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Large-scale CO_2 injection demos for the development of monitoring and verification technology and guidelines (CO2ReMoVe)

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Abstract

The objectives of the EU project CO2ReMoVe are to undertake the research and development necessary to establish scientifically based standards for monitoring future CCS operations and to develop the performance assessment methodologies necessary to demonstrate the long-term reliability of geological storage of CO_2. This could in turn lead to guidelines for the certification of sites suitable for CCS on a wide scale. Crucial to the project portfolio are the continuing large-scale CO_2 injection operation at Sleipner, the injection operation at In Salah (Algeria) and the recently started injection project at Snøhvit (Norway). Two pilot sites are also currently in the project portfolio, Ketzin in Germany and K12-B in the offshore continental shelf of the Netherlands.

Keywords: CO_2 storage, demonstration, performance assessment, monitoring, guidelines

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1. 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. 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, together with the Weyburn operation in Canada, are 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, a Joint Venture of BP, StatoilHydro and Sonatrach;
- Sleipner and Snøhvit sites operated by StatoilHydro;
- Ketzin site coordinated 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.

Site assessment:
- ❒ geological characterisation
- ❒ short & long term simulation (fluid flow, geomechanics, geochemistry)
- ❒ risk assessment

⇩

Design monitoring programme
Design leakage mitigation programme

⇩

Application / Site certification

⇩

Acquire monitoring baseline data

⇩

★ Start CO_2 injection

⇩

Monitor site
- ❒ Acquire monitoring data
- ❒ Interprete monitoring data

⇩

Update risk assessment (incl. update simulations)
Update future monitoring programme
Update leakage mitigation programme & site exit strategy

⇩

(Repeat monitoring and updates)

⇩

Eventually: site abandonment

Figure 1 Generalised workflow for assessment, monitoring and verification purposes

2. 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.

3. Results

This section gives a summary of some preliminary results from the CO2REMOVE project. More detailed information on some topics can be found in other GHGT-9 papers [1-3].

3.1. Assessment tools

A draft Performance Assessment framework became available, which will be used as guidance for the assessments of the individual sites. The state of the art in assessing other components in the captured CO_2 stream like H_2S, SO_2 and NO_2, was determined. Model concepts for qualitative (FEP approach) and quantitative performance assessments (TESLA) have been improved.

3.2. 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 1-D point sampling, 2D mobile sampling and 3D (areal) monitoring strategies [2]. A new underwater CO_2 flux monitoring tool is under development, focussing on robust long-term performance in deeper water. Field testing and trials at one of the CO2ReMoVe sites are planned for the future. A new EM tool has been designed, using a novel borehole-surface array, termed LEMAM. Sensitivity and feasibility analysis has 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. On the seismic front, 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.

Table 1 Overview of monitoring techniques to be deployed at the large injection sites

	Subsurface monitoring								Surface and near-surface monitoring				
	seismic methods				non-seismic and borehole methods								
	4D surface seismic	hi-res 2D seismic	well seismic VSP	micro-seismicity	EM / electrical	gravity	tiltmeters	well fluids	seabottom imaging	soil gas	surface flux / atmospheric	ecosystems	satellite remote sensing
In Salah	■		■	■		■	■	■		■	■	■	■
Sleipner	■	■			■	■			■			■	
Snøhvit	■												

3.3. 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 2).

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 (Table 1), including a wide range of subsurface and surface tools.

Figure 2 In Salah Site, Algeria (photo courtesy of BP, Sonatrach, and Statoil)

3.4. Sleipner

Since 1996, CO_2 from produced natural gas has been injected at Sleipner (Figure 3) 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 (Table 1), 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 [1], which indicates a steady rise in CO_2 flux arriving at the top of the reservoir, attributable to increasing relative permeabilities in the reservoir.

Seabed gravimetric measurements have also been taken in 2002 and 2005 with a second repeat survey planned for 2009. An initial seabed EM survey has also just been acquired in the summer of 2008. Results from the first two gravimetric surveys have been used to constrain CO_2 density and it is hoped that the new potential-field data will provide additional independent constraints on the seismic analysis.

Figure 3 Sleipner site (photo courtesy of Statoil)

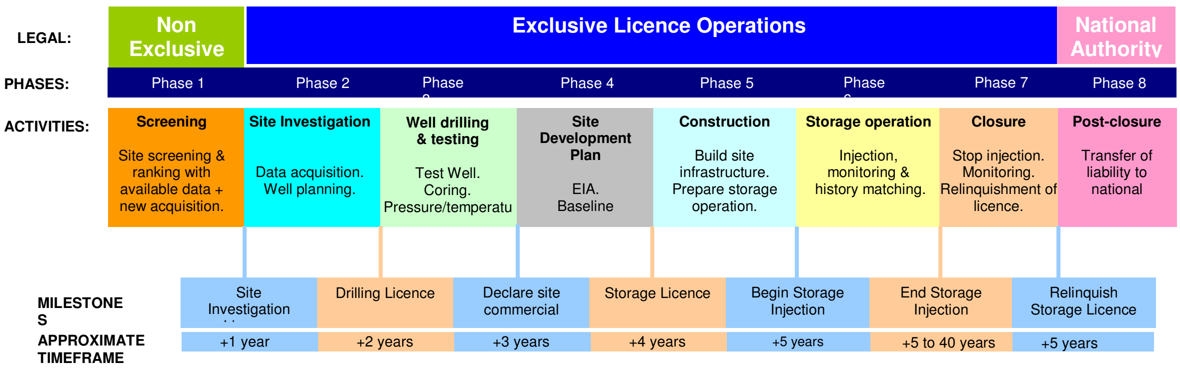

Figure 4 Phases in the realization of a CO_2 storage operation

3.5. 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 4). 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.

4. 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. In this respect we particularly want to thank Allan Mathieson and Iain Wright (BP), Kristin Øye and Hans Aksel Haugen (StatoilHydro), Conny Schmidt-Hattenberger and Frank Schilling (GFZ Potsdam), and Daan d'Hoore (GdF Suez) for their efforts.

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