateral variation and complex connectivity of reservoir facies
CAP ROCK EFFICACY		
Lateral continuity	Stratigraphically uniform, small or no faults	Lateral variations, medium to large faults
Thickness	> 100 m	< 20 m
Capillary entry pressure	Much greater than maximum predicted injection-induced pressure increase	Similar to maximum predicted injection-induced pressure increase

The BPM states that the aim of site characterisation is to confirm and refine the earlier screening studies and, more specifically, to provide basic data for the predictive fluid flow and geochemical simulations, the risk assessment and monitoring programme design. The BPM provides a summary of the workflow for site characterisation, which has been developed and expanded in the SiteChar project:

- Data are required at a variety of scales and densities, with seismic and well data as key to establishing preliminary structure and stratigraphy at both regional and storage site scales. Reservoir properties can best be determined by an analysis of seismic and well log data augmented by rock material (core and cuttings). Geological models of the reservoir have to be constructed as the basis for reservoir volume calculations for estimates of storage capacity and are parameterised with data obtained from logs and core samples.
- Pressure and temperature information estimated for the reservoir or measured in wells in individual compartments can be used in the calculation of the density of the CO_2-rich phase. The geological models can be used in reservoir simulation models to explore the effects of uncertainty via different CO_2 injection strategies and to predict sweep efficiencies.
- In order to establish the effective extent of a structure, knowledge of the hydraulic conductivity of faults in the vicinity of an injection site is required. This information can be derived from well tests. Variations of the effective aquifer radius in reservoir simulations can be used to study its impact on storage capacity.

Similarly, the US NETL produced a BPM for site screening, site selection, and initial characterisation for storage of CO_2 in deep geologic formations (NETL, 2010) which describes a workflow from project definition, site screening and initial site characterisation. In this scheme, the initial site characterisation comprises the following subsurface data analysis activities: (i) Geological, (ii) Geochemical, (iii) Geomechanical, (iv) Hydrogeologic and (v) Flux Baselines. Each of these topics requires site-specific analysis, including further data acquisition from seismic and well analysis, among which are well testing and core analysis. These baseline data are part of the overall site characterisation process which also includes:

- An assessment of regulatory requirement;
- The development of models and scenarios of possible site behaviour;
- Social site characterisation;
- A site development plan including a front-end engineering design study with updates to costs, objectives and specifications for tender requirements for specialist analysis and construction. Outreach assessment is embedded in the site characterisation program.

Den Norske Veritas have produced a summary report based on a joint industry project to develop a guideline for selection and qualification of sites and projects for geological storage of CO_2 (The CO2QualStore Guideline, DNV, 2010). This document provides a detailed summary of approaches to site selection and site characterisation, which has partly been used to develop the guidelines that describe how to meet the requirements of the EC Storage Directive. The CO2QualStore Guideline provides a list of the types of data that might be required to undertake a successful site characterisation:

- Geology and geophysics for quantifying reservoir, cap rock and surrounding formations;
- Hydrogeology and hydrodynamic regime;
- Reservoir engineering, including estimates of dynamic storage capacity;

- Geochemistry to estimate longer-term trapping processes;
- Geomechanics to estimate fault sealing behaviour, formation fracture pressures;
- Natural background seismicity;
- Natural and man-made pathways that may cause leakage;
- Background surface deformation rates.

The objectives of assessing each of these aspects of a potential storage site are reviewed before describing various approaches to risk assessment and uncertainty management. The objectives of monitoring plans and storage development plans are described, including possible approaches to defining performance targets.

Scope of the SiteChar best practices and guidelines

The scope of this report is the following:

- *Intended audience.* This report has been developed for the key stakeholders involved in CO_2 geological storage which are industry and regulators. Others are policymakers and the wider public;
- *Use.* This report does not aim to be prescriptive. It gathers recommendations based on research conducted within the SiteChar project. It has no official endorsement or approval;
- *Disclaimer.* It should not be assumed that following these guidelines will automatically lead to successful award of a storage permit.

2 Exemplar content of the SiteChar storage permit application

This section provides the proposed contents for a storage permit as defined by the EC Storage Directive including together the ‘exploration permit’ and the ‘permit to inject’.

2.1 Project description

2.1.1 Storage development plan

The storage development plan should describe the injection and operating plans for the site, based upon the project design to store CO_2 at the anticipated rates for the lifetime of the project. The injection plan will describe the expected rates of injection and the injection scheme including the injection infrastructure and operation. A summary of the storage site performance should also be included.

2.1.2 Project concept

The project concept provides a short summary of the objectives of the storage operation in terms of masses to be stored, capture, storage and transport infrastructure and overall relationships between storage operator and transport and capture operators.

2.1.3 Injection parameters

In relation to the CO_2 stream, the following will be described:

i. The total quantity that is to be injected and stored;
ii. A proposed date on which injection is to commence;
iii. The prospective sources and transport methods;
iv. The composition of the CO_2 streams that are to be injected;
v. The proposed injection rates and pressures;
vi. The proposed location of the injection facilities.

2.2 Site description

Though not specifically itemised within the regulations, it is considered fundamental to provide a description of the site characterisation undertaken. The objective of this description is to demonstrate that ‘‘the storage complex and surrounding area have been sufficiently characterised and assessed in accordance with the criteria set out in Annex I to the Directive’’[4].

This would include, *inter alia:*

i. *Boundaries* (in three dimensions) to storage complex and storage site, illustrated by appropriate figures and maps;
ii. *Information on site geology* – reservoir(s) including secondary storage reservoirs, cap rock, structure, nearby resources;
iii. *Past development* (especially for hydrocarbon fields). *N.B.:* a real permit should contain a list of all past and proposed permit holders which is assumed to include hydrocarbon exploration and production licences;

---

[4] The Storage of Carbon Dioxide (Licensing, *etc.*) Regulations 2010 (UK) http://www.legislation.gov.uk/uksi/2010/2221/contents/made

iv. *Total storage capacity* including description of methods for estimation and associated uncertainties.

2.2.1 Storage site and complex

The **storage site** is clearly defined in the EC Storage Directive as ‘‘a defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities’’. The storage site therefore contains the primary reservoir into which it will be expected that the CO_2 will be injected and most likely be contained. The upper boundary of the reservoir will be defined by the primary seal rock, above which CO_2 is not expected to migrate.

The **storage complex** is defined as ‘‘storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations’’. The definition of the complex boundary is particularly important as **leakage** of CO_2 is defined when CO_2 migrates beyond this boundary. The definition of the storage complex was found to be more challenging than expected and is discussed in detail in Section 4.The storage complex might therefore contain additional formations that could contain migrating CO_2 if it migrated out of the primary reservoir. These secondary reservoirs, and their secondary, complex seal rock might be included specifically where CO_2 migration is expected or as an additional safeguard against leakage. The complex seal rock will be expected to provide more regional containment of the CO_2. Sufficient evidence will naturally need to be presented in the storage permit to demonstrate that both the primary and secondary reservoirs and their seal rocks will permanently contain the CO_2.

Informal discussion with regulators indicate that the pressure footprint might receive lower emphasis in the definition of the complex boundary as it is recognised in some areas that including the pressure footprint would require impractically large storage permit areas, since pressure responses can extend far beyond the CO_2 plume. A further challenge to developing agreed methods for defining the storage complex boundary is the lack of consensus on the thresholds or consequences above which pressure effects should be included. However excluding the pressure footprint is not necessarily accepted in all jurisdictions. A clear prior agreement between operators and Competent Authorities will be needed on the methods used to define the storage complex.

In SiteChar we propose to define the complex according to the predicted maximum extent of the plume, including CO_2-saturated formation water, plus a margin to enable monitoring and to reflect inherent uncertainty in predictions.

2.2.2 Structure

The structure within which the CO_2 is expected to be contained must be defined. In open saline aquifers the structure will comprise the aquifer itself to the point of expected migration.

2.2.3 Past development

The past development of a hydrocarbon field will be of critical importance for development of credible predictions of future storage performance. Generally it is expected that owners of hydrocarbon fields will either be required to provide data on past production or more likely become storage operators and use this pre-existing knowledge to develop their site permits. Competent Authorities may have a role to play in ensuring that transfer of knowledge about past site development takes place to reduce risks in storage development.

2.2.4 Total storage capacity

The total storage capacity of the site should be described, including methods and assumptions used to derive the estimate. Competent Authorities will want to assess the robustness of the estimate and may wish to determine whether the storage field development plan makes optimum use of the estimated storage capacity. Access by third parties may be a consideration here.

2.3 Measures to prevent significant irregularities

This will include a description of identified risks including methods used to identify, rank and 'audit' risks.

i. *A risk register* identifying itemised key storage risks, rank, severity before and after mitigation, timing (*i.e.,* when would risks be greatest, *e.g.* during construction, injection, post-injection, decommissioning, post-closure, post-transfer);

ii. *A plan of risk mitigation;*

iii. *Dialogue (or plans for dialogue) with stakeholders:* key stakeholders might include members of the public, representatives of public opinion (Environmental Non-Governmental Organisations, *etc*) and other stakeholders (*e.g.* local authority planning departments, regional development agencies, *etc*) as well as the Competent Authorities and statutory consultees.

2.3.1 Risk register

A formal risk assessment process should drive the site characterisation for any potential storage site. It will enable investigations to be prioritised and focused on key areas of uncertainty and highest initial risk. Consequently, the storage permit application should demonstrate that a set of potential risks have been considered and furthermore that most of these risks have low probability and/or low consequence. The risks identified can be audited or compared with online Features, Event and Process (FEP) databases to ensure the assessment was as comprehensive as possible.

Analysis of leakage scenarios should be undertaken, including those that might include failure of multiple barriers.

Demonstrating expected continued sealing integrity of wells is likely to be *a priori*ty in many storage permit applications, especially in areas of high well density or wells of different ages or completions. A full application should include an assessment and safety statement for each well.

The risk register provides a useful audit tool that demonstrates how risk rankings have evolved as investigations and project design have reduced uncertainty and risk.

2.3.2 Monitoring and corrective measures plans

The **monitoring plan** should be closely integrated with the risk assessment and project design. Clear objectives for the monitoring will define the requirements for monitoring of storage site performance, for which a number of techniques have been demonstrated at a number of pilot storage sites. The plan should comprise a description of the specific objectives for each technique, where it is to be deployed, and the overall survey design, including the spatial distribution where relevant. Comprehensive descriptions of the different techniques, and their integration into a monitoring system together with an indication of likely frequencies of their deployment, should be included. Explicit links with specific risks, regulatory requirements and Permit Performance Conditions would demonstrate an integrated and robust monitoring plan.

The **corrective measures** plan should address all risks as appropriate requiring different scenarios to be evaluated, as quantitatively as possible, to determine expected response levels which would define a significant irregularity. The chain of events should be described in detail for each trigger scenario. Construction of a range of scenarios that describe possible deviations from expected behaviour should be defined and then simulations may be necessary to identify key trigger events. The monitoring plan must then demonstrate a capability to detect these trigger events at appropriate frequencies, locations and repeatability. Significant irregularities would be defined to avoid these extreme scenarios occurring in the first place. These might include unexpected plume movement, changes in pressure or results from well integrity monitoring, for example.

2.3.3 Permit Performance Conditions

The definition of Permit Performance Conditions (PPCs) has been a significant development of the SiteChar 'dry-run' permitting process. The purpose of these PPCs is to develop a set of *a priori* agreed criteria which will demonstrate appropriate site performance. The intention is that these criteria would form conditions of the storage permit, allowing both operator and regulator to demonstrate adequate performance both during injection and, importantly at the point of transfer of responsibility following site closure, decommissioning and abandonment. These PPCs should define site performance in terms of absence of leakage, agreement between prediction and observed plume migration, limits on reservoir pressure, maintenance of geomechanical integrity and costs per tonne of CO_2. The latter is considered important to define an upper limit above which permit requirements would make the project unviable, thereby protecting the operator from impractical or too costly conditions. This will be a specific metric for operators as project economics are unlikely to be a prime concern for permitting authorities as it is not their role to protect operators against financially risky projects. Furthermore it is likely that this metric would require very clear definition and justification in a full application, being central to the storage operators business case. CO_2 stream quality and variability should be included as a separate PPC, as this could have an impact on the integrity of containment. A PPC dealing with adverse environmental or health effects due to the operation may also be necessary.

PPCs include a range of metrics against which site performance can be measured, both during the operational and closure phases, providing a basis for the design of the geological monitoring program and the corrective measures plan. Whilst it might be relatively straightforward to define qualitative indicators, PPCs will need to be defined quantitatively for them to be effective.

Each PPC should contain a justification of the PPC and a description of the evidence, in the form of quantitative limits that will be obtained to demonstrate site performance has been met.

PPCs are not explicitly required by the EC Storage Directive but are considered as useful tools for discussion between the Competent Authority and operator. They provide a useful way to define and agree acceptance criteria against which a storage operation can be assessed. They are likely to be a combination of qualitative and quantitative metrics.

2.3.4 Dialogue with stakeholders

We here refer to stakeholders that must be consulted.

2.3.4.1 Regulators

Development of an exploration and a storage permit is a process during which the operator and the Competent Authority will need to share and agree the understanding of the site together with its opportunities as well as risks and uncertainties.

2.3.4.2 Operator for other use of resources

The nature and extent of interactions with other users is a key consideration for regulators and operators are expected to establish potential impacts on pre-existing uses of the surface and subsurface. However, it is recognised that assessing future interactions may be challenging for operators and Competent Authorities may be best placed to take an overview of future operations (*e.g.* hydrocarbon production and/or other storage) that may impact on the risk profile of a project.

As an example, CO_2 storage in formations can have an influence on drilling and drilling risks for (non-related) activities at deeper levels (*e.g.* oil and gas production). Liability will be an issue then, as well as technical barriers. In some jurisdictions, operators with existing rights such as geothermal heat producers can oppose new projects in their neighbourhood during a legally defined period (*e.g.* about six weeks in the Netherlands).

2.4 Social aspects

Whereas the EC Storage Directive does not prescribe public consultation, it is clear that a constructive stakeholder engagement process increases the likelihood of successful dialogue with members of the local population either politicians, citizens, *etc.*

For all stakeholders, operator, regulator and local public, the key point is to gain trust. Operators will have to be patient and take their time to get acquainted with the local stakeholders. Early communication with the local public is thus recommended, being transparent and having open dialogue. The local public needs to know about CCS and about the project. It must be kept in mind that CO_2 storage is part of the CCS chain with a CO_2 producer, a transport infrastructure and a storage site and that all these elements must be discussed with the local communities.

Operators will have to make their project part of the local political approach regarding energy and use of the subsoil. They will have to understand the main concerns of the local community, from a positive stance but also to outline any social and economic benefits.

2.5 Economic assessment

Economic assessment is essential at different steps of the project in particular to inform any decision points.

This calls first for collecting cost data, which might be quite uncertain at the beginning of the project but which will be more and more accurate as the design of the project concept progresses. Cost data collection involves discussions with industry partners and external stakeholders to define appropriate Capital expenditure (Capex) and Operating expenditure (Opex) cost categories. Capex estimates are based on the site-specific storage designs that are determined by results from site characterisation, including intrusive site investigations, *i.e.,* exploration well costs, injection test costs, site characterisation and Front-End Engineering Design (FEED) costs. Opex estimates include injection costs, Measurement Monitoring and Verification (MMV) costs, storage site leases and financial securities. In the SiteChar project only costs related to storage have been evaluated, *i.e.,* from the well head and down.

The project feasibility is then estimated computing the Net Present Value and profitability of the project. To infer uncertainty on some influential parameters such as the CO_2 price, project sensitivity analyses might be developed. The cash flow during the lifetime of the project, the financial exposure of the project, and the final Net Present Value are to be evaluated.

This raises questions about the real lifetime of a CO_2 storage project, costs associated with the abandonment phase and the real costs of the liability transfer.

3 Site characterisation for the completion of a storage permit: Lessons learnt from the SiteChar experience

3.1 The SiteChar experience

The research conducted in SiteChar focused on five potential European storage sites, representative of the various geological contexts, as test sites for the research work (Table 3.1): a UK northern North Sea multi-store site offshore Scotland (hydrocarbon field and host aquifer), an onshore aquifer in Denmark, an onshore gas field in Poland, an offshore aquifer in Norway and, finally, an aquifer in the Southern Adriatic Sea.

Table 3.1. *The SiteChar sites portfolio.*

	Outer Moray Firth	**Vedsted**	**Załęcze-Zuchlów**	**Trøndelag Platform**	**Southern Adriatic Sea**
Geology					
	North Sea UK	Denmark	Poland	Norway	Italy
	Offshore	Onshore	Onshore	Offshore	Offshore
	Depleted oil reservoir and host saline aquifer	Saline aquifer	Depleted oil reservoir	Saline aquifer	Saline aquifer
Reservoir	Sandstone	Sandstone	Clastic rocks	Clastic rocks	Carbonate rocks
Seal rock	Mudstone / Shale	Marine claystone	Salt	Shale	Marls
Main objectives					
	1- ‘Dry-run’ permit 2- Relationship between hydrocarbon fields and host saline aquifer 3- Risk-led site characterisation, risk mitigation and management	1- ‘Dry-run’ permit 2- Ways to supplement sparse data 3- Impact on the surrounding region 4- Monitoring program /Risk management	1-Whole workflow through to the development of an injection strategy 2- Behaviour of the reservoir rock and cap rock	1- Basin & compartment scale evaluation 2- Possibility of leakage 3- Injection strategy 4- Monitoring / remediation strategies	1- Methodology for characterisation in carbonate formations 2- Geomechanical and hydrodynamic behaviour

Two levels of characterisation have been investigated within SiteChar. At the Polish Załęcze and Żuchlów gas fields, the Norwegian Trøndelag platform and the Southern Adriatic Sea site, the characterisation has been performed from the early phases of the workflow to investigate new prospective areas for CO_2 storage. At the offshore UK North Sea multi-store site and the onshore Vedsted aquifer site in Denmark, a full-chain characterisation suitable for a ‘dry-run’ storage permit application has been performed. These two contrasting storage sites are representative of two realistic storage options, though neither currently being considered as near-term candidates. Even though the offshore UK North Sea site has been identified from previous reviews of UK northern North Sea storage targets, it is a theoretical study designed to test a credible scenario for CO_2 storage extending storage in an hydrocarbon field to large-scale CO_2 storage in a saline aquifer which would be commercially viable. The second case study extends existing investigations at the Danish Vedsted site, a deep onshore aquifer, processed by Vattenfall till late 2011 to be an industrial scale demo project but today abandoned. At these two sites, ‘dry-run’ storage permit applications have been produced and evaluated by a group of independent international experts and, via the Scottish Government for discussion with the UK CCS Regulatory Group.

A summary of these site characterisations is presented in Delprat-Jannaud *et al*. (2013) and the reader is invited to refer to this report for details on the sites characterisations. This section summarises the outcomes of the research regarding the understanding of site characterisation and the development of storage permit.

3.2 Lessons learnt from the investigation of the Załęcze-Żuchlów gas fields, the Trøndelag Platform and the Southern Adriatic Sea site

The first stage of a site selection process for CO_2 storage is a screening of geology at national or regional scale to identify large areas of potentially suitable sedimentary basins. A thorough site selection has been conducted on the Załęcze and Żuchlów cluster of gas fields (onshore Poland) as well as at two virgin areas, the Trøndelag platform (offshore Norway) and the Southern Adriatic Sea site (offshore Italy) to confirm the opportunities for CO_2 storage and identify of the key risk factors of the possible CO_2 storage project.

This section summarises the outcomes of the SiteChar research conducted at these three sites regarding the understanding of site characterisation.

3.2.1 The Załęcze-Żuchlów site, Poland

Scope of the site characterisation

The Polish Lowlands are one of the strategic locations for the upcoming national CO_2 injection program in Poland. The characterisation conducted in SiteChar is expected to confirm technical opportunities of CO_2 injection in the natural gas reservoirs in this area. The Załęcze-Zuchlów site is relatively close to industrial CO_2 producers and there are existing oil and gas pipelines that could be used for CO_2 transport.

The Załęcze and Zuchlów gas fields, as well as other gas fields in the area, have been operated for about 30 years. Thirty-five production wells were drilled in the reservoirs and relative many data were available, including geophysical log data and laboratory data.

The characterisation conducted in SiteChar started from the very early stages up to the design of an injection strategy.

Level of site characterisation achieved

A detailed regional model of the reservoir and its overburden was presented from the main identified structural horizons and faults for the whole Żuchlów and Załęcze area and a local modelling procedure enabled refined local reservoir models of Załęcze-Wiewierz gas fields as well as Żuchlów-Gora gas fields.

The dynamic storage capacity of both Załęcze and Zuchlów reservoirs was estimated, assuming initial reservoir pressure as the maximum value allowing safe long-term CO_2 storage. The injection strategy has been designed to fit the emission of one planned coal-fired power plant in the Silesia area where an annual rate of 1.8 Mt CO_2 is expected to be captured for a period of 20 years.

Geomechanical modelling studies were carried out to evaluate the geomechanical effects on seal rock and faults associated with gas extraction and prospective future CO_2 injection in the Żuchlów depleted gas reservoir. According to the available data, fault and cap rock integrity at Zuchlów did not appear to present any risk neither during the period of gas production nor during the envisaged CO_2 injection operation provided the reservoir pressure remains below the initial pressure.

A risk analysis identified abandoned wells as the major risk for the site integrity. A well integrity analysis has been conducted pointing out two main well leakage scenarios: a plug failure scenario for wells abandoned before 1998 and a cement-sheath failure scenario for wells abandoned after 1998.

It was concluded that the Żuchlów and Załęcze gas fields are strongly depleted natural gas reservoirs with sufficient potential in the context of geological CO_2 storage. Main issues connected with these sites are the very low reservoir pressure and a high number of wells. Further investigations of the thermal effects of CO_2 injection, low pressure reservoir as well as CO_2 leakage through the wells including remediation scenarios were recommended.

Lessons learnt regarding the understanding of site characterisation

As the analysed reservoirs have been in operation for about 40 years, a lot of production data are available. This abundance of data provided excellent support for the model validation process even if history matching such a long production period (with many wells in operation) was very time consuming.

Even for sites that have been explored by the oil and gas industry, some uncertainty still remain for the characterisation of the site for the purpose of CO_2 storage, *e.g.* information on the overburden, such as ensuring the cap rock continuity, faults properties and *in-situ* stress field.

A definitive assessment of the well-related risks and definition of possible leakage scenarios calls for detailed analysis of the quality of all individual abandoned wells which might be time consuming and costly.

3.2.2 The Halten Terrace/Trøndelag site, mid Norway

Scope of the site characterisation

The Halten Terrace/Trøndelag area is situated offshore Mid-Norway, and the basin covers an area of 150 by 50 km. The area contains gas with naturally high CO_2 content that can be extracted and stored. The Garn Formation within the Trøndelag Platform is a promising site for CO_2 storage activities with possible reservoirs compartmentalised by faults.

The Trøndelag Platform is a virgin area characterised on the basis of publicly available data so that there is no conflict of interest with other activities.

Level of site characterisation achieved

Initially, the Halten Terrace area was the focus of the study, but it appeared that the neighbouring Trøndelag Platform was more suitable for CO_2 storage since it is shallower and consequently without any conflict of interest with existing oil and gas production.

On the basis of data available for this study, the Garn Formation of the Trøndelag Platform seems well-suited for CO_2 injection and storage at industrial scale over a period of 40 years. The north-westwards dipping structure is characterised by a high sand content only moderately deeply buried. Consequently, porosity and permeability are excellent for CO_2 storage purposes. Formation thickness has been estimated between 100 and 150 m, and the number of faults is low on the Trøndelag Platform. In addition, the Garn Formation is overlaid by thick shale sequences further reducing risk of possible leakage through faults and also suggesting a low risk for cap rock leakage.

