CCS – Carbon Capture and Storage – a method for reducing CO₂ releases to the atmosphere

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Outline

• What is CCS
• Key processes
• Example industrial scale projects
• Key issues and challenges
• Examples of recent EU funded research at Uppsala including our pilot injection site and status of CCS in Sweden
Principle of CCS

- Several kilometers
- Supercritical CO$_2$
- A sufficiently impermeable seal (cap rock)
- A sufficiently permeable reservoir rock
- Brine
- CO$_2$
Conditions such that CO2 naturally in supercritical form – volume decreases
Estimate of role of CCS in reducing atmospheric CO$_2$

- **IEA ETP**: CCS plays a key role in 2°C scenario

![Graph showing global CO$_2$ reductions by technology area, 2013-2050](source: Tim Dixon, IEAGHG, May 2017)

- **Global CCS Institute** assessment (Major strides in 2017 for CCS): CCS critical if Paris Agreement climate goals are to be met.
Options for Geological Storage

- deep saline aquifers
- depleted oil and gas fields
- unmineable coal seams
- other options (e.g. basalts)

Depleted oil/gas fields:
- Well understood, lot of data, EOR possibility, proven capability to hold hydrocarbons
- Extensively drilled (leaks?), not sufficient volumetric capacity

Deep saline formations
- Largest overall capacity
- Less previous data, not as well demonstrated (sealing capacity)
Estimates of storage capacity

Geological storage potential

- **40 Gt**
  - <2% of emissions to 2050
  - 370-1100 Gt

- **920 Gt**
  - 45% of emissions to 2050
  - 740-1850 Gt

- **400-10,000 Gt**
  - 20-500% of emissions to 2050
  - 370-3700 Gt

IEA (at costs up to $20/t)
Parson & Keith, Science 282, '98
Global distribution of CO₂ sources

Geographic distribution of large stationary sources

Distribution of sources by sector
Prospective areas in sedimentary basins world-wide (IPCC, 2005).
Sources of emissions

Energy production remains the primary driver of GHG emissions.

- **Energy Sector**: 35%
- **Agriculture, forests and other land uses**: 24%
- **Industry**: 21%
- **Transport**: 14%
- **Building Sector**: 6.4%

*Source: Tim Dixon, IEAGHG, May 2017*
Distribution of CO$_2$ sources in Sweden/Baltic

Distribution of sources by sector

Geographic distribution of large stationary sources
Swedish geology

- Crystalline rock not usually considered suitable
- Some potentially suitable sedimentary rocks (see map and purple)

Prospective areas in sedimentary basins in Swedish territory (after Henkel et al, Erlström et al, 2011)
How is CO$_2$ stored in the deep aquifer?

Figure 5.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO$_2$ trapping and geochemical processes of solubility trapping and mineral trapping increase.
How is CO₂ stored in the deep aquifer?

CO₂ gets physically trapped beneath the sealing cap-rock and low permeability layers.

Figure 5.9: Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO₂ trapping and geochemical processes of solubility trapping and mineral trapping increase.
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CO₂ gets trapped as immobile isolated residual 'blobs' in the pore space.

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1. **CO₂ gets physically trapped beneath the sealing cap-rock and low permeability layers.**

2. **CO₂ gets trapped as immobile isolated residual 'blobs' in the pore space.**

3. **CO₂ dissolves into water.**

4. **CO₂ converts into solid minerals.**

*Figure F.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO₂ trapping and geochemical processes of solubility trapping and mineral trapping increase.*
Evolution from mobile to residual CO2
Main issue is obviously to keep the CO2 contained

- Proper characteristics of the reservoir
- Integrity of the seal
CO2 Release: Focused Flow Paths

Leakage through Abandoned Wells

Leakage through Faults and Fractures in Caprock

Limiting Factors:
Solubility Trapping, Mineral Trapping, Residual Gas Trapping
Possible effects to shallow groundwater systems

