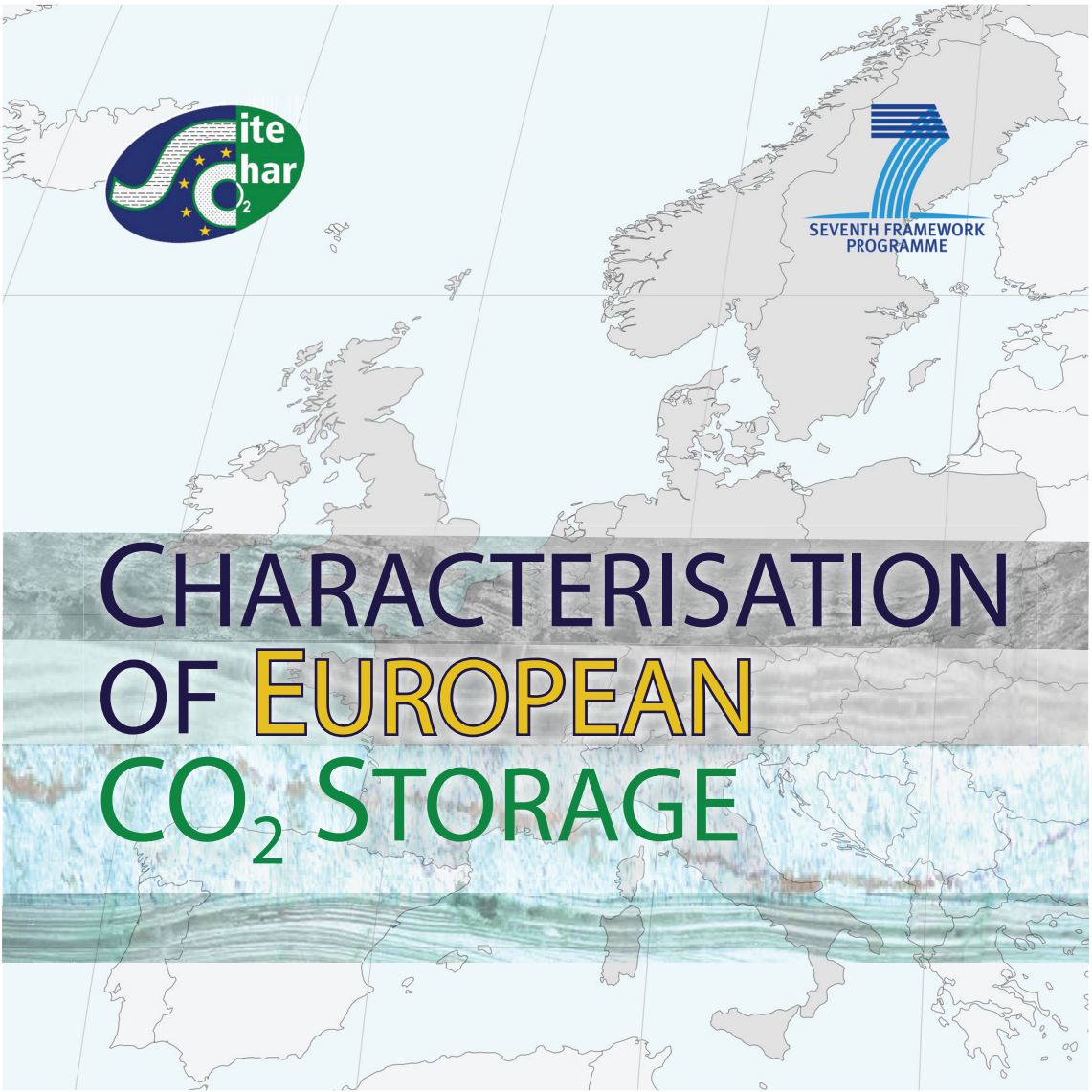

Site Char
CO2
SEVENTH FRAMEWORK
PROGRAMME
CHARACTERISATION
OF EUROPEAN
CO2 STORAGE

Introduction

The SiteChar project examined the entire site characterisation chain, from the initial feasibility studies through to the final stage of application for a storage licence, on the basis of criteria defined by the relevant European legislation: including estimations of storage capacities, predictions of plume migration in storage aquifers at basin or reservoir scale, evaluation of injection scenarios, risk assessment, development of the site monitoring plan, technical and economic analyses (assessment of all the costs related to storage) and public awareness.

