CO_2 Geological Storage: Research into Monitoring and Verification Technology - EU project CO2ReMoVe

Ton Wildenborg, 15 February 2011

(This short note presents an overview of the CO2ReMoVe project until the end of 2009)

Contents

Introduction

Two key challenges for enabling CO_2 Capture and Storage as a recognized emission reduction technology are the development of practical guidelines for monitoring and verifying the safety and effectiveness of storage sites, and the development of underlying performance assessment and monitoring methodologies and tools. The CO2ReMoVe project funded by the EU and industry, aims to address these challenges.

The objectives of CO2ReMoVe are to demonstrate the long-term reliability of geological storage of CO_2, and to undertake the research and development necessary to establish scientifically based standards for monitoring future CCS operations. This could in turn lead to guidelines for the certification of sites suitable for CCS on a wide scale.

The basis of the project is formed by three industrial-scale storage sites and several pilot sites. Crucial to the project portfolio is the continuing large-scale CO_2 injection operation at Sleipner (1996, offshore Norway), the more recently started injection operation at In Salah (2004, Algeria) and the CO_2 storage project Snøhvit (2008, offshore Norway). To date, these three sites are among the largest demonstrations of CO_2 injection and storage in the world. A number of pilot sites are also in the project portfolio, e.g. K12-B (2004, offshore the Netherlands) and Ketzin (2008, Germany). They provide an adjunct to the large-scale industrial sites, because they are ideal for monitoring CO_2 behaviour in, and close to, the borehole environment (considered to be the highest risk pathway for leakage) and for testing downhole and surface tools without interrupting industrial operations.

The CO2ReMoVe project largely thrives on the availability of injection sites and related data which have been generously provided by the license holders for the industrial sites and by the relevant funders for the Ketzin site. Some of the data acquisition is funded by CO2ReMoVe, which forms a smaller part of the efforts at the various sites. Access to the following sites and relevant data is greatly appreciated:

- In Salah site, operated by BP;
- Sleipner and Snøhvit sites operated by Statoil;
- Ketzin site operated by GeoForschungsZentrum Potsdam;
- K12-B site operated by GdF Suez.

The proposed scientific and technical research activities in CO2ReMoVe are summarised below:

- To develop, consolidate and disseminate all site-specific CO_2 storage experiences with Monitoring and Verification technology.
- To develop a set of Performance Assessment and Monitoring tools capable of predicting and measuring the key operational and long-term processes in CO_2 geological storage sites, and enabling the design of suitable remediation strategies if required. Development will include processes in each relevant compartment of the geosphere, such as reservoir, seal, aquifers and aquitards, as well as the soil, hydrosphere and atmosphere. It will also include innovations to assess impacts, in particular with respect to the coupling of various processes, such as fluid flow, multi-phase interaction, and geochemical, mechanical, thermal, chemical and also biological processes.
- To provide scientific and technological information to develop recommendations which can be used by regulators, legislators and policymakers to formulate a consistent and internationally accepted standard for Health, Safety and Environmental (HSE) risk management and certification under the Clean Development Mechanism (CDM), Joint Implementation (JI), Emissions Trading Scheme (ETS) and future national and intergovernmental mechanisms for greenhouse gas mitigation. These

recommendations encompass procedures, requirements and tools for the selection and characterisation of the storage site, the assessment of the site, the monitoring of the site, verification of the site and remedial (preventive and corrective) actions for the site.