Birkholzer et al. (2011)
Large scale industrial projects

Snohvit
0.7 Mt/y CO₂

Port Arthur
0.925 Mt/y CO₂

In-Salah
1.2 Mt/y CO₂

Sleipner
1 Mt/y CO₂

Weyburn
2.5 Mt/y CO₂

Modified from John Gale, IEAGHG
Sleipner (North Sea) project

- longest running environmentally motivated CCS project
- operating since 1996
- Ideal storage reservoir (uniform, thick, extensive, high porosity, high permeability reservoir layer, thick seal of shale)
Seismic monitoring to observe the plume at Sleipner
Weyburn (Canada) project

- EOR (Enhanced Oil Recovery) purposes
- largest amount stored so far
- seismic monitoring has been successful here too

Reservoir: “Midale Marley”

Seismic image of CO₂ in Weyburn reservoir (White 2009)
In Salah (Alger)

- Gas field, injection since 2004
- Application of seismic monitoring challenging
- **InSar maps of surface deformation** together with geomechanical modeling key to understanding CO2 migration

Map of surface displacements from InSAR Measurements; blue shows ground level rise in region of injection wells (Ringrose et al. 2009)
Snøhvit, implement CO\textsubscript{2} storage offshore in North Atlantic

Compliments; Tore Torp/ Statoil
Statoil’s CO₂ Storage Sites

- Snøhvit
- Sleipner
- In Salah

Unique blend of:
- offshore/onshore
- Shallow deep
- Horizontal/vertical wells

Compliments; Tore Torp/ Statoil
Storage Reservoir Characteristics

- **Sleipner** – open system
- **Weyburn**
- **In-Salah**
- **Snohvit** - closed system?

Compliments: John Gale, IEAGHG
Progress with integrated projects

- Power (pre-combustion)
  - Kemper, United States
- Power (post-combustion)
  - Boundary Dam, Canada
  - Rosemont, United States
- Iron and steel
  - ESI, United Arab Emirates
- Biofuels
  - Great Plains, (Weyburn), United States
- Refining
  - Enid, United States, 1982
- Chemicals
  - Shute Creek, United States, 1986
- Gas processing
  - Sleipner, Norway, 1996
  - Val Verde, United States, 1972

- TCEP, United States
- HECA, HPAD, United States
- Taylorville, United States
- Parish, United States
- Decatur, United States
- Quest, Canada
- Port Arthur, United States
- ACTL Sturgeon, Canada
- Medicine Bow, United States
- Lake Charles, United States
- ACTL Redwater, Canada
- Spectra, Canada

Source: Global CCS Institute data

Compliments: John Gale, IEAGHG
Key CCS project developments (2016)

CCS activity by region

Global CCS Update

Source: Tim Dixon, IEAGHG, May 2017
## Key challenges

**Technical**
- Storage capacity
- Cost - primarily capture
- Possible environmental risks
  - leakage
  - brine migration and pressure increase
  - mechanical integrity, induced seismicity

**Non-technical**
- Financial uncertainty
- Regulatory uncertainty
- Public acceptance
- Infrastructure
Key Geoscience Research Areas

• Reservoir processes;
  - behavior of the plume, trapping processes, reservoir pressure, seismicity and geomechanical stability

• Monitoring;
  - surface and subsurface; improved quantification, method integration

• Site Characterization
• Risk assessment
• Mitigation
• Storage capacity assessment
• Ongoing research at Uppsala, Dept Earth Sciences
Our recent EU funded R&D projects

**MUSTANG** – large-scale integrating project for quantifying Saline Aquifers for CO2 Geological Storage (2009-2014)

**Panacea** – project focusing on long term effects of CO2 Geological Storage (2012-2014)

**TRUST** – project continuing and expanding the field experiment of MUSTANG (Nov. 2012-Nov 2017)

**CO2QUEST** – project focusing on effect of impurities of CO2 stream (March 2013- June 2016)
• MUSTANG (www.co2mustang.eu)

• Develop **methodology and understanding** for the quantification of saline aquifers for CO2 geological storage

