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Thematic Report

Storage session – May 2013

A report from the European CCS Demonstration Project Network

Public version

Proceedings from the Doncaster knowledge sharing event 20 and 21 May 2013

Executive Summary

The European Carbon Capture and Storage (CCS) Projects Demonstration Network is a community of leading demonstration projects committed to sharing knowledge and experiences to achieve safe and commercially viable CCS. As Europe's most advanced projects, they are often faced with new issues and challenges, which the projects have had to negotiate.

Network projects at the time of the meeting in May were:

- Bełchatów in Poland (halted in April 2013)
- OXY-CFB-300 Compostilla in Spain, with a pilot scale demonstration (referred to as "Hontomín") and a commercial demonstration (referred to as "Compostilla").
- Don Valley in the United Kingdom, with a site exploring the use of the enhanced oil recovery technique (referred to as "Don Valley EOR") and a site planning to store in a saline formation (aquifer) (referred to as "Don Valley SF").
- Porto Tolle in Italy (halted in October 2013).
- ROAD in the Netherlands (Rotterdam Opslag and Afvang Demonstratieproject/ Rotterdam Capture and Storage Demonstration Project).
- Sleipner in Norway, a deep saline formation storage demonstration project in operation. To date, the Sleipner project has stored over 14 Mt of captured CO_2 from the Sleipner Vest gas field since 1996.

By sharing these experiences with a wider audience the Network provides other projects with the benefit of their experiences, both successful and unsuccessful, and delivers best practices for how to operate a CCS project thus saving new projects both time and money. Consequently the reports from the Network play a vital role in delivering information and experience to other CCS stakeholders, maximising the efficiency of achieving commercially viable CCS.

This report presents the information, discussions and key learning points from the 1st storage knowledge sharing event of 2013 held on 20 and 21 May 2013 in Doncaster, UK.

The event was spilt into 3 sessions which covered:

- A status update of the storage component of each project – progress since the last knowledge sharing event held in October 2012;
- A thematic discussion on flow assurance and designing a long term injection operation;
- A thematic discussion on baseline monitoring.

The main outcomes of the sharing of knowledge and resulting discussions can be summarized as follows:

Project Progress

While the Bełchatów project ceased activities, and ROAD is in slow mode while working on getting sufficient funding, other projects have been making good progress, despite reorganisations due to financial constraints like Don Valley and Hontomín.

The progress of Don Valley 'Saline Formation' is very promising as well as the progress of Compostilla, which is now the only remaining onshore project in Europe. The participation of Statoil

ASA, sharing its experiences and lessons learned from Sleipner, but also from Snøhvit, is of great value to the Network.

Compostilla

The feasibility study was completed as well as the work related to the appraisal wells. A long term monitoring plan has been prepared. The FEED is now in good progress. The project is currently consolidating its storage economic and risk assessment. The conclusions will be used to take a final investment decision (FID) in Q4 2013 for the OXY-CFB-300 project.

Hontomin

The technology development plant associated to the Compostilla project is building the infrastructures to start injection in autumn. The feasibility study and the FEED have been completed. The project is drilling its injection well while the long term monitoring plan is in progress. Since this is Compostilla's research and technology development pilot, it will inject less than 100,000 tonnes of CO_2 and thus does not require a storage licence.

Don Valley Saline Formation

The project has now completed its feasibility study. It has applied for a storage licence. The offshore carbon storage licence drilling application was granted by the Department of Energy and Climate Change (DECC) in November 2012. An agreement for lease was signed with the Crown Estate in February 2013.

Porto Tolle

The baseline surveys have been completed. The documentation for the request of an Exploration permit, including the drilling of an appraisal well, was arranged as well as the Environmental Impact Assessment, although the technical decrees of the Storage Regulation are still not implemented.

ROAD

The P18-4 reservoir has good injection and storage characteristics. The objective is to inject 7 Mt of CO_2, for which there should be sufficient capacity (reservoir capacity of 8 Mt). At present the start date should be 2016.

Sleipner

Operations continue with demonstration of safe storage for seventeen years now. The project is also taking part in a number of R&D projects, sharing data with the scientific community.

Flow Assurance and Designing a Long Term Injection Operation

This session was shared with the transport group. The main concerns evolved around the CO_2 stream composition and capture plant start-up and shutdown impacts, which showed that is it necessary to think 'entire CCS system' and not just 'injection operations at the storage site' since CO_2 availability will have a significant impact on the design and the costs. It is important to increase the whole system availability.

Baseline Monitoring

The session showed that there is a clear distinction between baseline monitoring and future operational monitoring, verification monitoring and assurance monitoring.

A range of onshore and offshore baseline monitoring techniques has been implemented at the storage sites using a variety of methods. There are a number of reasons for the variety displayed by the projects: partly because these methods are also used for characterisation, partly because methods are site specific (what can be measured or detected at a site depends of the local geology and environment), and partly because the projects need to anticipate what parameters may vary in time for their project.

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1 Introduction

This report gives an update on the work undertaken to progress the carbon dioxide (CO_2) storage component of CCS by the leading European projects since the knowledge sharing event held in October 2012, as well as a summary of the discussions and key learning points that resulted from the thematic event held in Doncaster and hosted by the Don Valley project on the 20 and 21 of May 2013. The meeting was one of three sessions held in parallel during the European CCS Project Demonstration Network knowledge sharing event. The other thematic groups were transport and regulatory development (see separate reports).

Reminder: Mission of the European CCS Demonstration Project Network

The European CCS Demonstration Project Network has been setup to:

- Help fulfil the potential of Carbon Capture and Storage by creating a community of projects united in the goal of achieving commercially viable CCS by 2020.
- Foster knowledge sharing amongst the demonstration projects.
- Facilitate the identification of best practices.
- Accelerate learnings and ensures that we can assist CCS to safely fulfil its potential, both in the EU and in cooperation with global partners.
- Leverage this new body of knowledge to raise public understanding of the potential of CCS.

Storage Knowledge Sharing Themes for 2013

Two storage topics were selected by the European CCS Demonstration Project Network Steering Committee for the year 2013:

- Designing long term injection operations
- Baseline monitoring.

Both topics have been addressed during this 1st event. The knowledge sharing session scheduled in October 2013 will follow-up on these topics.

2 Project Status Update

The projects gave an update on storage progress since the last event in October 2012 which was held in Oostvorne close to Rotterdam, in The Netherlands.

The below **project status table** presents a summary of the status of the storage sites under development (except for the Sleipner project since all boxes would be marked as completed):

	Compo-stilla	Don Valley Saline	Porto Tolle	ROAD	Belchatow	Don Valley EOR	Hontomin
Site screen	✓	✓	✓	✓	✓	✓	✓
Site select	✓	✓	✓	✓	✓	✓	✓
Feasibility study	✓	✓	✓	✓	O	✓	✓
Appraisal drill and/or seismic	✓	☐	O	n/a	O	n/a	☐
Baseline surveys	✓	☐	✓	n/a	O	O	☐
FEED	☐	O	O	O	O	O	✓
LT monitor plan	✓	O	O	O	O	O	☐
Storage License application	O	✓	O	✓	O	O	n/a
CO_2 Injectors	3-5	2-6	1	1	?	5-6	1
Injection backup?	yes	yes	no	no	?	yes	no

O not started ☐ in progress ✓ complete project suspended

(May 2013)

2.1 Bełchatów

The Bełchatów project announced in April 2013 that it will not be progressing at this time. According to the Commission, this was due to the failure to obtain NER300 funding and the difficulties in overcoming the existing risks posed by the lack of appropriate regulations, particularly regarding transport.

The project has requested that its EEPR grant agreement be terminated, and sent a letter to the Steering Committee asking to formally withdraw from the Network.

2.2 Compostilla – **Duero** and Andorra sites

As a reminder the project mentioned that it pre-selected seven potential sites and after investigations, two sites in deep saline formations (aquifers) were selected for further assessment, prior to storing the CO_2 from the OXY-CFB-300 plant, the “Duero Site” in the Duero basin (NW of Spain) and the “Andorra Site” in the Ebro basin (NE of Spain). Both sites are deep saline aquifers at depths greater than 800m located in Mesozoic formations (Triassic, Jurassic and Cretaceous periods). The Duero site was selected as the primary site, the Andorra site as a back-up option.

The project was divided into four contingent phases: 1) site assessment, 2) site characterisation, 3) extensive subsurface characterisation and 4) Front End Engineering Design (FEED).

1) Site Assessment:

The site assessment phase was completed. The main deliverable was an appraisal plan, to be executed during the next phases of the project. Key deliverables of this phase included:

1. Appraisal plan definition, and authorization of the Spanish Administration to develop the plan.
2. Basin-scale geological studies and models (structural, stratigraphic).
3. Seismic survey acquisition at the Andorra Site.
4. Seismic integration and interpretation with pre-existing data (past seismic lines) at both sites.
5. Magnetotellurics (MT) / Audio-magnetotellurics (AMT) surveys at the Duero and Andorra sites.
6. Resistivity maps of the Mesozoic deposits at both sites.
7. Correlation of existing wells (lithology), salinity data, MT/AMT data. Salinity variations maps.
8. Faults analysis at Basin-scale and at local sites based on existing well and seismic lines.
9. Hydrogeological studies and models at Basin-scale and at local sites.
10. Technical review of the existing wells and seismic surveys (Andorra and Duero sites). Re-interpretation of existing well tests and seismic data with new seismic and MT/AMT data.
11. Updated geological models.
12. First static and dynamic models of the Duero site.
13. Andorra – Ebro Site:
    a. Four potential structures identified.
    b. Ranking and screening → the Monegrillo sub-site was selected.
14. First static and dynamic models of Monegrillo.
15. First injection strategies definitions (3 scenarios for the Duero site and 2 for Monegrillo).
16. Seismic survey acquisition at the Duero Site.

At the end of the assessment phase, ENDESA concluded that the Duero site had the potential to store 1.37 Mt of CO_2 and that the Monegrillo sub-site at the Andorra site had the same potential. It was then decided to proceed with the characterisation phase.

2) Site Characterization:
   This phase was completed although with significant delays mainly due to issues with the appraisal plan development.
   I. Appraisal plan development:
      1. Requested permits modifications were submitted to the Administration and a new tendering process was launched for:
         - New MT/AMT survey at the Andorra -Monegrillo structure.
         - Andorra-Monegrillo 2-D seismic survey.
         - Duero site 2-D/3-D seismic survey.
         - Duero site wells.
         - Andorra-Monegrillo site wells.
      2. Requested the authorizations to execute civil works at the well sites from the Administration, for 5 projects at Duero and 4 at Monegrillo.
      3. Contracts signed with the landowners to rent the well sites and obtain necessary permits from the local administration.
      4. Drilling the wells at the Duero and Monegrillo sites. Data acquisition.

a. Leakoff tests (LOT) were performed. Extended LOT (ELOT) were carried out for cap rocks.
b. Extensive wireline logging suites.
c. Borehole cores were taken from each target formations (caprock and reservoir).
d. Well tests – slug-tests and injectivity tests were carried out -.
e. Water samples were taken and several analysis were undertaken to estimate total salinity and other parameters,
f. Conventional coring, special coring, specific core flood tests and mechanical analysis were undertaken to determine porosity, permeability, mineral matter and relative permeability,
g. Specific geomechanical tests were undertaken to test the suitability of the sandstone as a storage reservoir and test the caprock for long term CO_2 containment,
h. Formation Damage Study (FDS) was performed to evaluate the risk of potential damage near the injection wellbore and the water monitoring wells,

5. Monegrillo 2-D seismic survey: data acquisition, processing and interpretation.
6. Duero site 2-D/3-D seismic: data processing and interpretation.
7. A technical study was undertaken to check whether it would be feasible to replace the oil-drilling rig by a mining drilling rig: the study concluded that the SD-2 well could be drilled with a mining rig based on the SDE-3 (deep water well for controlling the boundary of the storage complex) experience. Changing drilling rig reduced costs close to 5 M€. All tools came from mining. The experience was satisfactory.

II. Reservoir Performance.

1. The hydrogeological model of the Mesozoic was upgraded (for both the Duero and the Monegrillo sites).
2. New faults analysis and interpretation for both sites.
3. New up-grading of the geological and hydrogeological models
   a. Detailed Characterisation of waters from the Tertiary formations.
   b. Detailed Characterisation of waters from the Utrillas formation. No connection between Utrillas and the other formations.
   c. Utrillas and Garumn waters characterization. Base-line definition.
   d. Development of the Utrillas flow and salinity models. Justification of saline reservoir.
4. Hydrogeological monitoring plan for the Tertiary and Mesozoic formations.
5. Up-grading of the static model, integrating all gathered data.
6. Chemical reaction model based on geochemical data.
7. Mechanical models and coupled processes.
8. Final dynamic model for the Duero Site.
9. Study to determine the presence and condition of natural and man-made flow-paths, such as wells or boreholes which could provide leakage pathways.
10. Study to determine the areas that could potentially be affected by the storage of CO_2.

III. Above-surface Performance.

1. Population distribution in the region overlying the storage site;
2. Study and analysis of valuable natural resources, including in particular Natura 2000 areas (Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds

and Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, potable groundwater and hydrocarbons).

3. Study of the existing activities around the storage complex and possible interactions with these activities.
4. Study of the potential sources of CO_2 and of adequate transport networks.

IV. Base Line.

1. Base line for CO_2 flux at soils.
2. Base Line for surface waters, vadose zone and skin deep aquifers. Deep water baseline was established taking water samples from the appraisal wells.
3. Base-line for atmosphere.
4. Base-line for crops and ecosystems.
5. Red-Nature 2000 study
6. Interferometric synthetic aperture radar (InSAR) images were acquired to generate reference maps of digital elevation.

During this phase of the project, no results were obtained that could have led to the cancellation of the project. As such, ENDESA decided to proceed to the next step.

3) Extensive Subsurface Characterization

The main activities during this phase can be summarised as:

I. Reservoir performance of the Duero site.

a. Capacity.
b. Injectivity & strategies.
c. Containments, cap-rock, seal. Natural and man-made pathways.
d. Base case for 1.47 Mt CO_2/year.
e. Worst Case for 1.47 Mt CO_2/year. Several scenarios were simulated to establish a base case and worst case. The results of the worst case scenario were used for the risk analysis.
f. Plume migration and its maximum extension.
g. Injection strategies definition: WHP (well head pressure), WHT (wellhead temperature), WHTP (well heat temperature & pressure) for base case and worst case.
h. Mono- and Multi-parametric uncertainty analyses were undertaken. The worst results were introduced into the risk analysis model.
i. Definition of the storage complex, the location of storage site and potential flowpaths (natural & human-induced).
j. Characterization and assessment of the potential storage complex and surrounding area as referred to in Article 11 40/2010 of the CO_2 Store Act.
k. Selection of the injection strategy and selection of the injection well location.

II. Risk Analysis.

1. Risk analysis and management. HAZID and HAZOP.
2. Monitoring plan definition, following the risk management requirement. Methodologies used: IEA, DOE and DNV.

3. Characterization and assessment of the potential storage complex and surrounding area as referred to in Article 11 40/2010 of the CO_2 Store Act.
4. Monitoring plan feasibility study.
5. Monitoring techniques selection.

This work is now complete and a monitoring risk and management plan has been defined. The risk assessment follows the following guidelines and recommendations:

- The IEAGHG review, ‘A review of the international state of the art of risk assessment guidelines and proposed terminology for use in CO_2 geological storage’,
- The European Guidelines, ‘implementation of Directive 2009/31/EC on geological storage of carbon dioxide’,
- The NETL references, ‘United States Department of Energy National Energy Technology Laboratory – Monitoring, Verification and Accounting of CO_2 stored in deep geological formations’,
- The Quintessa, ‘FEP Database for the assessment of long term performance and safety of the geological storage of CO_2 – QRS- 1060A-1’.

The extensive characterization phase produced satisfactory results. No results challenged the established feasibility criteria. As such, ENDESA decided to go ahead with the FEED Phase.

To conclude, the so called “CCS” Directive 2009/31 EC has been transposed and investigation (exploration) permits have been issued by the 40/2010 Act to ENDESA.

The project is currently consolidating its storage economic and risk assessment. The conclusions will be used to take a final investment decision (FID) in Q4 2013. Compared to the update given in October 2012, the feasibility study was completed as well as the work related to the appraisal wells. A long term monitoring plan has been prepared. The FEED is now in good progress.

2.3 Compostilla – Hontomín

The technology development project associated to Compostilla is making progress building the infrastructures at the Hontomín injection and storage test site which is expected to be operative in September/October 2013.

- Civil works are advancing: the injection gas plant contract has been awarded and the bidding for the water treatment facilities is in progress.
- The drilling of the wells started in March 2013, currently reaching approximately 1000m depth (May 2013) for the injection well. The wells should be completed in August/September 2013.
- The comprehensive monitoring of the wells includes the installations of:
    - Electrical resistivity tomography (ERT) electrodes,
    - Formation fluid pressure and temperature (P & T° of injection),
    - Fluid sampling from the injection level (U-tube system),
    - Permanent fibre optical system for temperature measurement,
    - Retrievable array of hydrophones,
    - Pumping system (Electric submersible pump (ESP) or similar).
- The characterisation and establishment of a monitoring baseline at Hontomín was completed and includes:
    - Magnetotellurics survey,
    - Gravimetry investigation,

- High resolution 3D seismic survey,
- A micro-seismic network with 30 stations,
- Gases Flow measurements,
- Displacement measurements from satellite: The project implemented both satellite DInSAR (to obtain high-resolution images with Terrasar-X satellite), and terrestrial SAR (GB-SAR) (a SAR sensor setup using a terrestrial platform),
- Arrays of 60 electrodes are installed at a depth of 1.5 to 1 m below ground surface using controlled source, pre-existing well casing and deep source in H-I (injection well).