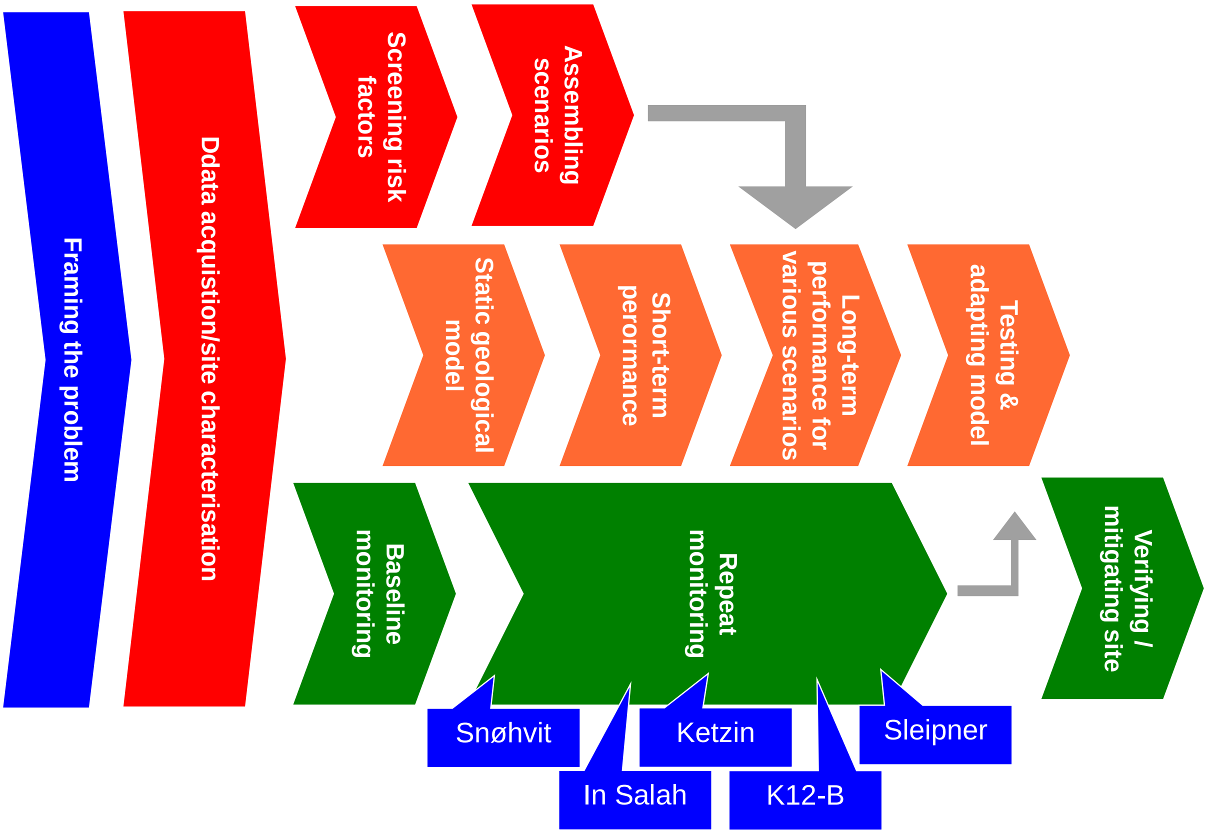

Figure 1 Simplified workflow for assessment, monitoring and verification purposes and status of the activities at the sites

Approach for site-specific assessment, monitoring and verification

The following generalized workflow is used to specify the activities for specific sites (Figure 1). The actual work can deviate from the generalised workflow depending on:

- Performance assessment work that has already been performed or planned in *other projects*; CO2ReMoVe will not duplicate this work
- The stage in the lifecycle of a CO_2 storage facility: characterisation and design phase, operational phase, closure phase. All monitored CO_2 storage projects that are included in CO2ReMoVe, are in the operational or closure phases.

Starting activities

1. Every performance assessment (PA) starts with defining the acceptance criteria, characterisation of the CO_2 stream to be stored, a description of the storage concept and a description of the geological and geographical setting of the site. This information is putting constraints on the performance assessment. A review of existing and planned PA work and a work-plan for remaining PA work will be included.

2. Site-specific earth models will be constructed on the basis of data from seismic surveys and wells.

3. Baseline monitoring activities will begin at this time setting reference levels for possible future repeat surveys.

Project in design phase

In the phase of site characterisation and design, the long-term performance in reducing CO_2 emissions and local safety and environment will be assessed. This will result in the identification of any crucial factors controlling the risk of the site, on the basis of which a monitoring plan will be made.

4. Long-term performance assessment starts with the identification of risk factors (also called FEPs or Features, Events and Processes) and the construction of a limited numbers of scenarios, each of which is representative for a specific group of linked risk factors. The work-plan for PA will be adjusted.

5. The scenarios are then transferred into quantitative models describing CO_2 migration in the geosphere and impact on the biosphere. Such an exercise can be done in a probabilistic or in a deterministic mode.

6. The most sensitive parameters will be identified and uncertainties will be assigned to them.

7. The results of the simulation work will be assessed with the help of the acceptance criteria for CO_2 emissions and local safety and environmental factors (including the possible effect of other gaseous components in the CO_2 stream). Additional measures for the storage design, monitoring and mitigation plans can be implemented lowering the overall risk profile of the site.