• **Large scale integrating project**, 19 partners, 24 affiliated organizations

• **7 test sites** including **one deep injection experiment** and **one shallow injection experiment** of CO2, as well as strong laboratory experiment, process understanding and modeling components
Understanding the site properties

Contributing: UU, SGU, UNOTT, CSIC, LIAG, UGÖTT, GII, IIT, EWRE, UB, CNRS, UEDIN

USA
- exchange with LBNL (Westcarb, Frío), natural analogue sites

Australia
- CO₂CRC, Otway site

Japan
- Oil, Gas and Metals Corp., natural analogue studies

Map showing test sites across Europe, including Southwestern Spain, Germany, and Romania.
Example – South Scania Site Sweden

Contributing: UU, SGU
Improving the field testing methods

CO2 Injection-monitoring – sampling system

Geophysical methods

Seismic Imaging at different frequencies

2D reflection imaging before and after injection of a small amount of CO2

O2 front and changing interface

Phenolacetate in CO2
Phenol and Acetate in H2O

Interface-specific tracers

Contributing: UU, UGÖTT, GII, EWRE, CNRS, Imageau, Vibrometric, CSIC, Class VI Solutions
Laboratory Experiments

Reservoir rock samples

Caprock samples

Reservoir rock samples

Brine-CO2 mixture properties

Fractured caprock alteration

Reservoir properties

Contributing: CNRS, UGÖTT, KIT, UEDIN, UU
Heletz, Israel CO2 injection site

- Developed within projects MUSTANG, CO2QUEST, TRUST
- Scientifically motivated small-scale injection experiment site with injection to a layer at 1.6 km depth
- EWRE, Israel and UU key developers of the site
- First injection experiment was carried out in Sept 2016, continuation during 2017-2018
Heletz deep CO₂ injection experiment site

- Scientifically motivated CO₂ injection experiment site of scCO₂ injection to a reservoir layer at 1600 m depth, with comprehensive monitoring and sampling
- Developed in the frame of EU FP7 projects MUSTANG, TRUST and CO2QUEST

Heletz

Total meeting 2018-01-22
Heletz site – well instrumentation and injection system

Fluid injection/withdrawal, P/T sensors, U-tube fluid sampling, optical fibre
Extensive site characterization and core analysis

- **old data from oil exploration studies** re-analyzed as background
  > main structures and porosity/permeability relatively well known
- **area near the injection site characterized in more detail** for CO2 relevant properties
  > surface and borehole geophysics, geological characterization, hydraulic testing on cores and in-situ, minararology, two-phase flow properties, rock-mechanical properties, thermal properties

- **Special Edition of International Journal of Greenhouse Gas Control** Niemi, Gouze, Bensabat (eds.); Volume 48, Part 1, Pages 1-186, May, 2016 *Characterization of formation properties for geological storage of CO₂ – Experiences from the Heletz CO₂ injection site* and other example sites from the EU FP7 project MUSTANG

Data from old oil wells for the entire region gave a good basis, locally refined based on data from the new wells.
Site Characterization: conductivity and porosity

‘A’ sand (average ~17.8%)

‘A’ sand (average ~150mD)

Table 10: Statistical data for Heletz sand layer permeabilities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Layer</th>
<th>Data base</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ, σ (m² and mD)</td>
<td>-13.25, 1.1</td>
<td>A</td>
<td>borehole porosity logs</td>
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<tr>
<td>of model to log-converted data</td>
<td>2.1, 1.1 (log mD)</td>
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<td>Vertical variogram for log(k)</td>
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<td>Separation distance (m)</td>
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</tbody>
</table>

Data from entire Heletz formation:

Parameter | Values | Layer | Data base                      |
μ          | 0.725   | A, K  | borehole porosity logs         |
σ          | 2.526   | A, K  | borehole porosity logs         |
A          | -13.25  | W     | borehole porosity logs, wells  |
B          | 1.1     | W     | borehole porosity logs, wells  |
C          | 1.1     | W     | borehole porosity logs, wells  |