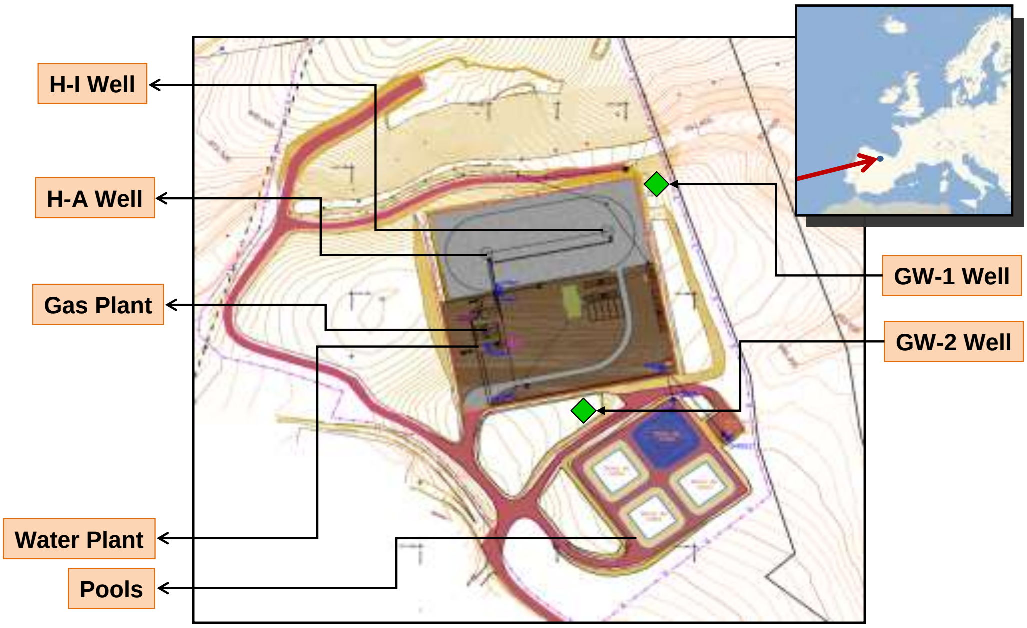


Fig 2.3.1 Aerial view of the TDP (technology development plant).

Compared to the October update, the project has now completed its feasibility study and is drilling its injection well. The FEED was completed and the long term monitoring plan is in progress. Since this is Compostilla's RTD pilot, it will inject less than 100,000 tonnes of CO_2 and does not require a storage licence.

2.4 Don Valley Power Project– Saline Formation

The project is making good progress and has reached several key milestones:

- The offshore carbon storage licence drilling application was granted by the Department of Energy and Climate Change (DECC) in November 2012; the commitment to drill is established,
- An agreement for lease was signed with the Crown Estate in February 2013. The project has exclusivity over the 5/42 region in the Southern North Sea,
- Appraisal drill consenting – the standard offshore UKCS regime applies, e.g. Petroleum Operations Notices (PONs) and DECC oversight,
- EEPR storage milestone: 5/42 saline aquifer selected as the sole storage solution for the Don Valley project.

Appraisal Drilling Programme[1]:

- ADTI is to provide comprehensive project management services for the appraisal drilling programme,
- The 'Energy Endeavour' rig is scheduled to be towed to the target site imminently (May 2013),
- The well will be drilled to a total depth of approximately 1,600 metres,
- Core samples will be taken for analysis and the injection and production capabilities will be tested,
- Culmination of nearly 3 years of work to reach this significant project milestone.

Post-Appraisal Drill Analysis:

- Conventional Core Analysis will be undertaken to evaluate reservoir porosity and permeability,
- Special Core Analysis will be undertaken using experimental protocols for analytical work including relative permeability determination and other specific core flood tests,
- Geomechanical Study: Test the suitability of the sandstone as a storage reservoir and test of the cap rock for long term CO_2 containment,
- Sanding Study: Assess issues related to sanding in the future injection and production wells,
- Formation Damage Study: Investigate the potential damage risk in near well bore region of the injection and water production wells,
- Water Sample Analysis: Assess the formation water chemistry from at least 3 samples taken from different depths,
- Sedimentology & Petrography: Production of core log with lithological, sedimentary facies and trace fossil descriptions to support the analysis of the acquired image logs,
- Chemostratigraphy: Analysis to generate zonation that is consistent with the existing semi-regional correlation scheme, highlighting any new correlations in the mineral assemblages.

The post-appraisal analysis should take 9-12 months, thus until mid-2014, and should improve the reservoir and caprock data at location for better characterisation of both and better depth correlation. The storage site is a deep very large anticline where no pressure management should be necessary for the expected Don Valley CO_2 flow rates.

Compared to the October update, this project has now completed its feasibility study. It has applied for and been awarded a storage licence.

2.5 Don Valley – CO_2 EOR

[1] Post Meeting Note: The appraisal programme was successfully concluded at the end of July 2013 with all coring, well logging and well testing objectives achieved.

The project was not selected in the UK CCS Competition (31 October 2012) and therefore not confirmed for NER300 funds. The project sponsors are currently evaluating options to re-structure the value chain, with reduced capital, before taking a FID.

The first storage option would be the Southern North Sea 5/42 site (site led by National Grid described here above in 2.4), where development continues.

The Central North Sea CO_2 EOR feasibility study was completed in December, but further development of that option is suspended. 2Co Energy continues to assess North Sea options for CO_2 EOR development in the future.

Development Concept:

- The initial target was a large oil field in Central North Sea (UK sector) sufficient for ~100 Mt storage,
- Very large oil column and high dip - initially thought feasible only for slow gravity drainage EOR,
- The project considered concurrent development of smaller neighbouring field with likely faster EOR response (better economics),
- It investigated a wide range of development concepts with one or both fields,
- It progressed the initial feasibility studies in both fields,
- Reservoir engineering indicated CO_2 EOR in larger field would be economic, so later studies focussed on it alone (for the initial development).

The EOR Studies consisted of:

Laboratory

- PVT and slim tube displacements for 2 oils with CO_2, including minimum miscibility pressures,
- CO_2-CH_4-H_2O hydrate stability for flow assurance,
- CO_2-brine interfacial tension at reservoir P,T° for geological integrity,
- Rock-fluid interactions at reservoir P,T° for formation damage.

Reservoir Engineering

- Thermodynamic equation of state (EOS) for hydrocarbons and CO_2 (tuned to new lab data),
- Finely gridded sector simulation models for reservoir mechanisms,
- 2011 compositional full field models (FFMs) (Eclipse 300),
- 2012 finely gridded FFM (Eclipse 300) with new static model (Petrel),
- Improved computing performance for very large simulation models.

Geological Integrity

- Seismic re-processing and re-interpretation,
- Identification of potential leakage pathways and risk assessment,
- 4D seismic feasibility study,
- Monitoring strategy.

Wells

- Integrity assessment of each existing well,
- Flow assurance for CO_2 injection and production,
- Basis of Design for injectors and producers,
- Initial assessment of drilling rig upgrades,
- Cost and scheduling.

Facilities

- Development concepts with 1 or 2 fields,
- CO_2 injection and availability,
- Gas handling – capacity, compression, dehydration, fuel separation, NGL recovery,
- Inherently safe design and venting of CO_2-rich gas,
- Benchmarking of process simulation with $CO_{2,}$
- Subsea approaches, risers and bridge landings,
- Facility Basis of Design,
- Greenfield and brownfield engineering scopes,
- Cost, schedule and contracting strategy.

General

- Integrated schedule and project economics.

Key Findings:

- High CO_2 injection rates are limited only by well size,
- No significant issues identified with CO_2 injection and production flow assurance,
- Import CO_2 injection availability >99% is achievable,
- Import CO_2 injection backup with spare well(s) and/or temporary reduction of gas recycle (in later years),
- Cr alloys probably preferable to produced gas dehydration,
- Storage capacity and reservoir pressure principally managed by water production (with or without oil),
- In this case, gravity drainage yields economic production profiles,
- Greater recycle capacity yields more oil, even >800 mmscfd (millions standard cubic feet per day; equivalent to 22.6 million cubic meters per day),
- Measured CO_2 MMPs (minimum miscibility pressure) significantly better than predicted from standard correlations,
- Economic oil recovery with continuous CO_2 injection (no WAG (water alternating gas)),
- In this case, finer reservoir simulation gridding did not yield significantly different results,
- Parallel machines and code improved computing performance,
- Uncertainty about well integrity status is an important driver of project schedule and cost,
- Offshore CO_2 EOR is economic over a wide range of scenarios,
- Commercial returns for first-of-a-kind (FOAK) project likely require (tax) incentives,
- Investment returns depend strongly on specific tax and decommissioning positions.

Concluding Remarks:

- CO_2 EOR and storage in the North Sea is technically and economically feasible,
- EOR offers inherently lower net storage costs and risks:
  - reduced (or no) appraisal cost
  - oil revenue,
  - existing infrastructure,
  - long-term dynamic reservoir characterisation.
- Offshore EOR is likely to require a large CO_2 supply (~4 Mtpa) and incentives to achieve commercial returns,
- CO_2 EOR deployment in the North Sea will be driven by CCS,
- Demonstration-scale CCS projects will have to rely on alternative storage with higher net unit costs.

To conclude compared to the October update, the project has completed its feasibility study. The acquisition of data to establish a monitoring baseline are now non-applicable considering the changes in the project timelines because of funding.

2.6 Porto Tolle

The project gave the group an update, starting with the status of its permit. Once the permit is granted, the project can proceed with the authorities.

Power Plant

> Since May 2011, the overall progress of the conversion to coal firing of Porto Tolle power plant has been affected by the Decision of the State Council that voided the Environmental Authorization (EIA).
>
> The Environmental Ministry required a new Environmental Impact Assessment to be issued.
>
> Due to the issues related to the Porto Tolle Power Plant permit, the CCS project is affected by significant delays and the schedule of the overall project is under assessment.
>
> Consequently the NER300 requirement to be in operation by 2016 cannot be met and no proposal was submitted.

CO_2 Offshore Storage

> The documentation for the request of an Exploration permit, including the drilling of an appraisal well, was arranged as well as the Environmental Impact Assessment, although the technical decrees of the Storage Regulation are not still implemented. As will be detailed in the session on baseline monitoring, the project has installed a permanent OBC (ocean bottom cable) array. No brine production will be necessary to manage pressure. No interferences with potable water or oil production activities in the area (30 km from the selected site).

Design of the Monitoring Plan

Rock and fluid physical properties studies constitute the bases to understand the sensitivity of the seismic properties to small variations in the fluid content within the rock. Moreover, they are the bases for the numerical modelling, aimed to calculate synthetic seismograms. From the tomographic analysis of them, it is possible to test the feasibility of monitoring CO_2 storage.

To conclude, compared to the update in October 2012, the baseline surveys have been completed.

2.7 ROAD

The project started with a description of the infrastructures.

The project will inject CO_2 into a depleted gas reservoir using the P18A platform. Other reservoirs are still producing natural gas through the same platform. Continuing storage beyond 2020 in other reservoirs is possible.

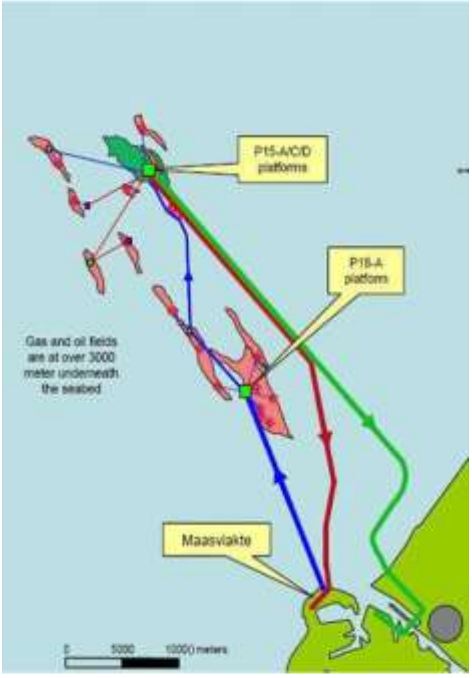


Fig 2.7.1 P18-A platform location and subjacent field

The Offshore Platform:

> The Platform P18-A dates of the early 1990s. P18-A is a six-slot well protector platform with a four leg jacket configuration. It is a Normally Unattended Installation (NUI) that is controlled from field P15.
> The platform currently produces gas from 3 reservoirs, with transportation of wet gas to P15-D for further processing and transport to shore.
> The reservoirs are depleting and the P18-4A2 well should be available for work-over to adapt to CO_2 injection in 2016.

History of P18-4A2 well:

> The well came on stream in 1993 and reaches a depth of 4352 metres (true vertical depth 3303 metres), producing natural gas, with no indications of any major well degradation. However, no existing well logs could be found to check cement integrity or corrosion. Mud losses occurred over a 9,5/8 inch casing section, which may indicate a poor cement bonding. There are no problems with the 7 inch liner.

Well integrity study:

> The Well Engineering Partners (WEP) conducted the well integrity study which consisted of:
>
> > High level abandonment programmes,
> > Detailed work-over & abandonment design,
> > Overview of current legislation and standards,
> > Overview of logging and monitoring tools.
>
> No cement bond logging (CBL) was performed in the existing wells, but the cementing reports indicated the completions are suitable for this project.

Reservoir:

> Static and dynamic models were created,
> Geochemical analyses were completed,
> Wells were reviewed (although high level compared to WEP),
> Seals were analysed.

Transport and Storage permit:

All previous work contributed to the permit applications.

TAQA / ROAD were the first to apply for a CO_2 storage permit after implementation of the geological storage of carbon dioxide directive 2009/31/EC under Dutch Law. The application included:

- Permit application,
- Monitoring plan,
- Risk mitigation plan,
- Corrective measures plan,
- Abandonment plan,

The competent authority is finalising the permits for publication in the `Staatscourant´ (the official Dutch State journal publishing the new laws and various governmental announcements).

Conclusions:

The P18-4 reservoir has good injection and storage characteristics.
The objective is to inject 7 Mt of CO_2, for which there should be sufficient capacity (reservoir capacity of 8 Mt).
With only one well and no abandoned wells the risk of leakage can only occur via the well.
The fault between field P18-4 and field P15-9 is sealing and further analysis could even show there is no juxtaposition.
At present the start date should be 2016.

The project status is unchanged as compared to the October update.

2.8 Sleipner

The project started with an overview. The project is developed by Statoil with ExxonMobil and Total as partners. In operations since October 1996, the project captures the CO_2 from a gas processing plant with conventional amine capture. A short flow line delivers the CO_2 to a deep saline formation (or aquifer) offshore where over 14 Mt of CO_2 have been stored to date (0.9 Mtpa, Dec 2012/Jan 2013).

(Apart from minor operational fluctuations, the main reason for annual changes in injection is the gradually declining CO_2 content of the produced gas. Maximum annual mass of CO_2 captured was 1.014 Mt in 2001, declining to 0.849 Mt in 2012.)

Fig 2.8.1 Aerial view of the Sleipner platform

A continuous monitoring programme is in place, consisting of Controlled Source Electromagnetic (CSEM), gravity and seismic surveys as well as seafloor mapping. To date 8 repeat 3D seismic surveys have taken place. Since the site is a pioneering project receiving a great deal of scientific and public attention it was felt that this monitoring programme was needed.

To date over 14 Mt of CO_2 have been injected and 4 Mt more are to be injected from the current field (98% CO_2, 2% methane and traces of C2-C5 natural gas hydrocarbons).

To conclude, operations continue with demonstration of safe storage for seventeen years now. The project is also taking part in a number of R&D projects, sharing data with the scientific community.

2.9 Concluding remarks

While the Bełchatów project ceased activities, and ROAD is on hold while working on getting sufficient funding, other projects have been making good progress, despite reorganisations due to financial constraints like Don Valley and Hontomín.

The progress of Don Valley 'Saline Formation' is very promising as well as the progress of Compostilla, which is now the only remaining onshore project in Europe. The participation of Statoil ASA, sharing its experiences and lessons learned from Sleipner but also from Snøhvit is of great value to the Network.

3 Thematic session: Flow assurance and designing a long term injection operation

It was decided to combine the 'designing a long term injection operation' session with the transport thematic group session 'flow assurance'.

This session started with a few presentations to illustrate the various cases, i.e. on designing a high pressure injection system (Don Valley EOR) and a low pressure system (ROAD), then on how to develop injection strategies including the modelling of liquid versus super critical CO_2 injection. The discussions during this combined session developed transversal synergies.

3.1 Design of a dense phase CO_2 injection system *(Don Valley EOR)*

In this session the main design aims and metrics of the Don Valley project's transport and storage system were presented.

In the case of the Don Valley CO_2 injection project with EOR, the aim is to limit the CO_2 export pressure to 250 bars and 15°C. With such a design pressure and transport over a 335-360 km long pipeline, the tail-end CO_2 pressure can still be at 100 bars at a temperature of 4 to 7°C (approaching the sea-bed temperature) without requiring any pressure boost between shore and the offshore platform.
The project performance priorities require being able to inject 155 kg s^{-1} (250 mmscfd, million standard cubic feet per day) of fresh CO_2 plus 245 – 490 kg s^{-1} (400-800 mmscfd) of recycle gas and maintaining the CO_2 in dense phase for efficiency. Dense phase allows use of pumps, which are more reliable and cheaper than compressors. The project would re-use existing well slots.

