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Characterization of European CO₂ Storage — European Project SiteChar Caractérisation de sites européens de stockage de CO₂ — Projet européen SiteChar

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SiteChar - Methodology for a Fit-for-Purpose Assessment of CO₂ Storage Sites in Europe

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Abstract — The FP7-funded SiteChar project examined the entire CO₂ geological storage site characterisation process, from the initial feasibility studies through to the final stage of application for a CO₂ storage permit based on criteria defined by the relevant European legislation. The SiteChar workflow for CO₂ geological storage site characterisation provides a description of all elements of a site characterisation study, as well as guidance to streamline the site characterisation process and make sure that the output covers the aspects mentioned in the European Community (EC) Storage Directive. Five potential European storage sites, representative of prospective geological contexts, were considered as test sites for the research work: a North Sea multi-store site (hydrocarbon field and aquifer) offshore Scotland; an onshore aquifer in Denmark; an onshore gas field in Poland; an aquifer offshore in Norway; and an aquifer in the Southern Adriatic Sea. This portfolio combines complementary sites that allowed to encompass the different steps of the characterisation workflow. A key innovation was the development of internal 'dry-run' permit applications at the Danish and Scottish sites and their review by relevant regulatory authorities. This process helped to refine the site characterisation workflow, and aimed to identify remaining gaps in site-specific characterisation, needed to secure storage permits under the EC Storage Directive as implemented in 'host' Member States.

SiteChar considered the important aspect of the public awareness and public opinions of these new technologies, in parallel to technical issues, on the onshore Polish and offshore Scottish sites. A new format to assist public opinion-forming processes was tested involving a small sample of local communities. Generic as well as site-specific information was made available to the general and local public via the internet and at information meetings. These exercises provide insight in the way implementation of CCS project plans may be perceived by local stakeholders, and inform approaches to develop effective local communication and participation strategies.

Key lessons from the research conducted in SiteChar were developed as technical recommendations for storage site characterisation and best practice guidance for storage permitting from the perspective of both applicant and regulator. A best practice guide for policymakers and regulators at Member States and European levels, potential storage site developers and operators has been presented.

Résumé — SiteChar – Une méthodologie pour une caractérisation appropriée des sites de stockage de CO₂ — Le projet européen SiteChar a examiné l'ensemble du processus de caractérisation des sites de stockage géologique de CO₂, depuis les premières études de faisabilité jusqu'à l'étape ultime du dépôt d'un dossier de permis de stockage de CO₂ sur la base des critères définis par la législation européenne en la matière. La méthodologie développée dans SiteChar fournit une description des éléments requis lors d'une étude de caractérisation des sites de stockage géologique de CO₂, ainsi que des guides pour rationaliser le processus de caractérisation du site et s'assurer que les investigations couvrent les différents aspects mentionnés dans la Directive Européenne sur le stockage géologique du CO₂. Les travaux de recherche menés dans SiteChar ont porté sur cinq sites européens, présentant différents contextes géologiques potentiels pour le stockage du CO₂ : un site multi-stockage de Mer du Nord (champ d'hydrocarbures et aquifère) au large des côtes d'Écosse ; un aquifère onshore au Danemark ; un champ de gaz onshore en Pologne ; un aquifère offshore en Norvège ; et un aquifère dans la Mer Adriatique Sud. Cet ensemble regroupe des sites complémentaires qui ont permis d'investiguer les différentes étapes du processus de caractérisation d'un site de stockage de CO₂. Un des éléments innovants du projet a été le développement de permis de stockage 'en blanc' sur les sites danois et écossais et leur examen par des autorités réglementaires compétentes. Ce processus a permis d'affiner la méthodologie de caractérisation des sites de stockage géologiques du CO₂, tout en identifiant les lacunes qui subsistent dans la caractérisation spécifique d'un site, et qui doivent être comblées en vue de l'octroi d'un permis de stockage conformément à la Directive Européenne et telle que transposée dans les États membres.

Au-delà des problématiques techniques, SiteChar a examiné l'important volet de la sensibilisation du public et de l'opinion publique relatives à ces nouvelles technologies, sur les sites onshore écossais et polonais, et écossais offshore. Une nouvelle approche pour la formation de l'opinion publique et la consultation du public impliquant un échantillon restreint de la population a été testée. L'ensemble de la communauté concernée a ensuite été informé *via* Internet et lors de réunions d'information. Ces expériences permettent de mieux comprendre comment des projets de Captage et Stockage du CO₂ (CSC) peuvent être perçus par les acteurs locaux, et apportent de précieuses informations pour le développement de stratégies efficaces de communication et de participation des communautés locales.

Les principaux enseignements tirés des travaux de recherche effectués dans SiteChar ont été élaborés sous forme de recommandations techniques pour la caractérisation de sites de stockage géologique de CO₂ pour le processus d'octroi d'un permis de stockage dans la perspective à la fois du demandeur et du régulateur. Un guide de bonnes pratiques pour les décideurs et les organismes de réglementation au niveau des États membres et au niveau européen, les promoteurs et les exploitants de sites potentiels de stockage a été présenté.

INTRODUCTION

Even if Carbon Capture and Storage (CCS) is recognised as a critical component of a coherent portfolio of low-carbon technologies, it is clear that the development of CCS projects has been slower than expected. Two main issues constrain its large-scale deployment: the lack of an effective business model and the lack of public acceptance of storage in deep geological formations. The role of CO₂ geological storage and in particular characterisation of potential storage sites is crucial to the whole CCS chain to reduce uncertainties and consequently de-risk potential CO₂ stores thus ensuring a safe and permanent storage. This is especially important for deep saline formations that provide the largest potential CO₂ storage capacity. Developing robust approaches to

CO₂ storage site characterisation, whilst considering the public acceptability of storage in geological formations, is thus a key step for the deployment of CCS. Therefore the aim of the EU FP7-funded SiteChar project was to provide the key steps required to achieve readiness for large-scale implementation of CO₂ storage in Europe and establish the feasibility of CO₂ storage on representative potential storage complexes suitable for development of CO₂ geological storage in the near term.

Several studies have addressed, at variable levels, site characterisation for CO₂ geological storage, such as, amongst others, the SACS¹ – Best practice for the storage of CO₂ in saline aquifers (Chadwick *et al.*, 2008) which

¹ Saline Aquifer CO₂ Storage Project.

provides a summary of data requirements for site characterisation, the best practice manual for site screening, site selection, and initial characterisation for storage of CO₂ in deep geologic formations (NETL, 2010) which describes a workflow from project definition, site screening and initial site characterisation, and the CO₂ QUALSTORE Guideline (DNV, 2010) which provides a detailed summary of approaches to site selection and site characterisation and which has partly been used to develop the guidelines on how to meet the requirements of the EC Storage Directive. Specifically, SiteChar aimed firstly to demonstrate the level of geological characterisation and assessment of long-term storage complex behaviour, rigorously tested in accordance with the relevant European legislation, needed to meet the criteria required to gain a CO₂ storage permit. Secondly, SiteChar undertook the refinement of a complete generic storage site characterisation workflow, focused on the storage complex, from a static 3D earth model to dynamic simulations of storage behaviour, monitoring programme planning, developing a framework for risk assessment and management, and including techno-economic evaluation and public outreach exercises. Thirdly, SiteChar planned to develop 'dry-run' storage permit applications and have these applications reviewed by a group of experts and regulators in order to identify key lessons and hence improve the site characterisation workflow and the associated permitting process.

This paper presents the learning from the SiteChar project and synthesises the main recommendations for site characterisation for the purpose of a storage permit. From January 2011 to December 2013, SiteChar has extended and tested standard site characterisation workflows on the basis of criteria defined by the relevant European legislation, including estimation of storage capacities, modeling of aquifers at basin or reservoir scale, testing of injection scenarios, risk assessment and reduction, and development of the site monitoring plan. The methodology has been tested at a portfolio of sites representative of European storage sites where CCS is most likely to develop in the near term: a northern North Sea multi-store site offshore Scotland, an onshore aquifer in Denmark, an onshore gas field in Poland, an aquifer offshore Norway and an aquifer in the Southern Adriatic Sea. Section 1 presents the project concept and the level of characterisation reached within SiteChar at each site as well as the learning from their characterisation. At the Danish and Scottish sites, the characterisation has been conducted as far as possible in the framework of a research project so as to develop 'dry-run' storage permit applications that 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, e.g. assessing the integrity of abandoned wells within a depleted hydrocarbon field, estimating the storage capacities in a multi-store complex with structural traps and open

saline aquifers, evaluating the geomechanical stability of a carbonate reservoir. Key learning from these site characterisations is presented in Section 2 that goes through each main step of the site characterisation workflow. In addition to these technical issues, SiteChar has considered the important aspect of current public knowledge and perceptions regarding the storage of CO₂ in both an onshore and an offshore site. The results of these activities are presented in Section 3. Finally, the research conducted in SiteChar resulted in recommendations for site characterisations that were synthesised as a methodological guide for the preparation of storage permit application adapted to European specific geological and regulatory contexts for use by storage site operators and regulatory bodies. These recommendations are presented in Section 4.

1 SITECHAR SITES CHARACTERISATION

The research conducted in SiteChar focused on five potential storage sites, representative of various European geological contexts, as test sites for the research work (Fig. 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 aquifer offshore Norway and, finally,
- an aquifer in the Southern Adriatic Sea.

Two levels of characterisation have been investigated within SiteChar. At the Polish Załęcze and Żuclów gas fields, the Norwegian Trøndelag platform and the Southern Adriatic Sea site, the characterisation has been performed for the early phases of the workflow to investigate new prospective areas for CO₂ 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 are currently being considered as near-term candidate prospects. 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 CO₂ re-dite extending storage in a hydrocarbon field to large-scale CO₂ 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* until late 2011 to be an industrial-scale demonstration 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.