Project in operation phase

8. As soon as the operational phase has started detailed short-term predictions of the system performance will be carried out. The underlying models for the short-term predictions should be consistent with those used for the long-term PA.

9. The predictions will be compared with the actual behaviour of the system as revealed by results from the monitoring programme. This comparison might lead to implementing mitigation measures and to adjustment of the original short-term PA. The work-plan for PA will be re-adjusted.

Project in closure phase

10. If necessary, the long-term PA developed in the design phase will be updated on the basis of the short-term PA and the monitoring results (see Activity 7). The aim is to demonstrate that long-term storage is safe and reliable. Uncertainties that were identified in the short-term analysis will be integrated in the updated long-term PA.

11. Before the site is closed, it will be decided if and for how long active monitoring will be required and what type of mitigation measures should be in place.

Finalising activities

12. The experience gained during the site-specific performance assessment will be assembled, evaluated and used for developing a common methodology and best practice.

Results

This section gives a non-exhaustive summary of preliminary results from the CO2REMOVE project.

Assessment tools

A draft Performance Assessment framework became available, which will be used as guidance for the assessments of the individual sites. Approaches for qualitative aspects of performance assessments have been refined (based on the FEP approach). A tool for supporting decisions by integrating qualitative and quantitative PA-relevant information (CO2TESLA-Excel) has also been developed, based on Quintessa's TESLA code (Figure 2).

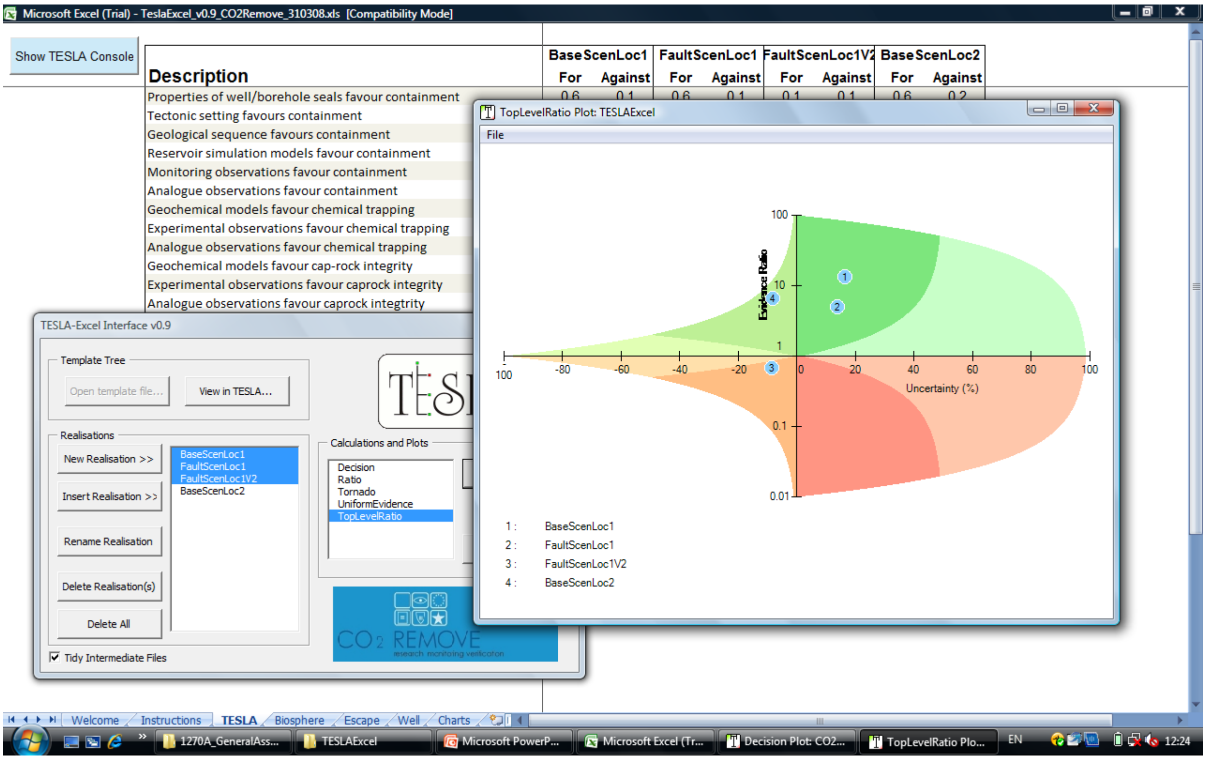

Figure 2 Screen shots from the performance assessment software tool CO2TESLA-Excel (Quintessa)