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

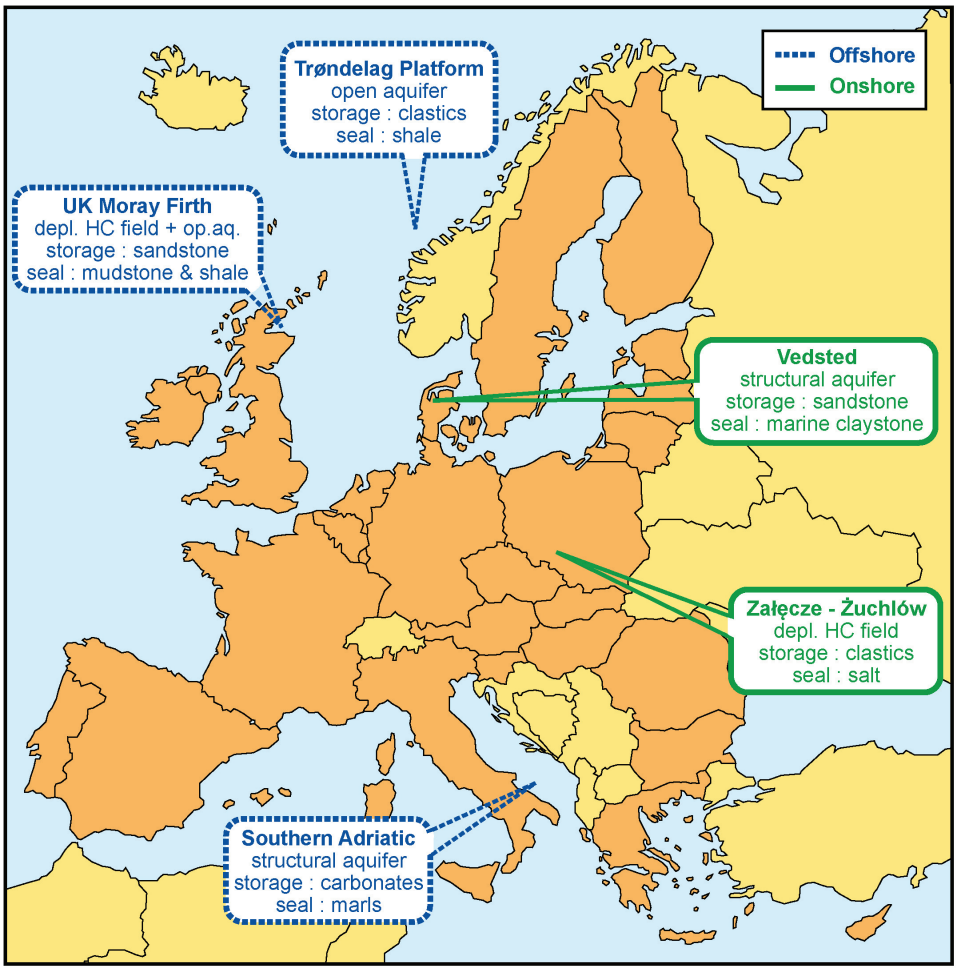
At the Scottish and Danish sites the site characterisations have allowed development of dry-run storage permit applications which have been evaluated by a group of independent experts and, for the UK site, by the competent authorities. The studies conducted at the other sites focused on specific barriers related to the site characterisation methodology. In addition to technical problems, SiteChar considered public awareness and opinions regarding these new technologies, which have been investigated on two sites, an onshore site (Poland) and an offshore site (UK North Sea) and providing important insights.

The aim of the SiteChar project was to supply a methodological guide adapted to each of these specific geological contexts for use by storage site operators and regulatory bodies.

It was shown clearly that the site characterisation workflow is site specific: even if the main steps to be achieved are quite common, the way to address each characterisation step depends on the site, the available data and the specific risk to be investigated.