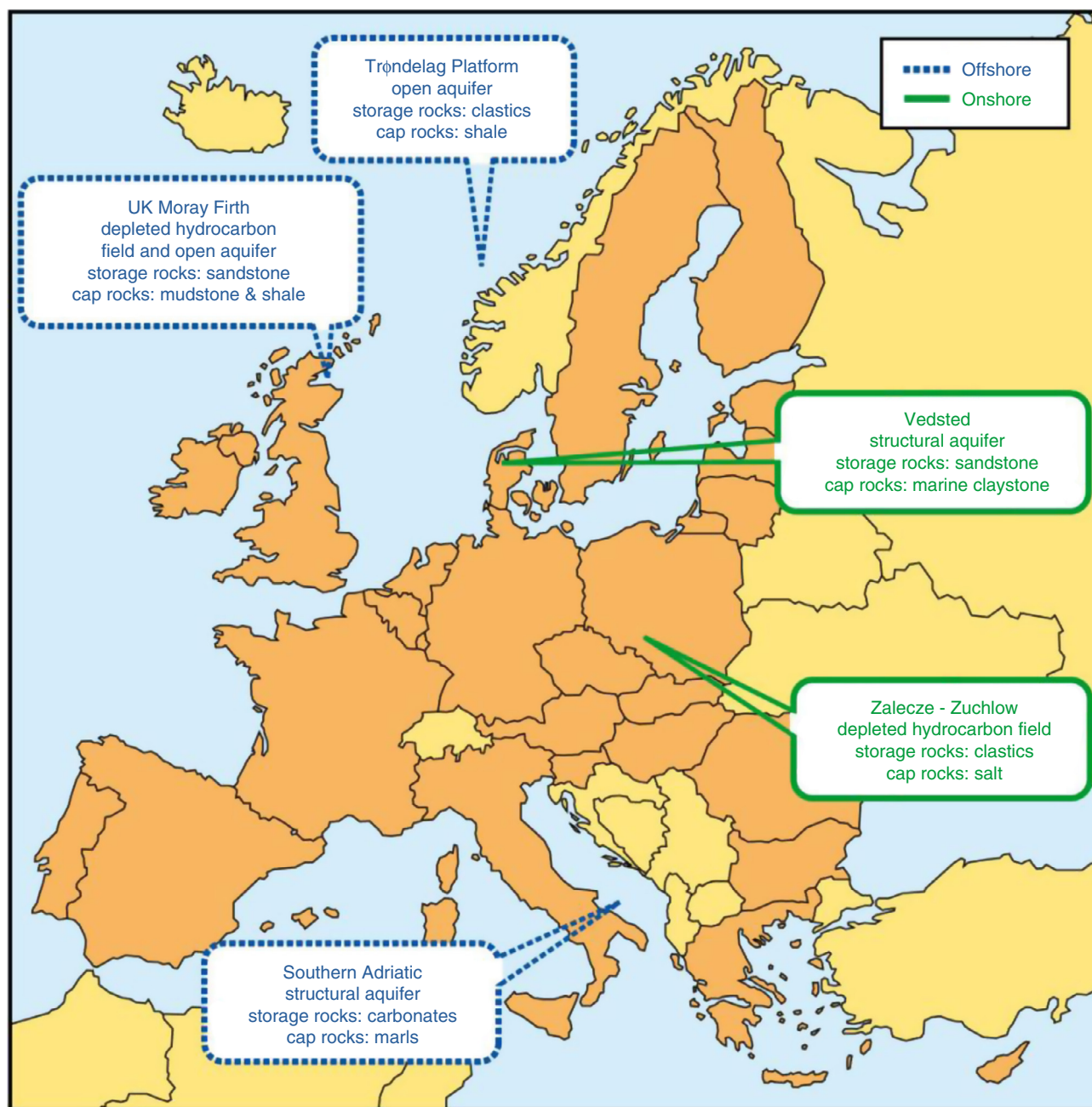


Figure 1

The SiteChar portfolio.

1.1 UK Northern North Sea Site

Site characterisation of a UK offshore site in SiteChar looks ahead to commercial-scale storage in a mature CCS industry where CO₂ is contained in a multi-store site, which comprises both a depleted hydrocarbon field and the surrounding

saline aquifer sandstone. Previous research studies (SCCS, 2009, 2011) have deemed the Captain Sandstone, in the Outer Moray Firth offshore eastern Scotland, to be feasible for storage and justify further investigation for CO₂ storage. Additionally, amongst sites that were short listed for consideration as prospective demonstrator projects by the UK

Government Department of Energy and Climate Change in October 2012, two prospective sites for CO₂ geological storage proposed storage within the Captain Sandstone.

Characterisation of the offshore UK Outer Moray Firth site demonstrates there is sufficient publicly available data within a mature hydrocarbon production province to investigate and prepare an outline storage permit application within research resources. However, even if this site is in an area of abundant legacy data, all site-specific data sought for characterisation were not publicly available. The SiteChar research has identified additional activities to further reduce uncertainties, and mitigate and monitor unmitigated risks that would be needed for a real permit application for a storage site. Characterisation of the UK multi-store site has enabled preparation of most of the key components (or 'criteria' as referred in Annex 1 of the EC Directive) required by the EC Storage Directive on the geological storage of carbon dioxide although some, such as details of financial security and a full environmental impact assessment, are beyond the scope of a research project. Characterisation to inform preparation of a 'dry-run' storage permit application demonstrated the very close interaction and integration of emerging technical findings across all site characterisation activities. Final decisions on essential elements of storage site design and predictions of the storage performance could not be made until the results of all technical investigations were available, the implications discussed and reassessment of risks undertaken.

The reader is invited to refer to [Akhurst et al. \(2015\)](#) for further details on the risk-led assessment process for the development of the UK 'dry-run' storage permit application.

1.2 Vedsted Site, Denmark

From 2007 to 2011, *Vattenfall A/S* planned to develop a full-scale demonstration project for CCS for the Vedsted site in Denmark. As a consequence of Danish political decisions on CCS and re-organisation within the *Vattenfall* company, the plan for the demonstration project was stopped in 2011, but this site can be considered as a 'realistic' case for CO₂ storage. The Vedsted structure is close to the Danish power plant Nordjyllandsværket which has a yearly CO₂ emission of around 2 Mt/year. A first estimate for the storage capacity for the site indicated that the storage capacity exceeds the potential captured CO₂ volume from the power plant in a 40-year lifetime and a nearby cement industry with emissions of up to 1 Mt/year could potentially be phased in.

Characterisation of the Vedsted site demonstrates that onshore storage in a saline aquifer sandstone should be possible. Preliminary modeling can be produced from sparse data and incremental phased development is proposed to progressively provide information that could improve future

operations and extrapolations of site performance. This would allow capture of the early reservoir response data for incorporation in the reservoir modeling and performance matching. Coupled geomechanical and fluid flow modeling provided first estimates of pressure footprints from the injection process and demonstrated synergistic benefits of concurrent fluid extraction from the storage formation ([Kempka et al., 2015](#)). In contrast to storage in a depleted hydrocarbon reservoir, only a single or few wells penetrate the overburden and reservoir interval minimising potential risk of leakage *via* existing boreholes. However, the abandonment state of old exploration wells might be a challenge to resolve. Development of a monitoring plan was of special interest for this onshore site. Surveys of near-surface gas geochemistry highlighted the utility of baseline surveys and the need for follow-up studies to clarify any unexplained anomalies before commencement of any CO₂ storage ([Beaubien et al., 2015](#)). The 'dry-run' permit application process demonstrates that close cooperation between all technical disciplines is crucial during all phases of the process to secure a successful outcome.

The reader is invited to refer to [Nielsen et al. \(2015\)](#) for further details on the process used for the development of the Vedsted aquifer storage permit application.

1.3 Załęcze and Żuchłów Gas Fields, Poland

The Załęcze-Żuchłów site is representative of sites in the Polish Lowland, which offer a series of natural gas reservoirs with CO₂ storage potential. This site lies 60 km north of Wrocław and 100 km south of Poznań where several industrial CO₂ sources are located.

A comprehensive but still preliminary characterisation of the Polish site was conducted on a large amount of data, however of varied quality ([Papiernik et al., 2015](#); [Békri et al., 2015](#)). The capacity of the Załęcze and Żuchłów gas fields was estimated sufficient to store the amount of CO₂ envisaged to be captured at a coal-fired power plant in close proximity to the site. The sealing capacity of the cap rock was estimated sufficient to ensure secure CO₂ storage. Geomechanical simulations did not predict any relevant damage to the cap rock integrity provided the reservoir pressure remains below the initial pressure. However, these assessments have to be taken with care since, even if quite an amount of data were available for these depleted hydrocarbon fields, there remains some uncertainty on the continuity of the Zechstein cap rock above the reservoir and lack of information on fault geometry, fault properties and the *in situ* stress field. Not surprisingly, well integrity has been highlighted as the main risk to containment of CO₂ within the storage site. A well integrity classification has been performed on the wells and injection scenarios assumed for site behaviour modeling but there definitely is a need for

the evaluation in more detail of all individual abandoned wells, which will require considerable efforts that were out of the scope of this research project.

1.4 Trøndelag Platform Site, Norwegian North Sea

The Trøndelag Platform, offshore Mid-Norway, covers an area of more than 50 000 km² that contains gas fields with naturally high CO₂ content that can be separated and stored. The Trøndelag site has been evaluated for CO₂ storage because of its two promising potential storage units of significant thickness, the Ile and the Garn Formations, present within the middle Jurassic sedimentary layers. These formations, which are the main oil- and gas-bearing reservoirs on the Halten Terrace area, have good to excellent storage characteristics.

The Trøndelag Platform has been characterised on the basis of publicly available data in order to investigate a new prospective storage area. Different modeling approaches have been applied to simulate CO₂ injection in the selected sites of the Trøndelag Platform, focusing on CO₂ containment and potential migration paths, as well as assessment of overpressure development. From this study, the Garn Formation of the Trøndelag Platform seems well suited for injection and storage of CO₂ on an industrial scale over a period of 40 years. This formation presents excellent porosity and permeability characteristics, its thickness is adequate for the geological storage of CO₂ and a low number of faults are evident from the available input data. In addition, the Garn Formation is overlain by thick shale sequences further reducing the risk associated to fault leakage and also suggesting a low risk for cap rock leakage. Several injection sites were evaluated using basin modeling tools with and without loss functions and reservoir modeling. Simulations of CO₂ injection indicated large volumes of CO₂ storage capacity, with low values of increased pressure due to CO₂ injection. Due to the limited data (only three wells), the heterogeneity of the storage formation could not be adequately represented in the models. To address this uncertainty, a sensitivity study was conducted to evaluate the likely impact on the simulation results.

1.5 Offshore Southern Adriatic Sea Site, Italy

The Southern Adriatic Sea site is a structural trap in a carbonate saline aquifer, close to the main Italian CO₂ emission power plant (Federico II power plant in Brindisi) where energy company *Enel* started a pilot plant for CO₂ capture in April 2010. It is one of the biggest power plants in Italy; it is characterised by very high CO₂ emissions, *i.e.*, more than 15 Mt/year in 2004 which is the highest emission rate in Italy. This deep saline aquifer is located only a few tens

of kilometres from the thermoelectric power plant. It is the nearest amongst the potential storage sites in Italy. Currently, there is no precise plan for CO₂ storage in the surrounding area. The investigated area thus represents a good opportunity to apply CCS at an industrial level, since CO₂ geological storage in the identified structures of the Southern Adriatic offshore would represent a strong contribution to reduce national CO₂ emissions.

The characterisation conducted on the Italian site was based on publicly available data (Volpi *et al.*, 2015a). The uncertainties were mainly associated to the scarcity and sparseness of available data: in particular, petrophysical properties and fault transmissivity. The approach adopted was to simulate several scenarios varying the petrophysical properties, the number of injection wells and the fault characteristics. The fluid flow modeling produced conflicting results, strongly related to the simulated scenario. Even if obviously a site with a poor seal assessment would never receive a storage permit, a scenario with faults open to fluid flow and the most pessimistic petrophysical properties derived from well logs analysis, was tested to infer a ‘worst case’ scenario. It shows that the CO₂ plume reaches the sea bottom 30 years after the start of injection. Geomechanical simulations performed to assess potential fault damage show that the Rovesti Fault, which is the closest to the injection well, remains below the Mohr Coulomb criteria for all the considered scenarios and stress regimes (Baroni *et al.*, 2015). A critical evaluation of the fluid flow and geomechanical simulation results led to consider the Grazia structure as a suitable site for a demonstration project, able to store a 10 Mt total amount of CO₂ at an injection rate of 1 Mt/year. The entire project duration should be 40 years; 5 years for exploration followed by 5 years of site development, 10 years of injection and 20 years of storage before the site liability transfer to the state.