Monitoring tools

A number of monitoring tools and methodologies are being assessed and developed:

- Optimised technologies for atmospheric monitoring are being designed, based around optimal combinations of 1D point sampling, 2D mobile sampling and 3D (areal) monitoring strategies [Jones et al 2008].
- A new underwater CO_2 flux monitoring tool is under development, focussing on robust long-term performance in deeper water.
- A new EM tool has been designed, using a novel borehole-surface array, termed LEMAM (Figure 3). Sensitivity and feasibility analyses have been carried out and field testing is planned at the Ketzin site.
- A number of downhole sampling and logging tools are being developed including multi-parameter hydrochemistry, gas sampling and development of the RST tool.

- Ongoing research is being carried out on advanced AVO analysis, pre-stack imaging, thin-layer quantification via spectral decomposition and velocity / attenuation tomography. The Sleipner time-lapse datasets are central to much of this research.

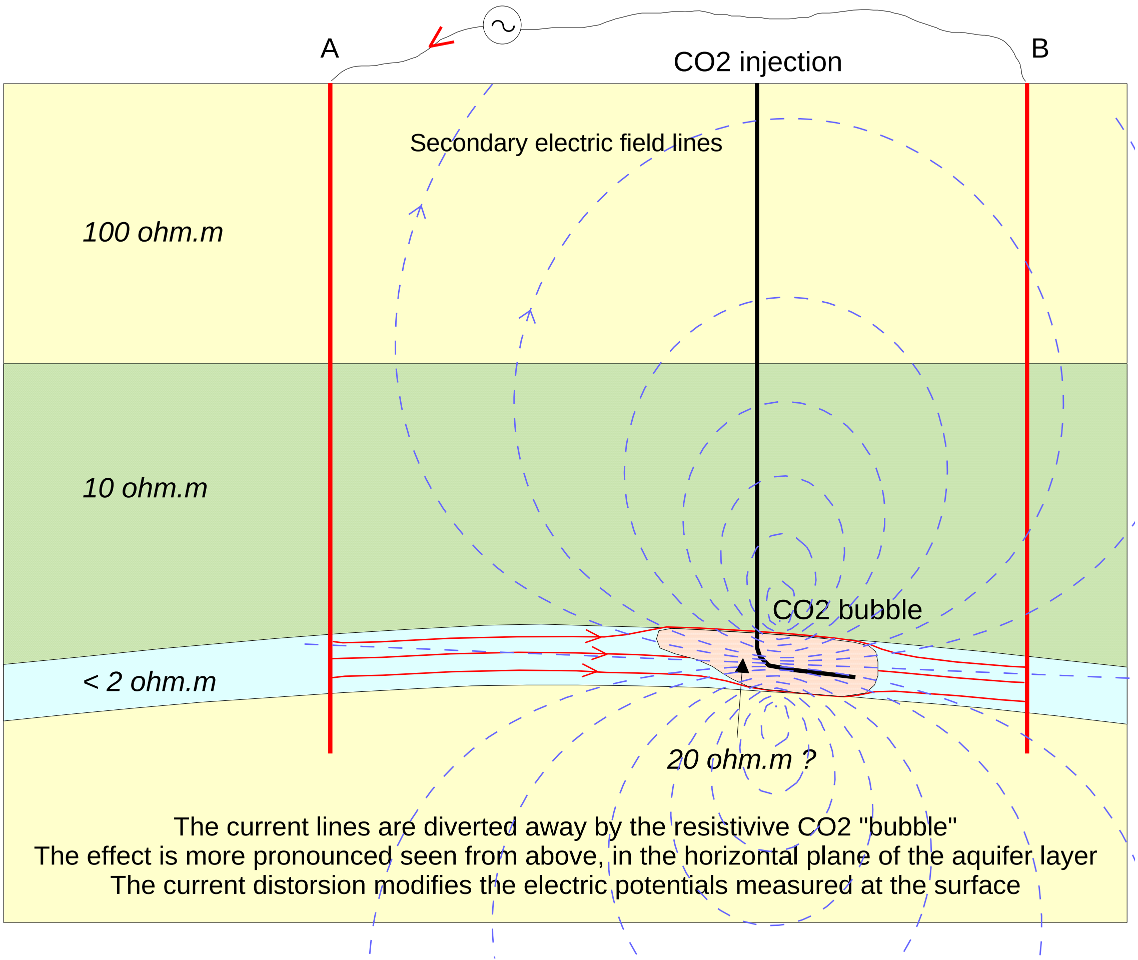

Figure 3 Concept of LEMAM electromagnetic monitoring techniques (BRGM)

In Salah

At In Salah, nearly 1 million tonnes of CO_2 per year, separated from produced natural gas, is being injected into a sandstone formation (of Carboniferous age) 2000 metres below the surface (Figure 4).

An assessment and review of the legacy data was performed and alternative interpretations of the reservoir and its caprock were investigated. An alternate Shared Earth Model has been developed and discussed. Dynamic simulations were performed to assess the different geological interpretation and investigate plume migration.

A comprehensive monitoring programme is planned, including a wide range of subsurface and surface tools.

Figure 4 In Salah Site, Algeria (photo courtesy of BP, Sonatrach, and Statoil)

2009 at the In Salah site saw several successful field monitoring operations, where working an arid environment presents its own challenges. A mobile open path laser system was deployed in March 2009; the results highlighted the potential of such systems as well as some of the technical difficulties of carrying out such measurements in such a dusty environment. The repeat soil gas flux measurements gave similarly low values to those in 2004, which were confirmed by preliminary laboratory analysis at the University of Rome. Both the soil gas and the mobile laser measurements were repeated in November 2009 and no significant anomalies were found. Given the very low gas concentrations this provided baseline data and was a feasibility study for carrying out work in a desert environment. In late 2009 the first studies of the soil microbiology and plant species over the site were conducted. The botanical and soil microbiology work particularly focuses on the area around the three CO_2 injection wells.