The characterisation of the Trøndelag Platform has been carried out at basin and reservoir scale, comparing different approaches to assess the impact of stress and pressure changes on CO_2 storage performance and related risk at basin and storage compartment scale. Several injection sites were evaluated using basin modelling tools and reservoir modelling tools. Modelling results indicate large volumes for storage, with increase in pressure.

Evaluation of storage capacities has been performed through the simulation of a number of scenarios according to three different injection sites and two different injection rates and taking into account migration pathways. Modelling of CO_2 pressure build-up in pressure compartments was performed in order to optimise the injection and keep the pressure below the fracture pressure threshold.

Lessons learnt regarding the understanding of site characterisation

Petrophysical data were derived from a small number of wells and analogues from the neighbouring Halten Terrace area so that it was not possible to infer the heterogeneity of the Garn Formation.

A main uncertainty is related to the understanding of the main faults in the area, the crucial issue being whether the faults are sealing or not. The properties for the faults should always be varied (open or closed to fluid flow).

The lack of meaningful data to characterise and identify risks has been a limiting factor when deriving a monitoring plan. One way to overcome this limitation has been to simulate possible generic risk scenarios that ultimately make the monitoring plan applicable to all three identified injection targets in the Norwegian sector.

3.2.3 The Southern Adriatic Sea site, Italy

Scope of the site characterisation

The main objective of the characterisation was to evaluate as a first attempt the CO_2 storage potential of the Southern Adriatic Sea area which benefits from the vicinity to the major Italian CO_2 point source, Enel Federico II power plant, where a pilot plant for CO_2 capture has already been started.

The Southern Adriatic Sea site is a structural trap in a carbonate saline aquifer. Analyses carried out in a screening study of the area revealed that the Adriatic Sea offshore of the Puglia region is an area that is structurally only mildly deformed. The potential reservoir-cap rock is only partly affected by tectonic deformation. Three structures suitable for CO_2 geological storage were identified and assessed within SiteChar. The reservoir-cap rock system is the same in all of the identified features. The reservoir is in the Scaglia Formation (middle-upper Cretaceous, 84 to 65 million years old) corresponding to mudstone and wackstone-like limestone lithology and deep carbonate platform facies. The reservoir is at 1650 to 3000 m (below sea level) depth and 50 to 100 m thick. The cap rock is in the Bisciaro Formation (Plio-Pleistocene, 12.5 to 17 million years old) corresponding to marl lithology and bathyal plain facies. Its thickness is a few hundreds of metres.

Level of site characterisation undertaken

The Southern Adriatic case study is specific since the reservoir is a carbonate formation. Investigation of carbonate rocks as potential reservoirs for CO_2 storage requires the classification of the pore space, which controls the petrophysical parameters of permeability and saturation. In addition, the wide range of pore size and the heterogeneous distribution of the porosity, through matrix and grains in carbonate rocks, make the determination of the effective porosity very difficult. Understanding the behaviour of the CO_2 plume in such a lithology thus requires accurate modelling. In saline aquifers, lack of direct borehole measurements creates specific issues that have been addressed through a sensitivity analysis approach to account for the uncertainties related to petrophysical properties.

The research on the Southern Adriatic Sea site focused on the investigation of the geomechanical and hydrodynamic behaviour of the storage complex due to the CO_2 injection in the specific reservoir, consisting of fractured carbonate formations with special attention to the effect that natural faults fractures may have on CO_2 migration; and the effect that injection might have on the stability of faults. The assessment of the geomechanical behaviour of faults has been performed via hydro–geomechanical weak coupling, while modelling fluid flow inside faults. Fluid flow and geomechanical parameters were derived either from laboratory measurements performed on samples from a reservoir analogue, or published literature. Various representations of faults were integrated in the model to simulate fluid flow along the fault plan and stress evolution due to CO_2 injection. Various scenarios were also simulated to take into account the uncertainties in the petrophysical and geomechanical properties of the model: different states of faults (*i.e.,* open, closed or mid-opened), various stresses (*i.e.,* normal faulting, or shear stress with a range of angles) as well as various fluid flow parameters. Post-processing analysis of the geomechanical criteria showed that the Rovesti fault, which is located near the injection well, remains below the chosen Mohr-Coulomb criteria.

Lessons learnt regarding the understanding of site characterisation

The size and the resolution of the model are limited by the low data resolution. This constrains the level of details of the characterisation that can be conducted and this is a limitation to the characterisation of carbonate reservoirs in which the distribution of porosity and permeability should play an important role.

The uncertainties are mainly associated to the scarcity and sparseness of available data, in particular regarding the petrophysical properties and the fault transmissivity values. Availability of data for geomechanical modelling appeared to be an issue for both faults geometries and properties and for overburden properties. The approach adopted was thus to simulate several scenarios varying the petrophysical properties, the number of injection wells and fault characteristics.

3.3 The ‘dry-run’ storage permit developed at the Outer Moray Firth site, North UK

3.3.1 Site and level of site characterisation undertaken

The UK northern North Sea site comprises the Captain Sandstone and a hydrocarbon field as an example of a multi-store site. The Captain Sandstone lies offshore the north-eastern coast of Scotland in the outer Moray Firth that is known from North Sea oil and gas exploration and production. The sandstone is approximately 100 m thick, it covers an area of approximately 50 km by 30 km in extent and it is investigated for CO_2 storage where it is buried at depths of more than 800 m.

The UK site in the northern North Sea was chosen to provide an example of the characterisation of large-scale offshore geological storage in saline aquifer sandstones in an area of active oil and gas production. Rocks under the North Sea are well known from exploration and production of oil and gas but most North Sea rocks contain brine. Deeply buried sandstone rocks containing salt water, *i.e.,* saline aquifers, have Europe’s greatest potential for the offshore geological storage of carbon dioxide gas. The Captain Sandstone and a hydrocarbon field, considered together, were assessed as an example of a multi-store site.

The reservoir rocks of oil and gas fields are known in great detail but their capacity to store carbon dioxide is considered relatively small (mostly tens of million tonnes) compared to the potential capacity of saline aquifer sandstones (hundreds to thousands of million tonnes).

Oil or gas fields are expected to be used for the first pilot and demonstration projects with the saline aquifers providing larger commercial-scale storage capacity. A realistic forecast of injection into this feasible multi-store site has been made over a period of 20 years at a rate of 5 million tonnes per year suitable for the storage of large volumes of carbon dioxide expected to be captured at existing and planned industrial plant.

Built on existing knowledge and reported storage site screening, storage capacity evaluation, data evaluation and access, data interpretation, static geological model construction and attribution, site characterisation and reported results of hydrodynamic simulation work (SCCS, 2009 and 2011; Jin *et al*., 2012), SiteChar research has greatly advanced understanding of the Outer Moray Firth site for CO_2 storage at a level of detail not investigated by the previous studies within the extent of a feasible storage site.

3.3.2 What was achievable and why

The objective of the UK northern North Sea site was to prepare a 'dry-run' application for a storage permit appropriate for any future multi-store site in the UK North Sea based on storage site characterisation, social site investigation and a techno-economic assessment undertaken within SiteChar.

The research was based on existing knowledge and publicly available data. In particular, previous research had deemed the sandstone as feasible for geological storage of CO_2 justifying further investigations in SiteChar. Selection of the hydrocarbon field component of the multi-store site was informed by assessment of suitability for CO_2 storage and calculated static storage capacity. The field was selected because it met geotechnical criteria and was large enough to hold at least 20 Mt CO_2. Availability of sufficient data to inform site characterisation was an important criterion when selecting the hydrocarbon field component, in particular, a released 3D seismic survey acquired in 1992 and data available from twenty-four wells within the extent of the field. Published peer-reviewed data on the sandstone and the field were used. During progress of the SiteChar research in 2011, much detailed additional information on site characterisation for CO_2 storage within the Captain Sandstone at the Goldeneye Gas Field further east became publicly available. Based on these data sources, detailed studies by specialist researchers informed a high level of technical site characterisation.

SiteChar researchers included key experience and expertise in previous screening, selection, interpretation, construction and attribution of the basin-scale static geological model allowing a ready understanding of the geology, data sources and use of existing basin-scale model.

Familiarity of the UK CO_2 storage regulations and their application to offshore storage sites within the research team guided the risk-led investigations and informed contributing researchers of the required output from site characterisation.

A high level of site characterisation was undertaken within the resources of a research project, sufficient to prepare an application containing the required technical components of the 'dry-run' permit application.

- Site characterisation for the Outer Moray Firth site has been risk-led, *i.e.,* driven by an assessment of risks to the prospective site that identifies issues to be investigated by all activities that are part of the site characterisation. This includes geological static modelling, well integrity evaluation and modelling, regional migration analysis, fluid flow simulation of CO_2 injection and water production, geomechanical stability assessments, geochemical evaluation and review of shallow geohazards in the vicinity of the site.
- Completed technical site characterisation and risk reduction results informed preparation of a monitoring plan for the site including a feasibility assessment for monitoring by seismic survey.

- Preventative measures and corrective measures plans which are essential components of the storage permit application and which draw on the technical site characterisation results, were also prepared.
- The application also describes and distinguishes where additional site characterisation would be undertaken and risk reduction activities should be completed.

Special interest has been put on the investigation of the relationship between carbon dioxide injection into a hydrocarbon field and the associated saline aquifer sandstone because, for commercial-scale storage, injection into the sandstone may start while there is active production from nearby oil or gas fields. The changes in pressure from injection of CO_2 into both types of store during and after injection have been calculated.

- The impact on the saline aquifer sandstone of injection into the depleted hydrocarbon field without mitigation of pressure relief produces reservoir pressures that approach the cap rock fracture pressure. Injection of CO_2 into the saline aquifer without pressure relief would also exceed fracture pressure. Neither injection scenario would be an acceptable injection strategy for CO_2 storage. Whereas, injection of CO_2 into the depleted field with pressure maintenance by water production from the saline aquifer ensures reservoir pressures remain less than one third of the predicted cap rock fracture pressure.
- There is either no effect on reservoir pressures at individual hydrocarbon fields within the vicinity of the storage site, with the modelled injection/production scenario, or a modest drop in pressure at commencement of injection followed by a gradual increase in reservoir pressure. Adjustments to the injection should be evaluated to minimise any disadvantage and maximise any advantage to other hydrocarbon fields.

The planned site characterisation and analysis were completed at first-pass level illustrating where additional investigations could greatly enhance and refine understanding of a proposed storage site if more resources had been available:

- Refinement of facies attribution using well data;
- Optimisation of storage capacity by hydrodynamic modelling of different injection and production wells;
- Fine-scale modelling of the storage complex to refine the predicted extent of the injected CO_2 plume;
- Modelling of geomechanical stability using the scenario with combined injection and water production;
- Modelling of the quantity of wellbore leakage for a much shorter period equivalent only to the duration of injection and a period of decline to ‘back ground’ reservoir pressure;
- Modelling of geochemical reactions with CO_2 in an oil field rather than inferring the effect from modelling of a gas field;
- Feasibility studies for all the proposed site monitoring techniques.

Testing and refinement of the site characterisation modelling activities using data sets that are not publicly available and confidential to the operator could include:

- Well cement bond logs and abandonment logs to inform well integrity assessment;
- Hydrocarbon fluid property data for simulation of CO_2 injection;
- Rock property data for geomechanical stability assessments;

- Fracture imaging and well break-out data for fracture network prediction;
- Pressure data for history matching to test reservoir facies attribution;
- Pressure data from other adjacent fields to assess the sealing properties of faults and boundaries;
- Impact and effect (positive or negative) on adjacent fields from the operator’s perspective.

3.3.3 Lessons learnt regarding the understanding of site characterisation

Even sites with abundant data will require information derived from other sources as input to site characterisation.

The larger size of CO_2 storage sites, compared to hydrocarbon fields, requires careful consideration of model grid size and computer capacity to ensure calculations can be achieved within the available computing infrastructure and time scales.

All site characterisation activities must be undertaken as a single fully integrated investigation with iteration of results between activities; results from one activity feed into another and demonstrate where risk-led investigations can be targeted. In practice it is also most important to test exchange of data between activities before the choice of modelling platforms is made. A single static geological modelling format must be used for all predictive activities.

Scenarios with injection into aquifers will generate higher reservoir pressures than storage within depleted hydrocarbon fields due to the greater compressibility of remaining residual hydrocarbons relative to fully water-saturated strata. In this context the extent of the pressure footprint and pressure management is a key issue, particularly with other users of the pore space.

3.4 The ‘dry-run’ storage permit developed at the Vedsted site, Denmark

3.4.1 Site and level of site characterisation undertaken

The Vedsted site is an onshore aquifer in sandstones of Upper Triassic-Lower Jurassic age at 1800 to 1900 m depth, situated in the northern part of Denmark close to the power plant ‘Nordjylland Power Station’. The target reservoir is situated in a small graben bounded by northwest-southeast trending faults and is part of a larger graben structure, the Triassic rift system forming the deep Fjerritslev Trough. The reservoir is of marine to fluviatile sandstones sealed by a thick package of marine claystones of the Jurassic Fjerritslev Formation.

The storage concept is a four-way dip closure for the reservoir. The bounding faults for the graben structure are outside the extent of the lowest closing structural contour. Further it is assessed that no major faults will constrain the plume development inside the structure. Minor faults exist on the structure but the fault properties are difficult to evaluate.

Hydrocarbon exploration campaigns during the 1950’s discovered the closure and a single exploration well was drilled on the structure. The well was dry and abandoned shortly after with only a sparse log suite acquired. The sparse well data in combination with only a few 2D seismic lines challenge the site characterisation.

A first estimate for the storage capacity for the site indicated that the storage capacity exceeds the potential captured CO_2 volume from the power plant in a 40 years lifetime and a nearby cement industry could potentially be phased in.

The characterisation of the site should meet the challenges with the sparse data set and evaluate that the expected stream of captured CO_2 could be safely stored.

3.4.2 What was achievable and why

The objective for the Vedsted site was to complete a site characterisation comprehensive enough to fulfil a ‘dry-run’ application for a storage permit. This has been achieved including geological, hydrodynamic, geomechanical characterisation of the site together with a comprehensive monitoring strategy.

The study of the Vedsted structure was carried out at a stage where the existing data have not been supplemented with new data. Among others, uncertain input includes:

- Geometry of the sandstone reservoir units and any lateral variations in porosity and permeability;
- Geometry of the mudstone layers, their lateral continuity and sealing potential, including effective permeabilities and their capillary properties;
- Possible regional trends in proportion of sandstone or other parameters across the 50 km width of the model;
- Properties of the intra-reservoir sealing layers;
- Possible presence of faults compartmentalising the reservoir sandstones and properties of the faults;
- Conversion of porosity model to fluid permeability.

The research has in particular investigated different ways to supplement the sparse data set usually available from saline aquifers only investigated by unsuccessful hydrocarbon exploration. By incorporating all existing geological knowledge on a regional scale, a site model was constructed that could be used with enough confidence to characterise the storage complex and the hydrodynamic behaviour during the injection operation. Some scenarios were run or envisaged to handle the uncertainties due to the lack of data, in particular on the petrophysical properties distribution, faults distribution and regional knowledge to infer boundary conditions in the models. To allow the operator to capture the early reservoir response data for performance matching with predictions of reservoir response (mainly pressure) and refinement of the reservoir behaviour modelling, it was decided to design the injection plan as a ramp scheme with a gradually rising injection rate, starting with a single well.

There was a special interest in exploring the impact on the surrounding region, especially the pressure development in the saline aquifer and any possible effects in the overlying layers for the single onshore site. Undesirable pressure development can be mitigated by pressure relief by net water production. It was found that the EC Storage Directive does not provide any clear definition on how much the pressure can increase in the surrounding areas of a site which might have given some implications for the definition of the storage complex. Environmental handling of excess water production was not addressed and considered to be out of scope for the present project.

Coupled hydrodynamic and geomechanical modelling were conducted on a reservoir model including the overburden. No dramatic geomechanical issues for the injection operation were identified. A methodology for setting up coupled hydrodynamic and geomechanical modelling was evaluated.

Hydrodynamic modelling helped to design a monitoring program and assure the best risk management. It was assessed that geophysical monitoring techniques are most suited for monitoring the site together with monitoring well(s). Modelling the extent of the CO_2 distribution also helped designing and acquiring a baseline study for any CO_2 leakage. Due to logistical challenges the baseline study had to be conducted in a different but analogue field area. Two soil gas surveys were acquired during the project and revealed the natural variation in the sampled soil gasses.

Risk analysis carried out for the storage project pointed out the old exploration well, Vedsted-1, to be a potential risk for leakage. The well was not abandoned in compliance with present day regulations, mostly due to insufficient cement plugs. A comprehensive well integrity study concluded that a well re-intervention to properly plug and abandon the well was suitable and cost efficient.

All issues in the EC Storage Directive could not be addressed in the study due in particular to

- The limited resources for acquiring new data and performing very comprehensive studies;
- The lack of production data for history matching and well tests to calibrate the hydrodynamic modelling;
- The necessity to perform baseline surveys at Voulund considered as an analogue site of the Vedsted site, since it presents similar climate, shallow geology, topography, land-use *etc.*

A comprehensive but preliminary site characterisation was achievable, even if the sparse data set was a limiting factor.

3.4.3 Lessons learnt regarding the understanding of site characterisation

Aquifers with sparse data can be characterised. A ‘dry-run’ storage permit application has been developed in compliance to regulation based on an incremental development to reduce risks and costs and increase confidence by integrating the learning of the ramp-up period. A strong interplay between the Competent Authority and the operator is needed to reach a common understanding of the specifics of the site, an agreement of the objectives of the characterisation to be carried out and an agreement on the performance conditions.

It is believed that a characterisation procedure suitable for an onshore site with sparse data is presented. Incorporating all existing data and the regional geological understanding is vital for the procedure.

As for the Outer Moray Firth site, the characterisation of the Vedsted site and the different elements of the storage permit has been driven by the risk assessment.

Following the nine steps of a site characterisation procedure outlined in the introduction, it was found that preliminary static geological and fluid flow modelling helped identify the potential risks for a safe storage operation. It actually appeared very useful to start fluid flow simulations as early as possible even with very simplistic and premature models. Model complexity can iteratively be incorporated at different scales as the project involves and knowledge enhances. In addition, preliminary modelling also helps identify the need for any new data acquisition and data analysis.

Lack of production data or well test data limited any calibration of the different models, but it is believed that a suitable model framework is constructed to guide an exploration/appraisal drilling campaign on the structure and subsequent testing.

Pressure management is very important for an onshore site and overpressure mitigation through water production is required.

3.5 Recommended process

The permitting process considered in SiteChar combines both the exploration permit and the permit to inject.

3.5.1 The different steps of the permitting process

The first step is the site selection that relies on a screening of geology at national or regional scale to identify large areas of potentially suitable sedimentary basins. Basins can be assessed and ranked using criteria such as storage capacity, injectivity potential, containment, site logistics, existing natural resources, *etc* which was conducted before the SiteChar project for most of the sites considered here. The SiteChar research focused on the characterisation steps which are described in Neele *et al*. (2013):

- *Risk assessment*, which starts at the beginning of the project so as to initialise the risk register and drive the characterisation activities that aim at reducing risks and uncertainties;
- *Static geological model building* to gather the geological characterisation of the site;
- *Hydrodynamic modelling* to simulate the behaviour of the CO_2 in the store and which is the basis for the prediction of the storage performance;
- *Geochemical analysis* to study the reactivity between the CO_2 and the store, both short-term and long-term;
- *Geomechanical analysis* to study the mechanical stresses induced by the storage process and investigate the geomechanical integrity of the storage;
- *Well integrity analysis* to analyse the safety of the wells and set up remediation plan where necessary;
- *Migration path analysis* to evaluate potential leakage paths out of the store;

All these activities inform the risk register that is thus updated and drives the purpose of the research. Results of these activities finally inform:

- *Monitoring plan*, to confirm modelling prediction, check the conformity with regulation and environmental policy and ensure the safety of the storage in the long term;
- *Remediation and mitigation plan* to identify corrective measures in the case of leakage or significant irregularities.

In parallel to these activities, two analyses have to be conducted:

- *Economic analysis;*
- *Public engagement activities*.

Integration between disciplines is a key for a successful characterisation: the level of integration must go up to the level of providing mutual understanding of key issues among each discipline.

3.5.2 Schematic timelines

The characterisation conducted in SiteChar, undertaken from the perspective of a ‘dry-run’ storage permit application, has allowed presentation of a schematic characterisation timelines (Figures 3.1a and 3.1b).