The reader is invited to refer to Volpi *et al.* (2015b) for an overview of the characterisation of the Southern Adriatic site.

2 LESSONS LEARNT FROM THE SITECHAR SITES CHARACTERISATION

This section consolidates the key findings of the application of the characterisation workflow on the SiteChar sites portfolio. The objective of site characterisation is to demonstrate that the investigated site has sufficient capacity to accept the expected CO₂ volumes, sufficient injectivity to receive the expected rate of supplied CO₂ and appropriate containment to store the injected CO₂ 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. It is thus closely related to, amongst others,

the storage development plan that describes the injection (including the expected rates of injection and the injection scheme) and operating plans for the site, based upon the project design to store CO₂ at the anticipated rates for the lifetime of the project.

The site characterisations conducted in SiteChar are essentially a geological assessment, including geological, hydrodynamic, geomechanical and geochemical modeling at basin and reservoir scales, design of injection scenario, risk assessment, development of site monitoring plan. Preliminary assessments of the costs of the storage and public engagement activities were also conducted on four of the five sites. These economic evaluations are focused on the storage part which was the scope of the SiteChar project, even if for a real project, the whole CCS chain development should be considered.

2.1 SiteChar Workflow for CO₂ Storage Site Characterisation

A first version of the site characterisation workflow was developed at the beginning of the SiteChar project, based on the compilation of previously completed site characterisation activities and experience gained in previous site characterisation studies (Chadwick *et al.*, 2008; NETL, 2010; DNV, 2010; CO₂CRC, 2008). This workflow was applied to the SiteChar sites portfolio and the experience gained from these sites was integrated at the end of the project in the final and consolidated version of the workflow (Neele *et al.*, 2013).

The SiteChar workflow for CO₂ storage site characterisation provides a description of all the elements of a site characterisation study, as well as guidance on issues arising as part of the process. Compared to previous studies, it addresses in particular the sequence of the different steps and the timing of the process, the interdependencies and feedback loops within the process, and the coverage of the different requirements of the EC Storage Directive (EC, 2009, 2011). Characterisation of a site relies on the following steps (Fig. 2):

- 1) data acquisition and quick analysis;
- 2) qualitative and quantitative risk assessment;
- 3) geological assessment;
- 4) dynamic behaviour;
- 5) geomechanical assessment;
- 6) geochemical evaluation;
- 7) migration path analysis;
- 8) well integrity analysis;
- 9) monitoring and remediation plans.

Qualitative and quantitative risk assessment is conducted iteratively throughout the site characterisation project. Dynamic simulations of CO₂ behaviour, geomechanical assessment, and geochemical evaluation have to be conducted

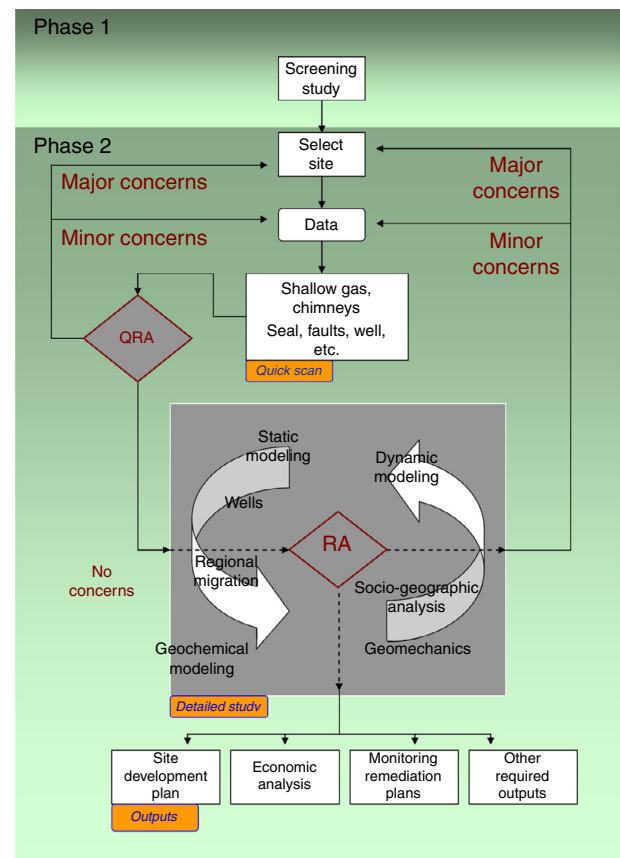


Figure 2

The SiteChar workflow for site characterisation.

simultaneously and in close coordination. Indeed exchange of emerging, interim and final results of all activities is required throughout site characterisation to reduce risks, in particular between hydrodynamic simulation and geomechanical integrity, static geological model attribution and hydrodynamic simulation, static geological model construction and geomechanical modeling, hydrodynamic modeling and well integrity, flow migration path analysis and shallow geohazards assessment, shallow geohazards assessment and monitoring planning. In addition to these steps,

- 10) social acceptability analysis;
- 11) economic assessment

have to be performed in parallel to the technical characterisation and for a real project overall the whole CCS chain development. The reader is invited to refer to Neele *et al.* (2015) for further details on the workflow.

All of these steps have been tested on some or all of the sites in the SiteChar portfolio (Tab. 1), highlighting the successes and the limitations of the application of the site characterisation workflow. The characterisation of the Polish

TABLE 1
Application of the characterisation workflow on the SiteChar sites portfolio

	Outer Moray Firth	Vedsted	Załęcze-Zuchłów	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
Step of the workflow addressed					
1- Qualitative & quantitative risk assessment	X	X	X	X	
2- Static geological model construction and attribution	X	X	X	X	X
3- Hydrodynamic modeling	X	X	X	X	X
4- Geomechanical analysis	X	X	X	X	X
5- Geochemical evaluation	X		X		
6- Well integrity analysis	X	X	X		
7- Migration path analysis	X			X	
8- Social acceptability analysis	X		X		
9- Monitoring plan including shallow geohazards assessment and seismic monitoring feasibility study	X	X		X	
10- Economic assessment	X	X		X	X
11- Compliance with regulatory context	X	X			

Załęcze and Żuchłów gas fields, the Norwegian Trøndelag platform and the Southern Adriatic Sea site aimed at investigating new prospective areas for CO₂ storage. These characterisations thus started from the early phases of the workflow with the construction of static models at basin and reservoir scales. These sites were used to study some specific barriers to the characterisation process, such as design of injection strategies with special emphasis on the storage capacity (Trøndelag Platform), coupled fluid flow and geomechanical simulations to assess the geomechanical integrity of the storage site (Southern Adriatic site) and the assessment of well integrity (Załęcze and Żuchłów). At the offshore UK North Sea multi-store site and the onshore Vedsted aquifer site in Denmark, a full-chain characterisation was conducted so as to address, as far as possible according to the limited resources and scope of a research project, all components required for a permit application, including a risk assessment and a monitoring plan.

Key learnings of the characterisation of the five SiteChar sites have been derived (Delprat-Jannaud *et al.*, 2013a) and integrated in the final version of SiteChar workflow. They are presented here after.

2.2 Fit-for-Purpose Characterisation Process

High-level objectives of site characterisation are common to all sites, reflecting the need to demonstrate permanent, secure containment of volumes of CO₂ at cost-effective rates. However, each site is unique and therefore even if characterisations of different sites rely on a similar workflow, the scope and detail of site investigations is intrinsic to each site. Site characterisation actually requires a fit-for-purpose workflow aiming to demonstrate that the permit applicant has sufficient understanding of the site and that the proposed site operation will permanently and safely contain CO₂. Characterisation of a site for the purpose of obtaining a CO₂ storage permit is a risk-based process designed to demonstrate safe and permanent storage and closely depending on the site- and project-specific characteristics, the available data as well as the uncertainties and the risks to be investigated. Risk analysis thus defines the scope of the site characterisation work that iteratively determines and constrains risks with the objective to reduce their consequence and/or likelihood to acceptable levels (Fig. 3).

SiteChar experience has emphasised the need for a multidisciplinary expertise based on a close cooperation

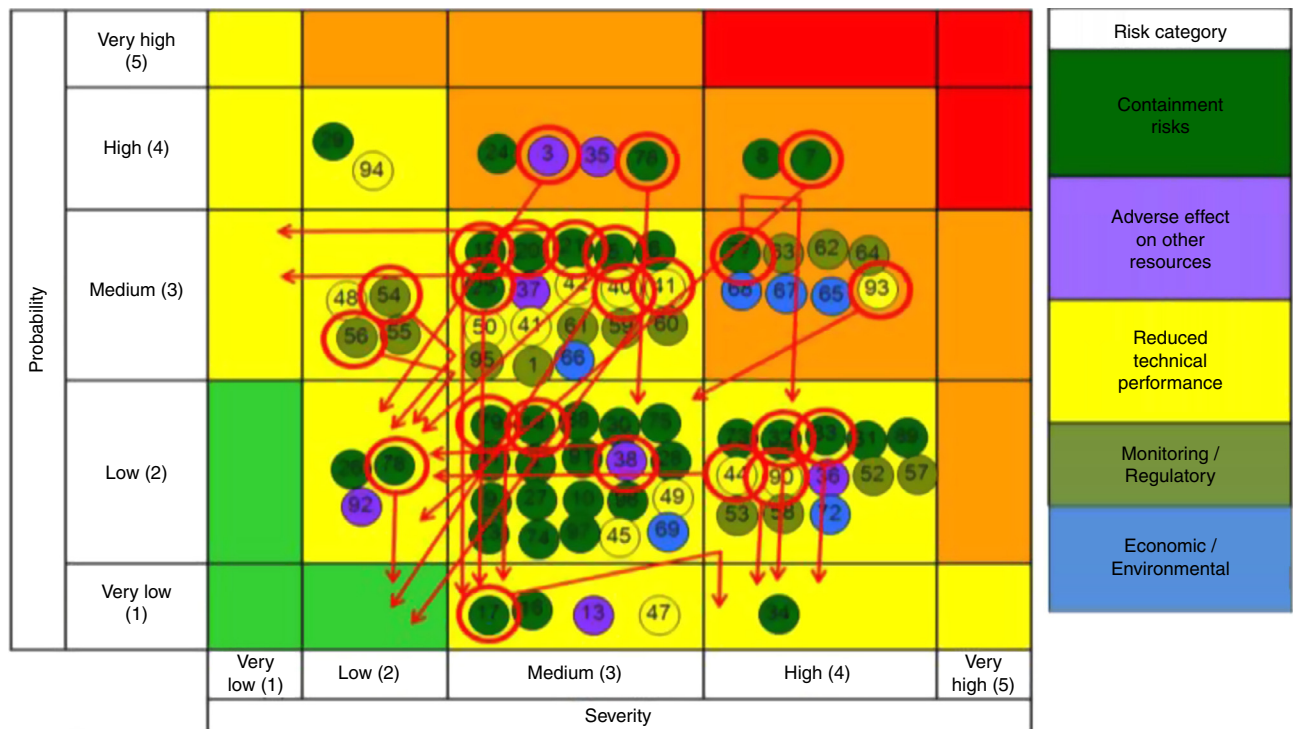


Figure 3

Example of risk reduction activities (UK northern North Sea site). Around one hundred risks were initially listed for the UK site, classified in five risk categories and ranked in the initial risk register according to their probability and severity. Arrows indicate the subsequent position of the residual risks after SiteChar mitigation activities.

between disciplines. Providing an adequate qualification of all aspects of the storage site appropriate to meet regulatory requirements requires in particular experts to share as soon as possible a common project vision, a common purpose for their activities and interdependencies, and, all along the investigation progress, any changes to the project concept or site design. Very close interaction between the static geological modeling, fluid flow modeling and geomechanical modeling should be planned for the site characterisation work schedule. For instance, hydrodynamic modeling is sensitive to geological attribution; geomechanical modeling requires specific extension of the model used for hydrodynamic modeling and attribution of faults, etc. Therefore, communication between the activities to discuss input data that are required to be used in common, as well as exchange of outputs from one modeling activity to another, must be included in the plan of work. Similarly, all the software to be used for static geological, hydrodynamic and geomechanical modeling of the storage site should be discussed at the outset of the characterisation. Compatibility and interoperability should be tested before decisions are made of which modeling software to be licensed for use and staff assigned with appropriate modeling skills.