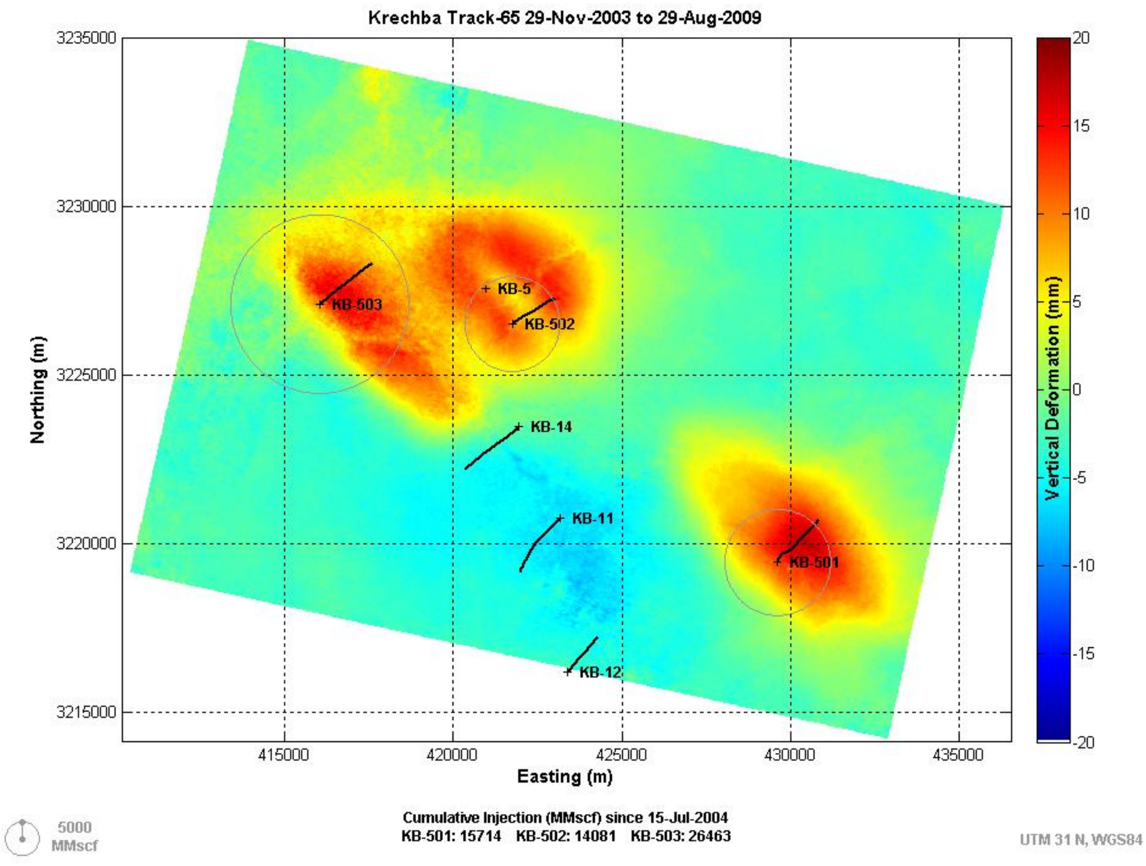

Figure 5 Ground deformation at In Salah (courtesy of MDA/Pinnacle ISG JIP)

The value of using tiltmeter/GPS and satellite imagery data at In Salah has been shown. The satellite data shows subtle (less than 5mm/year) but highly interpretable subsidence and uplift respectively related to the production and injection operations (Figure 5). Integration of the permeability pattern inverted from the surface uplift data into the reservoir simulation has lead to an improved prediction of the CO_2 plume migration around one of the wells. This is consistent with the surface monitoring data, as well as reservoir-based observations. The results show that the CO_2 plume migration extent and direction in the storage complex appears to be consistent with expectations.

Also being tested at In Salah is a microseismic survey before full deployment of ongoing measurements while additional three-dimensional seismic data was acquired in June 2009.

Sleipner

Since 1996, CO_2 from produced natural gas has been injected at Sleipner (Figure 6) into a saline aquifer at a rate of 1 million tonnes of CO_2 per year, at a depth of just over 1,000 metres. Legacy datasets for the Sleipner site have been gathered and a Shared Earth model has been constructed. In addition, a comprehensive seismic monitoring programme has been carried out, with repeat time-lapse 3D surveys in 1999, 2001, 2002, 2004 and 2006, the latter augmented by high resolution 2D seismic and seabed imaging surveys.

The seismic data clearly image the progressive development of the CO_2 plume as a prominent multi-tier feature comprising a number of bright sub-horizontal reflections, interpreted as arising from discrete thin layers of CO_2. The upper layers continue to spread laterally and generally increase in brightness, whereas the lower layers