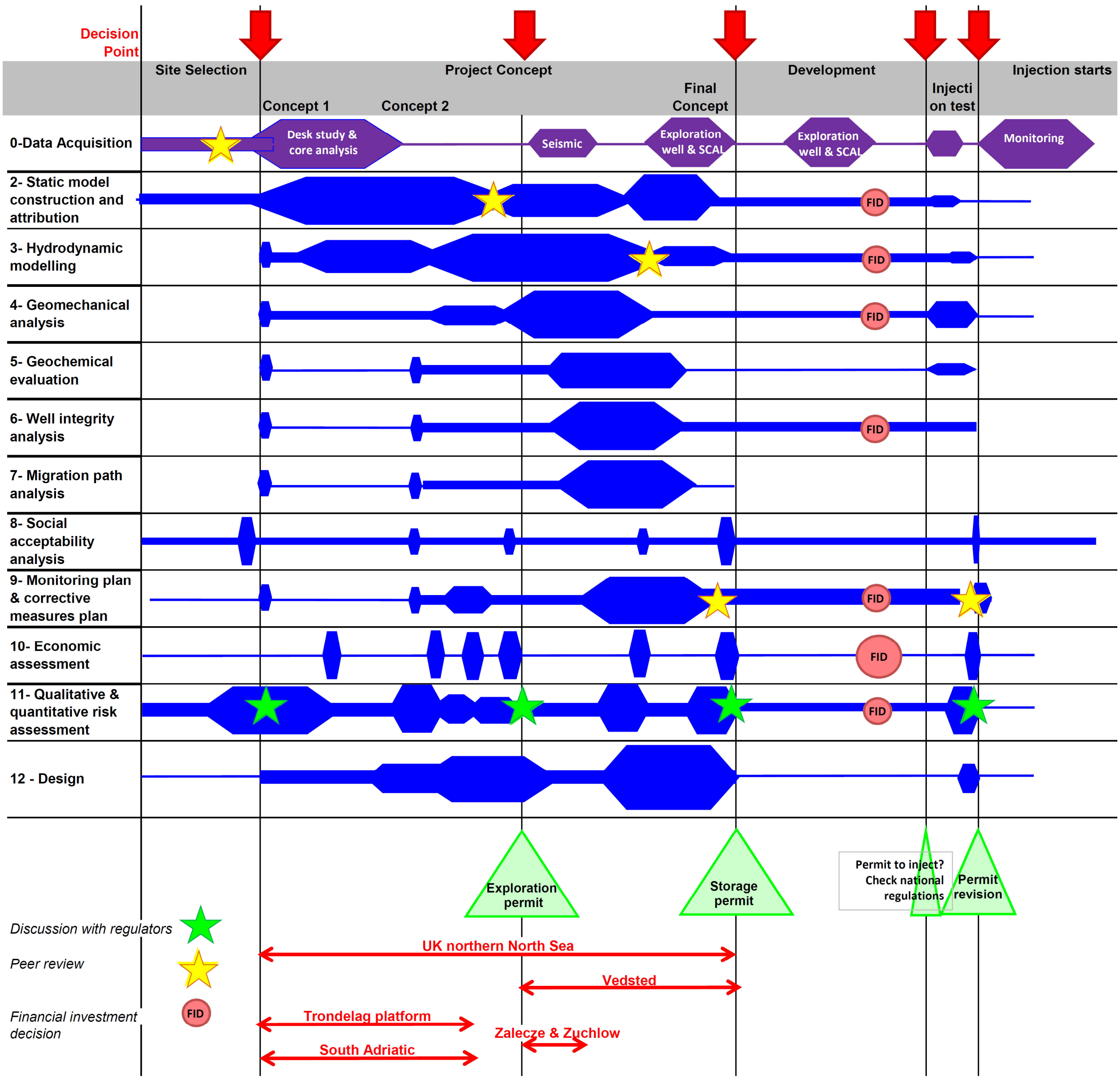


Figure 3.1a. *SiteChar recommended process. This timeline has to be understood as schematic, the height of the different boxes roughly indicating the amount of work required for each step of the workflow.*

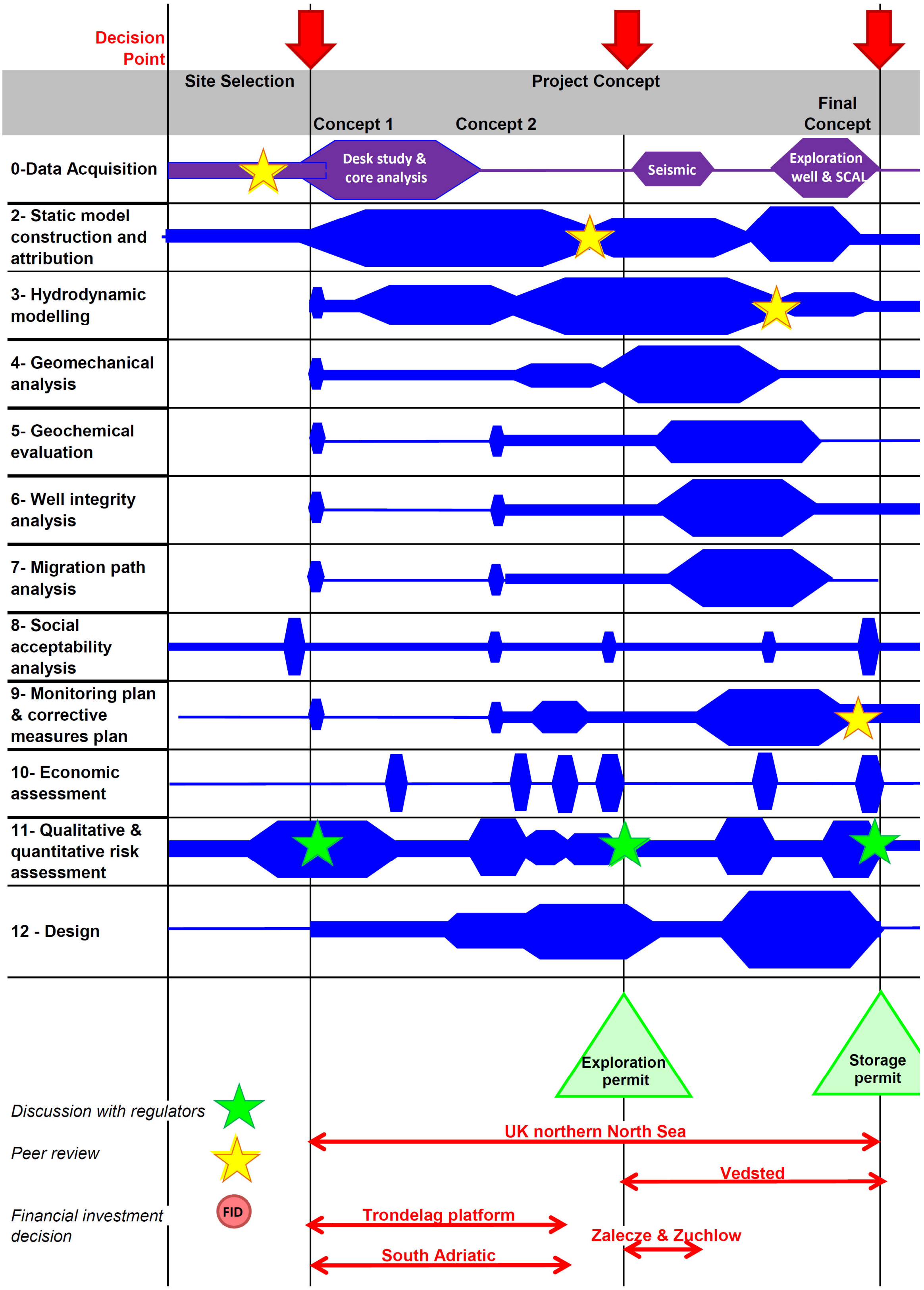


Figure 3.1b. *SiteChar recommended process. Zoomed-in on the project concept stage.*

The duration of the whole process is roughly three to five years. Although indications of duration and staff effort are given for the component site characterisation activities, based on the experience in SiteChar, each is not conducted in isolation from the others. Awareness of, input of requirements to and consideration of the implications of results from the other site characterisation activities is a key learning from the SiteChar research. The estimated duration and staff effort, summarised by activity in the following paragraphs, are solely for the technical components of site characterisation. Additionally, interaction with the other activities requires participation throughout the duration of the technical site characterisation work (Figures 3.1a and 3.1b).

- *Data acquisition.* The duration of this phase is very site specific. For the Vedsted site where existing data were available, it lasted approximately three months (around two man months). However acquisition of new seismic data is recommended. This would require two additional months for the design (two man months), three additional months for the survey (ten man months) and three months for the processing (three man months). For the UK North sea site, within a mature oil and gas province, much data have been previously acquired as part of commercial hydrocarbon exploration and production. The data collation activity comprises a review of data, their quality, availability and cost. Selection of data, negotiation of licence agreements and costs and delivery and checking of data may take only four months, but up to six months should be assigned to ensure a realistic estimate of the time needed to acquire data. The staff effort to review the data, discuss data requirements with the broader site characterisation disciplines and negotiation of the data access terms requires between around one and two months, engaging two or more individuals. No processing of data is presumed in this estimate.

- *Static geological model construction.* The construction of the static geological model can be very time consuming, up to one year. It took four months for the Vedsted site, but the update with the new additional seismic data would require approximately six additional months. This makes around five to ten man months in an iterative process. For the UK North sea site, the construction of a detailed 3D model benefited from previous work and availability of already constructed models but required considerable effort to present a model suitable for hydrodynamic modelling of CO_2 injection. Interpretation of the abundant seismic and well data, construction of 3D geological surfaces, and merging of the site model within the existing basin-scale geological model was of nine months duration. Generation of a geocellular model and attribution with geological properties require careful consideration of the data and are likely to require several iterations with the geological model to gain a reasonable representation of the properties and attribution of the modelled strata. For the UK site in SiteChar, the duration of static geological model construction was in total more than one year, due to difficulties experienced with the modelling software but such an experience might be expected for any part of the complex activity. Staff effort for the construction of the static geological model was around seventeen months. However, this should be considered a low value as the basin-scale model was already available and an additional staff effort of at least four months should be assumed for regional scale modelling of geological surfaces.

- *Hydrodynamic modelling and geomechanical modelling.* Hydrodynamic modelling requires at least eight months (and eight man months). For the Vedsted site, four months were required for the fluid flow simulations and six additional months to couple fluid flow and geomechanical modelling. Six months are also necessary to design the development plan. For the UK North sea site, hydrodynamic modelling and geomechanical modelling, like the static geological modelling activity, were similarly essential but time consuming components of site characterisation. Both activities were of approximately of six months duration running concurrently with close interaction between the activities. The staff effort within both activities is at least six months with a combined total of around twelve man months.

- *Geochemistry.* Geochemical analysis took three months at the UK North Sea site. Such an analysis was not performed at the Vedsted site but four to six months (two man months) are estimated to perform laboratory experiments and geochemical simulations.
- *Well integrity analysis.* Depending on the data availability, assessing well integrity can take between one to three months for a few wells. For the Vedsted-1 well, it took five months (four man months) including the collection of proper data, the analysis itself, the workshop dedicated to the related risks, the investigation of the different mitigation options as well as the estimation of the associated costs. For the UK North sea site, two wells were investigated for integrity analysis as cement bond log data were only available for these wells and one was chosen for further analysis. Approximately two months of staff effort was expended on analysis, including iterative modelling to accommodate the results of hydrodynamic and geomechanical modelling in two periods of activity. Twenty five wells lie within the predicted maximum plume extent of the injected CO_2 indicating the increased effort that would be needed to adequately analyse all the wells at the UK site.
- *Migration path analysis*. At Vedsted, it was included in the design of an injection strategy (two man months). For the UK North sea site, qualitative migration path analysis was conducted by ‘fill and spill’ modelling, substantially and excessively over filling the storage site. Approximately two person months were used. If quantitative analysis of volumes and timing of the CO_2 migration were undertaken, additional effort would be required.
- *Social analysis.* Social site characterisation is a crucial component and shall be conducted throughout the duration of the characterisation project. For the UK North sea site, social site characterisation, interaction with the public and local stakeholders and public information activities commenced before the technical site characterisation and was of approximately eighteen months duration. The activity, which took approximately seventeen man months of effort, was for a generic, hypothetical storage site in an offshore setting. For a real commercial storage site, with an industry operator, onshore industrial source plant, onshore to offshore CO_2 transport infrastructure and an offshore injection and storage site, many times the amount of social analysis and public information and awareness activity would be a necessity.
- *Economic assessment*. Some economic assessments and updates are performed at different phases of the project to allow decision. Around three months are required for such an analysis.
- *Monitoring plan and corrective measures*. At Vedsted which is an onshore site where monitoring is most important, the design of the monitoring plan and corrective measures plan took six months. Two baseline surveys of three months each were conducted and four months were necessary for the data analysis. This required twenty man months, including the risk workshop. Monitoring and corrective measures planning for the UK site was of relatively short duration, three months, including approximately one month each for the two activities. Additionally, the monitoring plan incorporates a feasibility study for the use of 3D seismic survey, taking three man months and conducted prior to monitoring planning. Seismic survey is one of the six main regular monitoring methods proposed in the plan. It is unlikely that a similar staff commitment would be required for each method but effort to test the feasibility and cost-effectiveness should be included for each.
- *Risk assessment*. The initial risk assessment requires about two months, but is ongoing all throughout the project driving the characterisation. Around five man months were spent at

Vedsted for this task. For the UK North sea site, a similar amount of staff effort was expended in an initial risk assessment, communication of the risk reduction activities to and between the technical site characterisation team and risk reassessment. The effort by the risk assessment staff was approximately two to three months throughout the two-year duration of the technical assessment. This does not include the participation, interaction and contribution of the technical participants in the risk assessment activities which is estimated to be between 10% and 15% of the technical site characterisation work.

- *Development design.* For the Vedsted site, six months were initially necessary to define the project concept, but this task is then ongoing all along the project taking into account the progress of the characterisation. For the UK North sea site, the project concept evolved during the progress of site characterisation based on the results of the technical findings. The storage site design, from outline concept, through testing by geological, hydrodynamic and geomechanical modelling to decision on the injection scenario and placement of injection and production wells was of two years duration. The effort was by contribution from all technical contributors.
- *'Dry-run' permit development.* For the Vedsted site, the development of the 'dry-run' application took three months (three man months), incorporating the research results and testing the regulations requirements. For the UK North sea site preparation of the 'dry-run storage permit application alone was approximately two and a half months of staff effort. However, this does not include the underlying effort in preparation of a preliminary application, discussions with regulators and interaction with technical contributors on risk reduction throughout the duration of the site characterisation project.

3.5.3 Discussion

The distribution of effort presented in the SiteChar timeline (Figures 3.1a and 3.1b) emphasizes the concurrence and interaction of all technical and social site characterisation activities. A significant finding of the SiteChar research is the degree of interaction that is required by all technical participants if they are to collectively contribute to the risk reduction activities that are the basis of the storage permit application. Effort is well spent on the integration of technical contributors in the risk assessment and reduction process to ensure resources are targeted to meet the needs of a storage permit application. This is an unfamiliar and significant effort for technical researchers but essential to effectively reduce risks to ensure containment of CO_2 within the subsurface.

The much greater resources available for storage site characterisation by a commercial, industry-led CCS project, relative to those available to the SiteChar research project, would not significantly change the distribution or interaction of the activities presented in Figures 3.1a and 3.1b. Rather, the amount of effort would be scaled up, *i.e.,* all risks would be reduced to as low as reasonably possible with corresponding preventative and corrective measures rather than only those most highly ranked in this research project. Also, the increased input of effort might not proportionally extend the duration, if a larger number of expert contributors participated in each activity.

The contrast between the site characterisation activities needed for the 'dry-run' storage permit applications for the Danish Vedsted site and UK North Sea site is not between an onshore or offshore setting, hydrocarbon field versus saline aquifer sandstone, but in the data available on which to undertake characterisation and corresponding balance of activities. The objective of site characterisation is to reduce risks sufficiently to demonstrate understanding of a prospective site for a regulator to award a storage permit application; where data are few and sparse a greater proportion of effort is required to model and predict the effect of risk reduction activities, whereas where data are abundant more effort is required to incorporate, integrate and resolve data in the risk reduction activities.

3.6 Lessons learnt

3.6.1 Project concept

The project concept needs early definition and is likely to be revised to take into account the progress of the characterisation. The results of even the earliest site characterisation activities will feedback and revise the project concept. It is likely that initial results may lead to significant revision to the storage concept and injection scenario, with later results leading to progressive refinement of storage site design. It is essential that the results from each site characterisation activity are discussed with all other fields of site characterisation expertise and the implications to the investigations and parameters used are fully understood whether investigations have not yet started or are in progress. This will ensure that all site characterisation activities coherently address risks to produce a revised and evolving project concept. In addition, metrics need to be defined on cost and storage capacity to allow evaluation of the predicted storage site performance.

A site characterised with abundant data will have a degree of uncertainty associated with each data type. A storage site with sparse data can be characterised. It requires greater input into the anticipation of risks and possible alternative site parameters. It is suggested an incremental development to reduce uncertainties, risks and costs, providing confidence and enabling the learning from the ramp-up period to improve future operations and extrapolation of site performance.

Pressure management looks necessary for most saline aquifers because of the lower compressibility of strata with 100% water saturation relative to the higher compressibility of any remaining hydrocarbons in a depleted field. Injection pressures are higher, accommodating lower storage capacity at injection rates less likely to threaten cap rock fracture pressure. Saline aquifer stores may need to assume pressure relief, for example, by water production or other methods.

Possible issues associated with water disposal have to be investigated. Treatment to meet environmental standards of water produced together with hydrocarbons and discharge is common practise in the UK sector of the North Sea. However, there are cost implications when the storage site is within a depleted hydrocarbon field. Where storage is solely within an aquifer and produced water is brine, dialogue with the regulator will indicate what level of testing and treatment might be required or what level of testing is required to demonstrate treatment is not needed. Other North Sea nations do not permit discharge of produced water by re-injection into subsurface strata. In this case, as for onshore storage, water disposal might be an issue.

3.6.2 The site characterisation workflow

Clearly the site characterisation has to be fit-for-purpose depending on the site-specific characteristics, the available data, the project concept and the uncertainties and the risks to be investigated.

Characterisation of a site for the purpose of obtaining a CO_2 storage permit is a risk-based process aiming at demonstrating safe and permanent storage. Risk analysis defines the scope of the site characterisation work that iteratively determines and constrains risks, intending to reduce their consequence and/or likelihood to As Low As Reasonably Practicable (ALARP) levels and determines the extent to which these can be mitigated.

Undertaking risk reduction-led site characterisation investigations on existing available data aims also to reduce uncertainties as to what is available, and to identify gaps in knowledge.

3.6.3 Available data and knowledge

Some key data are not available for most sites, among others:

- *The distribution of porosity and permeability* are most often poorly known. Attribution of 3D cells that comprise the static geological model porosity is an output that informs both the hydrodynamic simulated injection of CO_2 and geomechanical modelling. The results of the hydrodynamic modelling were found to be very sensitive to the geological model attribution so that the distribution of porosity and permeability remains a significant uncertainty in the character of the storage site. Alternative methods of attribution, by stratigraphical unit and by facies, have been published or investigated in SiteChar. Because of the constraints of a research project, the character of geological facies and their distribution in the subsurface, where informed only from seismic survey and well data, were too poorly known within SiteChar and are likely to always be associated with a degree of uncertainty. The attribution of the geocellular model thus requires much investigation, including modelling of alternatives and assessment of their probability of occurrence, to enable the greatest degree of refinement.
- *The initial pre-injection stress state for storage site strata* is an essential input to the assessment of any geomechanical instability induced by CO_2 injection. Such data inform the calculation of conditions predicted to either maintain storage site integrity or likely to cause failure in the reservoir and overburden formations. Well log and well test data needed for the calculation may be confidential to a hydrocarbon field operator and not publicly available. Publicly available data from the nearest available hydrocarbon field, Goldeneye Gas Field, have been used for the UK site in SiteChar demonstrating the importance of public release of subsurface data to inform storage site characterisation and appraisal.
- *Boundary conditions for fluid flow simulations* are influential parameters for detailed studies of injection and filling strategies, with limited size site models. They must be managed with proper and correct procedures based on information about the hydrodynamic behaviour at regional scale.
- *Cement Bond Log and well completion data* are often not available whereas existing wells or boreholes, that may or may not be abandoned, are amongst the highest risks as potential leakage points for geologically stored CO_2. Well integrity modelling calculates the volume of CO_2 that migrates via a possible leaking wellbore though the overburden to secondary storage strata or to the Earth's surface. Without the information on how the well has been completed and cement bond log data, a 'worst case' must be assumed for all wells within the predicted migration footprint of injected CO_2 yielding an overly pessimistic assessment of the potential for leakage via wellbores.

It is important to keep in mind that data are interpreted only when both data and experts are available. The wide range of specialist fields of investigation that together comprise a site characterisation team spans many disciplines of expertise. Some of the data sets used are in common; results to update and revise these data sets must be kept current for all participants, but some are unique for a given activity. The involvement of the specialists themselves, by the nature of the requirement of their own expert input to different projects, is much sought and needs to be timetabled. Inevitably, the optimum critical path through the site characterisation workflow can be impeded by the lack of data required when the expert investigators are available to do the work. Care should be taken to ensure contribution of a technical site characterisation is not undertaken before relevant data and input of results from other disciplines are available. In addition all participants should be aware of revisions to the project concept, the implications of results from one discipline is openly discussed with all contributors, and changes to the storage project concept and parameters used for modelling are fully understood. Such a consideration makes site characterisation most often longer than the optimum critical path but the very positive implication is that all the site characterisation results contribute to risk reduction of the revised project concept.

3.6.4 Reducing and managing the risks

The first activity in site characterisation is a risk (and uncertainty) assessment based on the requirements of the storage permit application.

It is important to create and maintain as far as possible an exhaustive list of risks. During the site characterisation work the risks ranking, based on their impact and severity on one side and their probability of occurrence on the other side, may evolve. Of course, in most cases, it will not be possible to investigate all risks with a same level of detail.

Existing wells, either abandoned or not, are the source of the highest risks as potential leakage points for geologically stored CO_2. Well integrity assessment is a very time consuming activity that requires individual studies of each well within the plume footprint.

3.6.5 Economic viability

Even if the cost of storage is considered much smaller than the cost of capture, the development of a storage site can require many years of effort and cost hundreds of millions of Euros (IEA, 2013). Even with this expenditure, the investigation may not lead to a successful award of a project storage permit.

It is difficult to get relevant information about the costs of the different elements of a storage project unless it is a real and well advanced project. It seems also hazardous to extrapolate costs of one specific project to another one, even if they look similar. In addition, the large error bars associated with these costs make any comparison attempt difficult.

In this context, it is not possible to derive any meaningful average cost for a CO_2 storage site. The structure of costs for a CO_2 storage project is very heterogeneous and the storage cost is consequently very site-dependent. The main parameters are the site’s location (onshore/offshore), the amount of CO_2 stored, the duration of injection, the injectivity of the wells, the number of CO_2 injection and water production wells, and the possible necessity for water production and treatment. In addition, the seismic monitoring plan often includes many types of survey, used in distinct ways and with various frequencies. The strategy of the site development is also fundamental together with the technical choices, such as the timing, rate and duration of injection. The way monitoring is managed, using observation wells and logging has a strong impact on the estimated monitoring costs. Options to lower monitoring costs, such as permanent survey arrays, exist and should be further investigated. A fit-for-purpose monitoring approach should be followed, which includes (only) those monitoring techniques that best measure the site’s performance, in terms of permanent safe storage.

In addition to uncertainties related to the data themselves, main uncertainties in the costs come from the choice of economic parameters (discount rate, contingencies) and to the technical choice of operations. Within SiteChar, techno-economic assessments were carried on using an 8% discount rate. For projects of long lifetime such a rate hardly discounts the late cash flow, especially after 40 years, so that a discount rate of around 4% could be advisable.

Lastly, techno-economic evaluation raises questions to policy makers about the real lifetime of a CO_2 storage project: how long should the abandonment phase last; what is the associated cost and what is the real value of the liability transfer after 20 years of storage?

To counterbalance the CO_2 storage cost, policy makers are recommended to set up incentives, either through tax credits or public funding.

3.6.6 Public communication and participation

Early communication is a key for a successful dialogue with the citizens, even before deciding to explore the site, being transparent, and having open dialogue. It is important to relate CCS to climate changes, place the CO_2 storage project in the whole CCS chain from capture to storage and raise positive sites of CCS and to focus on the citizens' concerns, *e.g.* employment. Trust and transparency should be the key words when communicating with the public as well as developing the project in a democratic manner.

Such a process requires firstly a social characterisation of the area aiming at identifying stakeholders or interested parties and factors that may drive their perceptions of and attitudes towards CCS. Desk research, stakeholder interviews, media analyses, and a survey among representative samples of the local community are efficient tools to reach this goal. When this information is available, specific activities can be undertaken aiming at increasing public awareness about the scientific, technical and social aspects of CCS technology and secondly about the specific project. It is crucial to build trust, to create a safe environment in which citizens do not feel inhibited to express themselves. To this end, experts from research, politics, industry and NGOs are invited to discuss with citizens giving a balanced information so that citizens can form their own opinion. A new format for public engagement named 'focus conferences' was tested within SiteChar involving a small sample of the local community. A third step consists in making available generic as well as site-specific information to the general and local public.

It is important to note, that even if communication with the local community is crucial, communication at a higher level, *i.e.,* regional, national, European is also essential since citizens are not isolated.

4 Recommendations

Site characterisation for the purpose of developing a storage permit must be fit-for-purpose to demonstrate that the permit applicant has sufficient understanding of the site and that the proposed site operation will permanently and safely contain CO_2.

High-level objectives of site characterisation are common to all sites, reflecting the need to demonstrate permanent, secure containment of volumes of CO_2 at cost-effective rates. However, each site is unique and therefore even if site characterisation relies on a similar workflow, the scope and detail of site investigations will be intrinsic to each site.

Essentially the application is a statement of:

- Risk/uncertainty identification, mitigation and reduction through investigation;
- Risk/uncertainty reduction through design, based on site characterisation;
- Plan for monitoring of site performance;
- Plans for corrective measures to be implemented in the event of significant irregularities, *i.e.,* significant deviations from expected behaviour that might lead to unwanted migration, loss of efficiency or storage capacity or leakage.

4.1 Risk-assessment-driven characterisation

Site characterisation should be driven by activities to reduce risk and increase certainty in the prospective storage.

An assessment of technical and non-technical risks to the feasibility of geological storage of CO_2 at the site determines and guides site characterisation activities. The site characterisation is thus driven by the risk analysis that identifies priority areas of uncertainty on which to focus. The findings of the individual components of the site characterisation work allow the update of the risk and uncertainty register. This iterative process should involve the whole team of experts so as to ensure that the results of the characterisation are shared, the updated project concept, the revised parameters and the revised areas of research on which to focus are shared and investigated in a coherent approach by the different experts.