A key learning of the SiteChar project is that characterisation of a site for the purpose of obtaining a CO_2 storage permit is a risk-based process with the objective of demonstrating safe and permanent storage. This means that focus should be put on issues that may lead to loss of containment. These might include possible CO_2 leakage via the seal, fault or well or laterally via a spill point, so as to assess potential risks of impacts on humans, animals and vegetation, brine displacement so as to demonstrate absence of degradation of the quality of fresh groundwater, ground movement so as to demonstrate absence of damage of infrastructure, as well as any specific legal and regulatory requirement. Risk analysis thus defines the focus of the site characterisation work that iteratively defines and constrains risks and hopefully reduces their consequence and/or likelihood to acceptable levels.

The SiteChar sites portfolio



The SiteChar workflow

The SiteChar workflow for CO_2 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 to ensure that it covers the aspects specified in the EU storage directive. Characterisation of a site relies on the following steps:

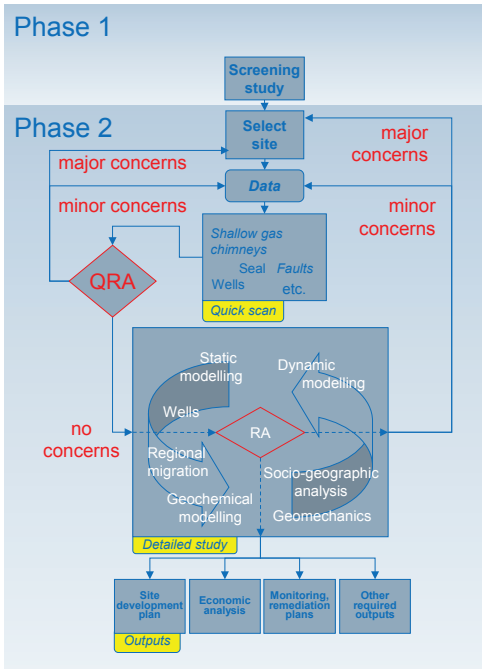
1) Data acquisition and quick analysis,
2) Qualitative and quantitative risk assessment,
3) Geological assessment,
4) Dynamic behaviour assessment,
5) Geomechanical assessment,
6) Geochemical assessment,
7) Migration path analysis,
8) Well integrity analysis,
9) Monitoring and remediation plans development,

where Step 2 is to be conducted iteratively throughout the site characterisation, taking results from the other steps as appropriate, Step 4 is preliminary to Steps 5 through 9 and Steps 7, 8 and 9 should largely be performed in parallel. It is important to note here that the above ordering is not set in stone and that the following steps need to be performed in parallel:

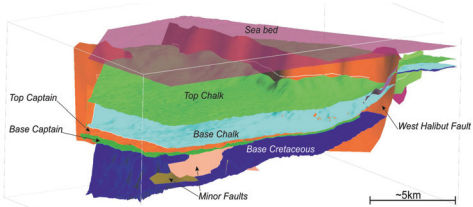
10) Social acceptability analysis,
11) Economic assessment.

These steps were conducted at the SiteChar project sites and are illustrated briefly here.

Characterisation of a site requires multi-disciplinary expertise, close cooperation between disciplines and sharing of data and assessment results from the beginning of the project. The purpose of the activities, their interdependencies, and any changes to the purpose during the progress of the investigations is necessary, so as to provide an adequate qualification of all elements of the storage site in line with regulatory requirements.



The UK Northern North Sea, Outer Moray Firth site

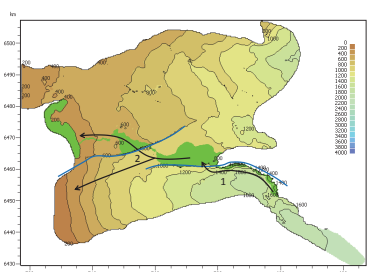


3D geological model of the UK multi-store site.