An important outcome of this multidisciplinary expertise is the definition of the storage complex, which is a fundamental component of the storage permit application as leakage of CO₂ is defined when CO₂ migrates beyond this boundary. The storage site contains the primary reservoir into which CO₂ is expected to be injected and most likely contained. The upper boundary of the reservoir will be defined by the primary seal rock, above which CO₂ is not expected to migrate. However the storage complex might also contain additional formations that could contain migrating CO₂ in the case it migrates out of the primary reservoir. These secondary reservoirs, and their secondary, complex seal rock might be included specifically where CO₂ migration is expected or as an additional safeguard against leakage. The complex seal rock will be expected to provide more regional containment of the CO₂. Sufficient evidence will 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 CO₂.

2.3 Geological Assessment

Assessing the impact of dynamic modeling of CO₂ injection on the storage formation and potentially on the overall storage system requires a structural and stratigraphical framework. Geological assessment (Fig. 4) results in the construction of a 'static' structural 3D geological model that will be refined for the storage complex when the site

characterisation process and the resulting project concept will be developed. This step is very time consuming, the duration depending on the availability of good-quality seismic data, corresponding borehole data and the results of borehole core analyses.

This step is very important since the geological model is the basis of dynamic modeling of the storage site behaviour and prediction of site performance. SiteChar experience highlights some uncertainties and risks factors related to low-resolution seismic data that cannot ensure a sufficiently detailed representation of the storage complex. High quality data are needed in sufficient abundance and with a spatial distribution that allows characterisation of the various geological components of the storage site. Size and resolution of the model should fit the resolution of the available data; this influences the level of detail of the analysis that can be conducted in the characterisation. For instance, on the UK site, attribution of the channel facies was found to be a very influential factor when assessing reservoir pressure during injection and further refinement of the distribution of petrophysical parameters was therefore recommended. In addition, the lateral and vertical extents of the model must be discussed and shared at the early beginning of the site characterisation with other modelers that might have specific requirements according to their specific objectives, *e.g.* prediction of the CO₂ plume extent, assessment of geomechanical integrity, etc. More generally, a close interaction between geologists and reservoir engineers is recommended from the beginning of the project to share the purpose of the models, agree their characteristics and avoid possible software incompatibility.

Last but not least, clear statements of confidence and uncertainty associated with the geological model are required. Focus should be put on assessing uncertainty related to features and parameters that have some impact on capacity and containment characteristics, as well as on the subsequent reliability of modeling of the storage behaviour. It is acknowledged that assessing the quality of the model for the purpose of demonstrating a good understanding of the site is not straightforward. Relevant criteria are to be discussed amongst the whole group of experts that use this model for their different purposes. In addition to the selected model, multiple realisations (around four) of the model data should be considered, as is standard in oil and gas exploration, to take into account the uncertainties of some important features, *e.g.* velocity distribution, structural interpretation, etc. Sensitivity scenarios to explore different parameter uncertainties and geological solutions are also to be conducted when necessary. Sometimes it might also be useful to have the set of model data analysed by another group of experts to infer the possible range of variability in the interpretation.

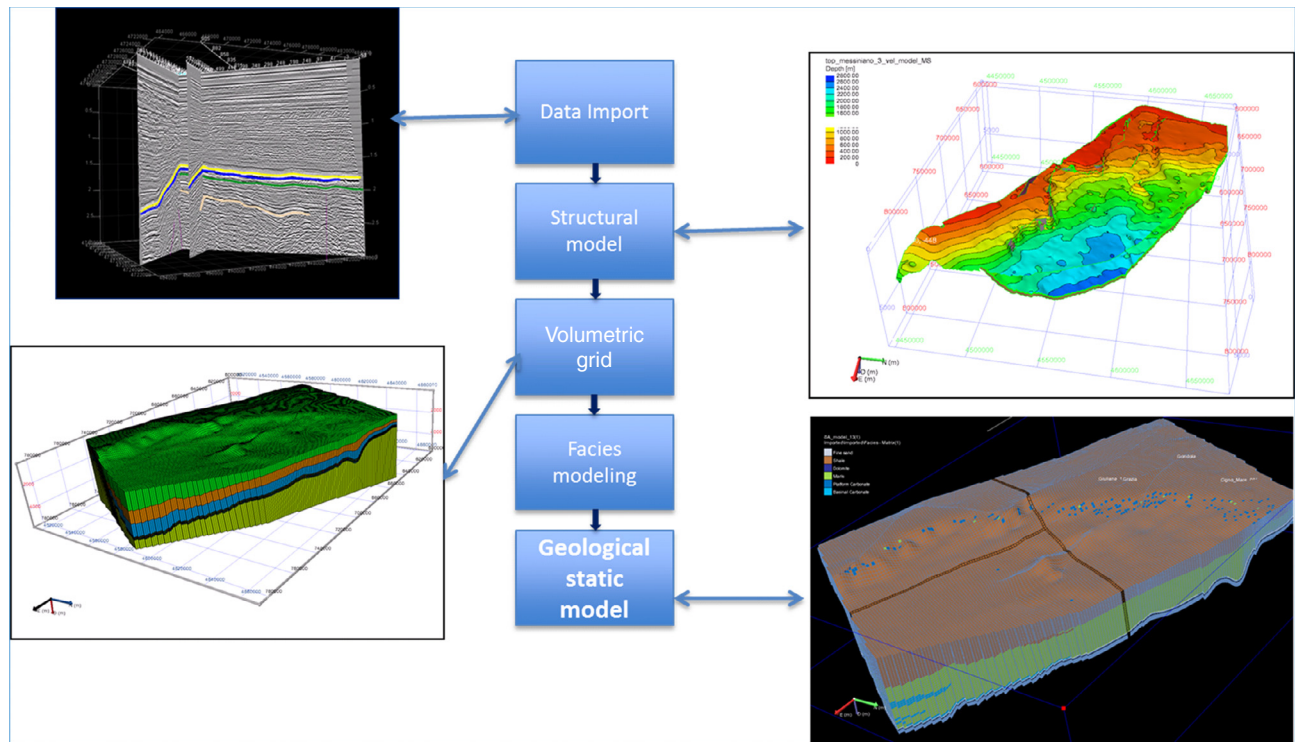


Figure 4

Workflow chart applied to build the geological model for the South Adriatic Sea site. The model has a regional extent of 227 km by 96 km. Its construction required more than a year without any further data acquisition. This duration is of course highly site dependent according to the availability of good-quality seismic survey data, adequate borehole data and specific core analyses.

2.4 Hydrodynamic Modeling

Reservoir simulations of CO₂ injection and migration predict several important features of storage behaviour, *e.g.* the injectivity, the injection scenario and the resulting storage capacity of the storage site according to a maximum allowable reservoir pressure, CO₂ plume migration to a spill point, or any other criteria likely to threaten the security of the site. It also assesses CO₂ containment in the short term, *i.e.*, during injection operations until transfer of responsibility to a governmental authority, as well as in the long term including the fate and migration of CO₂ in the storage site. Displacement of formation fluids such as brine in an aquifer, of natural gas in depleted gas field or of crude oil in reservoirs are also important to predict together with potential impact. For instance, on the UK site, brine displacement was identified as a potential risk to be investigated as it might increase the flow of natural shallow gas at the sea bed. This step can take a few months, depending on the nature of the injection processes to be simulated and planned, or longer in the case that an update of the initial geological model is

required by obtaining a good match with pressure history data.

SiteChar noted that modeling injection into depleted hydrocarbon fields benefits from previous reservoir modeling work, but it might be difficult to gain access to hydrocarbon production data from the operators. Modeling injection into virgin aquifers suffers from a lack of historical production data that are very useful to calibrate the models. Some information appeared difficult to obtain with the level of detail required to produce reliable results, in particular information associated with reservoir/basin heterogeneity which is a most influential parameter of model attribution, but also the distribution of petrophysical properties, fault behaviour and Pressure Volume Temperature (PVT) conditions which require strong interaction amongst geologists and reservoir engineers. Sensitivity analyses, using cautionary 'worst' and 'best' case scenarios are a practical way to address lack of site-specific data and assess impact on the simulation results. For instance, sensitivity analyses were conducted within SiteChar to evaluate the impact of the uncertainty on the distribution of the petrophysical parameters (Fig. 5);

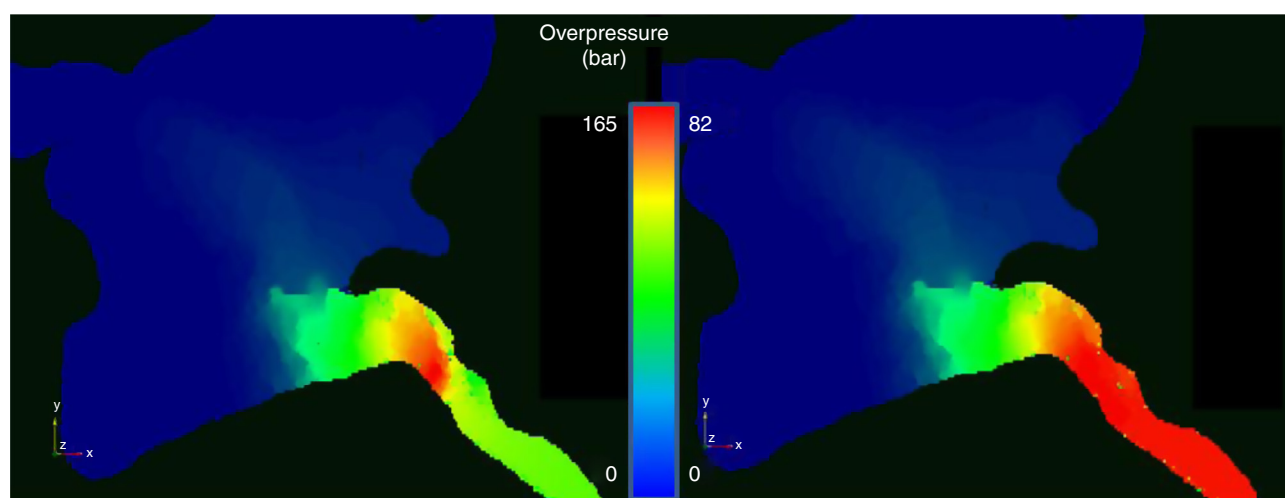


Figure 5

Illustration of the important role played by the distribution of petrophysical parameters when assessing reservoir pressure on the UK site; (left) considering an heterogeneous attribution of porosity performed by stochastic distribution based on the results of core sample analyses and permeability derived from the calculated relationship between core porosity and permeability measurements and proportion of sandstone from well log data; (right) considering an homogeneous attribution of the Channel facies reservoir using average porosity and permeability values from core measurements.

scenarios were run to infer the impact of the uncertainty on fault geometries and fault properties considering faults either fully transmissive or fully closed (Fig. 6). Results of ‘best’ and ‘worst’ case scenarios should be considered with care since they might present a too pessimistic or a too optimistic vision of the storage site behaviour.