All identified risks should be addressed and mitigating activities followed to reduce risks to as low as reasonably possible. The level of effort and activities required to reduce either the probability and/or consequence that define a risk will not be the same for each risk: some will require considerable effort to achieve the acceptable level. However, since the risk ranking might evolve with the progress of the site characterisation and the evolution of the project concept, it is important to have a complete risk register, with risks ranked according to their impact or severity on one hand and their probability of occurrence on the other hand.

In addition to risks that typically relate to hazards, there will always be a certain level of uncertainty related to lack of knowledge or limit of observation. Site characterisation aims also at reducing the uncertainty in key storage parameters down to an acceptable level for decisions to award a permit to be made. However, a certain level of uncertainty will remain, which should be acceptable where the permit applicant has an appropriate plan to reduce uncertainties during the process of operating the site, for example by refining predictions of site performance through integration of monitoring data.

4.2 Multidisciplinary teams with close integration

Site characterisation is a complex interdisciplinary process that requires close working and integration between the disciplinary teams. Key to success is to ensure resources, time and effort are focused. In this context, feedback between teams is fundamental to achieve consistent site characterisation and a fully integrated storage permit application.

4.3 Discussions with regulators to agree risk and uncertainty

Because of the great variability of the storage sites, there is a need for dialogue with the Competent Authority, which should be started as early as possible. During the development of the exploration permit and then during the development of the storage permit, operators and regulators will learn about each other and build trust. They will also learn about the project, so as to reach a common understanding of opportunities as well as uncertainties and risks.

The Competent Authority will have to reach an agreement with the operator on the criteria for the site assessment and the acceptable level of certainty. Even if not explicitly required by the EC Storage Directive, Permit Performance Conditions (PPC) developed in SiteChar are considered a useful way to define and agree acceptance criteria against which a storage operation can be assessed. They are likely to be a combination of qualitative and quantitative metrics that would form conditions of the storage permit allowing both operator and regulator to demonstrate adequate performance during the operational and closure phases and providing a basis for the design of the geological monitoring program and the corrective measures plan.

Clear statements of confidence and uncertainty are required, as well as a clear plan for risk and uncertainty reduction during the process of operating the site, with an adequate baseline and an appropriate monitoring program to detect any irregularities. Sensitivity scenarios to explore different parameter uncertainties and geological solutions are useful to identify credible performance. They should be agreed with the regulators. Evaluation of a range of credible, if unlikely scenarios, are useful since they give the ranges of the impact of uncertainty on some specific parameters.

4.4 Data collation

Data collection is of course an important task that has to be started at the beginning of the project. It is recognised that even for sites have been explored by oil and gas industry for instance, there will always be some missing data. Experts have to deal with data unavailability, addressing data gaps through scenario modelling and sensitivity analysis.

4.5 Definition of the storage complex

In the authors' experience, the definition of the storage complex can be quite challenging. It is an important element of the storage permit since its boundaries define the leased volume for exploration, including injection tests if appropriate and also define CO_2 leakage, as any migration beyond the storage complex. Its definition will require consideration of plume migration, pressure response and management, as well as the locations of necessary monitoring.

In some cases, including the pressure footprint would require impractically large storage permit areas, since pressure responses can extend far beyond the injected CO_2 plume. In addition there is little consensus on the thresholds or consequences above which effects should be included.

A clear and prior agreement with the Competent Authority will be needed on the definition of the storage complex. In this context SiteChar recommends, at least for offshore sites, to define the complex storage by the maximum extent of the CO_2 plume, including CO_2-saturated formation water, plus a margin to enable monitoring to reflect inherent uncertainty in predictions.

4.6 Permit revisions when necessary

It is recognised that significant additional site characterisation will be undertaken after the storage permit has been obtained and injection has begun. It is thus recommended to include some flexibility in the storage permit to reflect changes in operation. This might be based on a prior agreement on conditions under which permits should be changed. There may be a number of situations under which the original conditions or project design can no longer be met and the storage permit conditions require revision. Conditions under which changes to permits might be considered, for example to reflect changes in operation, should be agreed during the initial permitting application. Whilst open-ended permits are not advocated, nor is it expected that the permit should contain a range of possible future scenarios that might occur, it may be useful to discuss and agree the circumstances under which permits might need to be changed. Legitimate circumstances under which a permit could be revised might include, for example, increased injection rates and third party access, interactions with other users or changes to the predicted plume migration. One approach might be to provide a ‘master’ storage permit with additional permits for specific activities such as drilling wells.

4.7 Pre-competitive characterisation

It is recognised that states have to pursue energy efficiency and that the only way to rapidly decarbonize energy is to deploy every climate change mitigation option. In this context CCS is not an option; it is mandatory to meet the 2020 target. The Member States and the European Union have a role to play in encouraging CCS, supporting site characterisation, reducing risks, and providing storage strategy. It also essential that both at European and national levels there is some cooperation to try to de-risk some of the costs associated with CO_2 storage.

The nature and extent of interactions with other users is a key consideration for regulators who will expect operators to establish potential impacts on pre-existing users of the surface and subsurface. However assessing any future uses of the subsurface and their interactions might be challenging for operators. It is recognised that the ‘state owner of the resource (pore space)’ may be able to give such an overview. Governments and national authorities should play an active role in CO_2 storage projects.

Publicly available site characterisation information

CO_2 storage projects are in operation in some places in Europe and worldwide. It is clear that, as for oil and gas exploration, these first projects will be the most expensive. However any progress on these sites will be worthwhile for other similar sites.

This is why it is essential to make publicly available site characterisation information as well as ‘learning by doing’ from the operation of real CO_2 storage sites. This also calls for public funding to support demonstration projects.

Communication and management of uncertainty

It is important to distinguish between uncertainty, *i.e.,* relating to the degree of confidence in knowledge of specific aspects of a site, and risks referring to the probability of certain hazards occurring. The assessment of site performance will always be associated with a degree of uncertainty. One of the objectives of site characterisation is to reduce the uncertainty in the understanding of the site to an acceptable agreed level for the storage permit to be awarded. This might be comparable to uncertainty reducing workflows within petroleum exploration, but here communication with the regulator is required. One approach to uncertainty assessment, used in SiteChar, is to organize one or more workshops to collect geoscience experts and stakeholder viewpoints. Focus should be put on assessing uncertainty related to parameters that have an impact on capacity and containment characteristics, as well as parameters that have a strong influence on predictions of site performance. Statistical approaches, including error propagation calculations, Monte Carlo simulations, and comparisons with analogues provide methods for further assessing specific sources and impacts of uncertainty.

Uncertainties can be further assessed by evaluating a range of scenarios and undertaking sensitivity analyses to determine those areas of uncertainty which might affect the predictions of site performance to the greatest extent. Characterisation will aim at reducing the uncertainty in the geological model and calibrating parameters with observations. However, the need for acquisition of additional data should balance the benefit of reducing uncertainty against the cost of the data acquisition. The operator will have to undertake the cost-benefit analysis to decide the appropriate level of risk reduction prior to permit application.

Data interpretation might lead to more than one potential ‘solution’ that could be applied to the static geological model construction. It is likely that the available evidence would indicate that one interpretation is more likely than the other ones and this will form the basis of the permit application. However other interpretations might be possible and the degree to which these would affect the model and its application should be discussed, such that the Competent Authorities can gain a full overview of the level of interpretation applied and acquired information during site characterisation.

However, even if the storage complex boundaries are defined by the CO_2 plume extent and not the pressure footprint, overpressure is an issue that requires appropriate boundary conditions for hydrodynamic modelling to enable correct prediction of the pressure development and history.

It would be expected that all predictions would convey, to the extent possible, the uncertainty or degree of confidence that could be placed upon them, both in the statements made and the figures used.

4.8 Site closure and the storage permit

As implied by the EC Storage Directive, the ‘dry-run’ storage permits developed in SiteChar have 20-year post-injection periods. If sites are performing as expected, operators may wish to transfer responsibility as soon as possible and before the end of the 20-year period. For the two sites considered here, both predict (albeit with limited simulations) that safe steady-states will be achieved relatively quickly and certainly a few years after the end of injection. It will be crucial therefore to agree, during permit negotiations, the exact evidence and PPCs that will be required to enable site closure and transfer of responsibility. Any uncertainty in conditions for site closure may delay Financial Investment Decision (FID). It is recognised however that this may be challenging due to the multiple Competent Authorities that might be involved.

4.9 Competent Authorities

Competent Authorities may wish to undertake reviews of history matching between observations and predictions throughout the project which may require technical specialists.

At the moment it is currently assumed that all sites will be closed and infrastructure removed. However it may be beneficial for some sites to be kept open and a Competent Authority may wish to extend the storage life of a site. The circumstances under which this might occur should be discussed during the permit application process.

The Competent Authority(ies) may need to undertake its own risk assessment and supporting investigations to provide guidance to operators, including around third party access.

5 Review of the EC Storage Directive and guidance documents on the geological storage of CO_2

5.1 The ROAD project

The ROAD project in Rotterdam (Rotterdam Capture and Storage Demonstration Project) holds the first storage permit issued under the EC Storage Directive[5]. The ROAD project has published a summary of the permitting process, which contains a series of lessons learned during the process of compiling the material for the permit application (ROAD, 2011, 2013a and 2013b).

The most relevant lessons learned by the ROAD project are:

- Close cooperation with authorities and regulators in an early stage of the project is essential due to the complexity of CCS regulation. The ROAD project team had dedicated permitting and regulatory affairs officers, who focused on the coordination of the permitting process, both internally and with external partners. These persons had frequent contact with the authorities and maintained a (two-way) flow of information.
- There must be an open exchange of data, results and ideas between the operator and the authorities. Exchange of content (data and results) will improve the understanding of the authorities of the project.
- The procedure must be agreed upon with the authorities as early as possible. Contact persons should be appointed on both sides, who are committed, accountable and have appropriate authority levels.
- The operator should make clear that it is committed to meeting deadlines. This implies that the operator should keep the initiative throughout the permitting process. It also implies that the operator should support (local) authorities where needed.
- The relevant ministry played an important role for the ROAD project, by coordinating and informing permitting stakeholders (mostly lower, regional and local authorities).

These recommendations underline the need for involvement of the Competent Authorities, throughout the permitting process. It is fair to state that for this first storage permit under the EC Storage Directive, the ROAD project and the Competent Authorities have worked together to solve all issues.

Some issues related to the documents to be provided for the storage permit are also mentioned (ROAD, 2011). The EC Storage Directive requires that all elements of the permit are completed upon permit application. However, elements of the permit can be finalized only once the whole information about the installations is available and the set-up of the storage site is finalized. That stage of knowledge is reached only after a financial investment decision is taken. It is recommended by the ROAD project to alleviate this aspect of the EC Storage Directive, allowing permits to be adjusted later on.

---

[5] The storage permit for the ROAD project is held by TAQA, the operator of the gas field that is used to store the capture CO_2.

5.2 Review of the EC Storage Directive and guidance documents

5.2.1 Detailed guidance on defining complex boundaries

The ‘dry-run’ permits developed here and review of the permitting process for the ROAD project[6] (ROAD, 2013a) indicate that further guidance is required on approaches to defining the storage complex. This is required because the complex boundary effectively defines the limit of acceptable CO_2 migration in the underground, beyond which any further movement of CO_2 is termed as leakage in the EC Storage Directive.

The largest issue faced in the SiteChar study was the extent to which impacts from pressure should be included when defining the storage complex, since in some geological storage sites, the pressure responses arising during injection could be observed at significant distances beyond the predicted extent of the CO_2 itself. Since the storage complex, as currently defined, must include ‘‘surrounding geological domain which can have an effect on overall storage integrity and security’’, it was felt that this could be taken to imply that the pressure footprint should be included. However, because of the potential for this volume to be very large and the lack of consensus on the thresholds above which the pressure response should be included, this is considered impractical. Indeed, during informal discussions, it was felt by some regulators, that such pressure responses should not be included by some regulators. However this was not necessarily the approach that would be taken by all jurisdictions.

It is therefore recommended to develop a methodology for defining the storage complex boundary which is acceptable to operators and regulatory authorities. This would allow a common approach to defining storage complexes in Europe which could facilitate CCS deployment. However, it is recognised that a single narrow methodology may not be appropriate in all jurisdictions and development of common agreed methodologies should not create barriers to wider deployment.

Furthermore, it should be emphasized that it is not advocated that the potential impacts of large pressure responses should not be addressed during the permitting process. On the contrary, it is clear that the potential impacts on other users of the underground is a prime consideration for authorities and is also highlighted as necessary information in ‘Step 1: Data Collection of Annex 1’ of the EC Storage Directive. This aspect of the storage permit was not tested in the ‘dry-run’ permit applications in detail, but it has become clear from trial permit development for the Blake Field that such potential impacts could require careful consideration by the operator and Competent Authority. It is fully expected that the applicant will undertake much of the evaluation of the potential impacts of their proposed operations on other users, and may need to make specific agreements with some of these users prior to submission of the permit application. However, storage permit applicants may not always be best placed to have all relevant information especially with regard to future planned uses of the underground. In these cases, the Competent Authority may also evaluate the potential impacts of a specific project on the longer term strategy for exploitation of the underground. Considerations might include requirements for the provision of additional storage capacity, including future needs for site characterisation in nearby structures, efficient use of CO_2 transport infrastructure, hydrocarbon exploration and production including unconventional hydrocarbon production, natural gas storage, groundwater use, and mineral production. Different regions identified as having significant storage capacity are also likely to have some or all of these additional uses, which may be regulated and promoted by a range of authorities, requiring some close integration. Further clarification of the roles of competent authorities is recommended to further highlight this issue.

---

[6] http://cdn.globalccsinstitute.com/sites/default/files/publications/94946/permitting-process-special-report-getting-ccs-project-permitted.pdf

5.2.2 Conditions under which permits might need to be changed

Article 11 of the EC Storage Directive recognises that storage permits may need to be changed once granted, and focuses particularly on circumstances where significant irregularities occur or other failures may require the operator or Competent Authority to change the conditions of a permit. However there may be other circumstances when storage permits might need to be changed that are not required due to detrimental situations. Such situations, *inter alia,* might include third party access requirements, changes to rates of CO_2 supply and changes in pressure regimes as a result of other activities in the vicinity. As described in Section 4, further guidance is needed to describe the process by which such permit revisions might occur and the permitting framework(s) that could be implemented to enable this without introducing barriers to further storage deployment. This might include a storage permit in which conditions describe the circumstances under which revisions and additional permits might be needed, *e.g.* permits for additional wells or changes to operations and injection schemes, or changes to monitoring.

5.2.3 Approaches to agreeing site performance

As discussed in Section 4, SiteChar ‘dry-run’ storage permit applications developed a number of metrics that enabled acceptable site performance to be monitored. These Permit Performance Conditions could be a useful basis for discussion between the Competent Authority and operator, helping to define and agree acceptance criteria against which the storage operation can be assessed. They are likely to be a combination of qualitative and quantitative metrics. Behaviour outside these conditions may be considered as significant irregularities and are likely to trigger corrective measures. Importantly however, where performance has been demonstrated to be acceptable as defined by such PPCs, there should be greater confidence between applicant and Competent Authority that sites will be allowed to be closed at the end of the injection period and that transfer of responsibility for the site will be granted. This would greatly improve confidence in the storage permitting process and provide further encouragement for operators to take final investment decisions.

Such an approach is not explicitly discussed in the EC Storage Directive but elaboration of the approaches that could be taken to defining such performance metrics would provide further clarity for applicants and authorities on ways of defining acceptable storage performance. It is recognised that authorities will need to retain rights to review the metrics and adjust the conditions of storage permits as either site-specific or other evidence becomes available during the operation.

5.2.4 Site Characterisation costs for permitting and FID

SiteChar has estimated the costs of site characterisation activities for a number of conceptual projects, at least to the extent possible in a research project with limited resources. The costs of characterisation, whilst considered likely to be modest compared to costs for other parts of the CCS chain and the capital costs required for site development, are nevertheless significant in absolute terms. In particular, the two case studies that advanced the most towards developing ‘dry-run’ storage permits for SiteChar concluded that further detailed site characterisation would be necessary before a full permit application could be made.

In some sites, where the prior availability of data and knowledge is restricted, exploration wells may be necessary to provide the information needed to create sufficiently constrained predictions of site performance, establish more precisely the expected injectivity and match capacity with expected rates of CO_2 supply. The data and knowledge derived from these detailed activities will be required to more fully develop key aspects of the storage permit, including the operational, monitoring and corrective measures plans which will be supported by the detailed risk assessment.

However, such exploration and injection testing, permitted during the exploration phase within the EC Storage Directive, is very expensive. It is not clear that operators would be willing to undertake such expensive activities prior to FID which might in turn require a storage permit to be in place. It might therefore be reasonable to grant storage conditional permits, requiring on further site testing resulting in further development of some aspects of the operational design as listed above. Of course, a permit could only be granted where evidence is provided to demonstrate expected safe and permanent containment.

It is recognised that this might be challenging for some Competent Authorities who might be rightly reluctant to grant storage permits on this basis. Nevertheless such storage permits could be granted, conditional on sufficient further evidence to demonstrate expected safe and permanent containment being provided as part of an application for a ‘permit to inject’, at which point all necessary requirements as described in the EC Storage Directive would need to be met. A similar approach has been taken, for example, with the ROAD project.

6 Conclusions

1. The SiteChar project has assessed some of the key steps required to make timely effective large-scale implementation of CO_2 storage in Europe by demonstrating the level of geological characterisation needed to meet regulatory requirements, in particular the EC Storage Directive. A methodology and best practice have been developed for the preparation of storage permit applications, incorporating all available technical and economic data, as well as some social aspects.
2. The development of 'dry-run' storage permit applications at two credible CO_2 storage sites allowed identification of effective approaches to site characterisation, enabling robust and defensible permit applications to be developed by operators. The review of these applications and the lessons learnt will help regulatory authorities to identify the necessary levels of evidence required to assess the safety, containment and capacity of a potential storage site. This report presents the SiteChar recommendations which will enable operators to address key issues for cost efficient and effective storage permit applications.

Focused site characterisation: the key to success

3. The research conducted in SiteChar confirms that appropriate site characterisation provides a route to successful storage operations. Key for success is to ensure that the characterisation activities are fit-for-purpose and focus on reducing uncertainty and risk for the specific site and the specific CO_2 storage project. This requires the Competent Authority and operator to share a common understanding of the site and the storage project. Site characterisation should demonstrate that the site has sufficient capacity to accept the expected CO_2 volume, sufficient injectivity to receive the expected rate of supplied CO_2, and sufficient containment to permanently store the injected CO_2. Consequently, it is recommended that the priorities addressed during site characterisation are driven by risk and uncertainty assessment, aiming to anticipate, reduce and mitigate risks and identify objectives for subsequent storage performance monitoring.

Challenge: storage complex definition

4. Practical approaches to defining the storage complex are required and have been developed. Recommendations have been made to improve and clarify the EC Storage Directive on a number of topics including the benefits of establishing Permit Performance Conditions, the circumstances under which permits might be revised, the role of Competent Authorities in evaluating the potential impacts of storage projects on other future uses of the subsurface and the challenges of planning all details of the operation prior to final investment decisions and subsequent site testing.

Uncertainties and site performance

5. Managing uncertainty and conveying the level of confidence accurately without undermining the safety case require specific attention. All predictions of site performance will carry a level of confidence and uncertainty and it will be important for Competent Authorities and operators to agree the levels of acceptable uncertainty as well as a plan for uncertainty reduction during site operation. This will be supported by a baseline site characterisation and an appropriate monitoring program to detect any irregularities. Definition of acceptance criteria is the key to determine what is good enough to gain a storage permit, allowing both operator and regulator to demonstrate adequate site performance both during the operational and closure phases and providing a basis for the design of the geological monitoring program and the corrective measures plan.

Site performance

6. A significant aspect of site characterisation activities will be establishing agreement on the level of adequate evidence needed to demonstrate permanent safe containment to enable the transfer of the site to the State. This transfer is expected to be planned from the beginning and prepared for during the process. If dialogue between Competent Authority and operators is ongoing and if the understanding of the site is appropriate, there is no reason for the site not to be transferred to the State at the legitimate end of the storage operation. Both operators and Competent Authorities will need certainty on the metrics by which the site performance will be assessed and safe, permanent containment demonstrated.

Outlook

7. Governments and national authorities should play an active role to make CO_2 storage projects part of a local political approach regarding energy as well as use of the subsurface. In particular, assessing interactions with other users is a key consideration for regulators but this might very be challenging for operators since such an assessment requires an overview of any future uses of the underground interactions. Management of pore space is also a strategic issue that could require an evaluation by both operators and relevant authorities to consider the efficient use of the pore space in the selection and operation of sites. There is a need for demonstration projects to fully test the regulatory requirements and investigate cost reduction at a much larger scale.

7 References

CHADWICK A., ARTS R., BERNSTONE C., MAY F., THIBEAU S. and ZWEIGEL P., 2008. SACS, Best practice for the storage of CO_2 in saline aquifers.
nora.nerc.ac.uk/2959/

COM, 2013. 180 - Consultative Communication on the future of Carbon Capture and Storage in Europe.
http://ec.europa.eu/clima/policies/lowcarbon/ccs/docs/com_2013_180_en.pdf

DELPRAT-JANNAUD F., AKHURST M., PEARCE J., NIELSEN C., LOTHE A., VOLPI V., BRUNSTING S. and NEELE F., 2013. Characterisation of storage sites: synthesis and lessons learned from the application of the SiteChar workflow. SiteChar Report D2.1.
http://www.sitechar-CO2.eu/

EC, 2009. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006. Official Journal of the European Union, L 140/114.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

EC, 2011. Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide – Guidance document 2 – Characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures.
ec.europa.eu/clima/policies/lowcarbon/docs/gd2_en.pdf

DNV, 2010. Guideline for selection and qualification of sites and projects for geological storage of CO_2.
www.dnv.com.au/binaries/CO2QUALSTORE_guideline_tcm162-412142.pdf

GCCSI, 2013. THE GLOBAL STATUS OF CCS, 2013.
http://www.globalccsinstitute.com/publications/global-status-ccs-2013

IEA, 2012, Energy technology perspectives: Pathways to a clean energy system, OECD/IEA, France.

IEA, 2013. Technology roadmap: Carbon capture and storage, OECD/IEA, France.
http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

IPPC, 2013. IPPC Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis Summary for Policymakers.
http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

JIN M., MACKAY E., QUINN M., HITCHEN K. and AKHURST M., 2012. Evaluation of the CO_2 Storage Capacity of the Captain Sandstone Formation. SPE 154539, Presented at the EAGE/SPE Europe Conference and Exhibition, Copenhagen, Denmark, 4-7 June 2012.

NEELE F., DELPRAT-JANNAUD F., VINCKÉ O., VOLPI V., NEPVEU M., HOFSTEE C., WOLLENWEBER J., LOTHE A., BRUNSTING S., PEARCE J., BATTANI A., BARONI A., GARCIA B. and AKHURST M. C., 2013. SiteChar characterisation workflow. SiteChar Report D1.4.
http://www.sitechar-CO2.eu/

NETL, 2010. Best practices for: Site screening, site selection, and initial characterisation for storage of CO_2 in deep geologic formations.
www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf

ROAD, 2011. Permitting process, Special report to the GCCSI.
cdn.globalccsinstitute.com/sites/default/files/publications/27686/road-special-report-permitting-process-final-opt.pdf

ROAD, 2013a. Case study of the ROAD storage permit, Report for the EU CCS Demonstration project network.
http://cdn.globalccsinstitute.com/sites/default/files/publications/111356/case-study-road-storage-permit.pdf

ROAD, 2013b. Aanvulling op de Aanvraag CO_2 Opslagvergunning P18-4. *http://www.agentschapnl.nl/sites/default/files/sn_bijlagen/bep/70-Opslagprojecten/ROAD-project/Fase1/4_Aanvragen/A-06-2-Aanvulling-opslagvergunning-kl-354540.pdf*

SCCS, 2009. Opportunities for CO_2 Storage around Scotland — an integrated strategic research study, 56pp. Scottish Centre for Carbon Storage. *http://carbcap.geos.ed.ac.uk/website/publications/regionalstudy/CO2-JointStudy-Full.pdf*

SCCS, 2011. Progressing Scotland's CO_2 storage opportunities report. Scottish Carbon Capture & Storage. *http://carbcap.geos.ed.ac.uk/website/publications/progressingscotlandco2/ProgressingScotlandCO2Opps.pdf*

8 Appendix A: 'Dry-run' storage permit applications developed for the Outer Moray Firth site, North UK

This appendix presents a summary (*i.e.,* salient points only) of the storage permit application developed for the Outer Moray Firth site (UK) as well as its reviews.