The UK site lies offshore in the northern North Sea off the east coast of Scotland in the Outer Moray Firth. The site comprises CO_2 injection into a depleted hydrocarbon field, for storage during the early demonstration operation of a project, and extending into the surrounding host saline aquifer sandstone for later commercial-scale storage. The storage site is hosted in the Captain Sandstone. Containment within the site will be beneath cap rocks that have demonstrated trapping of hydrocarbonvs. The injected CO_2 is retained within the sandstone that pinches out in the hanging-wall sequence of an adjacent fault.

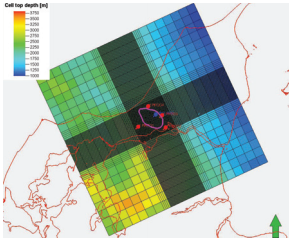
Site characterisation for the dry-run permit application is led by an initial assessment of risks to the containment of CO_2 followed by risk reduction investigations by technical experts. A geological model developed of the multi-store site was used for dynamic modelling to simulate the injection of CO_2 and production of water for pressure management. Geomechanical modelling predicted the effect of the injection of CO_2 on stress changes that might reactivate existing faults or cause failure of the cap rock and the likelihood of pre-existing vfractures forming a percolating network. Specific risks to the site were investigated by a regional flow path migration analysis if the site is substantially and excessively overfilled, numerical simulation of the integrity of abandoned wells as potential leakage points, an evaluation of the effect of chemical changes on the storage strata associated with CO_2 injection by geochemical modelling and an appraisal of geological hazards in the shallow subsurface as potential leakage points. A detailed feasibility assessment for the effectiveness of monitoring of the storage site by 3D seismic survey methods was undertaken.

Most of the components required for a storage permit application are presented, within the remit of a research project, including monitoring and preventative measures plans and provisional corrective measures and post-closure plans. The storage permit application also indicates additional activities, beyond the resources of a research project, for further risk reduction of the multi-store site.

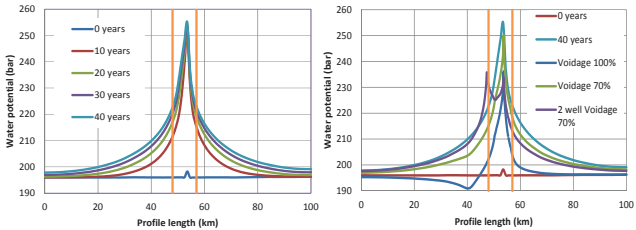


Migration pathway prediction if UK site is overfilled.

The Vedsted site, Denmark



Delineation of the Vedsted structure and well configuration. One CO_2 injection well (blue) placed down flank of the structure to the northeast. Four water production wells (red) placed outside the structural closure of the site.



Left: Pressure profile development during the injection period. The vertical orange lines indicate site delineation (lowest closing contour). Right: Pressure increase at site delineation after 40 years of injection with different voidage replacement from water production to manage pressure increase from the injection process.

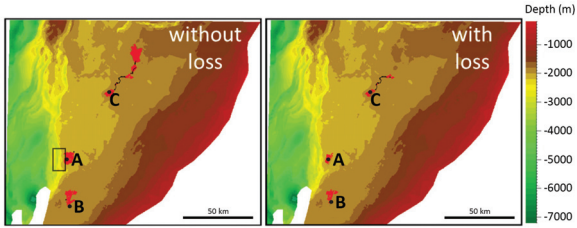
The Vedsted site is an onshore Upper Triassic-Lower Jurassic aquifer located at 1800-1900 m depth in northern Denmark.

The storage concept is a four way dip structural closure situated in a larger graben complex. The bounding faults are outside the delineation of the lowest closing contour. No major faults are expected to constrain the plume development inside the structure. Minor faults exist, although their properties are difficult to evaluate. A single legacy exploration well (Vedsted-1) penetrates the structure and represents a potential risk.

The dry-run permit application prepared includes geological, dynamic and geomechanical characterisation, a proposed monitoring strategy and a comprehensive baseline study. The potential risk of the Vedsted-1 well is also assessed. Geophysical techniques and monitoring of well(s) are proposed as the most suitable monitoring methods. The evaluation of connection between geological elements is considered essential part of the proposed monitoring program and to assure the best risk management. The research explored the impact of CO_2 storage on the surrounding region, especially pressure development in the saline aquifer, and any possible effects in the overlying layers for the onshore site.