Data from old wells in the vicinity of experimental area:

Parameter | Values | Layer | Data base                      |
μ          | 1.43   | A     | borehole porosity logs, wells  |
s          | 0.725  | A, K  | borehole porosity logs, wells  |
σ          | 2.526  | A, K  | borehole porosity logs, wells  |
A          | -13.25 | W     | borehole porosity logs, wells  |
B          | 1.1    | W     | borehole porosity logs, wells  |
C          | 1.1    | W     | borehole porosity logs, wells  |

Data from the new drilled wells:

Parameter | Values | Layer | Data base                      |
μ          | 100-410 | W     | Core samples, only tests with in-situ P/T conditions included |
σ          | ~13-12.4 | W     | Core samples, only tests with in-situ P/T conditions included |
σ          | 35/135  | A     | In-situ well test, provides an ‘upscaled’ value for the entire layer |
σ          | 35/135  | A     | In-situ well test, provides an ‘upscaled’ value for the entire layer |
Site Characterization - two-phase flow properties


Experimental program outline

Small scale injection experiments with focus on quantifying CO2 trapping and effect of impurities

(1) **Single-well residual trapping experiment I** (residual CO2 zone created by CO2 injection, followed by fluid withdrawal) (Autumn 2016)
- Thermal/hydraulic testing for determining interlayer heterogeneity (summer 2017)

(2) **Single-well residual trapping experiment II** (residual CO2 zone created by CO2 injection, then CO2 saturated water injection) (Aug – Oct 2017)

(3) CO2 injection and monitoring with **geophysical methods** (Nov-Dec 2017)

(4) Injection of CO2 with **impurity gases** (SO2 and N2) along with CO2 (beginning of 2018)
Important to characterize residual trapping in-situ

 injection-withdrawal of scCO2 and brine

 zone of residual trapped scCO2

- Hydraulic tests
- Thermal tests
- Tracer tests

Estimate of residual trapping when performed with and without residual CO2

- Otway, Australia experiment demonstrated that pressure signal was an effective measure for differentiating residual saturation of gas ($S_{gr}$)

Paterson et al, 2011. CO2CRC report RPT11-3158
Creating the residually trapped zone

**Option 1:** Inject CO\(_2\), then inject water to push the CO\(_2\) further and leave the residual zone behind

**Option 2:** Inject CO\(_2\), then pump it back and leave the residual zone behind

Option 2 was used in first experiment, the achievement of residual zone was followed by evolution (i) tracers\(^1\) and (ii) pressure difference in the borehole test interval (pressure difference between the upper and lower sensor relates to the fluid composition (CO\(_2\)/water) in the interval, Option 1 in the second one

Sequence of the Residual Trapping Experiment I

1) **Hydraulic withdrawal test** for getting the pressure response *prior* to creating the residual CO2 zone

2) Inject indicator tracer (Rasmusson et al, 2014)
3) Inject 100 tons of CO2
4) Withdraw of fluids *until residual saturation is reached* (follow both the tracer and the evolution of pressure difference in the well)

5) **Hydraulic withdrawal test** for getting the pressure response *after* creating the residual CO2 zone

- P/T was continuously monitored
- CO$_2$ mass flowrate, temperature, pressure and density recorded
- DTS was recorded during the entire sequence;
- Downhole fluid sampling and measurement of high pressure pH and low pressure alkalinity and gas composition, as well as measurement of partial pressure of CO$_2$ were measured during the production phase.
Heletz site – push-pull Residual trapping Experiment I
Main concept of the Residual Trapping Experiment II (Aug – Oct 2017)

1) Hydraulic injection/withdrawal of water and partitioning tracers Kr/Xe for getting the pressure and tracer response prior to creating the residual CO2 zone

3) Inject 100 tons of CO2
4) Inject water saturated with CO2 to push away the mobile CO2, to generate the residually trapped zone