Significantly, the SiteChar experience concluded that pressure management might be required in most CO₂ storage sites hosted in aquifer strata 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. The SiteChar UK ‘dry-run’ permit application presents an injection scenario that includes water production down-dip from within the saline aquifer. 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 which level of testing and treatment might be required or which level of testing is required to demonstrate treatment is not needed. In the case of other

North Sea nations that do not permit discharge of produced water by re-injection into subsurface strata, water disposal might be an issue as for onshore storage.

Migration path analysis can also be conducted to rapidly assess the areal extent of CO₂ stored in the underground over longer time periods and estimate potential CO₂ migration and leakage pathways. A rapid migration path analysis might rely on a simplified static geological model, incorporating mainly the layer geometry extracted from the regional model. Potential leakage points from wells can also be addressed as well as different scenarios associated with, amongst others, various injection well locations or different fault states (Fig. 6).

2.5 Geomechanical Assessment

Predicting the mechanical response of a reservoir to the increase in pressure resulting from CO₂ injection is essential to ensure the storage site integrity and to forecast the pressure propagation over time.

Geomechanical modeling establishes the crucial seal rock threshold fracture pressure which is a constraint when optimising the injection scenario through hydrodynamic modeling. For instance, coupled fluid flow and geomechanical modeling at the UK offshore multi-store site indicates the overpressure ratio generated by CO₂ injection over a 5-year period at a rate of 5 Mt/year is predicted to remain below the shear failure threshold. The results of shear failure

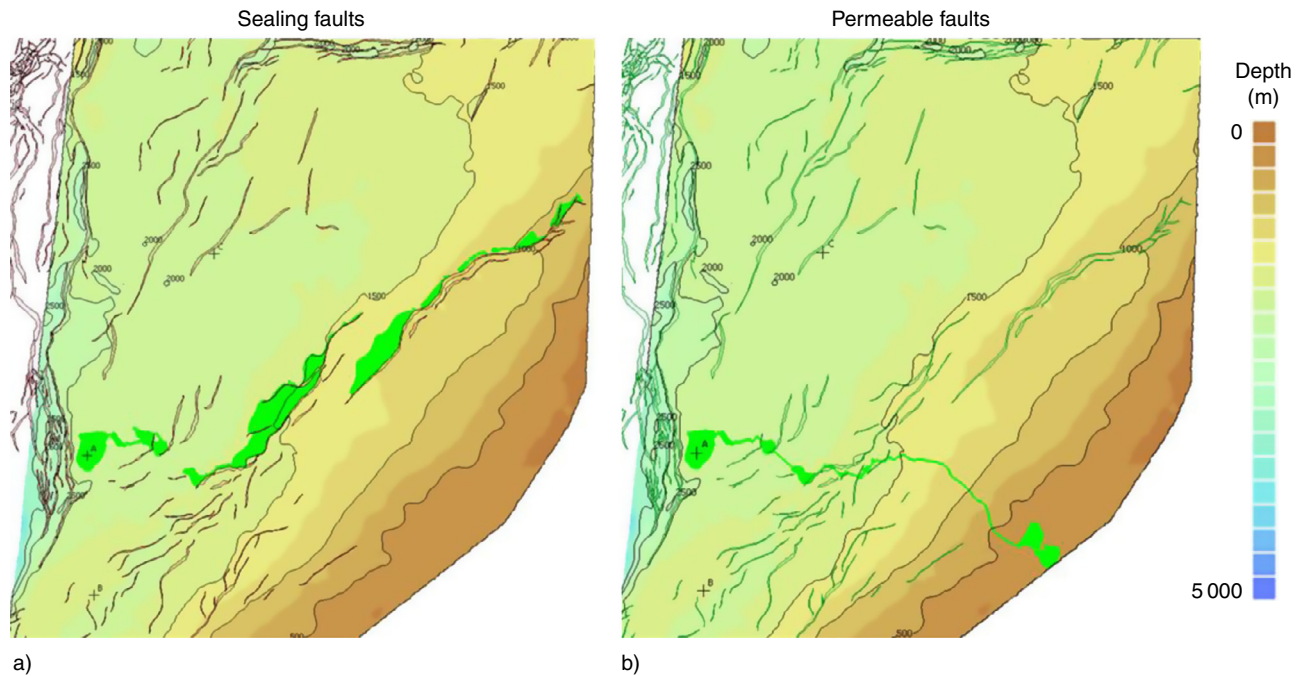


Figure 6

Migration path and CO₂ accumulations (indicated in green) illustrated in the Norwegian site when a) faults are considered sealing, b) faults are considered permeable. An 'infinite' amount of CO₂ is here considered to be injected.

assessment show that no failure would occur in both the Captain Sandstone and the cap rock for the stress scenarios considered. However fracturing is likely to occur if injection at the same rate is continued beyond 5 years, unless pressure reduction actions are taken, such as fluid production. In addition, the predicted maximum overpressure in the Captain Sandstone is smaller than the cap rock fracture pressure estimated from the difference between the minimum horizontal stress and the pore pressure ranges with a confident safety margin. This allows selection of appropriate injection scenarios.

Coupled fluid flow and geomechanical modeling simulates the changes in both the vertical and horizontal effective stresses in the storage site reservoir and cap rock. These stresses are used to evaluate potential damage in the storage site strata and the overburden formations, in particular the likely generation of new fractures in the matrix or the likely propagation of existing fractures or faults, as illustrated in Baroni *et al.* (2015). The models also predict expansion deformation of the storage sandstone due to CO₂ injection (Fig. 7).

Geomechanical modeling requires input data on the strength properties of the storage site rocks and knowledge of the *in situ* stress state. Where there was a lack of good measurements of the *in situ* stress state, these initial stress

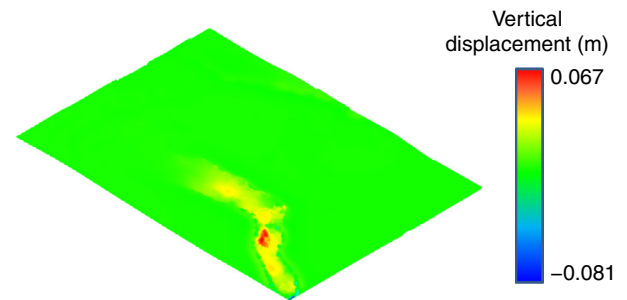


Figure 7

Simulated vertical displacement of the top of the reservoir (uplift) after injection of 50 Mt CO₂ (unit: m), UK Outer Moray Firth site. According to the model predictions at the UK North Sea site, the injection of 50 Mt CO₂ would lead to expansion of the reservoir by approximately 6.7 cm and uplift of between 6 and 7 cm at the sea bed.

conditions were derived from published literature. Information on fault properties appeared as a critical limitation for the characterisation of CO₂ storage sites and the assessment of their integrity. Understanding fault behaviour during CO₂ injection required additional activities, such as sensitivity analyses or use of cautious 'worst' and 'best' case scenarios for measurements of stress and injection tests.

Overburden properties were also often not sufficiently known since they have not been investigated by the oil and gas industry. Pressure history data indicating pressure communication within a regionally extensive sandstone could inform the likely sealing properties of faults and boundaries, but such information might not be publicly available even for strata that are well known from hydrocarbon production. Although such data may exist, they may be held in confidence by hydrocarbon field operators.

2.6 Geochemical Assessment

Once dissolved in brines, CO₂ can induce geochemical processes such as the dissolution/precipitation of rock-forming minerals, which are key trapping mechanisms and essential to understand long-term storage activities, but which may also affect the reservoir properties and/or cap rock integrity. For instance, on the UK site, predicted distribution of supercritical injected CO₂ showed that ‘break-up’ and shrinkage of the injected CO₂ plume commences once injection ceases and continues to shrink with a small area of gas remaining within the extent of the hydrocarbon field 1 000 years after injection started. Predicted distribution of the plume of dissolved CO₂ is larger than the injected gas plume and it continues to increase in size beyond the extent of the hydrocarbon field after injection has ceased. The plume of CO₂ in solution remains mostly within or in the immediate vicinity of the hydrocarbon field 1 000 years after injection has ceased. Mineral trapping by precipitation of magnesite is about 7% of the total CO₂ injected over hundreds of thousands of years.

Modeling of the fluid-rock interactions took a few months, assuming no further data acquisition is required. When input data were not available, assumed values were used or appropriate analogue data taken from published literature or previous work. The mineralogy of the host strata is a key input to the geochemical modeling. The more detailed the compositional information obtained by core analysis, the more appropriate the predicted changes associated with CO₂ injection will be. Ideally, the mineralogy data used should be derived from core in the immediate vicinity of the proposed injection well to minimise the possibility of any lateral changes in composition. The impact of CO₂ injection on the chemical character of existing well infrastructure and well cements used at the proposed injection site should also be modeled but information on well cement and other well materials were not available. It was pointed out a need for further development of geochemical modeling software able to predict reactions in oil-, gas- and brine-bearing strata.

2.7 Well Integrity

Potential leakage pathways *via* existing or abandoned wells have been evaluated as having the highest risk for leakage in

all the SiteChar sites containing existing wells. Assessing well integrity and future use or abandonment is a time-consuming activity that took a few months for a few wells. For instance, on the Polish site, an analysis of the present technical state of wells was performed, including a review of the technical state of the wells based on casing inspection made for selected wells, laboratory tests on cement rock samples and numerical simulations of possible CO₂ leakage into secondary aquifers through cement sheath and micro-annulus of a specific old abandoned well. The most extreme scenario that was considered leads to migration of around 1 000 tonnes of CO₂ within 500 years into the secondary aquifer so that leakage of CO₂ into the shallowest aquifer or to the surface has a low probability. Casing inspection was also conducted indicating low corrosion rates. However detailed analysis of the cement itself and the cement bond quality is necessary to further assess the well integrity and its impact on the storage integrity. Rates of corrosion for five standard cement rock samples of wells in Żuchłów gas field were evaluated in a CO₂ environment in order to evaluate the potential increase of permeability due to corrosion as well as the potential alteration of the mechanical strength of the cement.