- A comprehensive but preliminary site characterisation was carried out; the sparse data avalable was the constraining factor.
- Lack of production and well test data limited the calibration of the different models. Nevertheless, a suitable modelling framework was produced to guide the exploration/appraisal drilling campaign and for subsequent testing.
- A characterisation procedure for onshore aquifers with sparse data was produced. Incorporating all existing data and the regional geological understanding is vital.
- Pressure management is very important for on onshore sites and overpressure mitigation through water production is likely to be required.

The Trøndelag Platform, Norway



CO_2 accumulations projected onto the Garn Fm. depth map for injection without and with loss mechanisms included, 400 years after injection. Three injection sites are simulated (A, B & C). Frame idicates the study area used in detailed simulations.

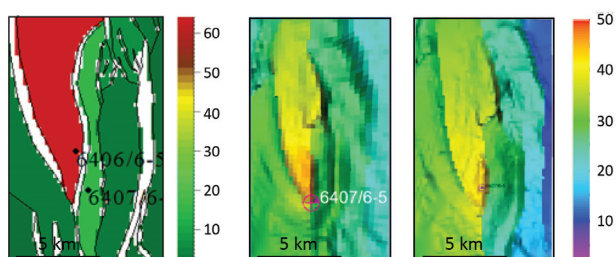
The Trøndelag Platform, offshore Mid-Norway covers an area of over 50,000 km2. One potential storage unit of significant thickness is the middle Jurassic Garn Formation. The sandstone has good to excellent storage characteristics, and is shallow buried (< 2000 m).

The overlying low-permeable clastic rocks have a thickness up to 1650 m and will most likely provide an effective seal. However, they are thinning towards east and intersecting with Quaternary sections close to the Norwegian coast, so possible migration routes in the storage unit have been an important subject for study.

- At basin scale, with industrial demo size injection volume scenarios of 1 Mt/a (over 40 years), no CO_2 migrates out of the target structural traps. If injection volumes are increased 5-fold to 5 Mt/a (over 40 years), simulations indicate that CO_2 starts tospill from the initial traps.

Additional loss functions were implemented in the simulator mimicking the physical and chemical behaviour of the (supercritical) CO_2 phase along the migration path and within the trap entity.

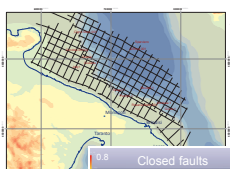
- At field scale, reservoir models of finer resolution were simulated and 3D pressure modelling simulations carried out resulted in the same pressure distribution, and pressure increase in the compartment where CO_2 is injected, although results give a coarser resolution of the distribution internally in the compartments.
- A generic monitoring plan has been derived for the Trøndelag Platform with example from the Alpha structure (injection site A).



Comparison of simulated overpressure using different methods: 30 years injection into well 6407/6-5, with 4 Mt/year.

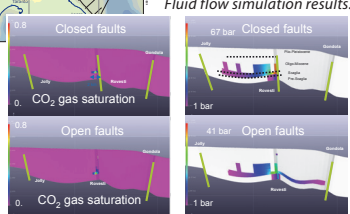
The South Adriatic Sea site, Italy

The Southern Adriatic Sea site provides the opportunity to develop a robust methodology for storage site characterisation in carbonate formations where diagenetic processes and fracturing play an important role in the distribution of porosity and permeability. The research focused on the simulation of the geomechanical and dynamic behaviour of the storage complex due to CO_2 injection in the reservoir. Special attention was placed on the effect that natural faults and fractures might have on CO_2 migration and the effect that injection might have on the stability of faults.



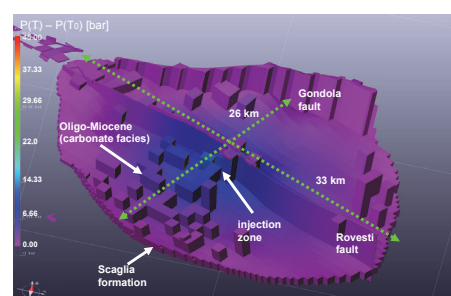
Location, seismic profiles, wells and depth map of the Southern Adriatic Sea site.