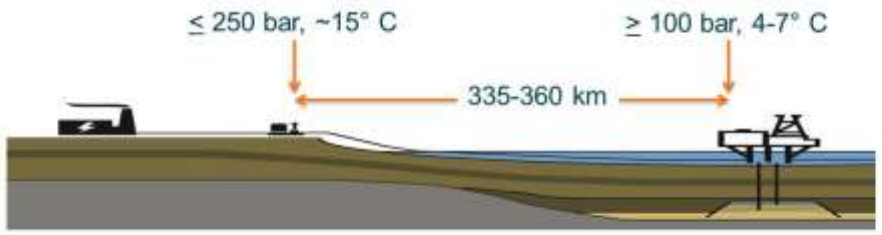


Fig 3.1.1 Cross-section showing the onshore facilities, the pipeline and the offshore facilities.

Considering that the project has to re-use existing wells, that the CO_2 has to be in dense phase, the well injection rates will be limited by the tubing. But since the reservoir has a high permeability and the CO_2 is in a low viscosity and high density state, very high injectivity can be achieved.

The EOR design requires using 6 to 12 injectors for best distribution in the reservoir, optimizing recovery of oil through 9 to 25 producing wells. Taking into account injection well capacity, the requirement came to 2 injectors to inject 'fresh' (imported) CO_2 and 3 to 6 injectors to inject 'recycle' CO_2. At the platform the 'fresh' CO_2 and 'recycle' CO_2 (with CH_4) extracted from the production stream can be co-mingled to cool the 'recycle 'CO_2 or when less 'fresh' CO_2 may be required.
The maximum number of wells used for the EOR operation will amount to 27.

One of the key questions the project faced is whether to dehydrate the CO_2-rich produced gas. Modelling and experimental hydrate formation temperatures and pressures of various CO_2-CH_4 mixtures saturated with CO_2 were examined. As well the project had to take into account that in transient conditions, typically when turning wells on and off, this could produce hydrates. The modelling indicated that there is potential for CO_2-CH_4-H_20 hydrates to form at low temperatures and high pressures in injection flow lines or wellheads. The experimental data however indicated that no hydrates will form in the operating range but the temperature margin is small. To address this, the project has incorporated temperature control in the facility design.

Corrosion is another issue that may arise – once past the wellhead, the water content of the CO_2 flux could be higher than in the pipeline because of the use of 'recycle' CO_2 and gas split from the produced oil. Options to mitigate this include use of chemicals to avoid corrosion. However, it is preferred to use Cr alloys which are corrosion resistant. This requires less maintenance and no dehydration units are required on the platform to process the CO_2 produced with the oil, which saves space and processing.

Other aspects to consider include the fact that the produced oil may contain an allowable amount of (0.5%) dissolved CO_2. As well with IGCC capture, there is a risk coming from small amounts of hydrogen in the captured CO_2 stream, that may induce metal embrittlement that must be considered carefully.

An important aspect of the project design was that the offshore oil field would be able to accept *all* CO_2 from the power plant (about 5 Mtpa) with no need for back-up or parallel storage in, for example, a saline formation. The CO_2 injection system has been designed so that 99.5% of the time, the capacity to inject is there.
This availability was reached by minimizing the risk of shut-down by providing independent power source to injection installations) as well as using a sufficient number of injectors (and back-up injectors).
It would be possible to have the same availability with WAG. The main driver for not using WAG is that it takes up storage space. No firm conclusion has been reached yet on whether to use WAG or not.

The injection system availability is high and only depends on riser, pumps and wells. The offshore production system (separation, oil and water treatment and gas recycle facilities) is, however, more complex and will have a lower availability than the injection system. Power plants shut down for maintenance and offshore injection shut down will need to be synchronized.

To conclude, the injection of 5 Mtpa of CO_2 using EOR for storage is technically feasible. In this case, the injection well capacity is limited by the well size, but high injection availability can be achieved at modest cost by using redundant wells and pumps with a tailored power configuration. Potential hydrate formation in (wet) produced gas systems can be controlled by simple measures to maintain temperature. Risks of unscheduled whole-platform shutdowns are similar to any offshore installation.

3.2 Flow Assurance Study: Operational procedures and phase behaviour for CO_2 transport pipeline *(ROAD)*

A flow assurance study of the ROAD project was presented.

In the case of the ROAD project, the injection of CO_2 is to occur in a depleting gas field, the aim is to limit the CO_2 export pressure to 129 bars, transport the CO_2 via 5 km of onshore pipeline and 20 km of offshore pipeline to the unmanned platform P18-A accessing reservoir P18-4.

Arriving at the platform the CO_2 could be at a temperature of -10°C , meaning that there is potential for hydrate formation. Glycol injection is possible or increasing the temperature to avoid hydrates.

The well has a length of 4200m and reaches the depth of 3300m with a bottom hole pressure range between 20 and 300 bar and a temperature above 15 °C. The offshore storage is designed to inject the CO_2 at subcritical pressure at the outset of 20-30 bar in a closed depleted reservoir.
One of the objectives of the injection system design was to avoid having to heat the CO_2 and thus the 16 inch 25 km long pipeline is insulated. If heating is needed, an electric cable will be required from shore to operate an electric heat exchanger at the wellhead. The maximum pressure is 129 bar,

and the normal operation range is 40-85-129 bar depending on the back-pressure which will gradually increase as CO_2 is injected into the reservoir.

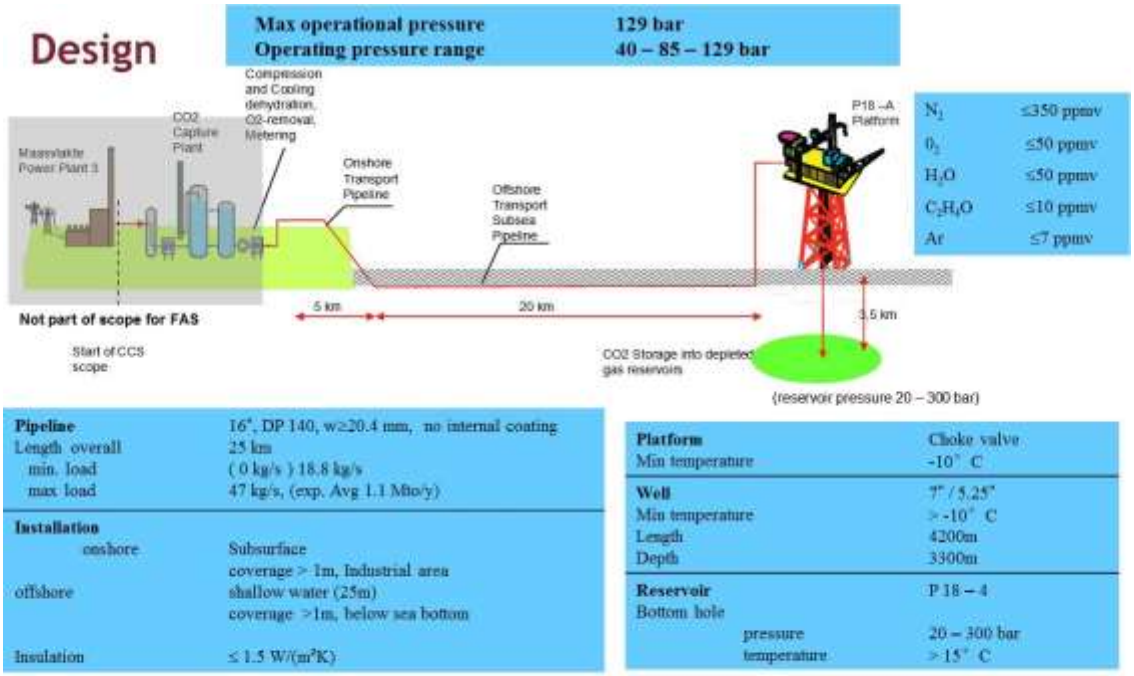


Fig 3.2.1 CO_2 system design from export to well.

The pipeline design has to take into account restarting after either a short process interruption (without phase change of CO_2 in the pipeline) or a long process interruption (with phase change of CO_2 in the pipeline). Flow rate is constrained by the diameter of the pipeline.

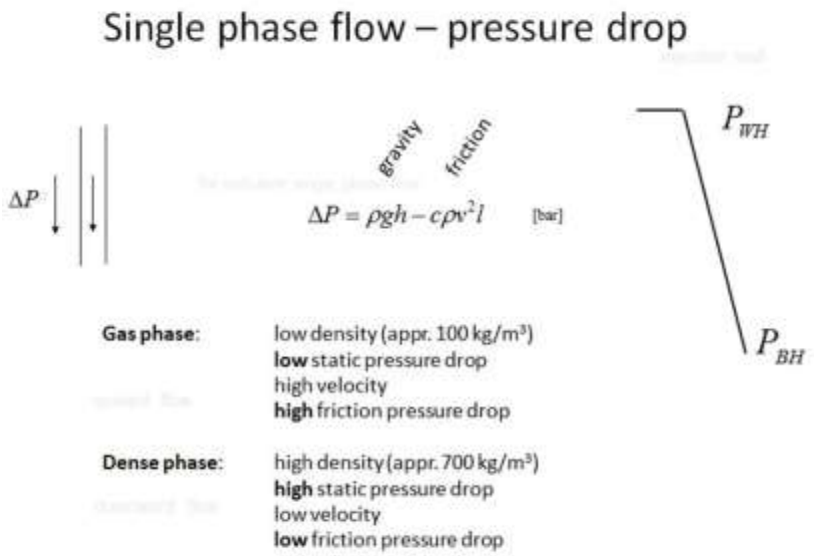
Several start-up scenarios have been considered; one scenario is to pressurize the pipeline to reach a single phase and then start injecting CO_2 slowly opening the valve at the platform. Heating up before any shut-down should prolong the stable phase conditions compared to additional pressurizing.

A start-up procedure with a closed pipeline at the platform would comprise:

- A compressor that injects CO_2 into the pipeline, increasing mass flow to full load,
- Pressurizing and heating up of the CO_2 in the pipeline,
- Reaching dense phase in the pipeline, open the valve at the platform to start the injection of CO_2.

This start up option pressurizing the pipeline with a closed valve at the platform then opening the valve once single dense phase conditions are reached, is one option, but there are alternatives. This option will generate high velocities and might cause vibration of the well piping.
As such, a preferred scenario is to open the platform valve as soon as the pipeline pressure reaches a pressure above the well head pressure, thus causing a lower flow rate and lower velocities.

Single Phase flow-pressure drop:



Before a planned shut-down, the pipeline content is heated by the compressor flow and at shutdown the compressor discharge valve is closed and the pipeline is emptied into the well. By doing this the pipeline will cool-down (in the early phase of operation, low reservoir pressures) almost without liquid formation and with no harm by slugging. Under such conditions slugs reaching the platform are controllable. When slugging is over, the flow will be reset to the normal operating values.

Future simulations of the start-up modes should confirm their feasibility.

3.3 Injection strategies; liquid vs. super-critical CO_2 injection *(Compostilla-Hontomín)*

A study was presented by Compostilla on injecting CO_2 in either liquid or supercritical conditions, for testing at the Hontomín site.

Injecting the CO_2 in liquid phase implies that the CO_2 is at a lower temperature, compared to injection conditions for CO_2 in the super-critical phase. Due to the higher density of liquid CO_2, lower injection pressures are needed (for storage in saline formations). This may be of interest to other projects, as the energy requirements for injecting liquid CO_2 are much lower than for gas or supercritical.

Once injected and reaching the aquifer or reservoir level, the relatively low temperature of the injected liquid causes some thermal stresses in the reservoir and cap rock. Analysis shows that, except for a reservoir in a compressive regional stress field, the effect of the thermal stress is to increase the injectivity of the CO_2 in the reservoir, while improving the stability of the cap rock. Under compressive stress conditions, an analysis of cap rock stability should be performed (cap rock thickness becomes more important).
The temperature of the CO_2 in the reservoir increases rapidly after injection and the CO_2 reaches a super-critical state.

To conclude, the modelling showed that it appears that injecting liquid CO_2 is better than injecting gas or supercritical CO_2:

- Injecting liquid CO_2 appears to be easier (no need for compressors or complex surface operations),
- It is cheaper (much lower wellhead pressure, one may recover energy, depending on transport conditions),
- It is safer (improved caprock tightness and reservoir injectivity) under normal stress conditions (but not under compressive conditions),
- It does not affect large scale behaviour (CO_2 becomes supercritical in the reservoir soon after injection),
- Additional work (and courage!) needed to make it industrially operative.

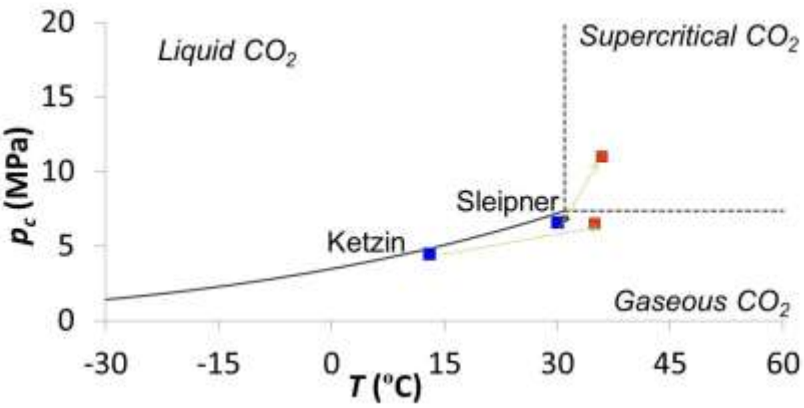


Fig 3.3.1 Conditions for the Ketzin and Sleipner projects, reported on a Temperature-Pressure graph. Blue indicates the conditions at the well head; Red the conditions in the reservoir.

The project looked into the concept of injecting cold, liquid CO_2 to reduce buoyancy resistance:

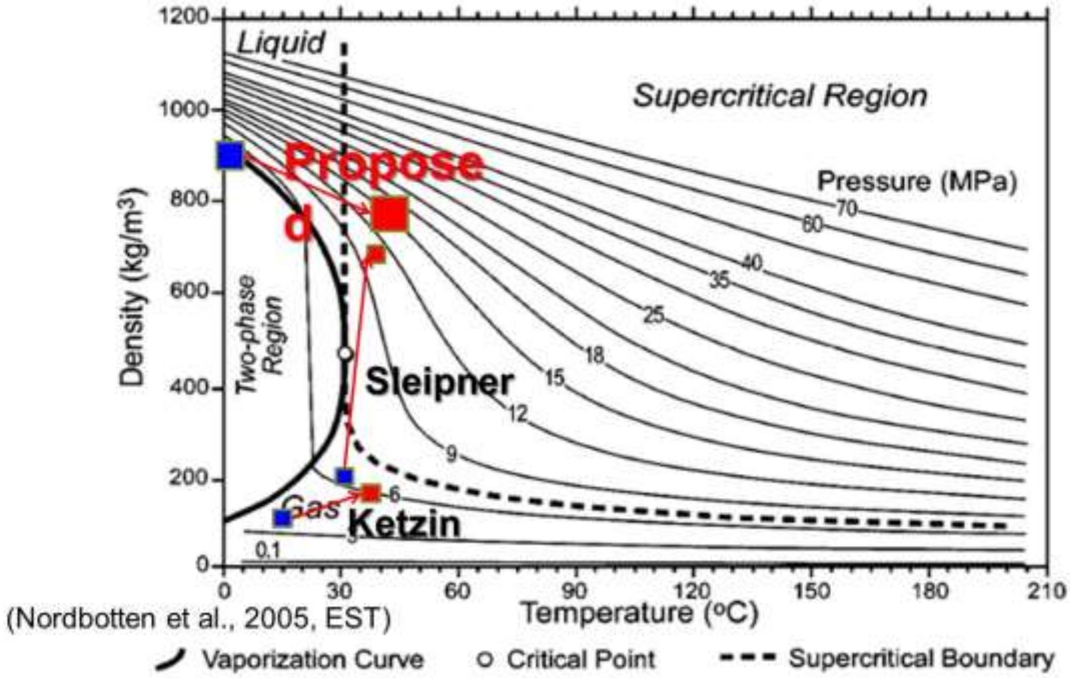


Fig 3.3.2 Shows proposed injection conditions for the Hontomin site, in blue the conditions at the wellhead and in red the conditions in the reservoir injecting cold liquid CO_2 (For reference Ketzin injecting gas and Sleipner injecting SC)

Temperature, pressure and density along the well:

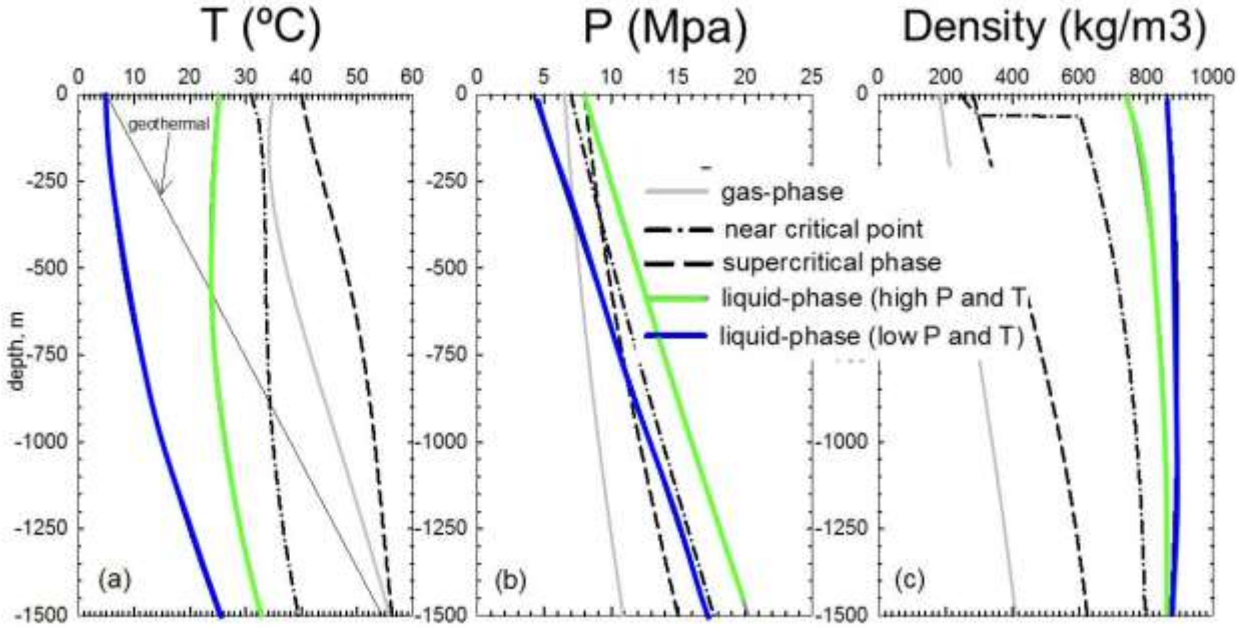


Fig 3.3.3 Temperature, pressure and density along the well, showing CO_2 behaviour in different states

The project then compared the energy consumption for each state.