have stabilised in size and are growing progressively dimmer. Within the reservoir overburden, there is no evidence of systematic changes in seismic signature, indicating that CO_2 is being contained within the storage reservoir. Recent work in CO2ReMoVe has concentrated on detailed quantitative analysis of the topmost layer, which indicates a steady rise in CO_2 flux arriving at the top of the reservoir, attributable to increasing relative permeabilities in the reservoir.

Figure 6 Sleipner site (photo courtesy Statoil)

Seabed gravimetric measurements have also been taken in 2002, 2005 and 2009. An initial seabed EM survey has also just been acquired in the summer of 2008. A repeat seabed gravity survey was conducted in 2009 the processing of this data concluded in early 2010. In the scope of validating methods for monitoring CO_2 migration, a pre-stack stratigraphic inversion method has been applied on the 2006 3D repeated seismic to map the CO_2 plume (Figure 7). Such results help updating the reservoir model improving reliability for long term simulations. Geological models have been generated in Petrel and populated with porosity and permeability using statistical methods. Several simulation models representing the Utsira Sandstone Formation (large and small scale) have been constructed. Work on the common and unified Earth model has been finalized.

The biomarkers laboratory is underway at Sleipner for which wild animals in the intertidal zone and deep-water shrimp have been collected. Experiments have been completed exposing animals to different concentrations of CO_2 (0.5, 1, 2 and 3% CO_2). Animals exposed to 1 % (10,000 ppm) CO_2 were subjected to acute (in 1-48 hours) and chronic (4-28 days) exposures in order to examine the changes, while animals exposed to the other levels of CO_2 were exposed for 14 days.