Effort is of course highly dependent on the number of wells to be analysed and the availability of data. In particular, old abandoned hydrocarbon exploration wells might be difficult to assess because of missing data and proper abandonment documentation. Availability of real data (status of cementation and well casing) is a major issue despite the large number of wells so that there is often a need for cautious approach and assumption of a worst case scenario to supplement the lack of data. It was concluded that *in situ* observations in wells should be required for a real project. Such operations being very expensive, SiteChar recommends to estimate the cost and the timing of the well operations as early as possible. Lastly, a dedicated risk assessment workshop was found very useful to evaluate future options for the wells.

2.8 Monitoring Plan

Uncertainties and residual risks will still remain even for the most detailed site characterisation. The objective of the monitoring plan is to monitor and thus allow reduction of these residual site-specific risks and uncertainties during the operation of the storage project. One objective of the monitoring plan is, in addition to control and validate containment, to verify the conformity of the injected CO₂ with the modeled prediction of the site. Provided adequate technologies for performance monitoring have been selected, monitoring observations provide relevant data, acquired all along the phases of the project, to update the storage site models and predictions of site behaviour. Monitoring

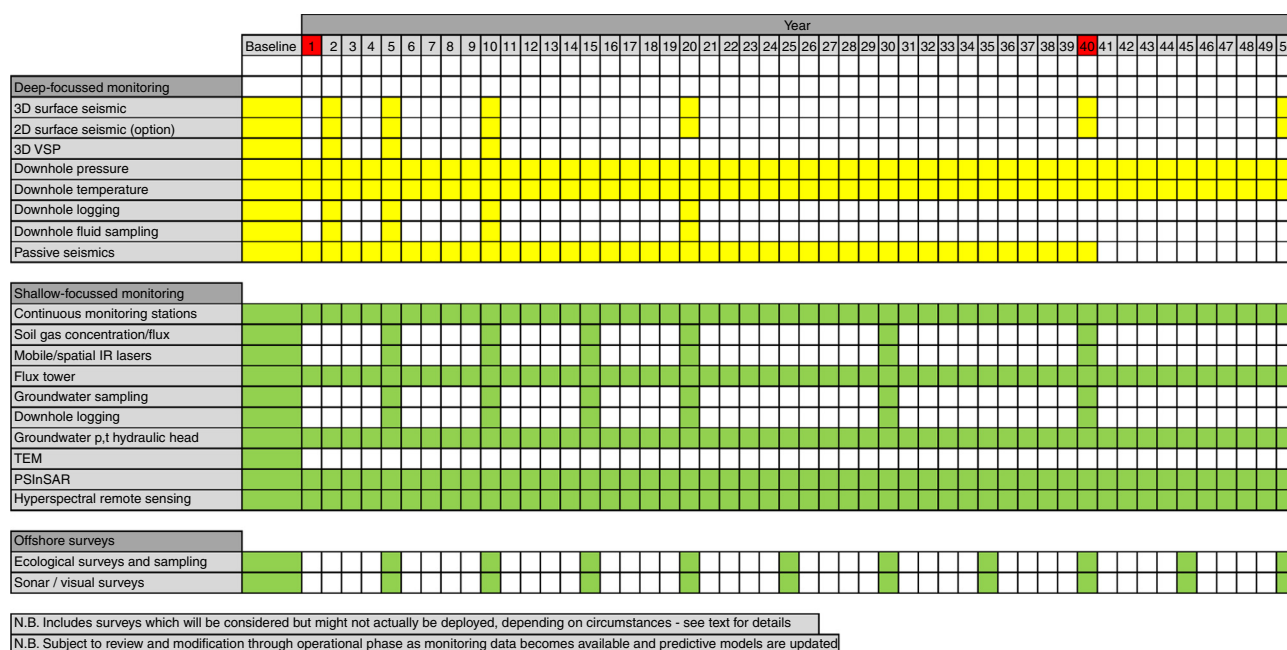


Figure 8

Proposed monitoring plan for the injection (operation) phase at Vedsted, Denmark. It is recommended to acquire a full baseline line 3D survey covering an area of approximately 55 km². During the initial plume development over a period of about 2 years, a limited repeated 3D survey or a repeated 3D offset VSP could be envisaged but an overlapping area between the two methods will be of great help when CO₂ plume tracking will no longer be covered by the 3D offset VSP. In the case 3D conventional seismic monitoring is too invasive in a populated area, 2D seismic lines and micro seismic survey where a monitoring well is available to pick up signs of induced geomechanical effects in the reservoir and the cap rock might be an alternative.

observations associated with relevant interpretation also provide an early warning in the case the CO₂ migration is not as predicted and allow implementation of remedial action if needed. Monitoring planning has to be fit-for-purpose, addressing areas of highest residual risk. Setting up a comprehensive monitoring plan may take a few months provided that all risks have been identified, from the risk assessment and different injection scenarios simulated from the hydrodynamic model. Baseline studies require a lot of effort and resources but they are essential to secure that enough data are collected against which to compare the response of the site. SiteChar recommends to conduct feasibility studies of the monitoring tools, at least the less conventional ones, proposed to be deployed to demonstrate storage site performance, ensure efficacy and also the cost-benefit for their use at the storage site.

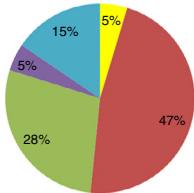
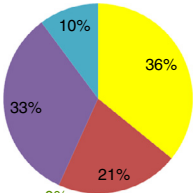
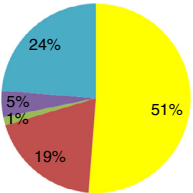
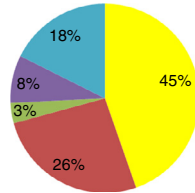
There are no generic recommendations for the monitoring plan: a fit-for-purpose monitoring approach should be followed, which includes those monitoring techniques that best measure the specific site's performance, in terms of permanent safe storage (Fig. 8). However it was noted that a critical issue related to potential leakage in the case of an onshore site is the risk to drinkable water in overlying aquifers.

SiteChar recommends dedicated observation wells. In addition, it is noted that natural CO₂ emissions at onshore sites are more variable than offshore. It would be thus particularly important to understand the occurrence and consequence of ‘extreme events’, *e.g.* for an onshore site a sudden release of CO₂ accumulated under snow might occur in spring when ice melts, and conditions for their occurrence. It was recommended that data are open to the public and actively disseminated, both during the baseline activities and during the monitoring phase to inform local stakeholders on what type of data are acquired and what type of values are typically encountered in this area. This could be a bridge for dialogue with the local stakeholders, both prior to and during the injection phases.

2.9 Economic Assessment of CO₂ Geological Storage

The SiteChar project gave the opportunity to perform techno-economic evaluations of four sites located onshore and offshore and related to aquifer or hydrocarbon reservoir storage (Tab. 2). The variability of the sites and their characterisation presents an interesting range for comparison. An economic assessment has been carried out at each site

TABLE 2
Comparable economic assessment of four sites

	Outer Moray Firth UK	Vedsted Denmark	TrøndelagPlatf. Norway	South Adriatic Italy
Context	Offshore	Onshore	Offshore	Offshore
Reservoir type	Depl. HC field & Deep Saline Aquifer	Deep Saline Aquifer	Deep Saline Aquifer	Deep Saline Aquifer
Project lifetime till transfer of liability (year)	40	70	70	40
CO ₂ stored (Mt)	100	60	40	10
Injection duration (year)	20	40	40	10
Injectivity (Mt/year)	5	1.5	1	1
Nb. injection wells	5	1	1	1
Nb. production wells	1	0	0	0
Estimated costs*	11.4 €/t	3.2 €/t	26.6 €/t	28.8 €/t
Share of estimated costs ■ Site exploration ■ Site development ■ CO ₂ injection ■ Monitoring ■ Contingencies and abandonment				

* The reader is invited to refer to [Gruson et al. \(2015\)](#) for details about the calculations of the estimated costs.

to analyse the cost of each phase of the storage project, from exploration and site characterisation, to site development, drilling and injection, up to monitoring and site abandonment. Compilation of cost data has been drawn from publicly available sources, previously completed research studies, and commercial cost data ([DECC, 2010](#); [SCCS, 2011](#); [SCCS, 2009](#); [Scottish Power CCS Consortium, 2011](#); [ZEP, 2011](#)).

Not surprisingly, the onshore Danish project is the less expensive and close to the ZEP cost estimations ([ZEP, 2011](#)). Site exploration is the main share of the storage cost related to the drilling of an exploration well and seismic surveys. The long period of monitoring (70 years) required before the transfer of liability to the public explains the high monitoring share. The offshore UK site is the less expensive offshore case although it includes costs for pressure mitigation by water production and treatment. The low exploration cost is mainly due to the relatively inexpensive access to the data which are existing data. The offshore context of the site impacts the development phase as a new platform is required to support 6 well slots. The high CO₂ injection cost is related to water production and treatment that corresponds to 30% to the total. The offshore Norwegian and Italian sites have the most expensive storage cost. These sites are virgin areas and thus require expensive exploration and development phases.

Clearly, the lack of existing infrastructure has a significant impact on the site development cost. However, the estimated storage cost has to be considered with care: the capacity of the storage aquifers is estimated larger than the amount of CO₂ stored so that several additional injection wells and a higher annual injection rate would significantly decrease the cost per tonne of CO₂ stored.

The four SiteChar techno-economic evaluations confirm that it is not possible to derive any meaningful average cost for a CO₂ storage site. The results demonstrate that the structure of costs is very heterogeneous and the storage costs are consequently very site dependent. In particular, the Italian and Norwegian sites present very specific features. For the Italian site, the short duration of CO₂ injection associated with a low injection rate makes the CO₂ storage project comparable to a demo project. The Norwegian site is an offshore site located in a virgin area with high infrastructure costs and a combination of injection duration and injection rate that makes the derived costs very sensitive to the discount rate. Comparison of the economic assessments of the four sites, as well as sensitivity analyses, have highlighted some influential parameters of the economic assessment of a CO₂ storage project. The main differences between the four site assessments are attributable to the site location (onshore/offshore), the amount of CO₂ injected, the well injectivity rate, the number of CO₂ injection

and water production wells, and the necessity or not to produce and treat water.

The reader is invited to refer to Gruson *et al.* (2015) for further details on the SiteChar economic evaluations.

2.10 SiteChar Recommended Process for Site Characterisation

The characterisation conducted in SiteChar, undertaken from the perspective of a 'dry-run' storage permit application, has allowed presentation of a schematic characterisation timeline (Fig. 3) for the development of an exploration permit and a storage permit. Permit revisions are envisaged if necessary.

The first phase 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. The SiteChar research focused on the characterisation steps which are:

- 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 construction to gather the geological characterisation of the site;
- hydrodynamic modeling to simulate the behaviour of the CO₂ in the store and which is the basis for the prediction of the storage performance;
- geochemical analysis to study the reactivity between the CO₂ 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 modeling 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;
- as well as:
- design of the project.

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 amongst all disciplines.

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 activity is not conducted in isolation from the others. Awareness of the input requirements and consideration of the implications of results from the other site characterisation activities is a key learning from the SiteChar research.

The distribution of effort presented in the SiteChar timeline 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 has to be 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 CO₂ 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 Figure 9. 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.