3.4 Injection strategy, Compostilla Phase I *(Compostilla)*

The Compostilla project also presented its injection strategy for the commercial site.

The saline formation is an open reservoir that can take large amounts of CO_2 without pressure build-up. Hence, it is not required to produce water from the formation.

The Engineering results show that 3 wells are sufficient to inject 1.4 Mt/year. The required injection pressure is significantly lower than the maximum allowable limit.

The injection stream composition should consist of 95.49 % of CO_2 (in mole fraction), and 4.51% of impurities. Various simulations were run to test the CO2 behaviour and response:

- Shut-in
    - During shut-in, the CO_2 mixture at upper sections of the wellbore starts to evaporate as the result of the pressure drop after shut-in. However, as the fluid gets gradually warmed up with depth, reaching the geothermal gradient temperature, the fluid density decreases and the pressure at the upper sections of well increases, which makes the gas phase CO_2 mixture condensate and moves the gas-liquid interface upwards.
    - It takes a long time for the wellbore and fluid to reach equilibrium with the surrounding rocks as it is mainly a thermal process from outside of the wellbore and a large mass of surrounding rocks gets cooled down during the steady state operation.
- Restart

- During the restart most of the changes in pressure, temperature, phase distribution and fluid properties in the wellbore occur in the first few hours (from 12 hours to 7 days after the restart). The temperature in the wellbore is the only property that shows a slight further decrease, the other fluid properties only show minor changes.
- The bottomhole temperature drops rapidly in the first 5 hours, as the cold CO_2 moves down from the upper sections, then it gradually decreases to reach steady state levels.
- The injection well pressure increases to a peak pressure and then gradually drops as the fluid cools down the well. However this pressure peak does not seem to be significantly high and appears to be much lower than the pipeline arrival pressure, and hence it may not pose a significant operational risk.

3.5 Discussion outcomes and conclusions

During the discussion, Porto Tolle mentioned that Cr alloys for the liner have been identified for their project to avoid corrosion. The CO_2 stream includes traces of oxygen and will be injected in a reservoir with high salinity values.

One of the key challenges raised by the projects is the availability of the CO_2 from the source. It is necessary to think 'entire CCS system' and not just 'injection operations at the storage site' since CO_2 availability will have a significant impact on the design and the costs. It is important to increase the whole system availability.

Composition of the CO_2 stream is very important as it constrains the entire chain. The design start point should be the well, working back to the Power Plant and capture system to specify the CO_2 stream composition and specify the stream availability.

Possible topics to further develop:

- Good reference material on CO_2 streams was produced (European Framework Programme 6) but it seems that well engineers do not agree with some of the values like the oxygen values. It may be worth using this document as a basis of discussion. A point of discussion could be how to reduce the level of oxygen before it reaches the injection facilities. Another point of discussion could be how to adjust pressure/ reducing the pressure drop; use a catalyser to adjust the injection pressure to the reservoir pressure?
- Transient flow is another topic of discussion to consider but it was unclear what should be said about it.

3.6 Details and data regarding CO_2 composition, injection and wells per project

See table in Appendix, at the end of this document.

4 Thematic session: baseline monitoring

This session was shorter than the previous session but was introduced to prepare for a follow-up session in October 2013.

Like the previous session, it consisted of a few selected presentations to illustrate some of the key aspects of baseline monitoring and was followed by a discussion.

4.1 Hydrogeological Monitoring for CO_2 storage in Hontomín (*Compostilla*)

The hydrogeological monitoring network of Hontomín Technological Development Plant (TDP) consists of eight control points; five are legacy wells and three are new shallow boreholes drilled in 2012, including a full logging suite (resistivity, SP, GR, T°, P, S wave velocity, electrical resistivity, clay content, etc.).

Two vertical wells 50m apart were drilled last year. GW-3 to the south will monitor any possible leak on a known shallow fault to the south of the TDP. Interference tests will be carried out between the wells Pumping test will be carried at GW-3.

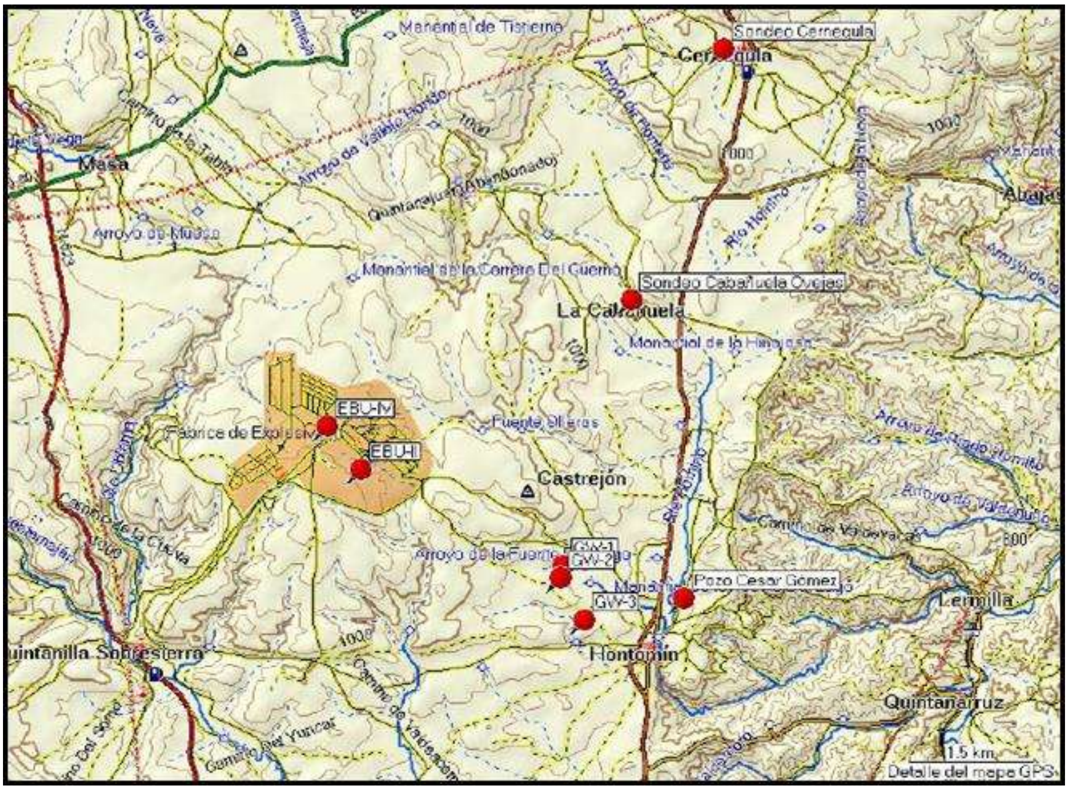


Fig 4.1.1 Map showing the location of the 8 wells.

The objectives of the monitoring are as follows:

- Control the state of the groundwater in the aquifers located above the targeted reservoir and seal complex for CO_2 storage (baseline prior to injection, then during the operational life time and post closure)
- Evaluation of the H-I (injection well at the TDP) and H-A (plume observation well at the TDP) well drilling effects on the superficial aquifers. These wells reach a depth of 1550m and are 50m apart.
- Determination of groundwater piezometry and chemical quality (prior and if potential CO_2 leakage).
- Hydrogeological and hydrochemical monitoring of the CO_2 migration.

Well Testing:

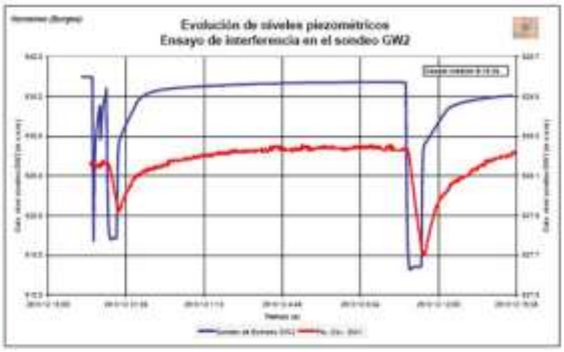
Once the well logging and the petrophysical interpretation were done, the project team worked on defining the hydraulic parameters (permeability, storage coefficient, etc.) of the Utrillas Fm. aquifers carrying out some tests. Hydraulic testing included:

- Interference tests between wells, including some of the legacy wells,
- Constant flow-rate pumping test in GW-3,
- Constant flow-rate pumping tests in the other wells of the network.

Test interpretation through graphical and numerical methods. Hydraulic parameter calculation used the EPHEBO code.

A summary of the tests represented in the below figures.

Ensayo	Pozo	Método de interpretación	Transmisividad		Permeabilidad		Coef. de almacenamiento
			m^2/s	$m^2/día$	m/s	m/día	
Aforo Parffarsa sondeos Maxam	EBU II	Theis	2.5E-3	216.0	9.6E-6	0.844	1.0E-3
Ensayo de interferencia sondeos Maxam	EBU IV	Theis	2.7E-3	233.3	1.1E-5	0.933	6.0E-5
1º Ensayo interferencia de Cañafuelas	Ovejas	Horner	6.1E-4	52.7	4.3E-6	0.369	-
		Jacob	6.4E-4	55.3	4.5E-6	0.387	6.5E-1
		Theis	7.1E-4	61.3	5.0E-6	0.426	4.7E-1
2º Ensayo interferencia de Cañafuelas	Ovejas	Horner	6.8E-4	58.8	4.9E-6	0.411	-
		Jacob	7.1E-4	61.3	5.0E-6	0.426	8.9E-1
		Theis	9.3E-4	80.4	6.5E-6	0.562	3.5E-1
	Pesadas	Theis	9.0E-4	77.8	8.2E-6	0.709	6.0E-5
Bombeo pozo Cesar Gómez	Cesar	Theis	1.9E-4	16.4	2.0E-6	0.249	4.0E-1
Bombeo sondeo Carrégula	Carrégula	Theis	2.7E-5	2.3	2.6E-7	0.023	7.5e-0



Ensayo	Sondeo	Método de interpretación	Transmisividad		Permeabilidad		Coef. de almacenamiento
			m^2/s	$m^2/día$	m/s	m/día	
GW2	GW2	Jacob	7.5E-5	6.5	3.9E-7	0.034	3.0E-1
		Numérico con fractura Opción 1	-	-	4.7E-6	0.409	1.7E-2
			4.7E-04	40.910	2.4E-06	0.203	7.3E-6
		Numérico con fractura Opción 2	-	-	5.6E-06	0.483	2.3e-4
			9.47E-04	81.8	1.0E-05	0.870	7.3e-6
	GW1	Theis	1.4E-03	125.3	1.4E-05	1.182	1.5E-4
GW3	GW3	Horner	1.6E-04	13.8	1.2E-06	0.102	-
		Jacob	1.1E-04	10.0	8.5E-07	0.074	7.4E-1
		Theis	1.3E-04	11.7	9.9E-07	0.086	4.6E-1

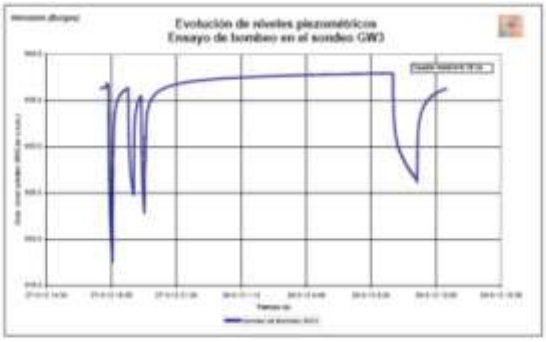


Fig 4.1.2 table shows well, method of interpretation used, transmissivity, permeability and storage coefficient values. Graphs show piezometric level changes during the interference test between wells and (graph with single blue line) the pumping test in GW-3.

The permeability is estimated to be of 1 to 1.2 m/day for the most permeable levels in the well in the Utrillas Fm.; permeability is about 0.1 m/day in GW-3 (Upper Cretaceous).

Instrumentation installed in the 3 wells -

The wells have been equipped with:

- Permanent pressure sensors to measure water level changes, with datalogging and transmission using GPRS
- 'Hydrolab' multiparametric probe to measure physiochemical parameters such as pH, temperature, conductivity, etc., working both simultaneously and in a continuous mode.
- The HYDRAS 3RX/iSOFT software has been installed on the server to receive and visualize the data in real time.

Data acquired so far can be displayed graphically to show the temporal evolution of the piezometric levels. Graphs show a clear correlation with rainfall and pumping regime (affected by the explosives factory site located on the map close to EBU-II and EBU-IV). The average piezometric level of the shallow aquifer is approximately at 930 m depth below ground surface.

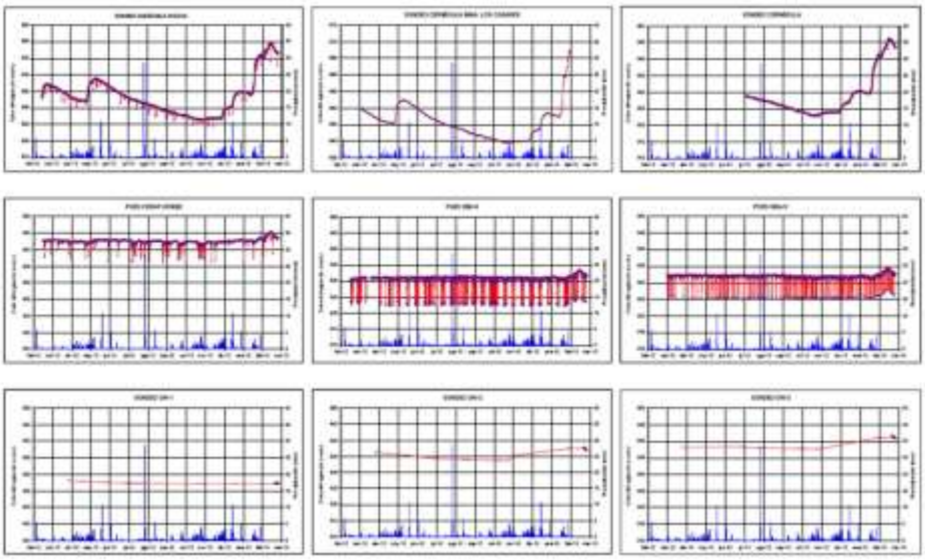
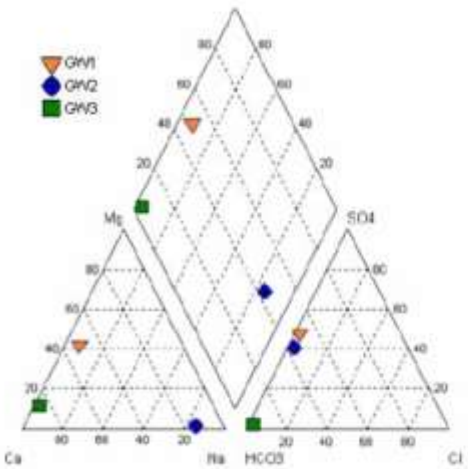
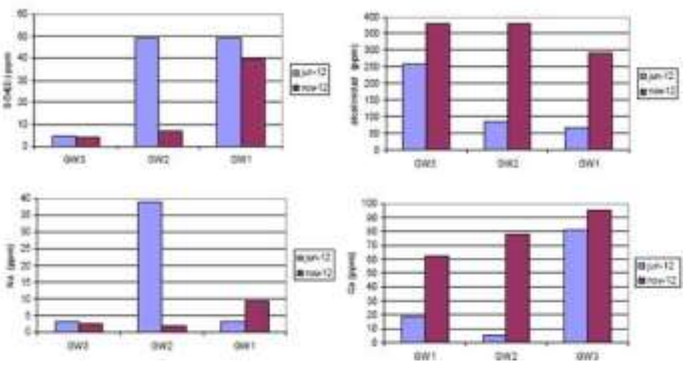


Fig 4.1.3 Results for the 3 wells: X axis is months, Y on the left is depth of water level (meters); Y on the right is precipitations in mm.