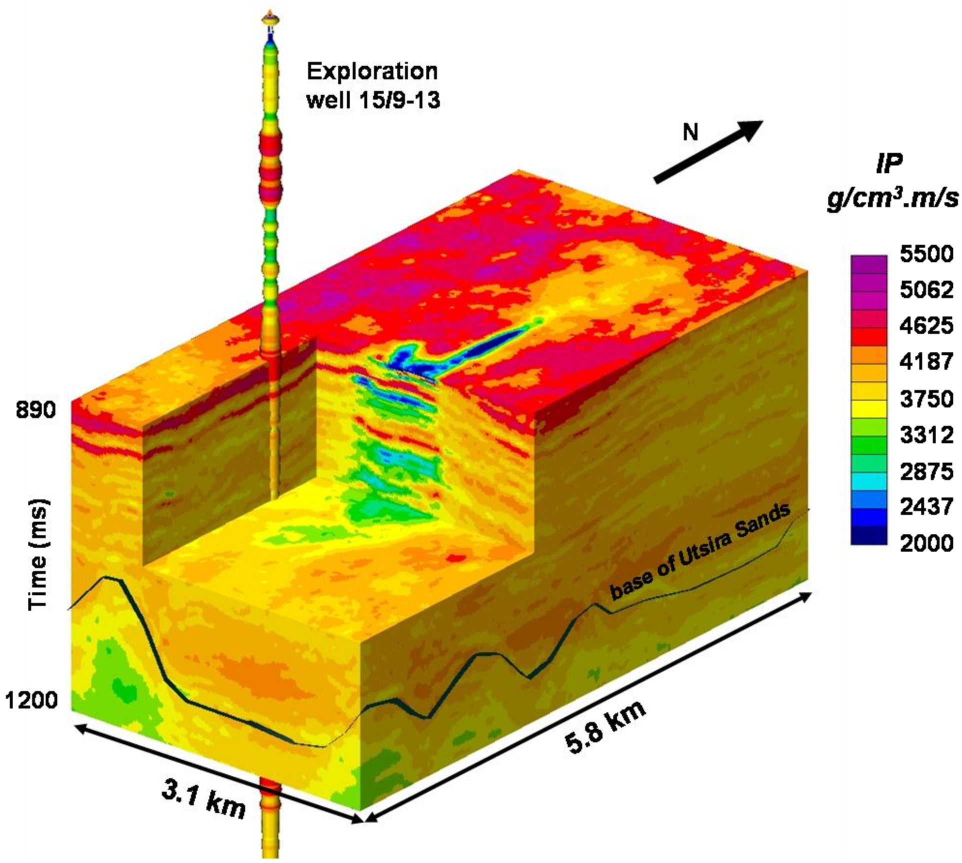

Figure 7 Cut-away view of the 3D P-wave impedance data cube computed by pre-stack stratigraphic inversion of the 2006 vintage. The figure also shows the exploration well used for the calibration step and the intersection between the base of the Utsira Sand formation with the boundaries of the cube. The CO_2 plume is identified by low impedance values displayed in dark blue, blue and green colours (IFPEN).

Snøhvit

At the Snøhvit field – Statoil is reinjecting Snøhvit's CO_2 emissions into the ground beneath the gas-bearing formation of the field. Since the project commenced operators have encountered problems in sustaining injection, this is because of the difficulties with gas separation due to the severe climate and remote conditions. Statoil is in the process of revising/updating the existing Tubåen reservoir simulation model based on the results of the new interpreted seismic data acquired in 2009. The revision of the reservoir simulation model is expected to be complex due to lack of obvious faults (or sealing faults) in the Tubåen reservoir that may act as barriers to water being displaced as a result of CO_2 plume development after injection. The reservoir pressure in the Tubåen reservoir during injection has risen to levels higher than predicted by the applied reservoir simulation model and has taken longer than expected to decline during the shut-in periods.

Ketzin

At Ketzin carbon dioxide injection into the aquifer commenced in 2008, and the intention is to monitor the behaviour of this injected gas for many years to research the long term reaction and safety of CO_2 storage in saline aquifer conditions. Monitoring techniques include seismic acquisition, geochemical analyses, temperature and geo-electrical measurements at the surface and within the wells.