8.1 Storage permit application developed for the UK Outer Moray Firth site

8.1.1 Project concept

The **project concept** is of a CO_2 storage site that initially demonstrates CO_2 storage in the Blake depleted Oil Field, followed by further storage in the surrounding saline aquifer, principally the Captain Sandstone Member of the Wick Sandstone Formation. The **injection parameters** proposed in the SiteChar storage permit application are injection of 5 Mt per year of CO_2 for 20 years starting in 2016. A single injection and a single water production well are illustrated and modelled but it is assumed that multiple injection/water production wells will be required for an injection rate of 5 Mt of CO_2 per year. CO_2 is assumed to be initially sourced from a single gas-fired power station source (demonstration scale) from onshore eastern coastal Scotland. Further, commercial-scale CO_2 injection will be sourced from either full capture from a single coal-fired power station or from multiple industrial sources. It is envisaged that CO_2 will be delivered via an existing pipeline that currently carries the produced hydrocarbon gas from the Blake Field. Pressure management will ensure that the integrity of the site will not be compromised and other subsurface users will not be adversely affected (outside of the inter-operator agreements). Pressure management via a water production well is therefore part of the permit application.

The **Storage Permit Area** shown in Figure 8.1 encloses:

- *The maximum extent of the injected CO_2 plume* predicted for the injection scenario with a 1 km-wide margin to reflect the uncertainty on the predicted plume extent. The uncertainty comes from the fact that only a single investigation of sensitivity to parameters affecting this scenario was run within SiteChar (Figure 8.1b);
- *The injection well and water production well*, the water production well being enclosed by the lowest closing structural contour (Figure 8.1c);
- *The up-dip area to the north-east of the predicted plume extent* to reflect uncertainty in property variation in this direction of facies within the Captain Sandstone (Figure 8.1a);
- *Existing licence blocks* for which agreement with existing licence holders would be expected to be sought for a storage site permit application.

The **Storage Performance Forecast** for CO_2 plume migration and pressure footprint predictions are described for the permit period (0 to 40 years from the start of injection) and post-closure period (50-1000 years from the start of injection). They are based on the hydrodynamic simulation results of the proposed injection scenario:

- *The oil saturation* (SO) shown Figure 8.2 accounts for the saturation of the CO_2 in the supercritical state and can be thought of as the 'supercritical CO_2';
- *The solubility of CO_2 in the water phase* (W-CO_2) or the 'dissolved CO_2 plume' is illustrated in Figure 8.3. Its extent is generally larger than the supercritical CO_2 saturation;
- *The maximum plume extents* are shown in Figure 8.4. These were taken as the maximum extents of the 'supercritical CO_2 plume' (SO) and the 'dissolved CO_2 plume' (W-CO_2) simulation results at each time step (Figures 8.2 and 8.3, respectively);

- *The overpressure distribution*, *i.e.,* the difference between the initial pressure and the pressure induced by CO_2 injection during the injection period and the post-injection period, is shown in Figures 8.5 and 8.6, respectively. The scale is based on the maximum and minimum overpressures and range from -10 to 27 bar above initial pressure.

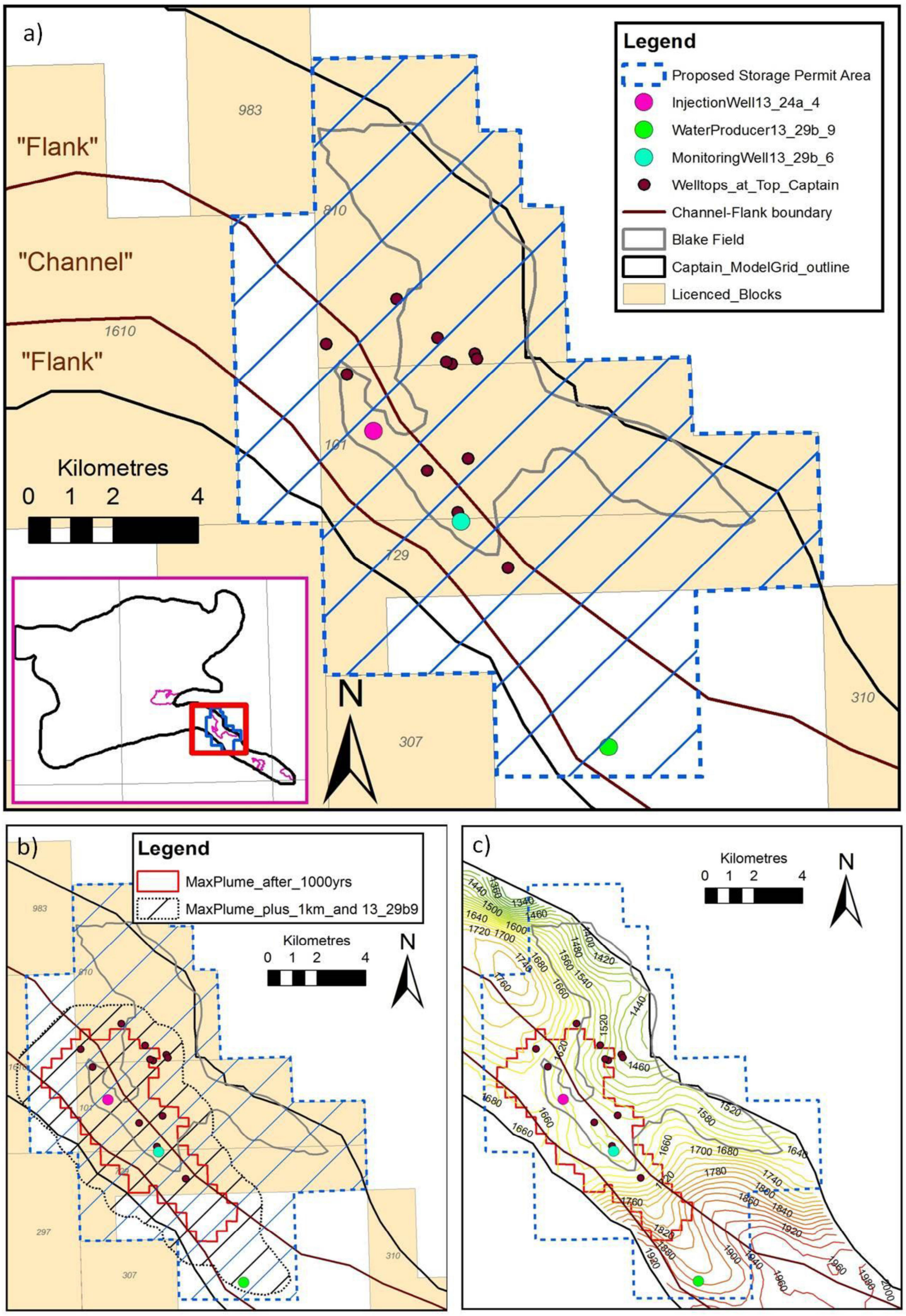


Figure 8.1. *a) Proposed location of Storage Permit Area, b) Elements used to derive the Storage Permit Area, c) Structure contours on the top of the Captain Sandstone in metres below sea level at 20 m intervals.*

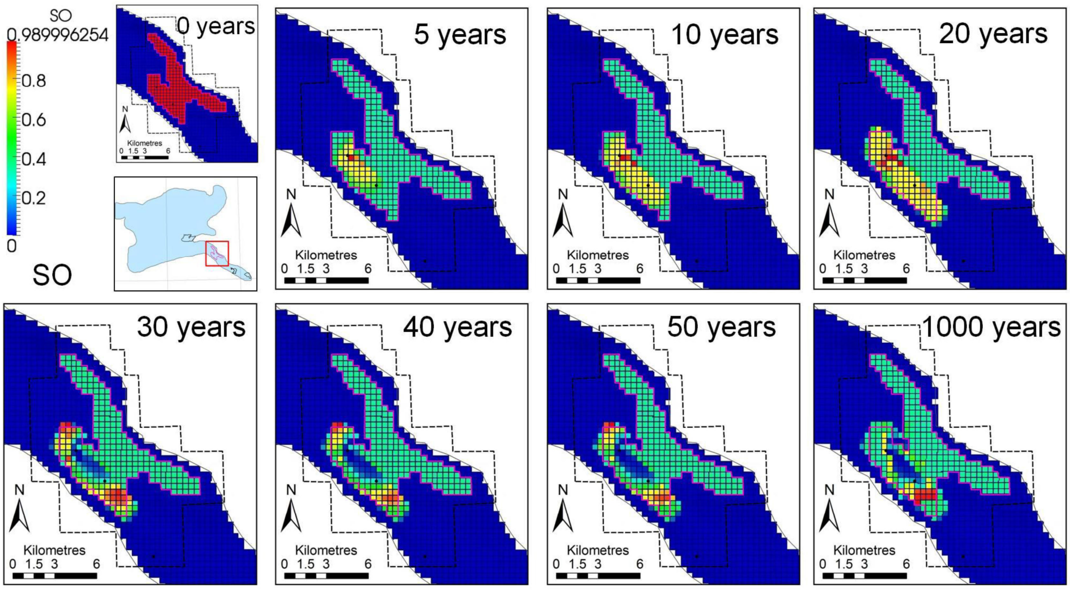


Figure 8.2. *SO, oil saturation, representing supercritical CO_2.*

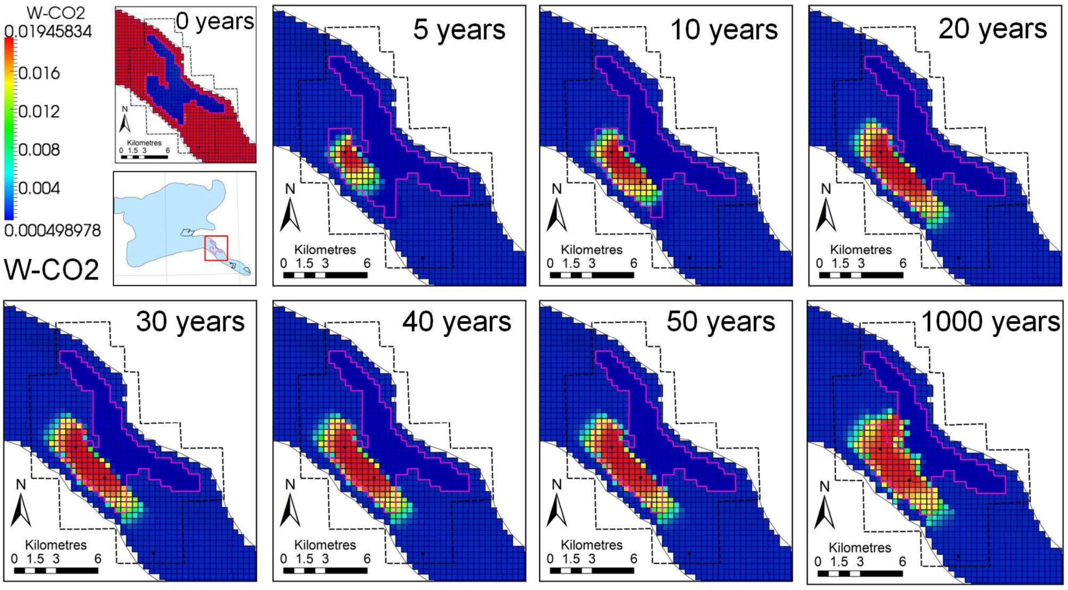


Figure 8.3. *W-CO_2 saturation 'Dissolved CO_2 in brine'.*

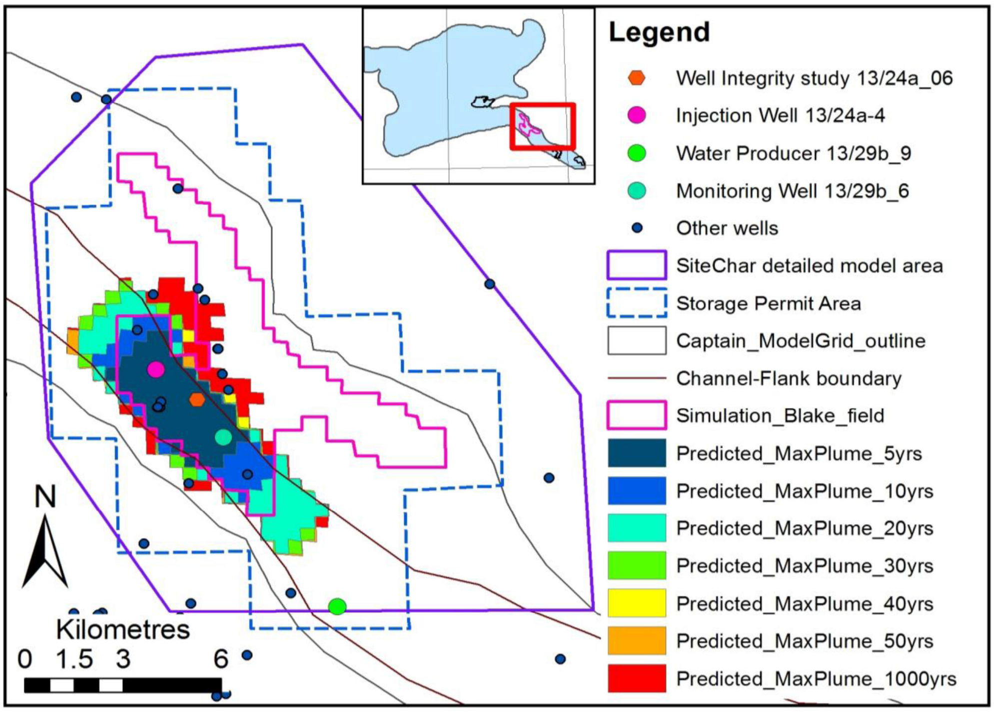


Figure 8.4: *Maximum plume extents and wells intersecting the plume. 'Detailed' model area is included to show how it relates to the plume extents.*

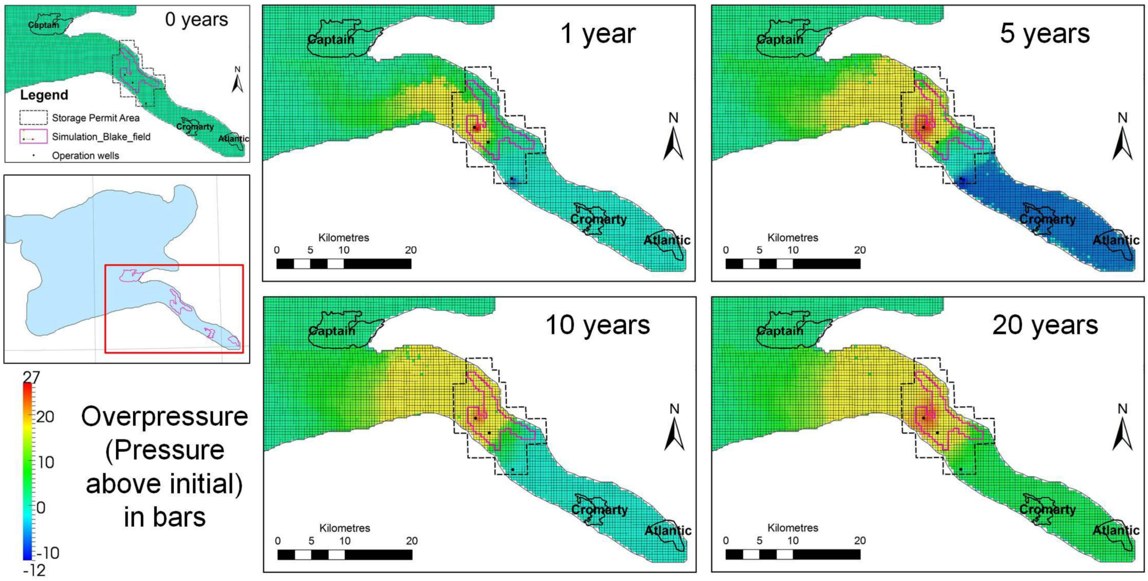


Figure 8.5: *Pressure change through time around Storage Permit Area during injection period (0 to 20 years after the start of injection).*

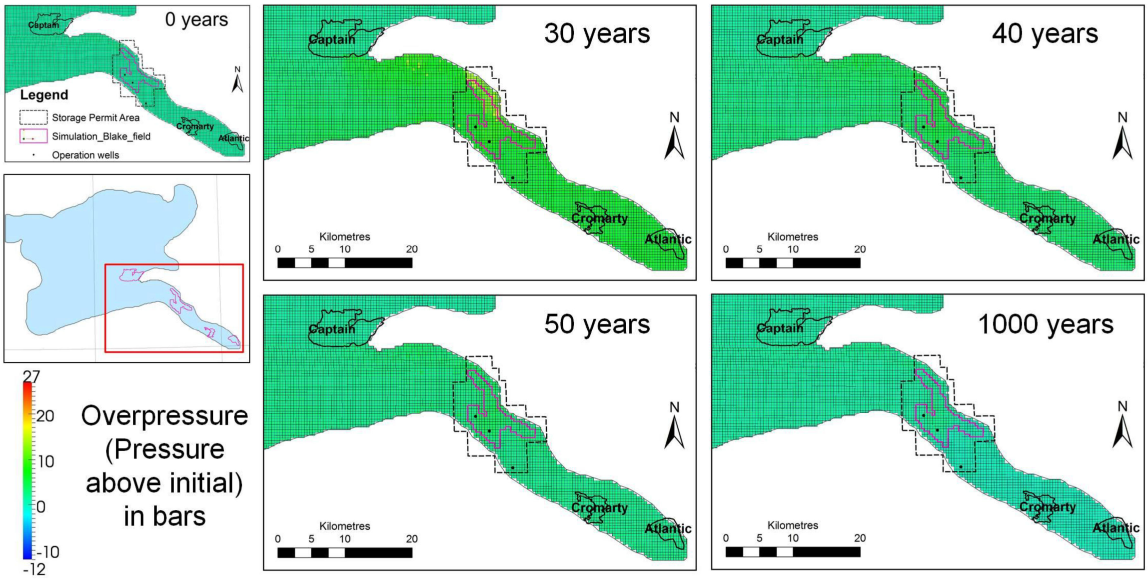


Figure 8.6*. Pressure change through time around Storage Permit Area post-injection (30, 40, 50 and 1000 years after the start of injection). 0 years shown for comparison.*

8.1.2 Site Description

The proposed **Storage Site** is located principally in the Captain Sandstone Member of the Lower Cretaceous Wick Sandstone Formation. Vertically, it is defined as the entire Wick Sandstone Formation because it is known that the Captain, Coracle and Punt sandstone members may be connected in the area. Laterally, it is defined by the envelope of the maximum extent of the CO_2 plume suggested by hydrodynamic modelling, surrounded by 1 km-wide margin (Figure 8.4). The Captain Sandstone, which forms the principal reservoir of the Blake Oil Field, comprises a NW-trending ‘Channel area’ and associated ‘Flank area’ (Figure 8.4) and is bounded to the north-west within the site by the West Halibut Fault. Static CO_2 storage capacities within the Storage Permit Area were calculated using a storage efficiency of 0.2 as 28 Mt CO_2 in the Blake Field (of which 20 Mt in the Channel area) and 186 Mt CO_2 in the Captain Sandstone (of which 101 Mt in the Channel area).

The **Storage Complex** is a defined volume that extends beyond the Storage Site and is defined laterally by the Storage Permit Area (Figures 8.1 and 8.4) and vertically as the rocks directly above the storage site extending up to the sea bed:

- **The primary seal rock** to the Storage Site are the mudstones of the Valhall, Carrack and Rodby Formations. Rocks of the overlying Chalk Group may also act as seal rock if they are of sufficiently low permeability.
- **Secondary reservoirs** for CO_2 will be provided by strata overlying and laterally continuous with the Storage Site that may be hydraulically connected. These include possible connection of the Storage Site reservoir within the Coracle or Punt sandstone members of the Wick Sandstone Formation and any rocks with available pore volume that overlie the primary seal rock.
- **Secondary seal rocks,** *i.e.,* seal rocks to the secondary reservoirs, are expected to primarily be the non-calcareous mudstones of the Lista Formation of the Montrose Group and the mud-prone Moray Group.

8.1.3 Measures to prevent significant irregularities

Site characterisation activities for the UK site in SiteChar have been led by a process of **risk assessment**, risk mitigation and reduction and risk reassessment. An initial risk assessment workshop by all technical experts identified risks to the secure containment of CO_2 within the prospective multi-store site. The list of risks, or risk register, was used to lead and inform site chracterisation activities for the UK site. The initial risk register comprised seventy-nine risks.

Each of the risks was described and organised into twelve overarching risk types. The experts were asked to assess the probability of the risk occurring and severity of occurence should it happened. The probability and severity assessments were used to rank the risks. The highest ranking risks only were addressed by the site characterisation research in SiteChar.

The technical research teams each received an extract of risks from the register relevant to their research, an illustration of how their risk reduction results contribute to the storage application. Written guidance was also given. A second risk workshop was held after the completion of the risk reduction technical work when the probability of occurrence and severity of impact were reassessed after completion. Additional risks were identified as the site characterisation work progressed. SiteChar is a research project; for a real storage permit application risk reduction would continue for all risks until they are mitigated to be as low as reasonably possible.

Risk mitigation and reduction results either determine or inform the required components of a ‘dry-run’ storage permit. The project and site description are determined by the results of the risk assessment-led site characterisation. The project description includes an injection strategy (how much CO_2 is to be injected, at what rate of injection and for how long), the site design defines the storage site and the number of injection and monitoring wells, and the storage performance forecast predicts the migration of the injected CO_2 and the injection pressure footprint.

Output from the risk assessment informs the preparation of the Preventative Measures, Monitoring, Corrective Measures and Post-closure plans.

The **preventative measures plan** outlines activities to further mitigate risks and reduce uncertainties. Only the highest ranked risks were addressed within the SiteChar research project. Each risk and its possible consequences are described and preventative measures are proposed. The preventative measures identified are to be enacted throughout the development of the site during the feasibility, technical design, construction and testing phases.