3 ADVANCING ON PUBLIC ACCEPTABILITY

SiteChar has investigated the social dimension of two prospective storage sites: the onshore Polish site and the offshore Scottish site, conducting social site characterisation and public participation activities (Brunsting *et al.*, 2013). The research consisted of four steps over a time period of 1.5 years, from early 2011 to mid-2012. The first step consisted of four related qualitative and quantitative research activities to provide a social characterisation of the areas: desk research, stakeholder interviews, media analyses, and a survey amongst a representative sample of the local community. The aim was to identify:

- stakeholders or interested parties;
- factors that may drive their perceptions of and attitudes towards CCS.

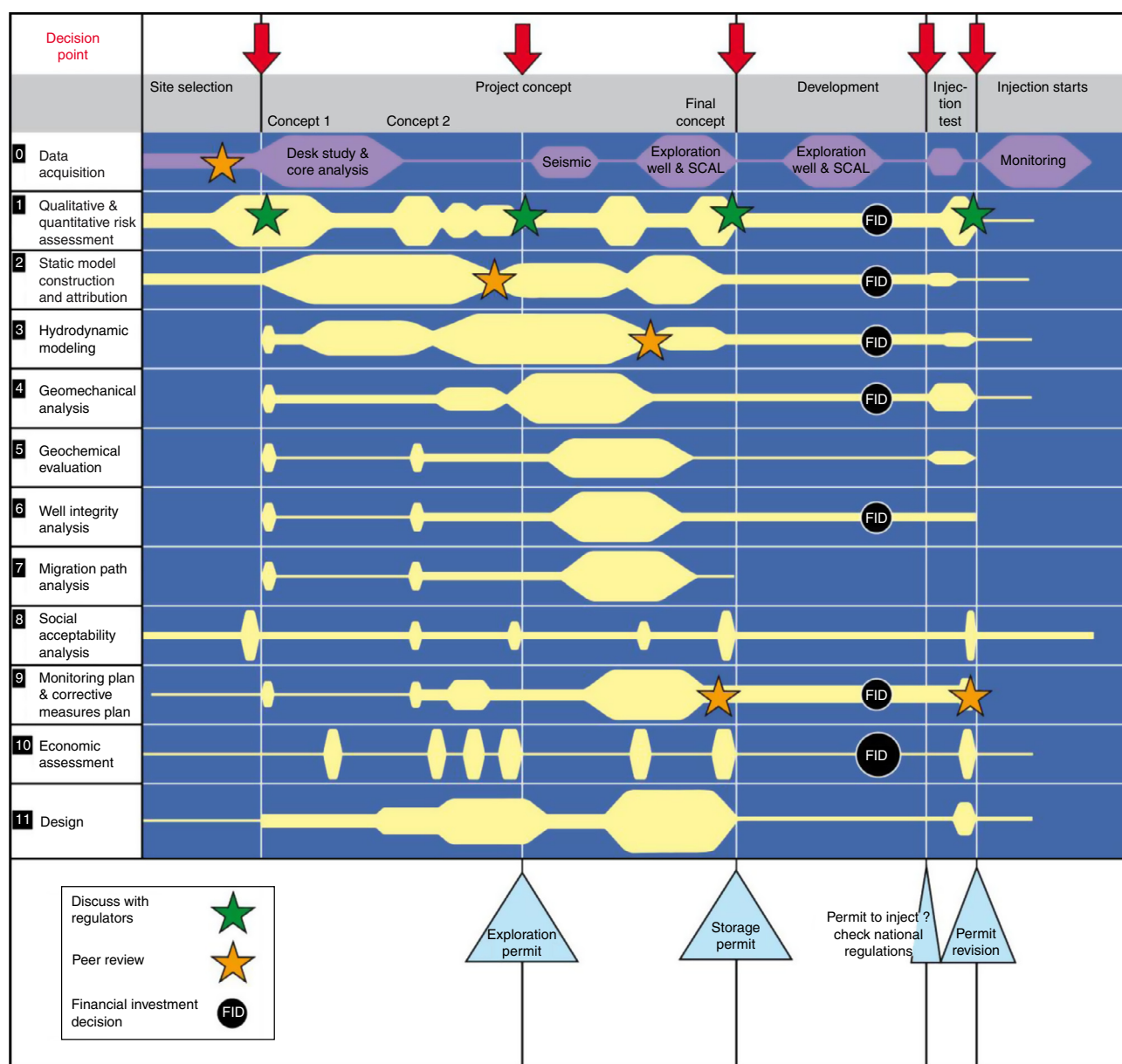


Figure 9

SiteChar recommended process for the development of an exploration and a storage permit. 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. Note that risk reduction activities take place throughout the duration of the project and that discussions with regulators (green stars) are recommended at each important step of the project development. Peer reviews are also recommended to validate the main conclusions of the research study (orange stars). The Financial Investment Decision (black disks) is taken at the end of the characterisation process considering the results of the whole characterisation process.

Results were used as input for the second step, in which a new format for public engagement named ‘focus conferences’ was tested at both sites involving a small sample of the local community. The third step consisted in making available generic as well as site-specific information to the general and local public, by:

- setting up a bilingual set of information pages on the project website suitable for a lay audience;

- organising information meetings at both sites that were open to all who took some interest.

The fourth step consisted of a second survey amongst a new representative sample of the local community. The survey was largely identical to the initial survey to enable monitoring of changes in awareness, knowledge and opinions over time. Additionally, the second survey was used to obtain a quantitative measure of some commonly held public

perceptions about CCS. In part these perceptions were derived from the focus conferences and in part from previous research.

Results provide insight on the way local CCS plans may be perceived by the local stakeholders, how this can be reliably assessed at an early stage without raising unnecessary concerns, and how results of this inventory can be used to develop effective local communication and participation strategies. Generally, differences in knowledge levels about the consequences of CCS (much lower in Poland) and proximity of the site to the local community (much closer in Poland) appear key explanations for the differences observed in the perceptions and appreciations of the environmental risks of CCS (most prominent in the Polish discussions) *versus* the economic benefits of CCS (most prominent in the Scottish discussions). Despite environmental concerns, the Polish respondents were as equally supportive of CCS in their area as the Scottish respondents.

In both countries, acceptability of CCS was related to the implementation of other preferred measures to combat climate change. The Scottish focus conference group stated that CCS should be a short-term solution implemented alongside an exit strategy as to not divert attention from other options such as renewable energy. The government is not entirely trusted on viewing CCS as part of a long-term strategy for curbing climate change instead of being just a 'quick fix'. The Polish focus conference group expressed concern that while the introduction of the technology in Poland could lead to increased influence of Poland on the European policy for climate protection, alternatively it could turn Poland into a 'garbage dump' for European CO₂ emissions. In contrast, Scottish participants discussed a possible role for Scotland as a main store of imported CO₂. In the end, most Polish focus conference participants did not vote in favour of CCS because of the many uncertainties associated to potential effects on environment and the absence of local benefits, as well as high costs of CCS. Participants argued that the role of national governments and the European government should be to develop a vision and to stimulate public involvement in decision-making regarding solutions to climate change. Both groups agreed that the public should not just be informed about CCS, but also about alternative solutions to reduce CO₂ emissions into the atmosphere.

Key findings relevant to policy makers are, amongst others, that agreeing that climate change happens and that measures should be taken does not imply agreement on CCS as a suitable method to curb climate change. Acceptability of CCS is in particular related to other measures to combat climate change. National and local advantages and disadvantages, such as unemployment, have to be addressed. Attention has to be put on risks and uncertainties, such as CO₂ leakage and its effects. There is a request for National and European governments to clarify their role and position

of CCS as part of their emissions reduction strategy. Lastly, citizens expect public communication and participation activities on European as well as national levels.

Key findings relevant to site operators are to keep in mind that awareness and knowledge levels of CO₂ storage remain quite low, including some misconceptions. Most prominent local discussion topic for the onshore site was related to environmental risk whereas it was mainly economic benefits for the offshore site. Nonetheless, at both sites about equal and overall fairly high support was reported for a local CCS project.

The reader is invited to refer to [Brunsting et al. \(2015\)](#) for further details on the SiteChar public engagement activities.

4 RECOMMENDATIONS

4.1 Development and Review of 'Dry-Run' Storage Permit Application

The FP7 EU-funded SiteChar project has developed 'dry-run' storage permit applications for two realistic storage options, though not currently considered as near-term candidate sites. The first case study is an assumed to be depleted hydrocarbon field and contiguous saline aquifer in UK northern North Sea, which anticipates storage in both the depleted field and the host aquifer sandstone. The second case study extends existing investigations of site characterisation at a deep onshore Danish aquifer where pre-existing data may be sparse. These site-specific applications have been evaluated by a separate team, acting as an independent regulator.

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 CO₂.

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.

The two SiteChar 'dry-run' applications illustrate some key issues of storage permitting requirements. The definition of the storage complex boundaries, defined in the EC Storage Directive as "the storage site and surrounding geological domain which can have an effect on overall storage integrity

and security; that is, secondary containment formations”, is challenging, in particular when pressure changes may be detected at significant distances beyond the storage site. Indeed the EC Storage Directive does not provide any clear definition on how much the pressure can increase in the surrounding areas of a site. In the SiteChar ‘dry-run’ applications, the complex storage is defined by the maximum extent of plume, including CO₂-saturated formation water plus a margin to enable monitoring and to reflect inherent uncertainty in predictions. Besides both permit applications consider the need to manage the induced overpressure from CO₂ injection by water production and discharge, although different approaches were used to assess the overpressure limit. SiteChar experience emphasised the need for a consistent approach to define the acceptable overpressure limit, according to the site specific characteristics, such as the onshore *versus* offshore context. In addition, discussions between the operator and the Competent Authority are recommended to agree the level of appropriate, robust site characterisation necessary to secure storage permits in areas of limited data availability. SiteChar has proposed the development of a set of agreed criteria to demonstrate site performance as a pragmatic way to address these issues. These criteria define limits to site behaviour which, if exceeded, indicate that a significant irregularity or leakage has occurred.

The reader is invited to refer to [Delprat-Jannaud *et al.* \(2013b\)](#) for an overview on the SiteChar experience on the ‘dry-run’ storage permit applications and the lessons learnt.

4.2 Risk-Assessment-Driven Characterisation

Site characterisation should be driven by activities to reduce risk and increase certainty in the prospective storage site. An assessment of technical and non-technical risks to the feasibility of geological storage of CO₂ at the site determines and guides site characterisation activities. 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 are used to update the risk and uncertainty register and so the work of others. This iterative process should involve the whole team of experts to ensure that the results of the characterisation are shared, the updated project concept is known to all, 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 associated to a risk will not be the same for each risk: some will require

considerable effort to achieve an acceptable level. However, since the risk ranking might evolve with the progress of 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.

4.3 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. Data sets that are used in common by different disciplines must be established at the commencement of characterisation and updates to these common data sets by one activity must be acknowledged and provided to others. Decisions regarding 3D modeling parameters suitable for all characterisation activities must be discussed and agreed at the outset. Selection of modeling software is especially important as the format, interoperability, exchange of input and output data are key parameters for successful 3D modeling of the storage site by all expert disciplines. Effort spent at the commencement of site characterisation to discuss and test specialist modeling platforms will minimise repetition or incompatible outputs later in the work. Interaction between the expert teams should continue throughout the characterisation work to ensure evolution in understanding of the site and decisions regarding site design are incorporated into all the specialist investigations. In this context, feedback between teams is fundamental to achieve a consistent site characterisation and a fully integrated storage permit application.