Fluid flow simulation results.



Construction of the regional model relied on the seismostratigraphic and structural interpretation of the 2D seismic profiles and the correlation with fifteen wells. Three sites potentially suitable for CO_2 storage have been identified (the Grazia, Rovesti and Grifone structures). The dynamic simulations conducted demonstrated that the reservoir is able to receive 1 Mt CO_2/year for a period of 10 years.

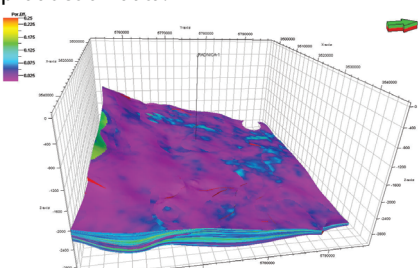
Site integrity focussed on the investigation of the geomechanical and dynamic behaviour of the site, including experimental analysis of samples from an onshore analogue, analysis of the cap rock integrity and of the geomechanical and dynamic behaviour of the Grazia reservoir. Various scenarios were simulated to take into account the uncertainties in the petrophysical and geomechanical properties of the model: different states of faults (i.e., open, closed or mid-opened), stress (i.e., normal faulting, or shear stress with various angles) as well as fluid flow parameters. The investigated scenarios results indicate that the Rovesti fault, which is located near the injection well, is unlikely to be reactivated. However, results have to be considered with care due to the limited available data.



Map of 3D overpressure (bar) for 1Mt/year injection in the Scaglia structure for a period of 12 years (open fault scenario).

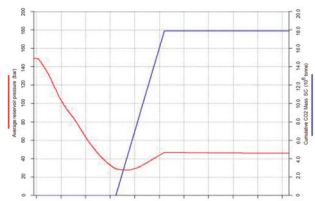
The Załęcze – Żuchlów site, Poland

The Załęcze and Żuchlów gas field reservoirs located in the South-Western Poland are composed of Rotliegendes sandstones found at over 1,200 m depth. The underlying Carboniferous formation has not been penetrated by wells. Of the 42 exploration, appraisal and development wells, 8 appraisal and 2 production wells have been abandoned, while 32 were producing gas in May 2013. The Załęcze and Żuchlów reservoirs are underlain by inactive aquifers. The adopted injection strategy aims at injection into the bottom layers of the aquifer to increase the CO_2-brine contact, enhance CO_2 dissolution and revsidual trapping, as well as delay CO_2 migration into the low pressure gas cap of the reservoir. The static geological model, developed for simulating CO_2 injection into the depleted reservoir, was first calibrated with the historical gas production data.



The Załęcze-Żuchlów static model porosity distribution.

Geomechanical modelling studies were carried out to evaluate the effects of gas extraction and prospective future CO_2 injection on the seal and faults. Assessment of rock and fault failure shows a significant occurrence of shear failure at the reservoir level as well as tensile failure at the faults but no disturbance of the cap rock integrity. A field scale geomechanical model was also developed for a preliminary assessment of depletion- and injection-related effects.



Average reservoir pressure and mass of injected CO_2 at the Żuchlów site.

Geochemical characterisation was performed on 6 reservoir samples and a long-term percolation experiment was conducted at simulated reservoir conditions, followed by 1D coreflood simulation.

The qualitative risk scenario analysis conducted was based on Features, Events and Processes (FEP) and aimed at identifying potential CO_2 leakage scenarios with the help of experts. Important risk factors, related to seal, fault and well integrity were identified. Recommendations for follow-up work include a definitive assessment of the well-related risks and definition of possible leakage scenarios will be possible once the quality of all individual abandoned wells has been evaluated in more specific detail.