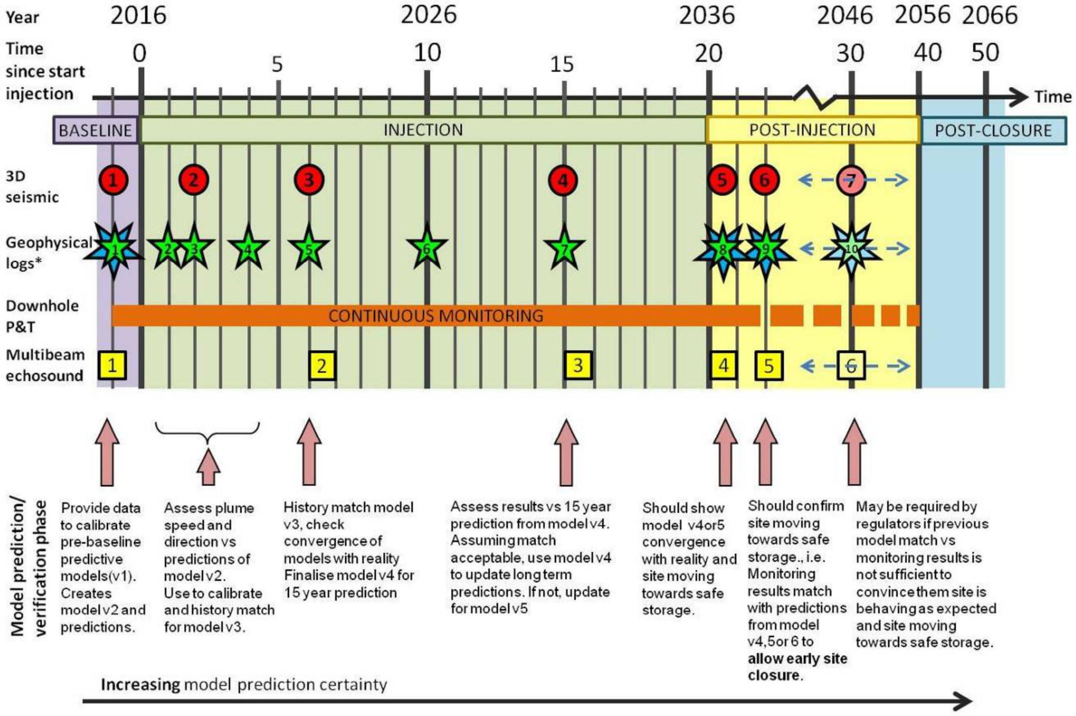
The **monitoring plan** addresses all unmitigated risks after site characterisation. The objectives of storage site monitoring plan are to adhere to regulatory requirements, to detect any significant irregularities, trigger corrective measures and to monitor any residual risks. A suite of regular monitoring techniques are proposed appropriate for the UK multi-store site (Figure 8.7): 3D seismic survey; programme of down-hole geophysical logging in monitoring, injection and water production wells including down-hole pressure and temperature measurements, fluid sampling and tracers; multi-beam echo-sounding/sidescan sonar; sea bottom gas sampling; ecosystem studies; bubble stream chemistry and sea bed gas flux; microseismic monitoring; monitoring of produced water. A feasibility study was undertaken for 3D seismic monitoring. The feasibility and cost-benefit should be assessed for all techniques proposed in the monitoring plan.

A provisional **corrective measures plan** is presented for the UK multi-store site. It is based on a list of criteria, *i.e.,* Permit Performance Conditions, that define storage site performance and demonstrate that the site complies with regulations. They also provide limits, which if exceeded, will trigger corrective measures to be implemented. The provisional Corrective Measures Plan specifies measures to be taken in the case that a significant irregularity or leakage is detected. Within SiteChar, as a research project, the extent of the corrective measures plan is restricted to only the highest ranked risks to storage site integrity. For each, the risk and the possible consequences should it happen are described, monitoring techniques relevant to that risk and observations that would trigger corrective measures are identified and corrective measures are proposed. Corrective measures may include additional monitoring to verify whether 'what is observed is real' before implementing corrective measures. For the UK multi-store site, the provisional corrective measures are presented for leakage from abandoned wells, leakage through the seal rock or at a spill point, to circumvent reduction in storage capacity or injectivity and prevention of adverse interference with hydrocarbon production.

A provisional **post-closure plan** is based on the proposed Permit Performance Conditions for the site. These criteria are assumed to be a consistent measure against which to measure storage performance throughout the storage site's lifespan. Thus at the end of the post–injection period, providing that these conditions have been met, it is anticipated that the site will be able to be closed. Observations from site monitoring (and their match to predictions) will be the main evidence which will allow site closure. Six Permit Performance Conditions are proposed:

- Environmental or human health will not be adversely affected by the storage operation;
- CO_2 will not pass beyond the Storage Permit Area boundaries;
- CO_2 plume shows migration within expected modelled behaviour;
- Pressure changes will remain within predefined/predicted ranges;
- Geomechanical integrity of the site will be maintained;

- Cost per tonne of CO_2 stored will remain within a set limit.



*Double stars represent logging in the injection and water production win addition to the monitoring well

Timing/frequency of surveys shown here are estimates and subject to previous survey and other monitoring results and updated predictions

Figure 8.7. *Proposed frequency and timing schedule of the four main monitoring techniques to be deployed at the UK multi-store site and associated predictive model certainty.*

8.2 Review of the ‘dry-run’ permit application

The following review is a summary of the detailed review undertaken as part of the ‘dry-run’ permit process for the Outer Moray Firth site.

8.2.1 Project Description

The project concept is CO_2 storage in the depleted Blake Oil Field, followed by further storage in the surrounding saline aquifer, principally the Captain Sandstone Member of the Wick Sandstone Formation.

The owner of the pore space, the Crown Estate in the UK, might wish to understand how the currently proposed project might contribute to, or affect, utilisation of the estimated capacity in full. It may be beyond the scope of an individual operator to undertake such an assessment, but regulators should encourage operators to provide sufficient evidence and data to enable this assessment to be carried out.

At the end of injection, reservoir pressures are expected to decrease rapidly, causing the CO_2-saturated oil to de-gas. It is assumed this means that CO_2 initially saturated in the oil becomes a dense phase fluid which will begin to dissolve into the formation water, as the gas-water contact rises due to aquifer recharge into the Blake Field. This serves to further contain the CO_2 plume which is not predicted to migrate significantly once injection has ceased. The natural concentrations of CO_2 within the formation water should be evaluated in a real application.

The proportion of residually trapped CO_2 is not discussed. Some exploration of this would provide further confidence of the degree to which the CO_2 would be safely and permanently contained. This might include summary plots against time of the proportion of CO_2 expected to be structurally trapped in the Blake Field, migrating in the Captain Sandstone aquifer, trapped within residual porosity, dissolved in oil and formation brines and ultimately trapped in mineral phases. This latter mineralisation would be expected to be very low.

The composition of the CO_2 stream has been assumed here to be greater than 99% of CO_2. However further description of the anticipated composition of minor constituents, their sources and ranges of concentrations should be described. The influences these minor components might have on a number of processes would need to be investigated and would be expected to form part of a routine risk assessment for a storage site.

At the Blake Field, the overall injection scheme was not fully optimised, though it was recognised very early in the design process that pressure management would be needed to meet the initial project goals of injecting 100 Mt over 20 years. It is assumed that in a storage permit application, the injection design will be optimised to ensure site performance objectives are met. At a high level, these objectives might include:

- Reservoir pressure thresholds;
- Interactions with other users;
- Storage capacity;
- Injection rates;
- Permanent containment;
- Maintenance of a small and contiguous plume footprint to store efficiently and reduce the size of the monitoring area;
- Costs.

Each of these high level objectives are likely to contain more detailed objectives to enable the injection scheme to be optimised to meet expected CO_2 delivery, regulatory requirements, costs and permanent containment. It is recognised that there might be some tension between these objectives. Whilst for the purposes of this project, maximising storage potential was the prime objective, this may not be the case at other sites, particularly in the early phases of CO_2 storage infrastructure development. Other objectives, notably reducing costs and minimising risks are likely to be higher objectives for the operator. Revisions to storage permits, once a site has been proven, may be anticipated to accommodate greater storage rates in the future. Such revisions would necessarily require the same burden of proof to which initial permit applications are subject.

The number, orientations and location of wells required for CO_2 injection and water production, including clean-up and offshore disposal, were not evaluated in this study, due to a lack of resources. However it is fully appreciated that a detailed study of this would be fundamental to optimising the storage project and minimising costs.

Size of permit area

The storage complex boundary is a fundamental component of the storage permit application and approaches to its definition have been discussed in detail for the UK site. The area enclosed within the storage complex boundary is called the Storage Permit Area and this term is supported as a clear definition of this boundary.

An appropriate justification and delineation of the storage complex area may not be possible without prior agreement with the permitting authority on the interpretation of the term “storage complex” and its definition.

Informal advice from a UK Competent Authority suggested that the storage complex boundary will be defined on the basis of the anticipated extent of the plume, achieved at its point of maximum extent, as determined by predictions of plume movement which in turn are based on pre-injection site characterisation. This maximum extent is taken to include both the dense CO_2 phase and that portion of the formation water in which CO_2 is dissolved at the point of transfer of responsibility. This raises a number of challenges for the operator and Competent Authority in defining the complex boundary. For some storage sites, such as the UK multi-store site, the biggest challenge is the relative uncertainty associated with the static geological model parameters, and the consequent impact this might have on predicted plume movement. A number of simulations are therefore required to capture the range of uncertainty. The storage complex boundary would then be defined taking a conservative approach by including the plume extent based on selected credible scenarios.

The inclusion of the CO_2-saturated formation water, which extends beyond the dense CO_2 phase, is included in the overall migration extent of the CO_2. This is an important consideration since it is the dissolved CO_2 that could lead to some of the leakage scenarios being realised.

Furthermore, site performance is predicated on the lack of leakage, which is defined in the EC Storage Directive (EC, 2009) as movement of CO_2 beyond the storage complex boundary. Whilst this undoubtedly is intended to prevent movement above the top boundary of the storage complex, this also means that operators are likely to take a conservative approach to defining the lateral extent of this boundary as well, to prevent uncertainties in static geological and fluid flow modelling from creating unnecessary significant irregularities. The margin applied to the site must be justified as the associated uncertainty will be site specific and must reflect the specific characteristics of the site. For example, for the UK multi-store site, the storage complex boundary is defined to enclose the up-dip area to the northeast of the predicted plume extent, to reflect uncertainty in the distribution of higher permeability channel facies which may allow higher than expected migration in this direction. In addition the down dip areas might be included to reflect the potential for downwards or lateral migration of denser CO_2-saturated formation water.

Another reason to extend the complex boundary beyond the plume limit is to provide a zone outside the plume in which some performance metrics can be monitored. These metrics might include pressure responses and the absence of CO_2 in key areas (*e.g.* reaching a fault whose relative permeability to CO_2 is uncertain and may pose a risk to containment, or poorly-completed wells).

Interestingly, the proposed Storage Permit Area also encloses the boundaries of existing licence blocks for which agreement with existing licence holders would be expected to be sought. This implies that, although these interactions are not investigated in detail for this permit, operators may need to include these areas in their permit area where such interactions are envisaged. This raises the possibility that storage permit areas may overlap with existing hydrocarbon production licences. Such an approach may also provide storage operators with a protective zone within which other users would be forced to also consider and mitigate any activities that could impact on the storage operation.

The pressure footprint has not been considered in the complex boundary. The EC Storage Directive suggests such effects should be included but there is currently little consensus on the thresholds above which effects should be included, and since pressure responses have been shown to extend far beyond the field boundaries at Blake (Figures 8.5 and 8.6), this would require impractically large storage permit areas.

In summary, the storage permit area will therefore be defined on the basis of predictions from reservoir simulations which are in turn based on pre-injection static geological models (often greatly simplified models), plus a margin to allow monitoring outside the plume and possibly to 'protect' the operator from other users. The approaches used to define the margin should be discussed further as described above.

Injection strategy

At the UK multi-store site, further simulations are required to optimise the number and location of CO_2 injection wells and water production wells in order to maximise storage. Whilst the re-use of existing wells is likely to be the preferred options for operators in order to minimise costs, the locations of previous hydrocarbon production wells (located in the crest of structures for example) may not be optimal for CO_2 injection, which might be better placed on the flanks of structures, more widely spaced and towards the base of the storage reservoir. Furthermore, confidence in the integrity of pre-existing wells may lead operators and Competent Authorities to conclude that the best option for longer-term containment would be abandonment of existing open or shut-in wells and drilling of specifically designed and located new injection wells. It is recognised that this would be likely to incur significant additional costs and may only be justified where, for example, the risk balance is countered by large storage capacities. Hence, in future permit applications, justifications for the locations and re-use of wells must be carefully made and reviewed. Regulators have a range of contrasting views on this issue and talking to the Competent Authorities early (before site screening) to assess their views on this issue is highly recommended.

8.2.2 Interactions with other users

The potential nature and extent of any interactions with other users have been discussed briefly for and are a key consideration for regulators. In the North Sea, other users include other storage site operators, hydrocarbon exploration and production with associated infrastructure owners and related activities (*e.g.* water extraction and disposal), including the consideration of future production of reserves, sand and gravel extraction, fishing, wind farms, military use, *etc*. It will be necessary to demonstrate that the proposed injection project does not have a detrimental effect on other legitimate users. The interactions should be defined and where possible quantified. Some evidence has been produced and included in the application which could be used to begin to constrain the possible interactions. The implications for resources that may have potential for future use should also be considered.

Where such interactions occur, it is preferred that operators of proposed storage sites enter into commercial agreements with affected users. However, it should be noted that an assessment of current and future risks may be challenging for operators due to confidentiality issues and unfamiliarity with longer-term strategic plans for all relevant users. In reality, the relevant 'state owner of the resource' (in the UK this would be the Crown Estate) might be the only organisation able to take an overview of likely risks arising from multiple operations within a given area. The Competent Authority may therefore need to undertake its own risk assessment and supporting investigations, to provide guidance to operators during discussions prior to granting of storage permits.

The extent to which other users could challenge a storage application has not been evaluated in detail in this process. It would be a very useful in a next step to assess the situations under which a challenge could be made and what would be required from the applicant to defend against such a challenge.

The specific interactions that might arise from multiple uses, both at the seabed surface and in the underground, are numerous and it is beyond the scope of this report to describe them in detail.

Geologically, however, the most significant process is the potential for pressure rises associated with injection causing changes in the pressure regimes experienced by other users, specifically other storage sites and hydrocarbon producers.

Changes to pressure distributions by future injection of CO_2 into nearby depleted fields have not been discussed. This may be of more importance in discussions over initial lease terms but would be expected to be considered in permit applications in regions of significant CO_2 storage potential, such as the Captain Sandstone. Furthermore, the permit holder at Blake, for example, may wish to evaluate the consequences of additional future CO_2 storage in nearby fields on their injectivity and overall storage capacity.

Furthermore the potential impacts of other uses, particularly hydrocarbon extraction, have not been assessed for the long-term evolution of the CO_2 plume. This would be expected to be included in some scenarios to determine the potential effects, if any, of increased or decreased oil production in the wider connected sandstone. However, it is recognised that operators may find it challenging to undertake a detailed evaluation of this issue when working in isolation from other fields. Some responsibility for this should also lie with the regulators who may be able to take a more informed overview, at least of long-term strategy for resource development.

Water production was deemed necessary to maintain reservoir pressures below estimated cap rock entry pressures. The production, treatment and disposal of produced waters have not been included in this permit application and would be a key component of the Environmental Impact Assessment in a more detailed application. It is the authors' current understanding that such waters would be subject to the same environmental considerations as produced waters from oil fields and treated in the same way, prior to disposal. Note that water is currently produced and discharged at Blake as part of hydrocarbon production under the Prevention of Oil Pollution Act (1971).

Discussions with regulators during the SiteChar project have indicated that disposal of water is not considered particularly challenging from an environmental perspective, as it is widely practised in the hydrocarbon production industry and expected to be regulated in the same way. However it might be expected that disposal of produced waters may be significantly more challenging onshore than offshore, from both a public-perception and from an environmental viewpoint. The estimated volumes of produced water and their disposal would be expected to be a key topic in the storage and environmental permits.

8.2.3 Site performance: Permit Performance Conditions (PPCs)

The definition of Permit Performance Conditions (PPCs) has been a significant development of the SiteChar 'dry-run' process. The purpose of these PPCs is to develop a set of *a priori* agreed criteria which will demonstrate appropriate site performance. The intention is that these criteria would form conditions of the storage permit allowing both operator and regulator to demonstrate adequate performance both during injection and, importantly, at the point of transfer of responsibility following site closure. The six PPCs define site performance in terms of absence of leakage, agreement between prediction and observed plume migration, limits on reservoir pressure, maintenance of geomechanical integrity and costs per tonne of CO_2.

The latter is considered important to define an upper limit above which permit requirements would make the project uneconomic, thereby protecting the operator from impractical or too costly conditions. This will be a specific metric for operators as project economics are unlikely to be a prime concern for permitting authorities as it is not their role to protect operators against financially risky projects. Furthermore it is likely that the definition of this metric would require very clear definition and justification in a full application, being central to the storage operator's business case.

PPCs include a range of metrics against which site performance can be measured, both during the operational and closure phases, providing a basis for the design of the geological monitoring program and the corrective measures plan. Whilst it might be relatively straightforward to define qualitative indicators, PPCs will need to be defined quantitatively for them to be effective.

Each PPC contains a justification of the PPC and a description of the evidence, in the form of quantitative limits that will be obtained to demonstrate site performance has been met.

PPCs are not explicitly required by the EC Storage Directive but are considered as useful tools for discussion between the Competent Authority and operator. They are considered a useful way to define and agree acceptance criteria against which a storage operation can be assessed. They are likely to be a combination of qualitative and quantitative metrics.

Six PPCs were defined for the Blake site. These PPCs were reviewed at a workshop between the permit development team within SiteChar, members of the SiteChar Regulatory Advisory Board and invited regulators from the UK and France. These PPCs might be considered as high-level performance targets. They describe the evidence required to demonstrate that target has been met.

CO_2 stream quality and variability should be included as a separate PPC, as this could have an impact on the integrity of containment.

In some storage scenarios, a PPC dealing with adverse environmental or health effects due to the operation would be necessary, primarily in onshore storage sites.

Once the baseline ‘normal’ site evolution has been defined, significant irregularities need further development. These will be defined, at least partially, by the risk register and consideration of the implications of the reservoir modelling. Some risks, or combination of risks, could be linked to generate descriptions of significant irregularities. These are likely to be described in the monitoring plan, as trigger points which require corrective measures.

PPCs should be cross-referenced to the specific risks they address. This would help to demonstrate that the risk register, PPCs, corrective measures plan and monitoring plan are closely integrated.

PPCs should be written with positive phrasing as the permits will be public documents.

8.2.4 Post-injection period

For the Blake Oil Field, the post-injection period is proposed to be 20 years, though it may be possible to seek transfer of responsibility earlier, due to the expected rapid pressure dissipation and minimal post-injection movement of the CO_2 plume. In addition, removal of all infrastructure, including the well-based monitoring is proposed within two years. Notwithstanding the ongoing costs of maintaining infrastructure following the end of injection and the associated loss of revenue, risks to long-term containment may increase if wells are left open for longer than necessary.

It is worth noting that operators are likely to seek confirmation as part of the permit agreement that, if the site performs as expected, then both the operator and Competent Authority can have confidence that the responsibility of the site will be taken back by the Competent Authority. Uncertainty in the duration of the pre-transfer period has been cited as a major cause of uncertainty and hence increased cost for operators. Although monitoring costs have been estimated as being approximately 5% of the total cost of the UK site and therefore costs associated with the pre-transfer period may be considered incremental, the uncertainty may be a barrier to final investment decisions. This would make it very difficult for some sites to obtain finance until there is a substantial body of evidence from low risk storage sites to lower the uncertainty and investment risk.

It will therefore be very important to establish, prior to injection, what evidence might be needed to demonstrate appropriate past, current and expected future performance, to enable site closure and abandonment and to give confidence to investors that transfer of responsibility will occur. It is recognised however that such an agreement may be difficult to reach as several Competent Authorities may need to be involved to define the conditions under which transfer of liability can take place. Initial projects may not be able to achieve this, prior to gaining operational experience and experience of closure procedures at scale.

Current regulations assume that when a permit is relinquished, the site would be closed and infrastructure removed. However, for sites with large storage capacities such as the Captain Sandstone, the leasor (*i.e.,* the Crown Estate in the UK) may wish to extend the field life beyond the current permit term and encourage transfer or extension of the permit to other operators. In these circumstances, the Competent Authority might wish to consider how best to approach the post-closure plan to ensure future costs for storage at the site can be reduced without compromising short- or long-term safety and containment. Mothballing of infrastructure, for short periods at least, might be considered, although costs of platform and pipeline maintenance in the offshore would need to be included in the assessment.

As part of the discussions between operator and Competent Authority, the degree of flexibility that might be envisaged in the permit might be discussed. The Blake permit describes a single project that has been clearly defined. However, there might be legitimate circumstances when the operation must be altered. At these points the permit might need to be altered. The conditions, events or findings, which might result in significant changes to this project concept, should be explained within the permit application. Those aspects of the project concept which are most ‘susceptible’ to change should be identified and the source of this susceptibility explained. The permits would only be issued when a change was proposed by an operator as it would not be possible to provide permits for alternative scenarios. An approach used in some jurisdictions is to provide a ‘master’ permit with additional permits for specific activities, *e.g.* for drilling new wells.

There are numerous credible scenarios which may result in a requirement to alter the permit conditions and these should be fully explored between operator and Competent Authority. These might include changes resulting from the actions of others: additional hydrocarbon production or CO_2 storage might change pressures resulting in changes to storage capacities for example. Experience from the initial injection may require updates to static geological models, and hence changes to predictions of longer-term performance, changes to commercial arrangements requiring changes to injection rates (up or down) or even changes in target storage reservoirs.

8.2.5 Communication and management of uncertainty

The values derived or obtained to calculate the storage capacity will contain some inherent uncertainty. Some indication of the range of sandstone content, total porosity and permeability values would be useful.

Site characterisations, such as those carried out at Blake and Vedsted, require assumptions to be made for a number of parameters. Whilst the general uncertainty in such assumptions is acknowledged, there is a general lack of consistency to describing this uncertainty for specific parameters, which have been measured or derived by calculation or simulation. This is primarily because these parameters have largely been based on very limited data obtained during previous studies. It is therefore difficult to predict accurately key parameters for the static geological models, such as permeability and porosity, distribution of channel and flank facies, presence of discontinuities and errors associated with derived parameters.

This can have important implications for the confidence which can be assigned to key values, such as the relative permeabilities or capillary entry pressures, and therefore the confidence that might be asserted for derived metrics such as reservoir pressures, storage capacities and plume extent.

Further site characterisation can significantly reduce some of this uncertainty and would include special core analyses for relative permeabilities, threshold pressures and reservoir quality, including potential for new exploration wells to target key horizons such as the cap rock, injection tests to assess injectivity and an increased range of sensitivity analyses whereby key parameters are varied to assess their impact on the site performance metric described above.

Furthermore, a coupled iterative process would be utilised to optimise the injection strategy with revised seal rock fracture pressures and/or fault reactivation pressures included to define upper acceptable pressure limits.

It would be expected that all predictions would convey, to the extent possible, the uncertainty or degree of confidence that could be placed upon them, both in the statements made and the figures used.

Sources of data have been adequately described here and are further described in more detail in supporting reports. Again the quality of these datasets and the impact this might have on subsequent static geological model construction and subsequent simulations of possible future behaviour should be clearly described.

The uncertainties relevant to each parameter used to construct the geological model should be assessed in order of their relative impact on the overall uncertainties within the model. Sensitivity analysis on key elements such as the storage capacity and potential leakage might help identifying the most influential parameters.

Due to the processing requirements to run multiple realisations of simulations of CO_2 injection, the model representation in the hydrodynamic model has been significantly simplified from the static geological model. The methodology for upscaling has been described but further discussion of the impacts of different approaches to upscaling, for example, by increasing grid resolution, applying more geological constraints obtained from well logs and using the detailed model for reservoir simulations, should be included. These sensitivity analyses would greatly enhance understanding of the expected plume evolution and the limitations of the predictions.

8.2.6 Storage Site and Complex

The geological interpretation and structural configuration of the storage complex are adequately described, key geological horizons mapped, site and complex boundaries described and illustrated. Well information has been integrated with the seismic interpretation, with the method of depth conversion explained. However the challenge of adequately constraining the Captain Sandstone surface itself from the available seismic data is not sufficiently discussed as a source of uncertainty in the geological description.

The difficulties in picking some key surfaces should be described. The degree of uncertainty that might be associated with the interpretation of these surfaces, and its impact on the robustness of the static geological model, and hence by extension, subsequent investigations of capacity and containment should be evaluated.