4.4 Data Collection

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 that have been explored by the 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 modeling 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 CO₂ 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 injection pressure 'footprint' would require impractically large storage permit areas, since pressure responses can extend far beyond the injected CO₂ plume. In addition, there is little consensus on the thresholds or consequences above which effects should be included. In this context SiteChar recommends, at least for offshore sites, to define the complex storage by the maximum extent of the CO₂ plume, including CO₂-saturated formation water, plus a margin to enable monitoring to reflect inherent uncertainty in predictions.

Nevertheless a clear and prior agreement with the Competent Authority will be needed on the definition of the storage complex.

4.6 Uncertainty Management and Communication

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, that has been used in SiteChar, is to organise 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. Containment risks will

have to be reduced to as low as reasonably practicable level. However, regarding performance risks, 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 cost-benefit analysis to decide the appropriate level of performance risk reduction prior to permit application.

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.

4.7 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 so as to reach a common understanding of opportunities as well as uncertainties and risks. The Competent Authority and the operator will have to reach an agreement on the criteria for the site assessment and the acceptable level of certainty. Permit Performance Conditions (PPC) developed in SiteChar (Akhurst *et al.*, 2015), even if not explicitly required by the EC Storage Directive, 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.

4.8 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. Situations or 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.

4.9 Pre-Competitive Characterisation

European member states have to pursue carbon reduction and the only way to rapidly decarbonise energy is to deploy every climate change mitigation option. In this context, CCS is a critical component in the low carbon energy technologies (IEA, 2013). 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 is also essential that both at European and national levels there is some cooperation to try to de-risk some of the costs associated with CO₂ storage.

The nature and extent of interactions with other users are key considerations 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 CO₂ storage projects.

SiteChar recommends publicly available site characterisation information about CO₂ storage projects in operation in some places in Europe and worldwide, considering that any progress on these sites will be worthwhile for other similar sites. It is clear that, as for oil and gas exploration, these first projects will be the most expensive. As a consequence it is essential to make publicly available site characterisation information as well as ‘learning by doing’ from the operation of real CO₂ storage sites. Such a consideration also calls for public funding to support demonstration projects.

4.10 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, it was predicted (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 PPC 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). However this may be challenging due to the multiple Competent Authorities that might be involved.

CONCLUSIONS

During three years, SiteChar has extended and tested standard site characterisation workflows (Chadwick *et al.*, 2008; NETL, 2010; DNV, 2010) on the basis of criteria defined by the relevant European legislation so as to establish a methodological guide for characterisation of CO₂ storage complexes for use by storage site operators and regulatory bodies. The SiteChar guide is based on testing of the site characterisation workflow at a set of representative sites in Europe suitable for CO₂ storage. In particular, development of internal ‘dry-run’ storage permit applications for two contrasting sites reviewed by relevant regulatory authorities 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. The SiteChar workflow addresses the sequence of the different steps and the timing of the process, the interdependencies and feedback loops within the process, and the coverage of the different requirements of the EC Storage Directive. It is a fit-for-purpose workflow aiming at demonstrating the understanding of the site for a CO₂ storage permit; convincing the Competent Authority that the permit applicant has sufficient understanding of the site and that the proposed site operation will securely contain CO₂ and complying with regulatory issues. SiteChar emphasises the need for a risk-led characterisation workflow aimed at anticipating, reducing, mitigating risks and monitoring remaining risks. SiteChar has also addressed the challenging cost of CO₂ storage pointing out some of the most influential parameters. Lastly, social site characterisation and public participation activities have been conducted at both an onshore and an offshore site revealing that the key to successfully incorporate lessons from social site characterisation into the permit application workflow is to make local stakeholders part of the application.

The SiteChar project has assessed some of the key steps required to make timely effective large-scale implementation of CO₂ 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. The development of 'dry-run' storage permit applications at two credible CO₂ 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.

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 CO₂ storage project. This requires the Competent Authority and the 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 CO₂ volume, sufficient injectivity to receive the expected rate of supplied CO₂, and sufficient containment to permanently store the injected CO₂. 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.

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REFERENCES

- Akhurst M., Pearce J., Hannis S., Shi J.Q., Delprat-Jannaud F., Bossie-Codreanu D. (2015) Risk-Led Characterisation of a Site for the Geological Storage of CO₂, *Oil & Gas Science and Technology* **70**, 4, 567-586.
- Baroni A., Estublier A., Vincke O., Delprat-Jannaud F., Nauroy J.-F. (2015) Dynamic fluid flow and geomechanical coupling to assess the CO₂ storage integrity in faulted structures, *Oil & Gas Science and Technology* **70**, 4, 729-751.
- Beaubien S., Ruggiero L., Annunziatellis A., Bigi S., Ciotoli G., Deiana P., Graziani S., Lombardi S., Tartarello M. (2015) The Importance of Baseline Surveys of Near-Surface Gas, Geochemistry for CCS Monitoring, as Shown from Onshore Case Studies in Northern and Southern Europe, *Oil & Gas Science and Technology* **70**, 4, 615-633.
- Bekri S., Renard S., Delprat-Jannaud F. (2015) Pore to Core Scale Simulation of the Mass Transfer with Mineral Reaction in Porous Media, *Oil & Gas Science and Technology* **70**, 4, 681-693.
- Brunsting S., Mastop J., Kaiser M., Zimmer R. (2013) SiteChar deliverable D8.5, *Final summary report on public awareness*, <http://www.sitechar-CO2.eu/>.
- Brunsting S., Mastop J., Kaiser M., Zimmer R., Shackley S., Mabon L., Howell R. (2015) CCS acceptability: social site characterization and Advancing Awareness at Prospective Storage Sites in Poland and Scotland, *Oil & Gas Science and Technology* **70**, 4, 767-784.
- CO₂CRC (2008) Storage capacity estimation, site selection and characterisation for CO₂ storage projects, *CO₂CRC report RPT08-1001*.
- Chadwick A., Arts R., Bernstone C., May F., Thibeuau S., Zweigel P. (2008) *Best practice for the storage of CO₂ in saline aquifers - observations and guidelines from the SACS and CO₂STORE projects*, Nottingham, UK, British Geological Survey, 267 pp., (British Geological Survey Occasional Publication, 14).
- DECC (2010) *Guidance notes for the sampling and analysis of produced water and other hydrocarbon discharges, the Offshore Petroleum Activities (Oil Pollution Prevention and Control) Regulations 2005*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/62697/produced-water-sampling-guidelines.doc.
- Delprat-Jannaud F., Akhurst M., Pearce J., Nielsen C., Lothe A., Volpi V., Neele F. (2013a) Characterisation of storage sites: Synthesis and lessons learned from the application of the SiteChar workflow, *SiteChar Report D2.1*, <http://www.sitechar-CO2.eu/>.
- Delprat-Jannaud F., Akhurst M., Pearce J., Nielsen C. (2013b) Characterisation of storage sites: Best practices and Guidelines developed from the SiteChar project, *SiteChar Report D2.4*, <http://www.sitechar-CO2.eu/>.
- DNV (2010) *Guideline for selection and qualification of sites and projects for geological storage of CO₂*, www.dnv.com.au/binaries/CO2QUALSTORE_guideline_tcm162-412142.pdf.
- EC (2009) *Storage Directive 2009/31/EC*, <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 – Characterization of the storage complex, CO₂ stream composition, monitoring and corrective measures, http://ec.europa.eu/clima/policies/lowcarbon/docs/gd2_en.pdf.
- Gruson J.-F., Serbutoviez S., Delprat-Jannaud F., Akhurst M., Nielsen C., Dalhoff F., Bergmo P., Bos C., Volpi V., Lacobellis S. (2015) Techno-Economic Assessment of Four CO₂ Storage Sites, *Oil & Gas Science and Technology* **70**, 4, 753-766.
- IEA (2013) Technology roadmap: Carbon capture and storage, *OECD/IEA*, France, www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf.

- Kempka T., Nielsen C., Frykman P., Shi J.Q., Bacci G., Dalhoff F. (2015) Coupled Hydro-Mechanical Simulations of CO₂ Storage Supported by Pressure Management Demonstrate Synergy Benefits from Simultaneous Formation Fluid Extraction, *Oil & Gas Science and Technology* **70**, 4, 599-613.
- Neele F., Delprat-Jannaud F., Vincké O., Volpi V., Nepveu M., Hofstee C., Wollenweber J., Lothe A., Brunsting B., Pearce J., Battani A., Baroni A., Garcia B., Akhurst M. (2013) SiteChar deliverable D1.4, *Site characterisation workflow*, <http://www.sitechar-CO2.eu/>.
- Nepveu M., Neele F., Delprat-Jannaud F., Akhurst M., Vincké O., Volpi V., Lothe A., Brunsting S., Pearce J., Battani A., Baroni A., Garcia B., Hofstee C., Wollenweber J. (2015) CO₂ Storage Feasibility: A Workflow for Site Characterisation, *Oil & Gas Science and Technology* **70**, 4, 555-566.
- NETL (2010) *Best practices for: site screening, site selection, and initial characterisation for storage of CO₂ in deep geologic formations*, www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf.
- Nielsen C., Frykman F., Dalhoff F. (2015) How to characterise a potential site for GCS with sparse data coverage – a Danish onshore site case, *Oil & Gas Science and Technology* **70**, 4, 587-598.
- Papiernik B., Doligez B., Klimkowski K. (2015) Structural and Parametric Models of the Zalcze and Zuchlów Gas Fields Region, Fore-Sudetic Monocline, Poland, *Oil & Gas Science and Technology* **70**, 4, 635-654.
- SCCS (Scottish Centre for Carbon Storage) (2009) *Opportunities for CO₂ Storage around Scotland — an integrated strategic research study*, 56 pp., <http://www.erp.ac.uk/sccs>, Accessed: September 2009.
- SCCS (Scottish Centre for Carbon Storage) (2011) *Progressing Scotland's CO₂ Storage opportunities*, 60 pp., <http://www.sccs.org.uk/progress-to-co2-storage-scotland>, Accessed: March 2010.
- Scottish Power CCS Consortium (2011) CCS Project Costs (UKCCS - KT - S7.21 - Shell – 002), *UK Carbon Capture and Storage Demonstration Competition Talisman Energy. 2011 Ross and Blake fields (Bleo Holm)*, http://www.talisman-energy.com/upload/media_element/112/04/bleo_holm_2011.pdf.
- Volpi V., Forlin F., Donda F., Civile D., Facchin L., Sauli S., Merson B., Sinza-Mendieta K., Shams A. (2015) Southern Adriatic Sea as a Potential Area for CO₂ Geological Storage, *Oil & Gas Science and Technology* **70**, 4, 713-728.
- Volpi V., Forlin E., Baroni A., Estublier A., Donda F., Civile D., Caffau M., Kuczynsky S., Vincké O., Delprat-Jannaud F. (2015) Evaluation and Characterization of Potential CO₂ Storage Site in the South Adriatic Offshore, *Oil & Gas Science and Technology* **70**, 4, 695-712.
- ZEP (2011) *The cost of CO₂ storage*, <http://www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html>.

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