The seismic work-flow was rearranged in order to optimise the deployment of the available seismic campaigns for detection of the CO_2 plume propagation direction (in collaboration with CO_2SINK). Furthermore, the seismic campaigns have to be multiplexed to share the expensive lubricator equipment. The planned VSP/MSP survey was implemented in autumn 2009; a 3D-MSP survey was carried out to record the shot points of the 3D-reflection survey with a 3-component receiver in one well. This technique provides high underground coverage and allows for the areal monitoring of CO_2 migration around the three Ketzin wells.

The evaluation of datasets from Distributed Temperature Sensor (DTS) system has been extended for as long as possible. The DTS plays an important role for safety monitoring of the injection string in well Ktzi201, providing information on the behaviour of CO_2 (supercritical phase). It is planned to evaluate the stability over long injection periods as well as the shut-in and re-start phases of the injection process.

K12-B

At the K12-B field a performance assessment has demonstrated, that should migration of CO_2 to shallower strata or even to the surface occur, the most likely migration pathways to be considered are along the wellbores penetrating the reservoir. Therefore monitoring of the CO_2 injected into K12-B is mainly focussed on the integrity of the wells.

Unable to cover for or insure any possible lost-in-hole charges for the pH logging tool the pH measurements are being carried out by analysing downhole fluid samples from the injection well in a laboratory rather than continuous downhole analysis.

Acquisition of PMIT (platform multi-finger imaging tool) caliper data and EMIT (electro-magnetic tubing and casing integrity tool) data was carried out in summer 2009. Gas composition and tracer analyses are also being conducted on regular intervals.

Draft guideline

Guidelines were drafted for licensing of CO_2 storage in saline reservoirs and depleted hydrocarbon reservoirs. It consists of detailed checklists for operators and authorities in each of the stages of a licensing procedure for a CO_2 storage operation (Figure 8). The draft guidelines will be updated as results from monitoring ongoing CO_2 storage operations become available in the project. They may serve as a contribution to the regulation of CO_2 storage anywhere in the world, and may be also be of use in evaluating the proposed EU Directive for the Geological Storage of CO_2 in the future.

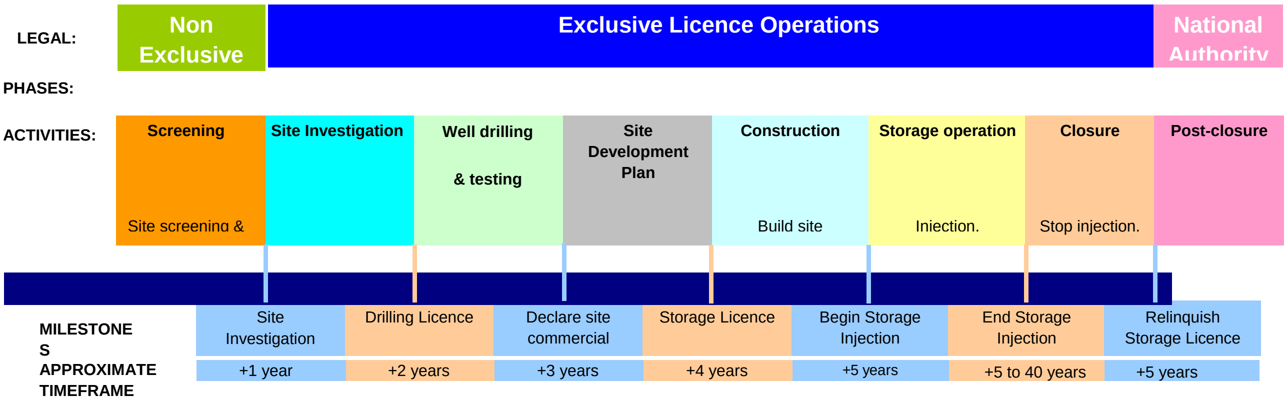

Figure 8 Phases in the realization of a CO_2 storage operation

Acknowledgements

The results presented here are part of the CO2REMOVE project, which is directed to the development of technology and procedures for monitoring and verifying underground CO_2 storage locations. The financial support of the European Commission and the industrial consortium consisting of BP, StatoilHydro, Wintershall, TOTAL, Schlumberger, DNV, ExxonMobil, ConocoPhillips, Vattenfall and Vector, is greatly appreciated. The success of the CO2REMOVE project depends to a large degree on the accessibility of the storage sites and the availability of site data, e.g. for In Salah, Sleipner, Snøhvit, Ketzin and K12-B.