A well testing programme is not included in the storage permit application; although this might be expected to be a natural next step for an operator once the permit had been awarded. In the Blake Field project, further appraisal could focus on testing injectivity, either by injecting water or small amounts of CO_2.

Structural configuration and compartmentalisation, at least between channel and flank areas is mentioned but further characterisation and testing (via test injection) may be warranted. Results from these tests would reduce uncertainty around injectivity as well as further demonstrating the required injection rates are likely to be maintained.

No special core analyses have been undertaken in this study but they are recommended by the UK Guidelines to provide further constraint on rock porosities and permeabilities.

Storage site

The potential for connection between the Tain and the Blake Fields means that CO_2 could migrate into the Tain field, or at least the pressure response might be felt in the Tain field. The impact of CO_2 migration into the Tain Field, and how this risk should be tested, including assessing the degree of connection between the Blake and Tain fields, and mitigated should be discussed.

It is stated that the Captain Sandstone Formation pinches out just before reaching the Halibut Horst. This appears to be a very significant result which supports the selection of the Blake Field as a suitable storage site. The evidence for this should be clearly stated. It would be useful to also include in the discussion consideration of the degree of confidence that can be placed in this result: is the pinch out visible throughout the whole area of interest, for example?

Storage Complex

A cross-section through the regional and detailed models, derived from well-logs and seismic data as appropriate, would greatly benefit the understanding of the conceptual static geological model and definitions of key boundaries, *e.g.* storage site, top/base and lateral seal rocks, secondary containment, secondary containment seal rocks and complex boundaries.

A number of important surfaces have not been identified, *e.g.* Punt, Coracle, Lista and Dornoch. All relevant surfaces should be identified and included in the static geological model or, if excluded, reasons for their absence explained, including a discussion of the potential impact their absence might have on subsequent evaluations of overburden trapping and potential for CO_2 migration within the complex.

Primary reservoir

The potential for lateral continuation of the Coracle and/or Punt appears to be poorly constrained and yet might have a significant impact on the potential extent of the CO_2 plume, particularly if they extend up to the West Halibut Fault. It is noted that the Coracle is in connection with the Captain Sandstone in two producer wells in flank facies. The extent to which this might be considered a significant uncertainty in the static geological model and the potential impact of this on predictions of plume extent, should be further investigated.

The proposed project exploits the storage capacity within the better quality reservoir sandstones of the channel facies. It would be useful to also discuss what might be required to more fully exploit the capacity provided in the flank areas, given the estimated lack of connectivity between the channel and flank areas.

The evidence presented provides some confidence that suitable injectivity is likely to be found in both channel and flank areas. It would be useful to include some sensitivity calculations, by applying minimum and maximum pororosity/permeability data, to estimate the likely ranges of potential injectivity in each facies.

A discussion of additional investigations (for example, review of current pressure maintenance activities through water injection) would be needed to increase the confidence in the injectivity.

Primary cap rock

Primary cap rock capillary entry pressures are estimated from published results on the same formations from other areas. Where possible, further special core analysis would be expected for a full site characterisation to provide detailed values for reservoir simulations. Sealing properties of secondary cap rocks are mentioned briefly, including low-permeability horizons within the Chalk. It would be expected that the properties of the secondary seal rocks would be established to the same level of confidence as the primary seal rocks.

The primary cap rock fracture pressure threshold is considered to be more important than the capillary entry pressure since it may lead to more rapid migration of CO_2 out of the primary reservoir. The potential for previous Blake Field production history to impact on the fracture pressures should be explored in significantly more detail. For operators, this implies that previous production data and any relevant information, including ground movement, microseismicity, pressure changes, and site surveys undertaken as part of oil field construction, should be made available to the storage permit development team. It is assumed that, at least initially, storage site leaseholders are likely to have been involved in the hydrocarbon production at the site, but this may not always be the case. In the UK, existing hydrocarbon licence holders will be given priority over other operators for a specific storage site as the transfer of data is assumed to be very important. A duty of appropriate data archiving and transfer (subject to appropriate commercial terms) should be applied to hydrocarbon licence holders to enable storage permit applicants to demonstrate that past production does not lead to unacceptable risks for CO_2 storage. This would include well data. Information from neighbouring fields, such as expected life and pressure depletion profiles, would be very useful information that relevant authorities might have access to and could form part of both the permit application and evaluation process.

The potential thinness, or absence, of the seal rock, within and outside the Storage Complex might provide a scenario for vertical leakage, if CO_2 or brine reaches an area of thin or absent cap rock. Further assessment of the risk this might pose will be reliant on simulations that assess the extent and rates of possible CO_2 migration out of the reservoir in areas of thin seal rock, and would need to include further assessment of the behaviour of the Chalk.

The potential for the presence of a percolation network within the primary seal rocks of the Valhall, Rodby and Carrack Formations, is deemed likely. The absence of evidence for past hydrocarbon leakage has been put forward to suggest that such an open fracture network has not led to previous fluid migration. However this has not been adequately assessed for CO_2 specifically, particularly considering the higher relative permeability of CO_2 and potential for movement of CO_2-saturated formation fluid (albeit slowly).

8.2.7 Storage Complex – secondary reservoirs and seal rocks

Secondary storage reservoirs have been identified in the Maureen, Mackerel and Lista Formations. The capacity, or basic reservoir properties, would be required for a full storage permit application. A detailed characterisation of the secondary seal rocks is particularly important. This should include, for the Blake storage complex specifically, further detailed mapping of the lateral extent of the secondary seal rocks and quantification of the sealing properties from cores and logs.

Setting aside the highest ranked (but still low) risk of migration via wells of poor integrity, the pathway that is most relevant to the containment potential of these rocks is migration through the chalk along faults and fractures, which have been cited as providing some potential secondary fracture porosity. Detailed characterisation would be required to demonstrate that such pathways might allow CO_2 migration into the Maureen and Lista Formations (implying breaches in underlying mudstones) but that overlying mudstones are not breached by upwards extension of these faults, which might allow continued upwards leakage of CO_2. It is accepted that such a risk is likely to have very low probability due to the absence of faults which extend through the overburden within the storage site. Nevertheless, the evidence should be presented to demonstrate that the

Montrose and Moray Groups, with interbedded reservoir, seal rock and intermediate lithologies are capable of trapping the CO_2.

The distribution of faults should be a prime focus for site characterisation, as robust arguments regarding their influence on containment and injectivity within the storage complex are likely to be a significant part of the demonstration of safe and permanent storage. In this case study, this assessment should include consideration of the impacts of the West Halibut Fault allowing CO_2 migration and the presence of the fracture network within the Chalk providing migration pathways through to the secondary reservoirs and seal rocks. A regulator may even require detailed characterisation, possibly including testing of hydraulic properties, assessment of the width of the fracture zone adjacent to the fault and the connection to the Captain Sandstone Formation.

It is stated that the CO_2 would be expected to be contained within any strata with available pore space that overlie, underlie or are laterally equivalent to the Storage Site. The extent of potential secondary containment also depends on the nature of CO_2 migration to these strata. If higher permeability pathways extend though these for example, this proposed secondary containment might be bypassed to a significant degree. Therefore the potential for secondary containment should be investigated with credible scenarios of migration taken into account.

The Cenozoic succession has been provisionally identified as providing substantial secondary storage capacity. The potential for these sandstones (*e.g.* Mey Sandstone Member) to provide secondary or back-up storage, or even used as future primary storage sites, might prove beneficial to regulators and especially the Crown Estate as the issue of leases and thus should be quantified.

Back-up or alternative storage should be included.

8.2.8 Measures to prevent significant irregularities

Risk assessment

A formal risk assessment process has driven much of the site characterisation at Blake. It has allowed investigations to be prioritised and focused on key areas of uncertainty and highest initial risk. Consequently, the storage permit application demonstrates that a set of potential risks has been considered and, furthermore, that most of these risks have low probability and/or low consequence. The risks identified were formally compared with the online FEP database to ensure the assessment was as comprehensive as possible. Uncertainties relating to several risks have been reduced.

The risk register also includes two new risks that were identified during the study. This is to be expected as more knowledge about likely performance may lead to the identification of areas of new uncertainty. It is worth noting that the Competent Authority may assess the consequences differently to the applicant.

Regional migration pathways have been provisionally identified but significant further analysis are needed to fully assess the risks from migration of CO_2 along potential fill and spill pathways. In the Blake Field case, migration through breaches in cap rocks, or where cap rock may be absent, are considered of low risk because regional migration of the scale modelled requires injection of amounts significantly greater than those proposed for this project. In addition, natural attenuation and speed of the migration have not been taken into account. Further uncertainty surrounds the lateral distribution of reservoir and seal rock properties.

Failure of well integrity, leading to migration and possible leakage of CO_2, remains the relatively highest ranked risk to permanent containment, although the risk is still ranked as low. Mitigation of this risk includes ensuring that, during injection, reservoir pressures are maintained below pressures that might allow CO_2 to migrate along poorly sealed wells.

Further analysis of other leakage scenarios, beyond those considered should be undertaken, particularly those that might include failure of multiple barriers, including upper plugs and increased micro-annulus permeabilities.

The additional mitigation measures proposed contain further well characterisation, including an extended study of all fifteen abandoned wells that the plume is predicted to intersect. Monitoring of these wells could be prioritised once their relative risks have been assessed and a more detailed monitoring plan developed. A full application should include an assessment and safety statement for each well.

The risk register provides a useful audit tool that demonstrates how risk ranking has evolved as investigations and project design have reduced uncertainty and risk.

Similarly, further site characterisation to assess the integrity of primary and secondary seal rocks includes both further review of existing data and if necessary, further acquisition of seismic data to map extents and thicknesses of seal rocks.

Other risks to containment and injectivity are discussed in a similar fashion with additional studies proposed. In a full storage permit application, it is expected that many of these studies would be undertaken during the site characterisation phase, prior to submission of the permit application.

8.2.9 Monitoring and corrective measures plan

The monitoring plan comprises a comprehensive description of the different techniques, together with an indication of likely frequencies. The monitoring plan could be further strengthened by inclusion of descriptions of the specific objectives for each technique, where it is to be deployed, and the overall survey design, including the spatial distribution where relevant. In particular closer explicit links with specific risks, regulatory requirements and PPCs would demonstrate an integrated and robust monitoring plan.

The corrective measures plan is here limited to addressing the highest ranked risks identified on the Blake Field risk register. A full application would be expected to address all risks as appropriate. It is recognised that to undertake a full corrective measures plan, different scenarios should be evaluated, as quantitatively as possible, to determine expected response levels which would define a significant irregularity.

The monitoring plan must then demonstrate a capability to detect these trigger events at appropriate frequencies, locations and repeatability. In the ‘dry-run’ application developed for the Blake Field, these significant irregularities have been qualitatively described. Further development of a corrective measures plan is required whereby the chain of events is described in detail for each trigger scenario. Construction of a range of scenarios that describe possible deviations from expected behaviour should be defined and then simulations may be necessary to identify key trigger events. This could be one focus for further work to extend SiteChar.

Significant irregularities would be defined to avoid these extreme scenarios occurring in the first place. These might include unexpected plume movement, changes in pressure or results from well integrity monitoring, for example.

The timing and frequency of surveys suggest that the match of monitoring results to model predictions will be tested at 15 years. However, it would be anticipated that regulators will be regularly reviewing the history matching and questioning any deviations, which, if significant, might require model recalibration.

9 Appendix B: 'Dry-run' storage permit applications developed for the Vedsted site, Denmark

This appendix presents a summary (*i.e.,* salient points only) of the storage permit applications developed for the Vedsted site (Denmark) as well as its reviews.

9.1 Storage permit application developed for the Danish Vedsted site

9.1.1 Project concept

The Vedsted structure is an onshore aquifer in an anticlinal closure (Figure 9.1) in the Gassum Formation, an upper Triassic - lower Jurassic sandstone, which was identified by early hydrocarbon exploration and further investigated within the SiteChar project for candidate for CO_2 storage. The structure is close to the Danish power plant 'Nordjylland Power Station' located in the vicinity of the city of Aalborg.

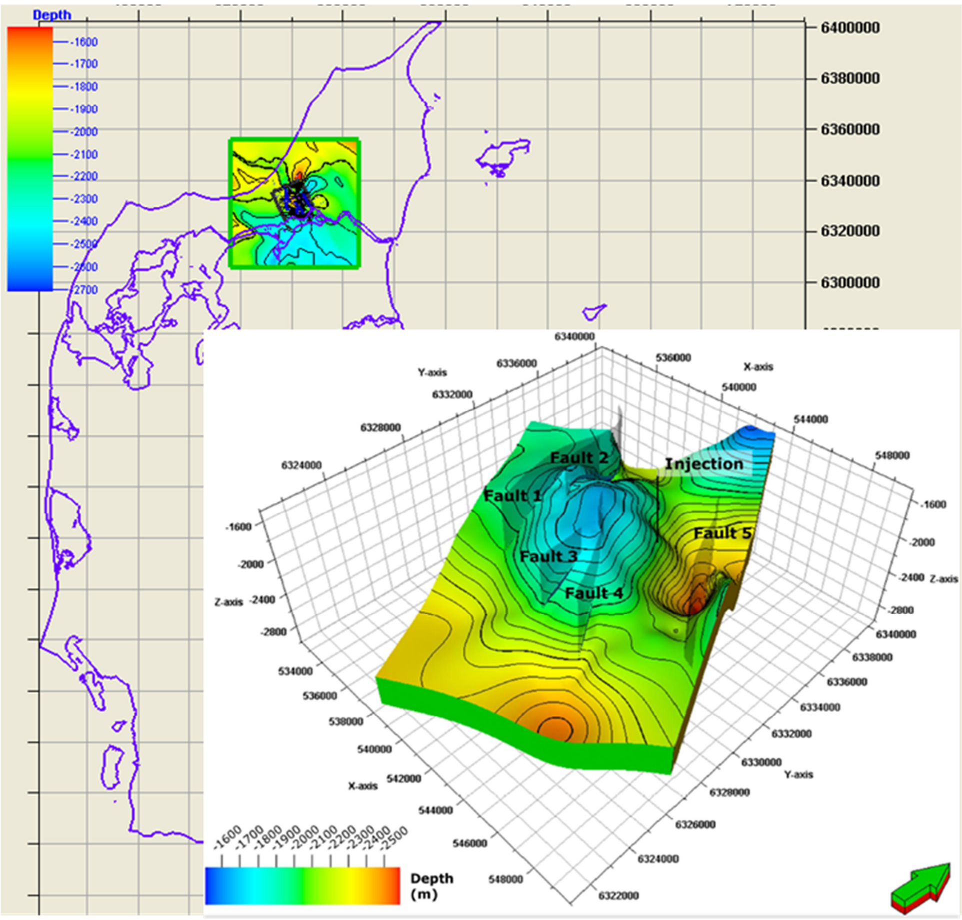


Figure 9.1. *Vedsted site located in the northern part of Denmark. Insert picture; Vedsted structure with major fault plans and proposed injection site down flank to the east.*

Nordjylland power Station is a highly efficient coal-fired power plant with a capacity of 470 MW. The annual CO_2 emission is 1.8 Mt. The distance from the plant to the Vedsted structure is approximately 30 km and the CO_2 can be transported by pipeline. A secondary source of CO_2 is a cement factory operated by Aalborg Portland with an emission up to 1 Mt/year. Therefore the total amount to be planned for could be as high as 3 Mt/year.

An optimistic date for **injection start** is August 2020, and a planned operation period of minimum 40 years.

The initial sparse data coverage for the aquifer in the Vedsted structure makes it instructive to develop the storage site in several phases. For the full potential for the storage project incorporating both the power plant and the cement industry, *i.e.,* an **injection rate** of approximately 3 Mt/year, it may be practical to have up to three injections wells. With three injection wells, the injection rate can be kept below 1 Mt/year, which may be realistic according to the relative low permeability sandstone formation.

The **injection plan** basis is a ramp scheme with a gradually rising injection rate, starting with a single well. This is chosen to allow to capture the early reservoir response data for incorporation in the reservoir modelling and performance match. The injection well head pressure monitoring, temperature response in the well, observation well pressure recordings will be exploited for history match and learning's.

9.1.2 Modelled storage performance

As the Vedsted structure is an anticlinal (four way dip closure) the maximum **distribution of the CO_2 plume** is defined by the spill point of the structure, the shallowest spill point having been identified to the north of the structure.

For the Vedsted storage considering a predefined 40 years injection period with an injection rate of 3 Mt/year CO_2, the spill point is far from being reached (Figures 9.2 and 9.3). Buoyancy will secure the CO_2 plume inside the structural closure even after a long equilibration period of 475 years.

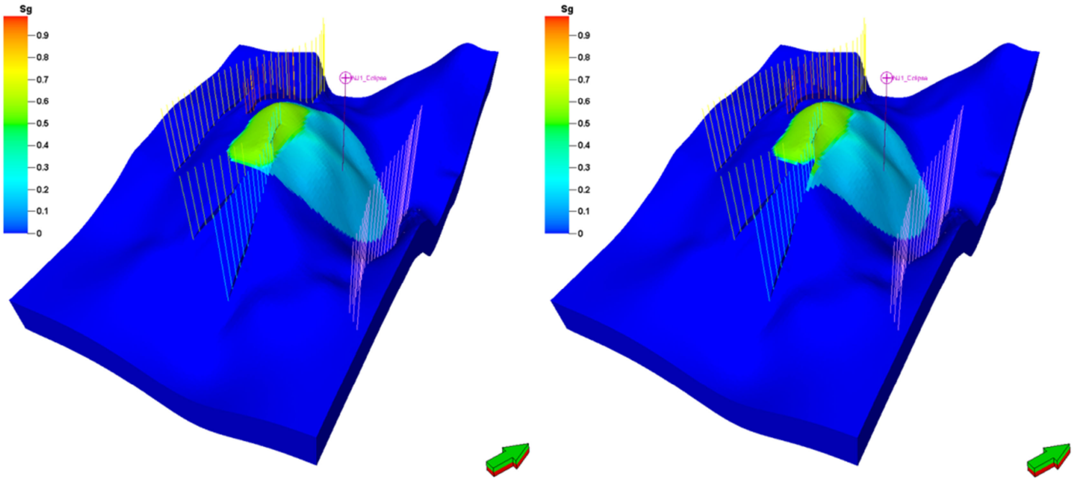


Figure 9.2. *CO_2 (free) distribution after 40 years of injection followed by 475 years of equilibration considering that (Left side) faults on the structure are fully open, (Right side) faults are closed.*

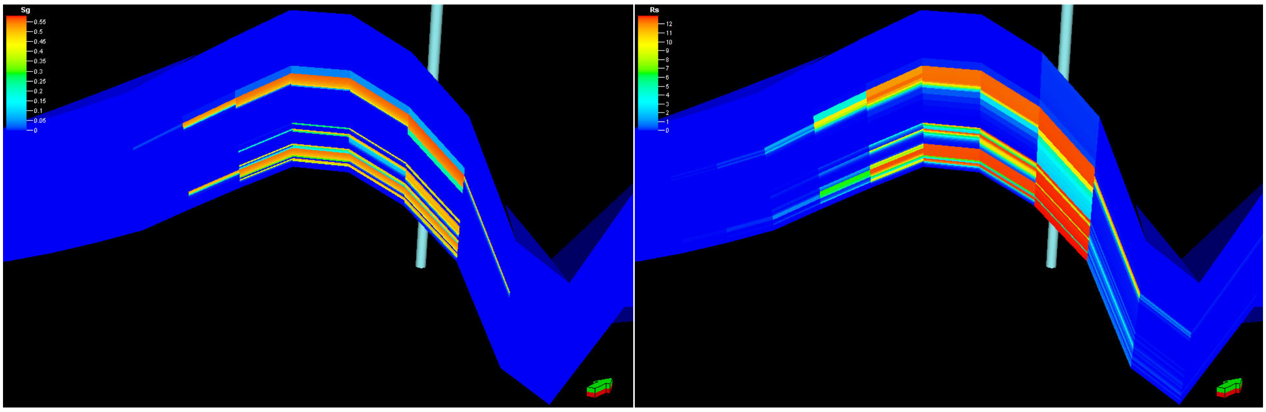


Figure 9.3. *Extent of the free (left) and dissolved (right) phase CO_2 after 40 years injection.*

Modelling results indicate that the structural closure is large enough to contain the whole amount of CO_2 planned to be captured from both the power plant and the additional cement industry resulting in a total volume of 120 Mt.

A major concern when injecting CO_2 in to the subsoil for permanent storage is the **overpressure** development in the surroundings of the storage site (Figure 9.4).

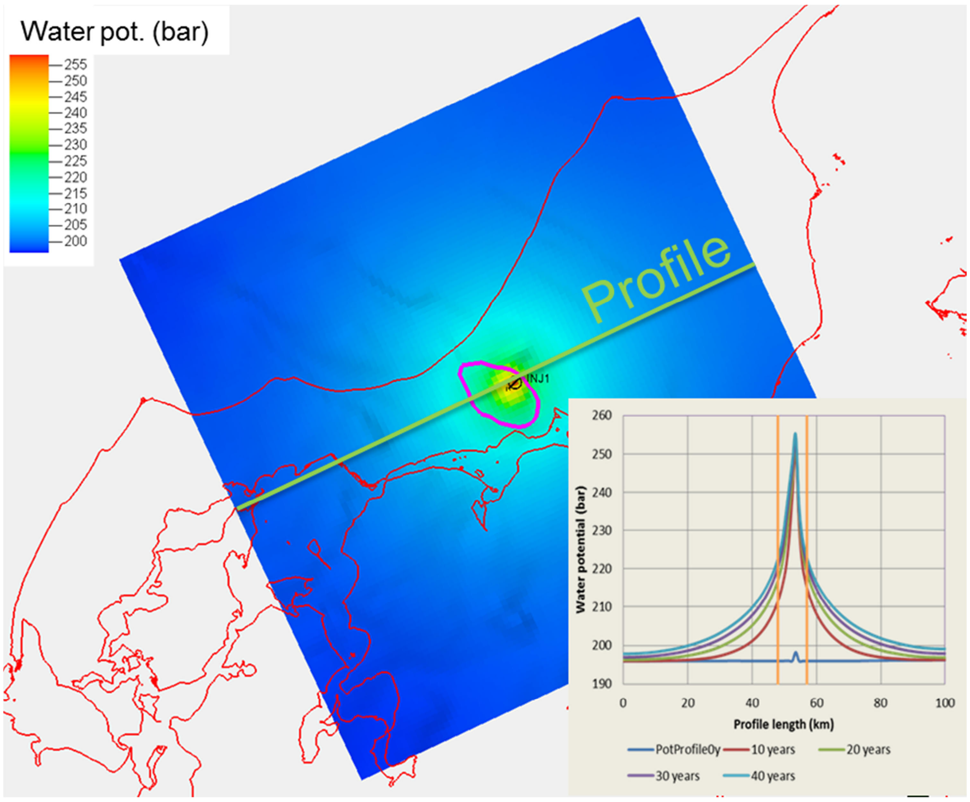


Figure 9.4. *Over-pressure (water potential) distribution after 40 years of constant injection at 3 Mt/year with a single injection well in to NW flank of the Vedsted structure. Insert picture displays the pressure profile to different times of injection. The orange vertical lines delineate the storage site.*

Figure 9.4 shows the over-pressure (or water potential) development during the injection period. It is clear that the pressure develops far beyond the storage site. A 100 by 100 km large regional simulation model was used for simulating the injection process.

For an onshore storage site, as Vedsted, it is not clear from the EC Storage Directive (EC, 2009) how much the overpressure can develop outside the storage complex or structural closure. The national regulator (Danish Energy Agency) and the Danish Subsurface Act with the EC Storage Directive implemented do not provide further insight in to the issue. Therefore the pressure development issue must be addressed in dialog with the regulator while processing of the application.