Hydrochemical analysis results:





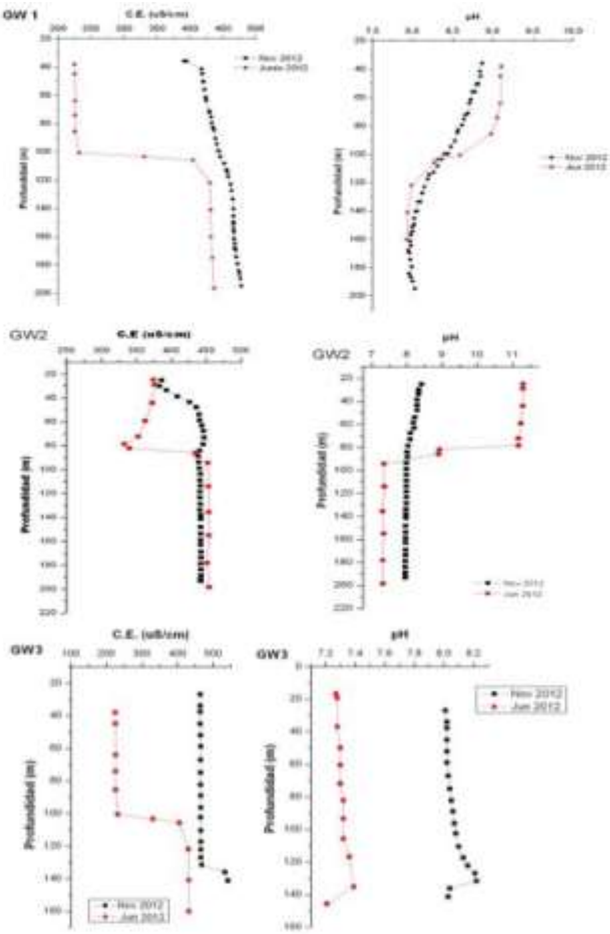


Fig 4.1.4 Results from the hydrochemical analysis (sampling for major, minor and trace elements; note that sampling at the TDP H-1 injection well uses a U-tube system)

The groundwater coming from the 3 wells is neutral or slightly alkaline, with pH values between 7 and 9 and electrical conductivity values of about 450 microSiemens per centimetre.

With the representation of the chemical composition on a Piper diagram and compositional graphs, like those above, it can be concluded to a calcium and bicarbonate dominant nature, with noticeable percentages of sodium and sulphates due to the presence of cement and bentonite (sampling during second well development, carried out in November 2012)
The hydrogeochemical profiles from pH and conductivity values before and after the second well development show a more linear morphology, indicative of a major homogeneity and a progressive variation of these parameters with depth.

Hydrogeological Monitoring Applications:

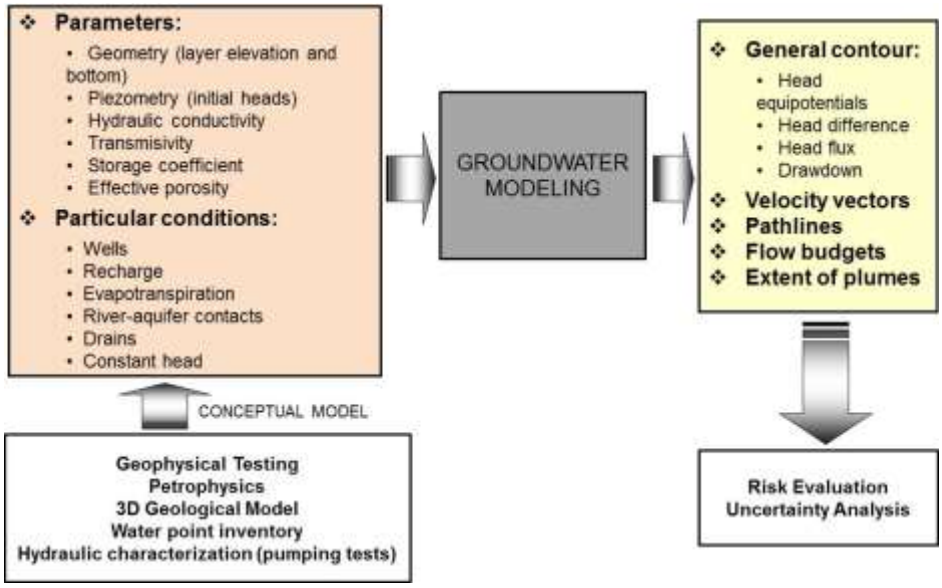


Fig 4.1.5 Hydrogeological Data Flow

The site hydrogeology, based on the geophysical, petrophysical, geological and hydrogeological information allows definition of aquifer geometry, piezometry, hydraulic conductivity, storage coefficient, effective porosity, etc.

If any leakage were to occur, changes would be noticeable from the gas content analysis.

One of the most interesting applications carried out by CIUDEN is the design and development of conservative and reactive groundwater models, allowing calculation of the velocity vectors, the path lines of groundwater and the extent of CO_2 plume, and the flow budget as well; all this information is essential to create a risk analysis model like the one based on the Bayesian networks that CIUDEN is currently developing for this project.

The same methodology is applied at the Compostilla commercial site.

4.2 Baseline monitoring for offshore storage (*Sleipner*)

Sleipner is operated under the Norwegian Petroleum Activities Act (NPAA, 1996). That breaks down into the following three tiers:

- The NPAA has a number of Activity Regulations.
- Health & Safety, this is overseen by KLIF, HD and Ptil (KLIF is the Norwegian environmental agency; HD is the Health Directorate, and Ptil is the petroleum safety authority).
- The actual data collection and reporting comes under Environmental monitoring, overseen again by KLIF.

The data and reports are disseminated to Norwegian environmental monitoring database (MOD, 2002). It also has to follow the OSPAR (Oslo 1972, Paris 1974… 2007) and London Protocol (London 1972… 2009).

Monitoring is mandatory and the monitoring data is placed in the public domain.
These monitoring requirements include:

- Environmental sea chemistry and biology,
- Acoustic seafloor mapping,
- Shallow seismic acquisition,
- Logging of the overburden,
- Geophysical surveying of the storage system,
- Sampling and analysis of the caprock,
- Sampling and analysis of the reservoir.

To date, eight 3D repeat seismic surveys have been carried out at Sleipner which is well above the regulatory requirements, but since Sleipner is a pioneer site, and as such is subject to much scientific and public attention, the project felt that it was necessary to conduct expensive monitoring campaigns: so far 8 seismic surveys, 3 seafloor mapping surveys, 3 gravimetric surveys and 1 electromagnetic survey have been acquired.

The site-specific baseline data sits within a much wider regional data context. The challenge is to define what is reasonable and what is fit for purpose. In this case seismic and gravity are a good combination.

Despite these comprehensive baseline monitoring campaigns, the project had to spend extensive time and effort in dialogue with the media after the ECO2 project detected a seafloor ”fracture-like” feature more than 50km NNE of the injection site in block 16/4. The feature is related to a Pleistocene glacier tunnel valley, that lies within a pre-existing regional seismic merge (Fig 3 and 4). The large coverage of this data allows for a clear analysis of this remote seafloor feature, which is equidistant to a number of oil and gas fields in the area, making the association with Sleipner spurious. The feature is not related to the Sleipner storage site.

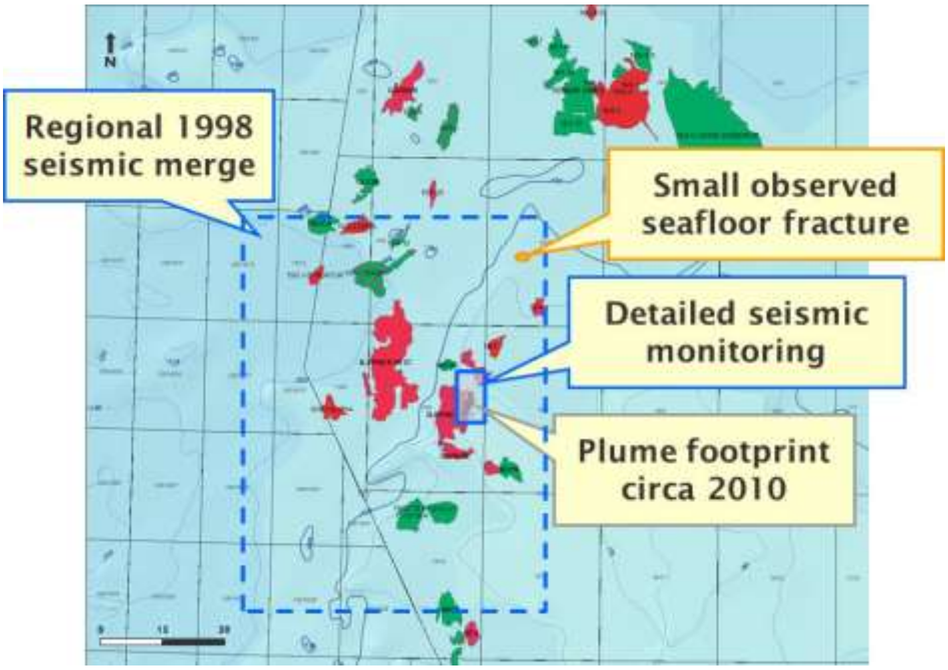


Fig.4.2.1 Map of the Sleipner project area; NPD national resource mapping (2012)

A bespoke survey of a size that would enclose the ECO2 project location is beyond the remit and budget of a storage operation, so the baseline monitoring always sits within a regional context.

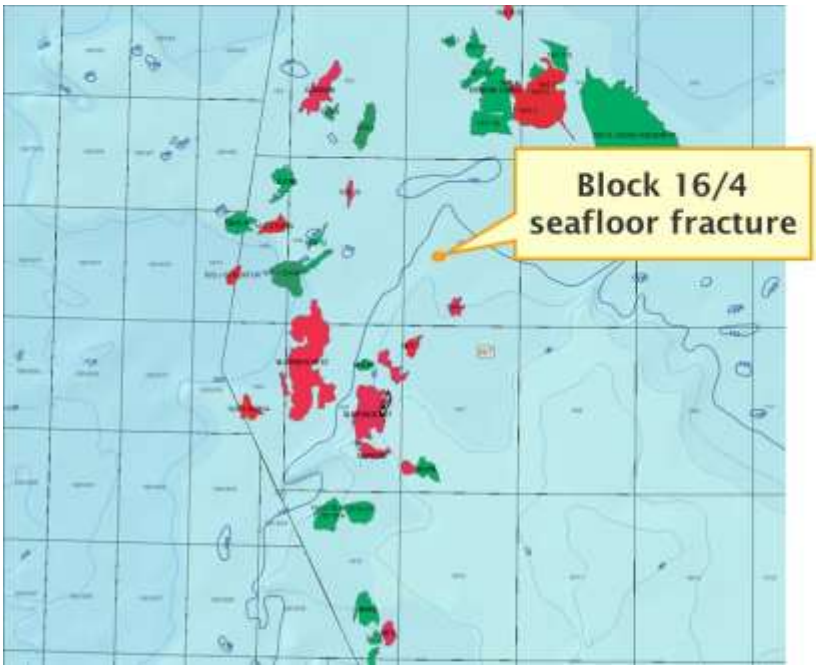


Fig 4.2.2 If the baseline data is stripped out, it can be seen that the seafloor fracture is almost equidistant from any number of oil and gas fields.

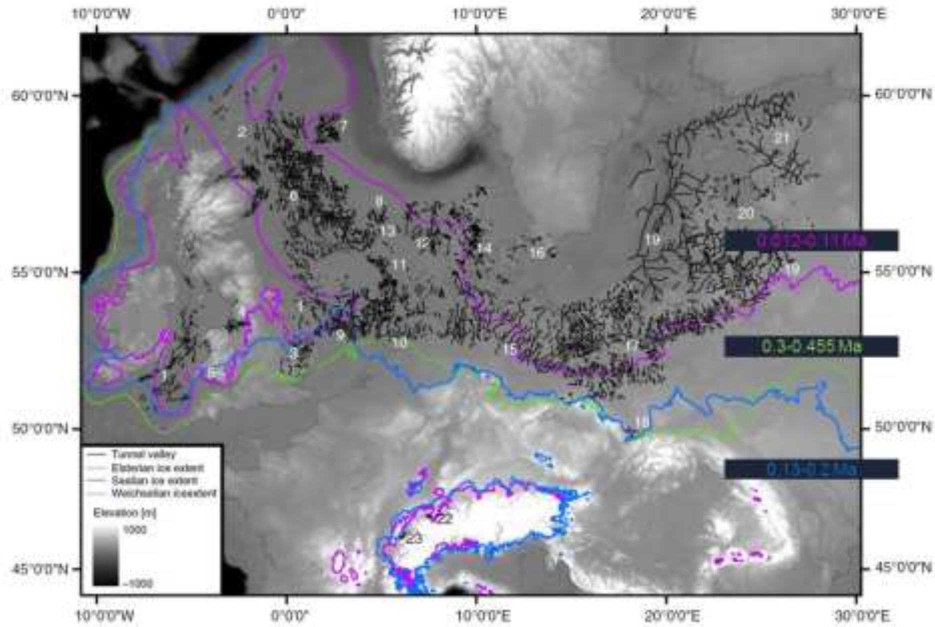


Fig 4.2.3 (van der Vegt et al. (2012), Pleistocene tunnel valleys. Colours show extent of ice at various epochs.

Block 16/4 where a 'fracture like' feature has been mapped lies within a much larger regional picture of ice-related Pleistocene tunnel valleys (publication by van der Vegt et al. on glacial morphology).

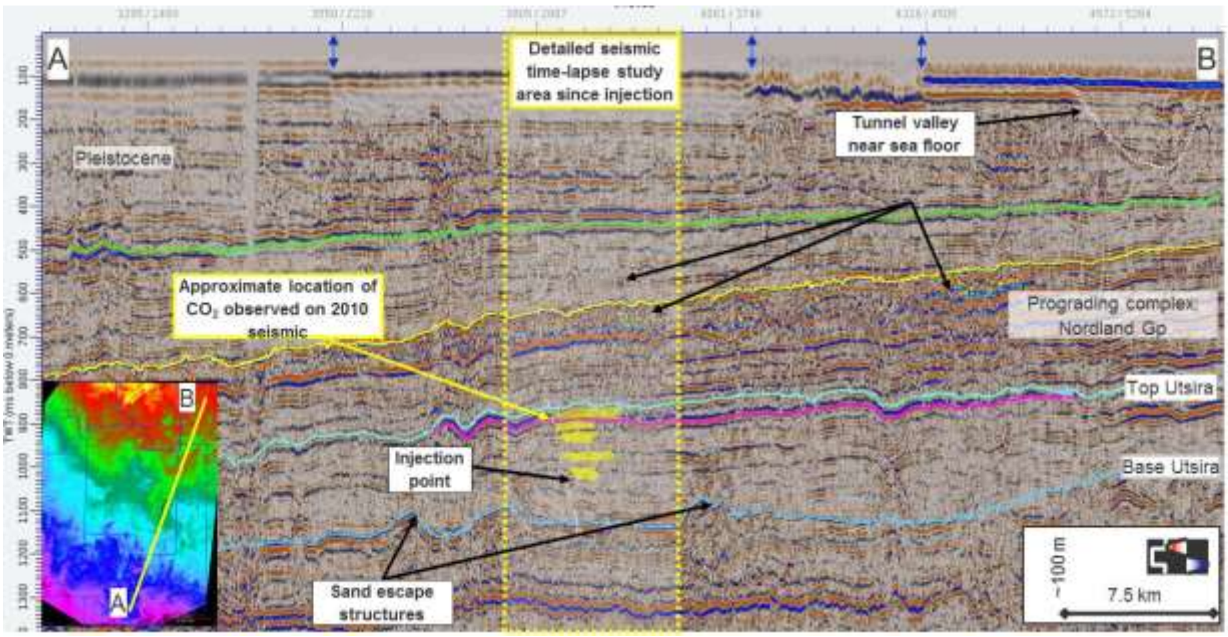


Fig 4.2.4 Seismic cross section showing CO_2 injection area in broader context

The picture above shows it is important to look at the entire storage system and understand data acquired at various scales. It is therefore important to place baseline data in context, which requires an interdisciplinary approach, relying on geology, geophysics, petroleum system analysis, etc.

More generally Statoil stresses the need for a good baseline, as it is often difficult to use legacy data. Subsea cables, high-resolution shallow surveys using wide frequency ranges are recommended for this type of setting.

The frequency of the repeat surveys should decrease progressively with time assuming that no anomaly is detected (for example, repeat surveys after 1, 2, 4, and 8 years).

To conclude, there is no definitive list of monitoring tools to be applied. Statoil is going beyond the present legislation. Each site must be handled on a case-by-case basis. The regulatory framework itself is evolving and requires more large operations to mature. European legislation defers to sovereign authorities and industry experience.

4.3 Baseline Design - Seismic data resolution & analysis (*Porto Tolle*)

Monitoring is currently being carried out offshore (400 km^2) and onshore.

Main monitoring technologies carried out at the Porto Tolle site:

On-shore	soil gas and diffusive degassing, shallow aquifer and dissolved gas, microseismicity.
Off-shore	physical and chemical characterization of the column and dissolved gases, characterization of sediment interface and water/sediment, benthic communities, oceanographic measurements, chemical-physical parameter continuous monitoring.