Storage permit application dry runs

The Outer Moray Firth Field in the UK and the Vedsted aquifer site in Denmark, were selected for the development of dry-run storage permit applications. The aim was to identify the best approaches to site characterisation to enable robust and defensible permit applications. The results were reviewed by independent experts and compared against the requirements in the Storage Directive and the associated Guidance Documents. For the UK site, the guidance documents produced by the UK Department of Energy and Climate Change were also used. In conclusion:

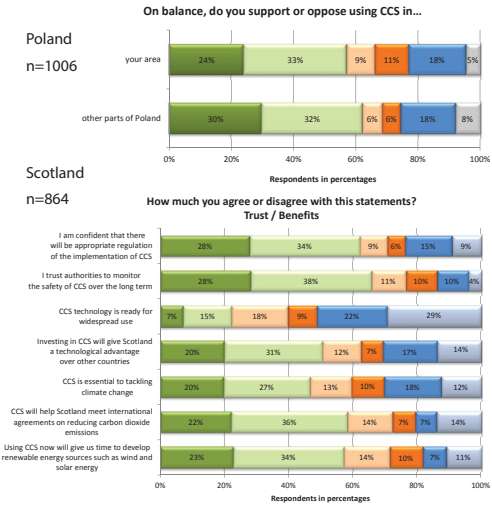
1. Although the site-specific geology results in different risks at the two sites sites, a common approach has been undertaken whereby site characterisation activities have been defined by a preliminary assessment of risks.
2. Both permit applications have described the appropriate approaches to developing the evidence base to submit successful permit applications.
3. There remain some key gaps in the applications due to lack of resources and limited scope of the research project (e.g. lack of data on CO_2 relative permeabilities, detailed correlations between well logs and seismic data and an understanding of fault properties).
4. Each permit application proposes further characterisation from newly drilled appraisal wells. Such wells would also provide an opportunity to undertake test injections.
5. Characterisation at both sites retain a degree of uncertainty, some of which will have to be reduced for a real permit, some others will not. It might thus be useful to develop a uncertainty management plan in addition to the risk management plan. .
6. Both permit applications considered the need to actively manage the reservoir pressure by producing water from a production well. Neither case study considered in detail the environmental regulatory implications of water production.
7. The definition of Permit Performance Conditions (PPCs) has been a significant development of the SiteChar dry-run process. The purpose of PPCs is to develop a set of a priori agreed criteria which will demonstrate appropriate site performance, thus providing a basis for the design of the monitoring program and the corrective measures plan. Whilst it might be relatively straightforward to define qualitative indicators, PPCs will need to be defined quantitatively for them to be the most effective.
8. Both monitoring plans include the need for a monitoring well placed at an appropriate distance from the injection well on the path of likely plume migration to allow monitoring of pressure response, plume migration and fluid chemistry, microseismic monitoring and detailed reservoir imaging.

Public awareness

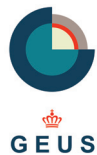
Social site characterisation and public participation activities were conducted at two prospective CCS sites: the onshore site of Załęcze & Żuchlów, Poland; and the offshore site of Moray Firth in Scotland, focusing on the communities in Morayshire.

The research consisted of four steps: (1) desk research, stakeholder interviews, media analyses and surveys of representative samples of the local community; (2) public engagement through focus conferences; (3) making available generic and site-specific information to the general and local public; (4) a follow up survey for a new representative sample of the local community aiming to establish whether changes in awareness, knowledge and opinions had developed. The main findings are:

- Relevant issues that may affect opinion about local CCS plans *Polish site*: Unemployment, infrastructure, Natura2000 area, brown coal mine, shale gas; *Scottish site*: Unemployment, tourism, other energy operations, marine life/fishing.
- Preferred and trusted communication channels and stakeholders *Both sites*: internet; local newspapers, councillors, political parties; *Polish site*: local radio.
- Level of awareness and knowledge of CO_2 and CCS (still reporting 'never heard about it' at the end of the research, %) *Polish site*: Very low, 78%; *Scottish site*: Low, 53%.
- Misconceptions on CCS, CO_2, and related concepts *Polish site:* 'reduces toxic waste', 'reduces smog' *Both sites*: results very tentatively suggest that public outreach may have led to more uncertainty and questions.



In both countries, acceptability of CCS was linked to implementation of other, preferred measures to combat climate change. Participants to focus conferences argued that the role of national and the EU government should be to develop a vision and stimulate public involvement in decision-making regarding climate change solutions. Both groups agreed that the public should be informed about CCS and other alternative solutions to reduce CO_2 emissions.



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