If overpressure is an issue, it might be necessary to drill additional pressure release wells outside the structural closure to mitigate the pressure development without introducing a risk of potential leakage by drilling inside the trap.

Hydrodynamic simulations have been coupled to **geomechanical** simulations in order to assess the stresses in the reservoir and overburden and possible fault re-activations.

The pressure development at the fault at the top of the anticline is of major concern for a potential CO_2 leakage as it will be reached by the CO_2 plume after a certain time (Figure 9.5). A maximum difference of about 18 bar can be observed after 10 years of injection in the closed fault scenario, while a difference of about 2 bar occurs for the open fault scenario. Consequently, it might be necessary to study the faults behaviour with regard to potential reactivation.

Hence, it can be concluded that geomechanical effects may occur during the injection phase, where up to 18 bar difference in pressure can be observed at the faults in the Vedsted anticline.

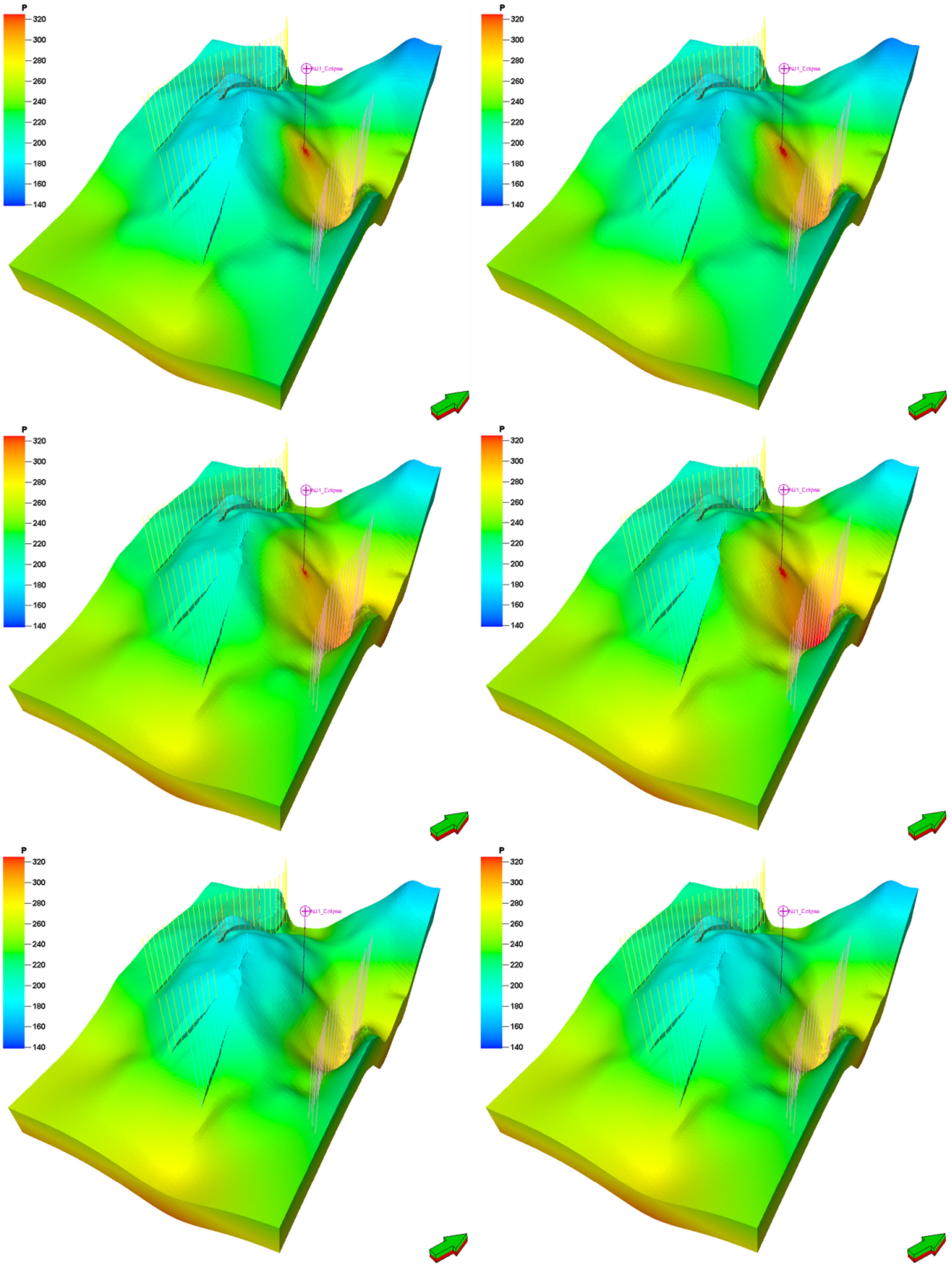


Figure 9.5. *Pressure development in the open fault (left) and closed fault scenarios (right) for simulation times of 1, 10 and 100 years, respectively (top to bottom).*

9.1.3 Site description

The Vedsted structure has been identified as a possible geological structure suitable for safe geological storage of CO_2. The structure has been investigated by two old oil exploration wells (Haldager-1, 1950 and Vedsted-1, 1958) and old regional seismic lines (1967 and 1983). It is an anticlinal closure within a fault block. The closure includes several sandstone reservoirs of good quality at depths of 1200 to 2000 m. Several hundred metres of thick claystone intervals provide an excellent cap rock above the reservoirs. The Gassum formation forms the primary reservoir whereas the shallower Haldager sandstone can be used as a secondary reservoir. Additionally a several hundred meters of thick chalk section provides a secondary seal rock.

The storage capacity of the Vedsted structure has been preliminarily estimated to approximately 160 Mt of CO_2 based on a review of existing data and reservoir simulation. In order to verify the closure of the anticline structure, the existence and location of the bounding faults and the storage capacity and quality, a new 2D seismic survey was acquired in 2008.

The **storage complex** for the Vedsted site is illustrated in Figure 9.6. The storage complex delineates the anticlinal structural closure together with the potential leaking faults. At this stage faults can be identified on the seismic interpretations, but the state of the faults is still unknown, *i.e.,* open or non-open characteristics of the faults, as well as termination points are to some degree uncertain.

Further, the state of the old legacy well, Vedsted-1 plugged and abandoned (P&A) in 1958, is also a potential leakage risk and must be included in the storage complex. Because the abandonment of the well in 1958 is poorly documented and the quality of cement plugs is uncertain, the storage complex actually has to be defined up to the surface.

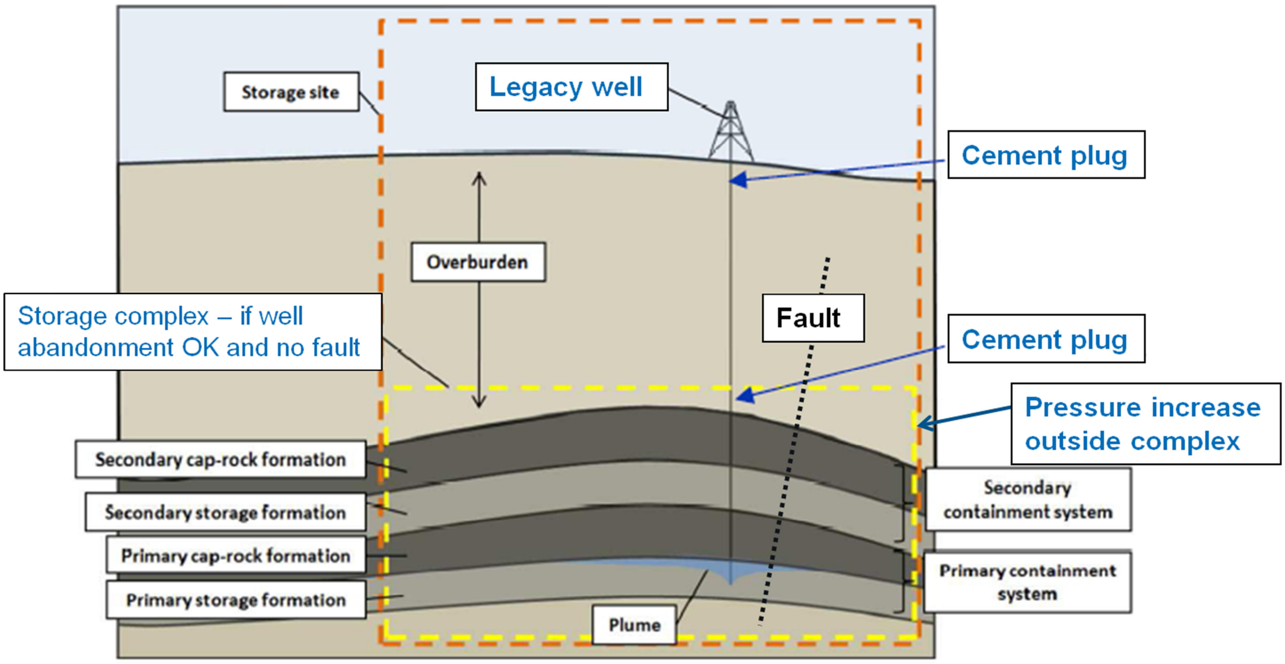


Figure 9.6. *Principal sketch of the Vedsted site. Primary containment: Gassum Fm. with the Fjerritslev Fm. acting as seal rock. Secondary containment: Haldager Fm. with the Boerglum Fm. acting as seal rock.*

9.1.4 Measures to prevent significant irregularities

Four major risk areas were identified:

- Abandoned Vedsted-1 well;
- Uncertainties about the Gassum reservoir which consequently needs a more detailed characterisation;
- Fault properties that need a better understanding;
- Pressure propagation outside the storage complex.

A crucial issue related to the well is the state of abandonment, as the well was P&A in 1958, where no detailed description for proper abandonment was described in the Danish Subsoil Act. The state of the Vedsted-1 well was assessed and re-intervention and proper plug and abandonment was recommended.

The need for a more detailed characterisation of the Gassum Formation calls for additional data acquisition and interpretation, especially 3D seismic data in combination with an appraisal well and flow test(s).

Risk of fault reactivation has been addressed in the present application from coupled fluid flow and geomechanical modelling.

Pressure propagation in the surroundings of the storage site can be assessed by proper regional modelling and correct handling of simulation boundary conditions. Regional geological understanding is thus crucial.

Input from the **risk assessment** was condensed into twenty-two discrete hazards. Safeguards and actions that can reduce the probability and/or reduce the consequence form the individual risk have been described. A risk matrix for the twenty-two hazards visualise how each should plot before and after a **safeguard** is put in action.

Operating an onshore storage site situated in a deep saline aquifer places great demands on the **monitoring plan**. Baseline monitoring data are crucial to justify any irregularities. A baseline study was performed, although on an analogue field area due to logistical challenges. Specific objectives for a monitoring plan for the Vedsted site were considered: four for the deep subsurface and four for the shallowest part or surface (Figure 9.7).

To cover the eight monitoring objectives, five main scenarios have been developed, which were each further divided into sub-scenarios resulting in twelve different scenarios. Most of the scenarios involve several monitoring techniques that can be applied at different time schedules during the life-time of the project. Some of the monitoring techniques have to be run before CO_2 injection starts to provide proper baseline measurements and some will continue after injection has ceased. It is anticipated that the injection period runs for 40 years.

		Year																																																	
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Deep-focussed monitoring																																																			
3D surface seismic	🟨		🟨			🟨					🟨										🟨																				🟨										🟨
2D surface seismic (option)	🟨		🟨			🟨					🟨										🟨																				🟨										🟨
3D VSP	🟨		🟨			🟨					🟨																																								
Downhole pressure	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Downhole temperature	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Downhole logging	🟨		🟨			🟨					🟨										🟨																														
Downhole fluid sampling	🟨		🟨			🟨					🟨										🟨																														
Passive seismics	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨										
Shallow-focussed monitoring																																																			
Continuous monitoring stations	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Soil gas concentration / flux	🟩					🟩					🟩					🟩					🟩										🟩										🟩										
Mobile / spatial IR lasers	🟩					🟩					🟩					🟩					🟩										🟩										🟩										
Flux tower	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Groundwater sampling	🟩					🟩					🟩					🟩					🟩										🟩										🟩										
Downhole logging	🟩					🟩					🟩					🟩					🟩										🟩										🟩										
Groundwater p,t hydraulic head	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
TEM	🟩																																																		
PSInSAR	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Hyperspectral remote sensing	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Offshore surveys																																																			
Ecological surveys and sampling	🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩
Sonar / visual surveys	🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩					🟩

N.B. Includes surveys which will be considered but might not actually be deployed, depending on circumstances - see text for details

N.B. Subject to review and modification through operational phase as monitoring data becomes available and predictive models are updated

Figure 9.7. *Proposed monitoring plan for the injection (operation) phase at Vedsted. N.B.: This monitoring plan will be subject to modification through the operational phase as monitoring data become available and predictive models are updated and improved.*

9.1.5 Regulatory requirements for monitoring

Vedsted is primarily regulated under the EC Storage Directive. The Directive requires that monitoring is carried out throughout the lifetime of a project to verify that storage performance behaves as predicted, to detect possible CO_2 leakage and to ensure that the storage operations do not lead to adverse environmental or safety impacts. These high-level aims are to be translated to more **site specific monitoring** objectives and **a corrective measures plan** is to be constructed from a number of identified **performance indicators**.

9.2 Review of the 'dry-run' permit application

The following review is a summary of the detailed review undertaken as part of the 'dry-run' permit development process for the Vedsted site.

9.2.1 Appraisal Term

There is a useful discussion of the range in permeabilities that might be expected and the impact this would have on injectivities. Such clear and comprehensive explanations of the causes of variations in estimated values, when uncertainty is considered to be large, should be comprehensively addressed in storage permit applications.

9.2.2 Storage development plan

An incremental development is proposed with three injection wells injecting at a rate of approximately 1 Mt per year each, which helps to reduce risks and costs, providing back-up capacity to allow well maintenance and to enable reservoir responses to be observed during the injection ramp-up. Expected data obtained during the monitoring plan are clearly related to this process and provide confidence that the learning from the ramp-up period will improve future operations and extrapolations of site performance.

Due to the initial sparse data, the injection plan is a ramp scheme with a gradually rising injection rate starting with a single injection well up to three wells injecting 1Mt/year each. This will allow to exploit the early response data for history matching. This would imply approximately 120 Mt of CO_2 would be injected. A summary of this would be necessary in a full permit.

The ramped injection approach is a sound approach to evaluating the reservoir and reducing technical risks. However the economic risks of reduced injection, despite significant capital expenditure, would need to be carefully evaluated as part of the operators business case though it may not be a concern of the Competent Authority. Contingencies would also need to be developed in the case injectivities were found to be lower than expected.

The application highlights the need to establish the extent of overpressure resulting from injection into the saline aquifer structure and a requirement for discussions between operators and regulators to establish an acceptable pressure response beyond the storage complex. While such discussions would be important, the responsibility lies with the operator to demonstrate that the expected pressure response will not have unacceptable or excessively detrimental effects. These effects will be specific to each site; they could include movement of brines, changes in pressure for other users or, in extreme cases, damage to seal rocks. Increases in pressure are likely to be limited by *inter alia:*

- Fracture reactivation pressures;
- Capillary entry pressures;
- Pressure responses in adjacent hydrocarbon fields;
- Impacts on other regions of the hydraulic unit or nearby units that might limit other (future) storage capacity.

Where these potential impacts can be demonstrated to be low and acceptable, it is more likely that a permit would be granted, albeit with appropriate conditions attached.

The potential for water production at Vedsted, as at Blake Field, has been investigated. The lack of production data to constrain predictions of the lower limit of the hydrodynamic storage capacity is noted. An estimate of the dynamic storage capacity, derived from fluid flow simulations, would be expected in a full permit application.

The lack of data on the likely behaviour of the faults is highlighted and therefore two end-member situations are considered; either the faults are considered as being fully transmissive, *i.e.,* permeable, or closed, *i.e.,* having very low permeability. The simulations highlight the risk of reactivation from increased pressure at the top of the anticlinal structure. The need to focus attention on a specific high-risk fault that would be affected by a significant overpressure is highlighted. This would be a target for monitoring with regard to potential reactivation and further assessment of the vertical permeability changes that might allow CO_2 or brine migration. Similarly, low case and high case scenarios are proposed for petrophysical properties.

9.2.3 Site description

The potential for induced and natural seismicity to affect the integrity of the storage structure has not been addressed. An evaluation of the natural (or induced from other activities such as natural gas storage) seismic activity in the area would be very useful to develop a baseline.

It is stated that the Skagerrak Formation may provide further storage potential below the Gassum Formation which has been selected as the primary target for CO_2 storage. In the Vedsted area little is known about the underlying Skagerrak Formation, although preliminary evidence suggests that structural closure may also be found in the deeper Skagerrak, which would be encouraging for prospective operators wishing to store more CO_2 in the area. Appraisal or injection wells constructed for the Vedsted operation could be extended, together with 3D seismic baseline surveys that allow detailed evaluation of Skagerrak and overlying Gassum Formations, to assess the potential for the Skagerrak in the immediate area as an additional storage target.

The presence of two coincident potential storage reservoirs raises interesting opportunities for operators and leaseholders in the area which are discussed below. It is assumed that the Gassum Formation has been targeted here because it is shallower and therefore cheaper to inject into as well as being sufficient to meet the present planned capture rates from the power station and cement works.

The potential for connection between the Gassum and Skagerrak Formations, including the potential for denser CO_2-rich formation water to migrate into the Skagerrak should be investigated. This may require injection testing on the first injection well.

The lack of fluid relative permeability data for the Gassum Formation has required estimates to be derived from air-permeability data. A factor of 0.5 has therefore been applied. It is recognised that other factors, as low as 0.21, have been reported in the literature. To account for this lack of data, two scenarios, including higher and lower permeabilities, were used to constrain expected storage capacities. This demonstrates a conservative approach and highlights the possible range of capacities and injectivities that could be expected, whilst recognising that this approach is too simplistic. Additional special core analyses and further testing on either existing material or material obtained during future appraisal and well construction would also be necessary to reduce uncertainty in this important parameter.

The storage complex boundary has not been explicitly defined in the storage permit application. However, the complex boundary is implied to be the shallowest spill point which occurs to the north of the closure. It would be expected that the storage complex boundary, whilst relatively straightforward to define here on the basis of likely plume extent, should be clearly shown in plan and section view in a permit application. This is a fundamental requirement as movement of CO_2 beyond this boundary would be determined as leakage under the terms of the EC Storage Directive.

Furthermore, it is stated that the faults may need to be included but as their status with regards to permeability is currently uncertain, this decision cannot be taken. It is unlikely that site characterisation would be able to definitively assess the status of all these faults, unless highly targeted and costly coring of faults and subsequent well and core testing were undertaken. A monitored injection test into the reservoir where it abuts the fault would be more useful.

Two very different approaches can be taken to deal with this issue:

i. Define the storage complex excluding the faults, even though it would be necessary to demonstrate they are unlikely to allow migration of CO_2;

ii. Taking a precautionary approach, define the storage complex so as to include potential leakage pathways, *i.e.,* the Vedsted-1 well and principle faults the potential for allowing CO_2 migration of which has yet to be established.

While it is clear these potential leakage pathways fall within the area of site characterisation, they should not necessarily be the basis for defining the area of the storage complex. Indeed it is unlikely that a permit application would be successful without determining that these features are unlikely to act as leakage pathways. In other words, once it is established that these features will not act as leakage pathways, there is no reason to include these faults in the volume of the storage complex. Indeed, the fault may form the lateral boundary to the storage complex for example. However the degree of certainty required by a regulator on the likely behaviour of a fault would need to be taken into account.

The storage complex should not be defined to the surface as this implies a lack of subsurface containment which would imply storage should not be considered at the site.

9.2.4 Measures to prevent significant irregularities

Previous preliminary risk assessments carried out on behalf of Vattenfall identified a total of twenty-two separate risks that address issues of incorrect constraint on model properties (due to lack of data), reduced injectivity, unexpected migration, leakage mechanisms and their impacts, and uncontrolled pressure propagation. The most important risks were identified as lack of sufficient data on the reservoir (predominantly seismic and relative permeability data), the integrity of an old abandoned well and pressure propagation outside the storage complex.

For each of the risks identified, safeguarding actions were developed, which included both preventative measures, which might be considered as mitigation activities to reduce risks prior to or during operation, and protective measures, which might be considered as corrective measures following the occurrence of a significant irregularity. The application of these safeguarding measures has reduced the consequence and/or probability to low or very low of all but three risks that were originally ranked of high consequence, and five risks that were originally ranked medium consequence but low probability. The remaining high-consequence risks are:

i. CO_2 in groundwater – low probability;

ii. Old abandoned well leaks – high probability;

iii. New abandoned well leaks – very low probability.

The site characterisation undertaken here has addressed some of these risks, specifically the development of pressure beyond the storage complex (though consequences of this have not been addressed in detail) and fault-controlled leakage mechanisms. Other risks, such as loss of injectivity and the impacts of leakage, have not been addressed due to resource limits. A full storage permit application would include consideration of all identified risks and especially the consequences if the risks occurred.

For each of the risks, the preventative measures include monitoring. In the case of abandoned wells, some workover is assumed. This approach provides some confidence that the risks will be reduced through design and construction and that remaining residual risks will be monitored. The preventative actions would be expected to be designed and described in significantly more detail than it has been possible in this ‘dry-run’ application. The permit application would need to demonstrate that the remedial or corrective measure would be capable to achieve the stated objective and reduce the risk or correct the irregularity once it has occurred, as well as have monitoring that adequately demonstrates effective corrective measures.

9.2.5 Monitoring and corrective measures

The monitoring aims are clearly defined and have been used to define twelve different scenarios. These scenarios are designed to assess the effectiveness of monitoring different domains of the system under different conditions: for example, monitoring containment in the reservoir, or monitoring CO_2 accumulations in a groundwater. This approach can provide a useful method of ensuring risks are appropriately addressed in the monitoring plan which would have to cover all the relevant domains.

The monitoring plan briefly describes the different techniques that have been selected and their applications. The basis for tool selection should be described. Further consideration of the constraints for each technique, such as site-specific minimum detection limits or areal coverage, would be beneficial in helping regulators to assess the effectiveness of the techniques proposed. It is likely that in some cases, these trigger events can be further defined following acquisition of baseline data to determine the range of natural variations present at the site.

Monitoring for public assurance, including soil gas geochemical surveys and continuous shallow groundwater monitoring, is rightly considered important at Vedsted, as it is an onshore storage site. In addition, remote sensing based techniques for ground movement and fault reactivations, as well as hyperspectral measurements for detecting vegetation stress above locations of higher risk *i.e.,* above fault outcrops at surface, are proposed. The need to deal with false positives, likely detection limits and identifying appropriate trigger events would further strengthen the arguments for using these techniques.

The monitoring plan is divided into core monitoring surveys that are pre-planned and scheduled based on pre-injection predictions of site evolution, and a set of further monitoring activities that are very briefly described in the corrective measures plan. The events or thresholds that might trigger the use of these additional monitoring activities should be described.

High level indicators of performance have been proposed for the Vedsted site as part of the brief corrective measures plan. A detailed corrective measures plan was deemed to be out of scope of the SiteChar 'dry-run' applications. PPCs have not been developed for the Vedsted site. The proposed performance indicators provide 'targets' against which site performance could be assessed and would be developed into more formal PPCs which are cross-referenced to the site-specific risks they address. This would help to demonstrate that the risk register, PPCs, corrective measures plan and monitoring plan are closely integrated. Nevertheless, at this stage, they provide a useful framework for developing corrective measures.

The monitoring plan would be improved if the relationship between risks, both spatially and temporarily, and the proposed monitoring activities could be further developed, which might then be able to reduce, for example, some of the intensity of the near-surface monitoring.