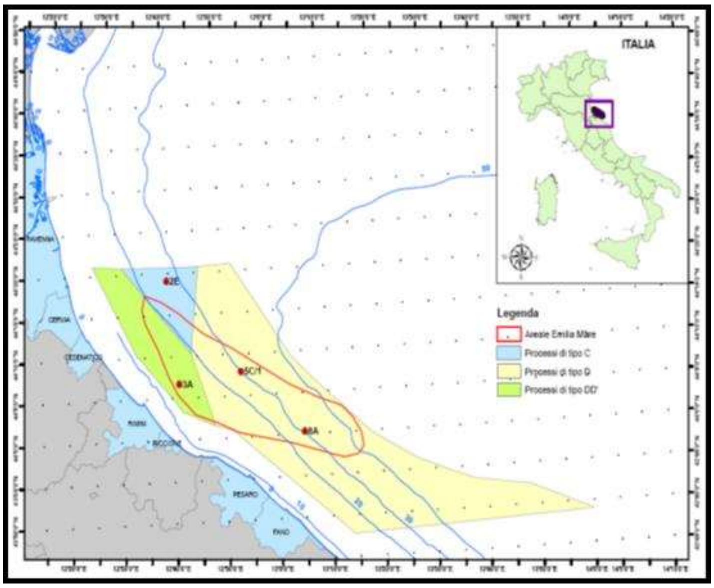


Fig 4.3.1 Areal view of the monitored zone

The baseline study covers a 400 km^2 area around the more probable injection locations in water depths ranging from 13 to 40 m.
Measurements include chemical, biological and physical analyses of both the water column and the near-surface sediments during four different periods of the year to define the ranges of baseline values in the area, both spatially and temporally.

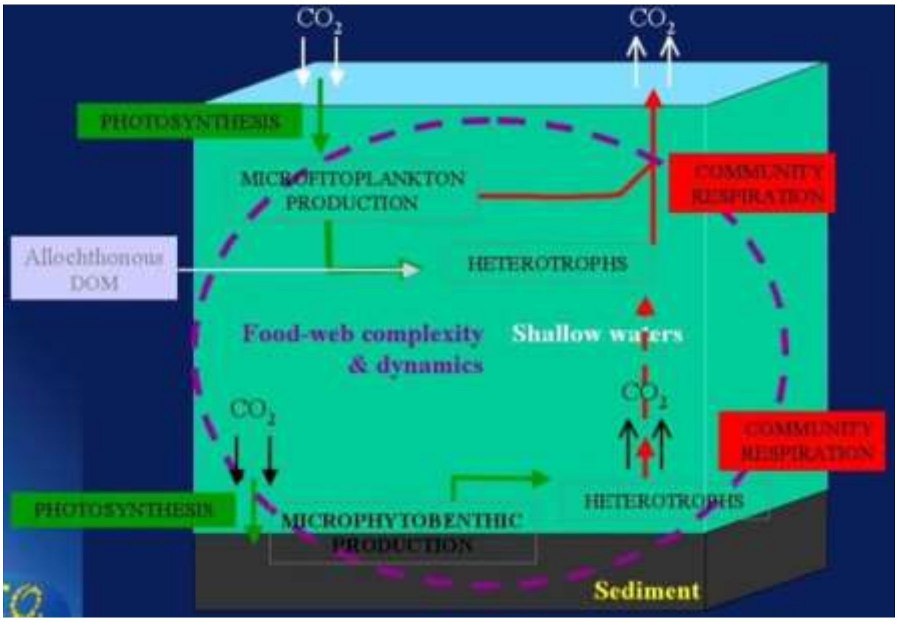


Fig 4.3.2 Courtesy of OGS-CO_2-Geonet

The increase of CO_2 in seawater reduces the availability of carbonate ions, ions that are necessary for marine organisms such as corals, molluscs, echinoderms and crustaceans to produce their skeletons or shells made of calcium carbonate ($CaCO_3$). Besides the impact of an increased amount of CO_2 on calcification, the increase of pCO_2 influences a number of other physiological processes associated with adjustment mechanisms such as acid-base survival, growth, development, or metabolism.

To summarize, **the potential effects of CO_2 on marine ecosystems could result in changes in**:

- pH and pCO_2,
- biogeochemical carbon cycle,
- diagenetic processes,
- mobilization of pollutants in sediments deposited,
- processes of production and respiration,
- physiology,
- calcification in different organisms,
- …

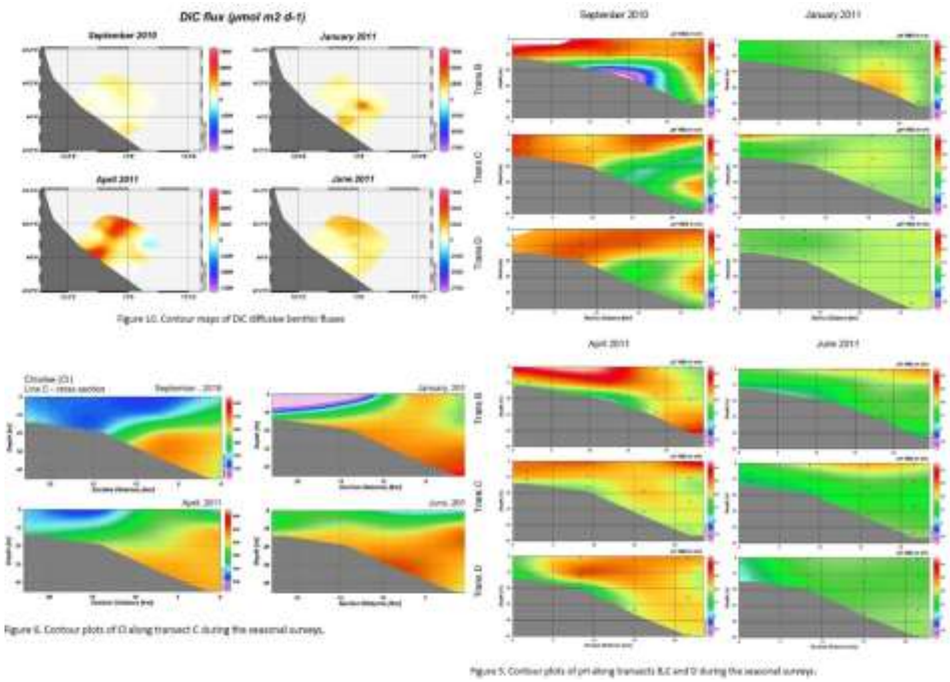


Fig 4.3.3 Contour map of DIC (dissolved inorganic carbon) diffusive benthic fluxes; Contour plot of Cl during the seasonal surveys; Contour plots of pH during seasonal surveys

Continuous monitoring - Deep laboratory station:
The two stations record time series of physical-oceanographic and chemical parameters of the bottom water and of the water column by using the following self-recording instruments:

- a CTD probe SeaBird 16 Plus for temperature, conductivity, pressure and dissolved oxygen measurements,
- an upward facing Acoustic Doppler Current Profiler RDI 600 kHz Self-Contained Sentinel for current direction and speed measurements at several depths, directional wave, temperature and sea level measurements,
- a CO_2/CH_4 probe,
- an acoustic transponder-releaser for position detection (acoustic telemetry) and retrieval of the station.

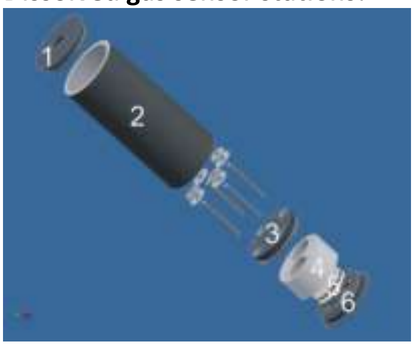
Fig 4.3.4 deep laboratory station

Each station is constituted of a stainless steel pyramidal with triangular base frame (of about 1.6 m of leg) which holds the instruments and the sensors. Using acoustic commands sent from a deck unit and a transducer on board, a releaser-transponder fixed to the station permits to locate it by calculating the distance from the ship, and to release a buoy for its recovery without the need of divers.

PARAMETER	RANGE	ACCURACY	RESOLUTION
Temperature (°C)	-5 to 35	0.005	0.0001
Conductivity (S/m)	0 to 9	0.0005	0.00005 S/m typical
Pressure (strain gauge)	0 to 100	0.1% of full scale range	0.002% of full scale range
PH	0-14 pH	0.1 pH	
Dissolved Oxygen	120% of surface saturation	2% of saturation	

Fig 4.3.5 Deep laboratory station close-up.

Dissolved gas sensor stations:



Type	Parameter	Range
NDIR-1	CH4 CO2	0-5% 0-5%
NDIR-2	CO2	0-100%
Digital sensor	Temperature	-20°+80°

Fig 4.3.6 Showing dissolved gas sensor

- Top cap, USB connection and T sensor,
- PVC cylinder hosts battery and electronics,
- Electronic support for NDIR sensor,
- sensor support,
- Teflon AF membrane (diameter 35 mm) and supporting porous metallic disk,
- Bottom cup.

The configuration allows the system to record up to 5000 measurements and to have autonomy of 500 acquisition cycles with a warm-up time of 10 minutes.

Site Survey:

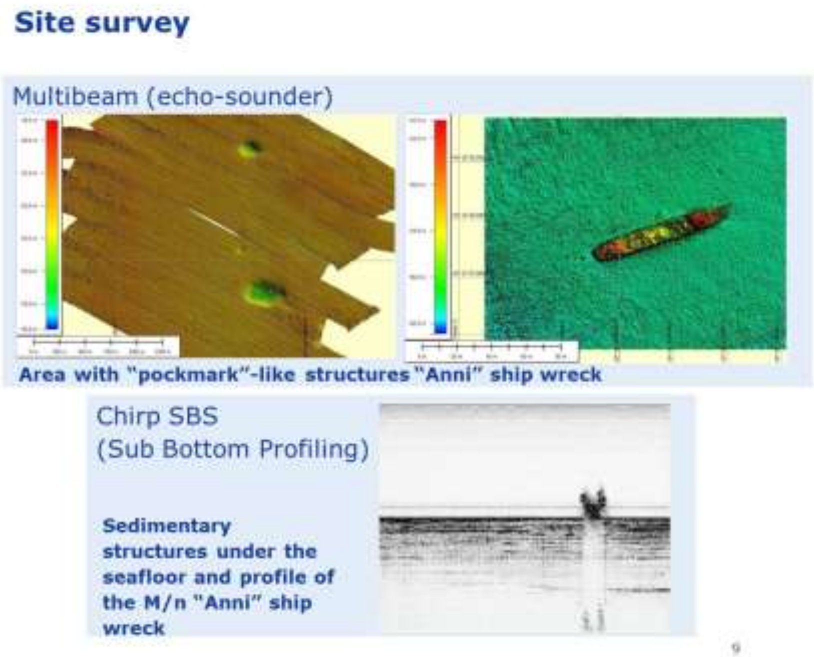


Fig 4.3.7 Showing echo-sounder image of the seafloor and sub-bottom profiling.

Pre-injection on-shore Survey:
The development of the pre-injection grid was carried out through:

- soil geo-gas measurements (CO_2 and CH_4 fluxes),
- geo-gas concentrations (CO_2, CH_4, He, 222Rn, H_2S, CO, H_2, N_2, O_2, and light hydrocarbons),
- shallow and deep aquifer fluids in terms of physico-chemical parameters (temperature, salinity, pH, redox conditions), chemical composition (major, minor and trace elements) and dissolved gases content.

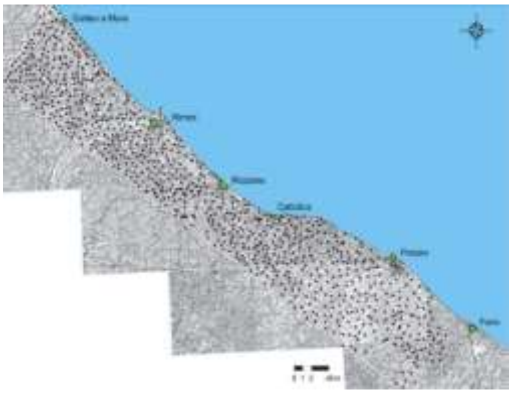


Fig 4.3.8 Aerial view showing onshore measurement locations (brown dots)

The survey objective was to:

- define the origin of shallow and deep fluids and the relationships between them on the basis of their physical-chemical, chemical and isotopic features,
- to investigate the role of water-gas-rock interaction and the buffer capacity of the shallow aquifers relative to dissolving gases, both of shallow and deep (including the injected one),
- to establish the presence of preferential migration pathways (i.e., fractures and faults) for the faster ascent of deep-originated fluids toward the surface.

Role of the structural settings:

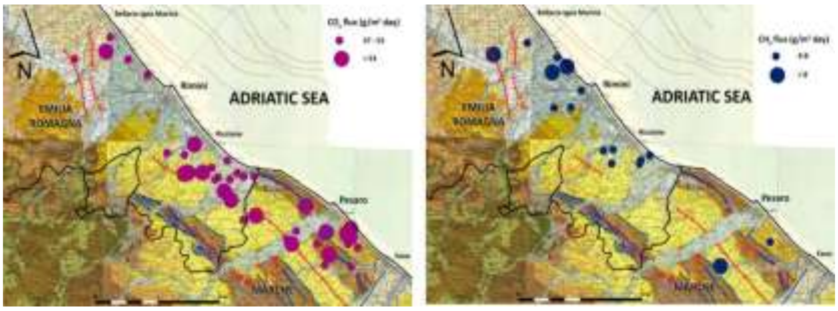


Fig 4.3.9 Aerial views showing CO_2 flux and CH_4 flux measurements

To investigate the role of the structural settings on the distribution of flux data, the spatial distribution of CO_2 and CH_4 fluxes have been plotted on the geological map of the study area. The classed post map of methane fluxes overlapped to the geological-structural map of the study area highlights the absence of a correspondence with the structural elements of the study area as well as lack of correlation with CO_2 fluxes, confirming the hypothesis of a shallow and biogenic source of these gas species.

Evaluation of pre-injection seismicity:

Fig 4.3.10 Aerial view showing the seismicity recording locations

Study of historical seismicity of interesting areas.

The goal of the feasibility studies is the collection of a new passive seismic dataset, in order to increase understanding of both the seismic behaviour and the deep geological and tectonic setting of the area.

The aim of the seismic experiment is to increase the grid of the permanent seismic networks already available (Italian National Seismic Network and Marche Seismic Network) in order to increase the sensitivity of the networks and locate earthquakes with ML <2.

Integrated modelling history:

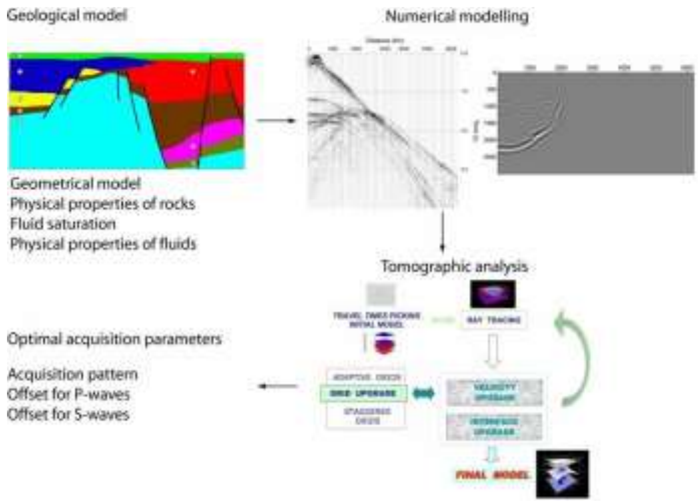


Fig 4.3.11 Seismic data integration into the models.

To evaluate the feasibility of seismic monitoring, a methodology was used to integrate the simulated seismic (synthetic) data into the numerical model based on physical reservoir property variations. The model requires understanding the laws controlling the physical property variations of the rock and of fluid in the pore space

Construction of the poro-viscoelasctic model:

Fig 4.3.12 Schematic representation of the poro-viscoelastic model

Properties of gas, fluids and rocks need to be calculated. The poro-viscoelastic model provides the rock formations seismic properties as a function of the pore space gas saturation and the signal frequency. This model is used to simulate the wave propagation in the rock formations.

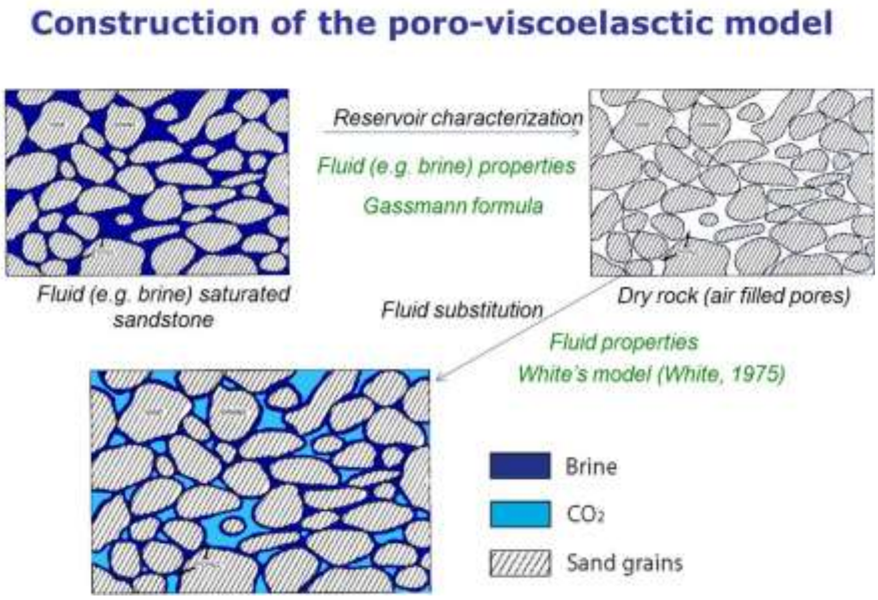


Fig 4.3.13 Model construction

In order to calculate the seismic properties of the rock containing gas, based on a rock totally saturated with brine, the rock elastic modulus is calculated without fluid content in the pore space, using the sonic logs data as a start and reversing Gassmann law. Gas and brine are then added and White's model is used to calculate velocity and attenuation in presence of gas.

Building the model requires having the following information, usually provided by borehole logging data:

- Geological section with depth intervals for each formation. Eventually, a seismic section, providing the interval velocity (unless a sonic log is available),
- Components of the rock, with relative percentages, for each geological formation,
- Porosity,
- Permeability,
- Type of fluids present in the pore space and their saturation. For aquifers the fluid is brine, and in this case saturation and salinity is needed,
- Average geothermal gradient in the zone.

Gas density and bulk modulus computation, The Peng-Robinson EoS:

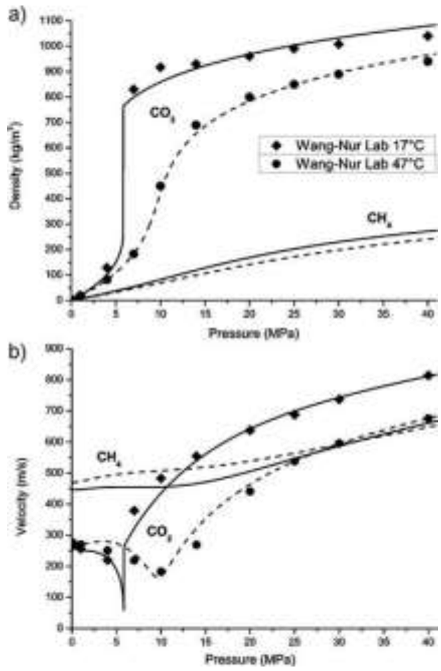


Fig 4.3.14 Experimental and computed densities and sound velocity for CO_2.

The good performance of the Peng-Robinson equation of state: the experimental data of Wang and Nur (1989) are perfectly fitted.

To calculate the properties of the gas the equation of state of Peng-Robinson is used. This equation is simple and allows obtaining excellent results.

The stratigraphic sequence indicates the presence of clay in various proportions and very fine sands. The clay content of C was derived from the Gamma Ray. This data was used to calculate the permeability of the rock, combining the partial permeability of the clay matrix and that of the sandstone.
Using the empirical relationship between porosity and permeability, the project calculated the porosity. Finally, the elastic moduli of the rock without fluid in the pore space was obtained by reversing the law of Gassmann from the sonic log.

A model 'in depth' was produced, (i.e. model deduced from the conversion of the section 'in time' obtained from the velocity stacks).
Since the velocity stacks are inaccurate, the model was refined using the most reliable sonic-log and numerical simulations.
In practice, a series of numerical simulations plane-wave were launched, changing from time to time the structure of the model, to best fit the interfaces of the real seismic section. There was an excellent correspondence between the interfaces of the synthetic and the seismic section.
At the end of the procedure, the model in depth was refined. The caprock is represented by the formation Santerno, while the Upper Porto Garibaldi is the reservoir. This is divided into three compartments, separated by 20-35m thick clay layers (a situation similar to that observed in the Utsira formation at the Sleipner site).

A plume similar to that observed in the case of Sleipner was designed. The CO_2 expands from the point of injection, spreading upwards because it is lighter than brine. Upon meeting the first barrier

this widens, until it finds a path to move to the compartment above. In this image, the plume is represented by the saturation of CO_2, i.e. the fraction of the pore space occupied by CO_2.
Using the poroelastic model of White, the speed and attenuation of seismic waves in the rock saturated with CO_2 and brine was calculated.
This image represents the speed P corresponding to a dominant frequency of 35Hz.
As can be seen, the speed of the formation decreases in the presence of CO_2.
This is due to mesoscopic that is when the rock is partially saturated with gas.

P-Wave quality factor:

The Q factor is a measure of the attenuation, which can be obtained from the White poroelastic model. A low Q indicates a large attenuation.
It is notable that there is a large attenuation when the saturation of CO_2 is around 5-10%.

Simulation of wave propagation:

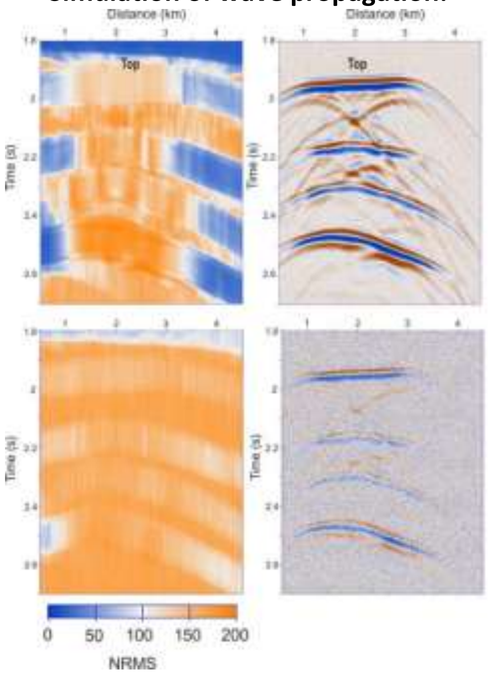


Fig 4.3.15 Difference (right) between the synthetic plane-wave sections in the presence of random noise; the correspondent NRMS sections are shown on the left.

A standard procedure, when assessing the similarity of two time-lapse data sets, is to use some repeatability metrics, as for example the normalized root-mean-square (NRMS). Both the baseline and the seismic sections after injection have been contaminated by Gaussian random noise with a Signal to Noise Ratio of 20dB (top) and 3dB (bottom). The critical threshold of signal / noise ratio seems to be 3dB.

Design of an effective monitoring plan:

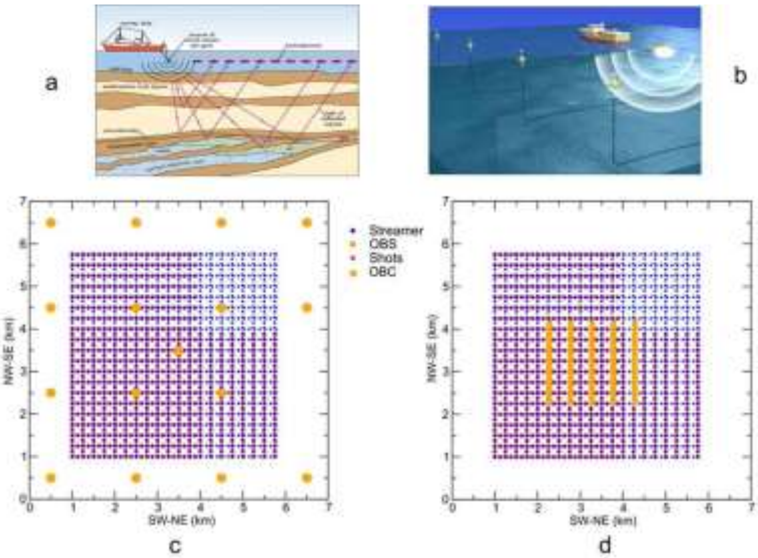


Fig 4.3.16 a) Classic marine seismic acquisition; b) Marine acquisition with an ocean bottom cable (OBC); c) plan view of the synthetic seismic acquisition with an OBS array; d) plan view of the synthetic seismic acquisition with an OBC array.

An Ocean Bottom Cable (OBC) is a seismic cable placed on the seabed by means of an auxiliary vessel and can be equipped with hydrophones or multi (three-) components sensors to record converted waves. Compared to the Ocean Bottom Seismometers (OBS) it has the advantage of presenting a denser number of sensors, allowing a conventional processing of the S waves. The disadvantage of OBC compared to OBS is a smaller illuminated zone (OBC higher capital cost but lower operational cost).
The OBS array is sparser (low of resolution), but covers a larger area which enables more effective detecting of possible microseismic activity generated by CO_2 injection.

Example:

- The minimum streamer length was of 3 km (a streamer is a cable structure containing hydrophones and three orthogonal geophones (when four-component sensors), connected by electronic equipment along its length and used in marine seismic surveying),
- Use of Ocean Bottom Cables (OBC) or Seismometers (OBS) (OBC: streamer deployed on the seafloor; OBS: individual seismometers),
- Microseismic monitoring took place during injection,
- Accurate log measurements before, during and after injection.

	Baseline	*Repeat surveys*
Date acquisition	Pre-injection	Post-injection every 3 years
Source direction	SW-NE	SW-NE
Source tow depth	5-6 m	5-6 m
Source inline separation	50 m	50 m
N. Sources ("GI" air guns)	2	2
Shot point interval	12.5	12.5
N. Cables	2 (or more)	2 (or more)
Cable separation	100 m	100 m
Cable length	3000 m	3000 m
Near offset	25 m	25 m
Group interval	12.5	12.5
Tow depth	5-6 m	5-6 m
Record length	5000-6000 ms	5000-6000 ms
Sample interval	2ms	2ms
Optional/recommended		
OBS (4C) number	From 17 to ...	From 17 to ...
OBS (4C) inline spacing	Max 2 km	Max 2 km
OBS (4C) crossline spacing	Max 2 km	Max 2 km
OBC (4C) number	5	5
OBC length	3000 m	3000 m
OBC Group intervals	12.5 m	12.5 m

Fig 4.3.17 Summary table

The results showed that:

- It is important that the baseline and repeat surveys are acquired using the same parameters, in order to ensure a high repeatability.
- Long offsets are recommended for velocity analysis, illuminating a larger volume and therefore obtain a better representation of the structures.
- A seismic source with a wide frequency band is also recommended for better analysis.
- Overpressures seem to have a greater effect on shear waves than on compressional wave. Therefore, the decrease of the ratio Vp / Vs and of the Poisson ratio with increasing pore pressure can be used as a physical basis for overpressure monitoring.
- Overpressures may be due to a too rapid injection process, with consequent alteration of the balance and induction of microseismic events.
- It is important that from the beginning, an array of OBS (Ocean Bottom Seismometer) or OBC (Ocean Bottom Cable) is adopted to record any changes in velocity and S wave attenuation. (S waves are necessary to reliably localize eventual microseismic events.)

A permanent OBS or OBC array at the bottom of the sea, can continuously record any microseismic events in the intervals between the repeated active seismic surveys.

To conclude:

The reservoir formation characteristics and depth for the selected structure are such that the CO_2 presence should be detectable with the seismic method.

The change in P- and S-wave velocity and quality factor (and hence the attenuation) should enable the monitoring of the CO_2 migration within the reservoir. Moreover, the conditions are even more favourable for the overburden formations, and hence an early detection of possible leakages through fracture systems and/or degraded well casing should be possible.

The simple imaging of the reservoir after injection may be not enough to clearly detect the presence of CO_2. As a result the comparison between repeated seismic surveys must be done with the simple difference and NRMS techniques. Repeatability and high signal-to-noise ratio can be a key issue.

Amplitude versus offset (AVO) analysis (for example at the reservoir top) may help in detecting changes in reflectivity due to the presence of the CO_2.

Without seismic, it is difficult to build a good model.

4.4 Monitoring at Compostilla (*Compostilla*)

A presentation of the various baselines and monitoring plans at Compostilla was added at the end of the session.

Importance (and distinction) between baseline surveys and monitoring:

Baseline surveys

The main objective of the storage complex Baseline is to serve as a reference to assess the progress of the identified environmental resources along the project lifetime.

- During Phase I of the project the following baseline was established:
    - Atmospheric CO_2 levels,
    - Hydrogeology (potable aquifers and surface quality and quantity),
    - Soils CO_2 concentration and fluxes),
    - Terrain deformation (InSAR).

During Phase II of the project several baselines will be carried out for the selected monitoring techniques of the OXYCFB300 Project in order to establish the initial conditions of the storage complex before injection begins.

- Baseline monitoring will make possible the following:
    - Analysis of the progress of those environmental resources that have been identified,
    - Determination of potential impacts on those resources by project elements.

Monitoring

The main objective of the monitoring is to observe the performance of the injection operations and controlling the risks inherent to storage. It will be the primary source of information for:

- leading to the identification of the occurrence of a specific undesired event,
- leading to the activation of the appropriate mitigation measures,
- forms the base of the entire risk management process (which could not exist without it).

Monitoring will include time-lapse surveys of the baseline and will be a fundamental tool to control the reservoir performance.

A fit for purpose monitoring plan for a CO_2 injection project has to take into account:

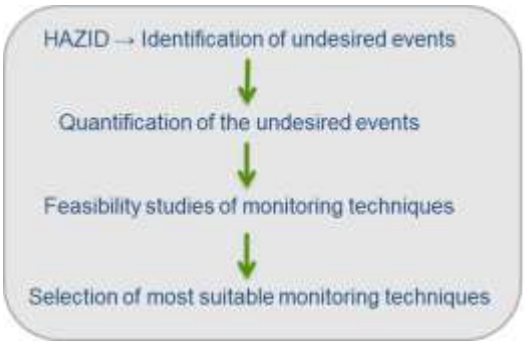
- legal aspects,
- geological constraints,
- risk factors,
- costs,
- available technologies.

Methods for considering unexpected events and new technology when developing the baselines:

Monitoring activities will be performed through the storage complex with the aim of observing the performance of the injection operations and controlling the risks inherent to storage.

Monitoring will be the primary source of information leading to the identification of the occurrence of a specific undesired event, leading to the activation of the appropriate mitigation measures.

Monitoring Process:



Objectives of the baseline and future monitoring, and the importance of its consideration in the project's strategy:

- A monitoring plan it is a requirement to obtain a storage permit.
- The main objective of the monitoring plan is to determine the performance of the injection operations and controlling the risks inherent to storage.
- Before injection starts, a baseline has to be established for each of the selected monitoring methods in order to define the initial conditions of the storage complex and compare them with the successive monitoring campaigns.
- Monitoring plans will be updated through the lifetime of the project based on the update of the dynamic models and if needed redefinition of the storage complex could be performed.

Based on the implementation of the European guidelines some measurements are mandatory:

- Fugitive emissions of CO_2 at the injection facility.
- CO_2 volumetric flow at injection wellheads.
- CO_2 pressure and temperature at injection wellheads (to determine mass flow).
- Chemical analysis of the injected material.
- Reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

Additional measurements should be performed in order to honour the legislation:

- Technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at surface.
- Technologies that provide information about pressure-volume behaviour and areal/vertical distribution of CO_2 plume.
- Technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond.

Spatial and temporal boundaries of the area to cover in terms of baseline monitoring:

A more detailed baseline is needed around the Storage Complex area, defined based on the worst case scenario (larger possible plume extension) obtained by an uncertainty analyses of the parameters with bigger impact on plume migration (horizontal permeability, relative permeabilities, and the sealing behaviour of faults).

What the project measures:

Baselines recorded during phase 1 of the project:

- Soil CO_2 concentration and flux.
- Aquifer and superficial water quality and CO_2 levels.
- INSAR.
- 3D Seismic.
- Reservoir temperature, pressure and tensional state (to determine CO_2 phase behaviour and state).

Fig 4.4.1 Soil CO_2 concentration and flux measurements

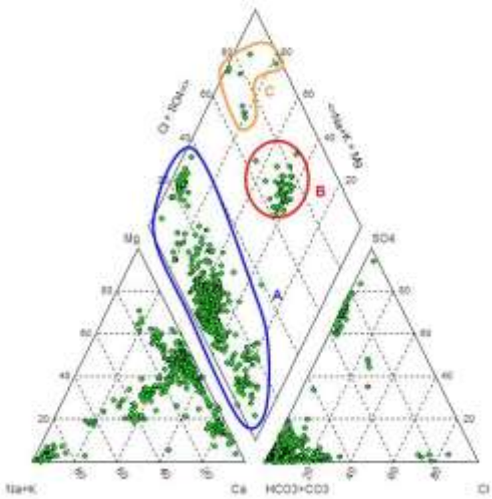


Fig 4.4.2 Aquifer hydrochemical facies

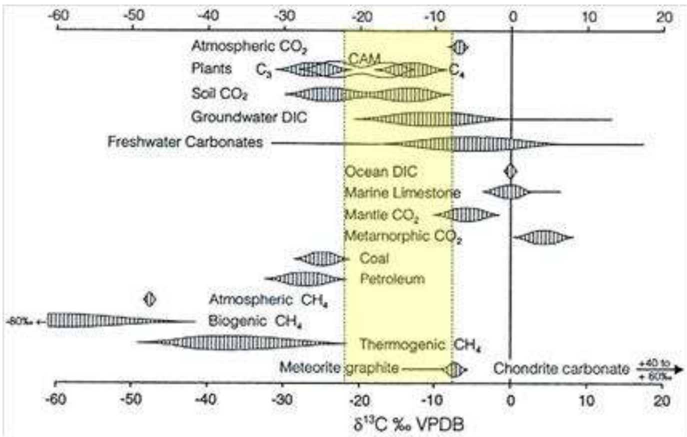


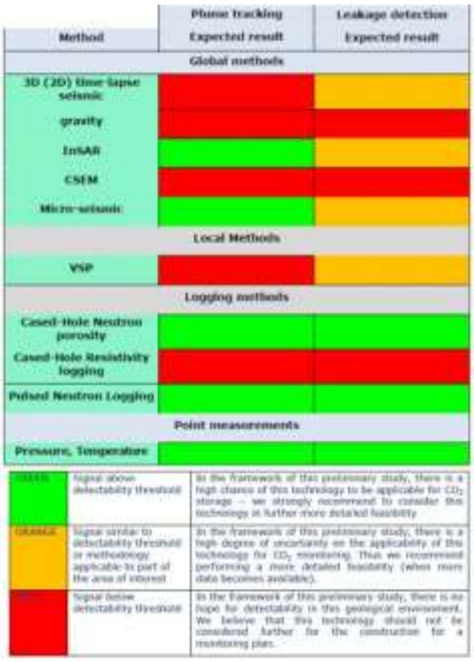
Fig 4.4.3 Isotopic studies on water and gas

<u>Baselines planned for phase 2 of the project (before injection begins):</u>

- Baseline Well Logging (on new injection and monitoring wells),
- RST Logging (on monitoring wells),
- 2D Seismic,
- Micro-Seismic through shallow wells,
- INSAR update,
- Soil CO_2 concentration and flux (update),
- Aquifer and superficial water quality and CO_2 levels (update).

Baseline measurements are first carried out over a large area. A more detailed baseline is performed over the storage complex area (larger possible plume extension). Six campaigns have been performed over different seasons ensuring repeatability over three years.

Level of resolution:



Method	Advantages	Drawbacks
Global methods		
3D (2D) time-lapse seismic	High vertical and lateral resolution in comparison to other methods No monitoring well needed	Need for baseline before injection starts Expensive (3D)
gravity	Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts 2D image only/poor lateral resolution
InSAR	Cheap Complementary to seismic methods No monitoring well needed	Need for baseline before injection starts. 2D image only/poor lateral resolution
Local methods		
VSP	High vertical resolution, small level of noise	Need for baseline before injection starts small area imaged cannot be run in injecting well
Well logging methods		
Cased-Hole Neutron porosity	Neutron porosity decrease with increasing CO_2 saturation	Tool limitation (4 5/8" casing); Change in Sw needs to be present
Cased-Hole Resistivity logging	Medium resolution CO_2 plume detection and tracking	Tool limitations (e.g. casing, cement bond and resistivity) need to be considered first; 100 ohm-m resistivity limit
Pulsed Neutron Logging	High resolution quantitative plume saturation measurement	Has limitations in low salinity and low porosity environments
Point measurements		
Pressure, Temperature	Direct measurements, quantities that have a wide footprint	Information at one point only

Fig 4.4.4 Summary table

A feasibility study was carried out in order to select the most suitable techniques to track plume migration and leak detection.

2D and/or 3D seismic monitoring is considered within the best techniques to track CO_2 migration. Due to the low CO_2 saturation expected in the Duero site, detection limit is below level of resolution.

Accuracy and precision for future repeat surveys:

- For any time-lapse acquisition, repeatability is very important. Therefore sources, receivers and its positioning must be reproduced as accurately as possible.
- In case future improvement of the monitoring techniques is available with an increase in accuracy and precision its replacement should be (whenever possible) overlapped with the existing equipment.
- If overlap is not possible, the improvement in data quality and resolution should be analysed in detailed in order to be able to compare old data with new.
- New monitoring techniques or detectability improvement of the existing ones will be available throughout the project lifetime. Monitoring plan updates will take into account any advance in monitoring issues.

Recommendations for onshore monitoring actions:

Before injection begins, the following actions have to be completed:

- Drilling of monitoring wells and completion of equipment installation,
- Drilling of hydro-monitoring wells and completion of equipment installation,
- Drilling of microseismic wells and completion of equipment installation,
- Logging baseline for the monitoring and injection wells,
- Update of the existing baseline (Soil, atmosphere and water CO_2 levels and InSAR),
- Monitoring equipment installation of the injection wells (DTS and Pressure gauges).

How to collect datasets:

a) Injection wells

- Continuous pressure and temperature control through the well and tubing with automatic data transmission system.

b) Monitoring wells

Neutron logging in monitoring wells

- 2 per/year first 2 years of injection
- 1 per/year 3rd to 5th year of injection
- 1 per/2 years 6th to 10th year of injection
- 1 per/5 years 11th to the end of injection

Well integrity logging in monitoring wells

- 1 every 5 years during the injection and pre-transfer periods

Continuous pressure and temperature control through the well with automatic data transmission system.

c) Micro-seismic network

23 to 25 shallow wells (30-50 meters) are proposed to be drilled and equipped with geophone strings.

Data processing:

- 1 every/month during initial 10 years of injection,
- 1 per/year from year 10th to 30th of injection and pre-transfer period.

d) Time Lapse InSAR Acquisition

Interferometric Synthetic Aperture Radar (InSAR) data will be processed and will provide a large scale view of the pressure changes due to injection, in and above the reservoir.

Planned data processing:

- 2 times during the first 5 years of injection,
- 1 per/5 year from year 5th to 30th year of injection and during pre-transfer period.

As surface deformation is more likely at the later stages of the project, when reservoir pressure is higher, data processing frequency is to increase.

e) Hydrogeological control

3 hydrogeological wells will be drilled next to the injection wells and continuous monitoring devices will be installed to control pH, Tª, Conductivity and piezometric level.

Data collection:

- 2 campaigns per year during injection and pre-transfer periods,
- 1 campaign per year during post-transfer period.

f) Soil gas survey

Continuous flux measurement equipment (accumulation chambers) will be installed next to each injection well, with an integrated weather station and atmospheric CO_2 concentration device.

Annual campaigns with portable flux chamber equipment will be performed through a mesh covering the total extension of the CO_2 plume.

Data collection and processing:

- 6 campaigns per year during injection and pre-transfer periods,
- 1 campaign per year during post-transfer period.

g) Seismic Surveys

2D and/or 3D seismic surveys test will be performed during injection period.

In case signal detectability is achievable, time-lapse seismic acquisitions could replace the drilling of three monitoring wells, SDM-3, SDM-4, SDM-5 (important cost reduction and better plume extension tracking).

Data collection and processing:

- Initial test 2 years after injection begins (update models, reservoir performance)
- 1 survey every 5 years once tested positive.

Total monitoring cost over the lifetime of the project (80 to 90 years) is expected to reach 100 M€.

- 30 years of injection,
- 20 years after injection,
- 20 years after transfer of site,
- 30 years where owner or project promoter still has to assume the monitoring costs.
  Overall 70 years of ownership plus 30 years of service, thus 100 years (Spanish law).
  The authorities can decide to change the 30 years post transfer into 40 years. Monitoring is intensive during injection and 20 years post injection. After that it will gradually decrease.
  Last 30 years will mainly be water monitoring.

4.5 Discussion outcomes and conclusions

Onshore and offshore baseline monitoring has been implemented at the storage sites using a variety of methods, partly because these methods are also used for characterisation, because methods are site specific (what can be measured or detected at a site depends of the local geology and environment), and partly because the projects need to anticipate what parameters may vary in time for their project.

In most cases seismic surveying methods are a preferred method as much for characterisation as for the establishment of a baseline and later verification (pressure, displacement, fate) and assurance monitoring (potential leakage outside of storage complex). To monitor using seismic, a good acoustic impedance variation is needed to detect the change in pore content. Positioning and tracking the CO_2 plume will depend on the resolution that can be achieved at a particular field.

As seismic velocities should change with CO_2 injection, well-based methods such as crosswell tomography and distributed temperature sensor (DTS) for phase change of CO_2 could be considered to track changes close to the wellbore. However crosswell tomography is often ruled out for various reasons:

- It has a very small radius of investigation (<1 km), thus it is a localized measurement and not adequate for the expected plume size. VSP has been proposed in some cases as a local verification method;
- It is expensive as it requires drilling an additional well (which moreover would be an additional potential leakage path, cutting across the seal and reservoir).

DTS can be installed in one well and can be deployed in more wells if the response is satisfactory.

Baseline acquisition through a full set of well testing methods is particularly interesting to control the state of the aquifers above the storage complex. This is being particularly well designed at the Hontomín site.

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APPENDIX 1Details and data regarding CO_2 composition, injection and wells per project

General Information – Injection

	Compostilla	Hontomin	Don Valley SF	Don Valley EOR	Porto Tolle	ROAD	Sleipner
Operating hours (load factor)	5606 h/year (64%)	-	Not known (driven by capture plant)	99.5% availability (injection design target)	6000 h (68%)	6500 (approx. 90% of running hours power plant) (74%)	24/7 continuous operation
Shut downs	Operating factor 64%	-	Not known (partly a matter of capture plant requirements)	Offshore & capture plant (coordinate plant & offshore)	Not defined	Dependent on power plant	Minor (summer maintenance only)
Average/maximum injection rate	64 – 70 kg/s	0.5 – 3 kg/s (planned)	137 (avg), 194 (max) kg/s (rates based on those estimated for capture plant)	150 – 185 kg sec^{-1} (imported) 400 – 640 kg sec^{-1} (with recycle)	31.7 – 55 kg/s	1.5 Mtpa (47 kg/s) max, 1.1 Mtpa av.	0.85 – 1.01 Mtpa (max injection in 2001)
Mass CO_2 per injector (rates)	23 – 35 kg/s	-	-	50 – 110 kg sec-1 (limited by tubing size)	-	See above (only 1 well)	0.9 Mtpa
Cumulative injection to date	-	-	-	-	-	-	14 Mt (as of Jan 2013)
BHP during injection	230 – 280 bar	2 – 120 bar (planned)	140 – 230 bar(g) (subject to further dynamic reservoir model refinement)	< 485 bar (injection pressure control)	311 bar abs @ 2900 m (max)	20 bar	No down-hole gauge (well head inj. Pressure 62-65 bar)
Average reservoir pressure	190 – 240 bar	150 bar (expected)	118 bar(g) at 1100 m tvdss; 0.115 bar/m estimated pressure gradient; 200-2500m thick formation (ave. res, pressure across formation not available;	425 bar (project 20-yr average)	220bars @ 2200m	100 bar (range 20-300 bar)	80-100 bar

			res. Pressure dependents on depth & pressure gradient)				
Reservoir Pressure/Temperature conditions	60 – 110 barg, 5-30º C	60º C (expected)	45 – 65 ºC; 38 ºC/km estimated (dependent on depth, pressure gradient & geothermal gradient)	395 bar, 140° C (initial conditions)	32° C	@ platform 60° C & 80-90 bar	25^{o} C (well head temperature)

General Information – Wells, CO_2

	Compostilla	**Hontomin**	**Don Valley SF**	**Don Valley EOR**	**Porto Tolle**	**ROAD**	**Sleipner**
Status existing wells	P&A (1 appraisal well within storage complex)	Drilling H-I and H-A wells	2 plugged and abandoned wells on structure (exploration wells > 20 years old)	Mostly operating (Oil prod and water inj.)	-	Gas production well In operation	CO_2 injection Well 15/9-A16 (in operation)
Corrosion control	CRA casing, CO_2 resistant cement, coating (design ongoing)	Cr22 stainless steel	Will probably be required (CO_2 stream specification)	To be determined (probably Cr alloy tubing and well heads)	13Cr martensitic stainless steel	New tubing	High chromium stainless steel
CO_2 breakthrough at old wells	Not expected from simulations	-	Not available (MMV plan will address)	Old wells either active or abandoned	-	-	none

Type of injection tests (push pull, tracer, etc.)	No CO_2 inj. Test	Push-pull, tracer and high pressure tests (planned)	Appraisal expects to carry out production test and sea water injection test (high P, large vol. CO_2 source unachievable offshore for CO_2 inj. Testing)	>25 years production and waterflood (plus several years gas injection)	-	Under discussion	Injectivity tests during start up (Well re-perforated in August 1997 to improve injectivity)
CO_2 stream composition	CO_2 95.4% (design parameters)	Pure CO_2 (99%)	Specs developed for safe CO_2 transportation (key points: <4% non-condensable impurities; 50 ppm water) (additional compositional constraints may be required to avoid wellbore corrosion)	>97% CO_2, N_2, H_2, CH4 (to be confirmed)	CO_2>99.6% H_2O <100 ppm Incondensable gases < 0.4%vol Sox < 50 ppm Nox < 20 ppm	Main importance: 50 ppm H_2O and O_2	98% CO_2 methane is main other component

Specifics

Injectors	**Compostilla**	**Hontomin**	**Don Valley DSF**	**Don Valley EOR**	**Porto Tolle**	**ROAD**	**Sleipner**
Injection location (at crest structure, downdip)	South flank of synclinal, up to around 2200 m deep	1 injector. Downdip of dome	Along flanks; deviated and/or horizontal wells possible (Well config. Not yet finalised; aim to optimise number of drill centres	Crestal (to be confirmed)	1 injector	-	Well 15/9-A16 (close to the base of Utsira). Long-reach horizontal well deviated at 83^o. Top of injection interval at 1010m TVD MSL
Above / below hc – water contact	n/a (no hydrocarbons)	Below hc-water contact (little O&G expected)	Not applicable (no h/c contact)	Above (possible minor below)	No contact	Above	-
Number of Wells	3 (1 use, 1 reserve, 1 depending on	1 new injector, 1 new monitoring (H-I & H-A, respectively)		27	1	1	1

	conditions)	(currently being drilled – May 2013)					
Number of existing wells	3 old exploration wells and 4 new appraisal wells	4	2 plugged and abandoned wells on structure (>20 yrs. Old) (no reuse planned; wells assessed for leakage risk)	30 (1 abandoned)	-	1	-
TD above / below hc – water contact	n/a (no hydrocarbons)	-	Not applicable (no h/c contact)	Variable (depends on location)	-	-	
Reservoir	Sandstone	Carbonates (calcite. Dolomite)	Sandstone	Sandstone	-	Clastic (Bundsandstein)	Sandstone
Water drive				Moderate		Almost none	
Initial res. Pressure				395 bar		20 bar	
Final res. Pressure				485 bar (depends on EOR)		<320 bar	
Miscible / immiscible CO_2 injection	n/a	n/a	n/a	miscible	n/a	n/a	n/a
Minimum miscibility pressure	n/a	n/a	n/a	215 bar (pure CO_2)	n/a	n/a	n/a
WAG, SWAG?	n/a	n/a	n/a	Probably not (to be confirmed)	n/a	n/a	n/a
Amount of CO_2 recycled	n/a	n/a	n/a	55–120 x 10^9 m^3 (~105-220 Mt (w CH_4)	n/a	n/a	n/a

Structured aquifer: geometry, volume			4-way dip closure; double crested site. Static capacity estimated at 900-1200 Mt. Dynamic capacity estimated at 200Mt. (static capacity very large but less relevant; dynamic capacity in part dependent on development plan (e.g. brine production)	Anticline; pore volume 250 x 10^6 m^3	Anticline		
Unstructured aquifer: inclination, depth	Unconfined aquifer 5º dip to 2100 – 2800 m deep (top reservoir)	-	n/a	n/a	2500m		Near horizontal sandstone formation (minor topography which does control CO_2 plume)
Brine production (pressure management)	No	-	None currently planned	Incidental to oil production; possibly increased for pressure management	-		No (some water production from Utsira regionally)
Brine displacement	Negligible	-	Will occur, details not currently available, will be modelled	Expected to be minor; depends on details to be determined	-		Insignificant (behaves as open aquifer)
Interference with other activities if any	No	-	Offshore wind licences; & hydrocarbon activity (discussions with relevant parties and regulatory authorities	Co-located Petroleum Production License (UK)	-		None (CO_2 plume unlikely to intersect any exploration wells in the area)

APPENDIX 2: Glossary

AMT	Audio-magnetotellurics
AVO	Amplitude versus offset
Ar	Argon
BAT	Best Available Technology
BarA	Absolute pressure
BarG	Gauge Pressure
CAPEX	Capital expenditure
CBL	Cement bond logging
CCS	Carbon capture and storage
CCS Directive	European Directive 2009/31/EC on the geological storage of carbon dioxide
CCSR	CCS ready
CCUS	Carbon capture use and storage
CH4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CPS	Carbon Price Support
CSEM	Controlled Source Electromagnetic
DTS	Distributed temperature sensor
EC	European Commission
EEPR	European Energy Programme for Recovery
EIA	Environmental impact assessment
ELOT	Extended Leak off Test
EOR	Enhanced oil recovery
EOS	Equation of state
EPC	Engineering, procurement and construction
ERT	Electrical resistivity tomography
ESP	Electric submersible pump
FDS	Formation Damage Study
FEED	Front end engineering design
FFMs	Full field models
FID	Final investment decision
FIT	Feed-in tariff
FOAK	First-of-a-kind
Gt	Gigatonne
H_2	Hydrogen
H_2S	Hydrogen sulphide
HAZID	HAZard Identification
HAZOP	HAZard & Operability analysis
InSAR	Interferometric synthetic aperture radar
ISO	International Standards Organization
Kg	Kilogram
km	Kilometre
LOT	Leak off test

MEA	Monoethanolamine
MMP	Minimum miscibility pressure
mmscfd	Million standard cubic feet per day
MMV	Monitoring, measurement and verification
Mt	Megatonne (one million metric tonnes)
MT	Magnetotellurics
MVA	Monitoring, verification and accounting
Mtpa	Million tonnes per annum; million tonnes a year
MW	Megawatt – a unit of power
Mwe	Megawatts electrical capacity
MWh	Megawatt hour – a unit of energy
MW/h	Megawatt per hour (change of power per hour)
MWth	Megawatt thermal
N_2	Nitrogen
NH_3	Ammonia
Nox	Nitrogen oxides
NPAA	Norwegian Petroleum Activities Act
NUI	Normally Unattended Installation
O_2	Oxygen
OBC	Ocean Bottom Cable
OBS	Ocean Bottom Seismometers
OEM	Original equipment manufacturer
OPEX	Operating expenses
ppm	Parts per million
PVT	Pressure, volume and temperature
R&D	Research and Development
RD&D	Research, Development and Deployment
SO_2	Sulphur dioxide
SOx	Sulphur oxides
WAG	Water alternating gas
WEP	Well Engineering Partners
WHP	Well heat pressure
WHT	Well heat temperature
WHTP	Well heat temperature & pressure
VDL	Variable density log

The European CCS Demonstration Project Network was established in 2009 by the European Commission to accelerate the deployment of safe, large-scale and commercially viable CCS projects. The Network that has been formed is a community of leading demonstration projects which is committed to sharing knowledge and experiences, and is united towards the goal of achieving safe and CCS. The learnings that are gained will be disseminated to other projects, stakeholders and public to help gain acceptance of the technology –and support CCS to achieve its full potential as a vital technique in our fight against climate change.

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