5) Hydraulic injection/withdrawal of water and partitioning tracers Kr for getting the pressure and tracer response after creating the residual CO2 zone

- P/T was continuously monitored
- CO₂ mass flowrate, temperature, pressure and density recorded
- DTS was recorded during the entire sequence;
- Downhole fluid sampling and measurement of high pressure pH and low pressure alkalinity and gas composition, as well as measurement of partial pressure of CO₂ were measured during the production phase.
- Tracer concentration analysis
Conclusions of the Residual Trapping Tests I and II so far

- **Test I** essentially analyzed, both with an analytical model and TOUGH2 shows relatively low residual trapping at Heletz.
- Analysis with well-reservoir model underway and should provide more information in support of the TOUGH2 analysis.
- **Test II** successfully completed and meaningful tracer breakthrough curves obtained. Analysis underway.
- **Together** these tests should provide a good understanding of CO2 residual trapping at Heletz and provide procedures and methods for other sites as well.
Insight is also being gained by means of pore-network modeling.

- **Pore network modeling** to analyze the residual trapping in the 450 mD cores.

  > the model has now been successfully fitted to the Stanford University experimental data (Rasmusson et al., 2017) and now the higher permeability cores by Göttingen (Tatomir et al., 2016) are being modelled > different residual saturation?


Possibilities to store CO2 in Sweden/Baltic?

- Two feasibility studies since May 2012, financed by the Swedish Energy Authority
- **SwedeStoreCO2**: to look at possibilities for a pilot scale injection experiment in the Swedish territory
- **BASTOR**: to look at possibilities to store CO2 in the Baltic Sea
  - So far financing by Finland and Sweden
  - Contact person Per Arne Nilsson, PanaWare
THE DATA BASE – about 50 wells
Model region for dynamic modeling

Table 1. Summary of the geo-hydrological properties mapping from the static model

<table>
<thead>
<tr>
<th>Data Resolution</th>
<th>1000m</th>
<th>20,60%</th>
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<tbody>
<tr>
<td>Porosity</td>
<td>4,30%</td>
<td>-</td>
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<tr>
<td>permeability</td>
<td>8,5 mD</td>
<td>- 300 mD</td>
</tr>
<tr>
<td>formation top</td>
<td>-225 m</td>
<td>- -1756 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0 m#</td>
<td>- 82 m</td>
</tr>
</tbody>
</table>
Example BASTOR outcome - First dynamic simulation estimates of the storage capacity in the main geologic formation in the Baltic Sea

Figure 13 Porosity (to the left) and Permeability (to the right) of the Dalders Monocline.

SLR ‘Final report on prospective sites for the geological storage of CO2 in the southern Baltic Sea’ (http://www.globalccsinstitute.com/publications/final-report-prospective-sites-geological-storage-co2-southern-baltic-sea)


For introductory reading about CCS

CO2GEONET is a European network disseminating about CCS > see

http://www.co2geonet.com/
The Intergovernmental Panel on Climate Change (IPCC) Special Report provides information for policymakers, scientists and engineers in the field of climate change and reduction of CO2 emissions. It describes sources, capture, transport, and storage of CO2. It also discusses the costs, economic potential, and societal issues of the technology, including public perception and regulatory aspects. Storage options evaluated include geological storage, ocean storage, and mineral carbonation. Notably, the report places CO2 capture and storage in the context of other climate change mitigation options, such as fuel switch, energy efficiency, renewables and nuclear energy.

This report shows that the potential of CO2 capture and storage is considerable, and the costs for mitigating climate change can be decreased compared to strategies where only other climate change mitigation options are considered. The importance of future capture and storage of CO2 for mitigating climate change will depend on a number of factors, including economic incentives provided for deployment, and whether the risks of storage can be successfully managed. The volume includes a Summary for Policymakers approved by governments represented in the IPCC, and a Technical Summary.

The IPCC Special Report on Carbon Dioxide Capture and Storage provides invaluable information for researchers in environmental science, geology, engineering and the oil and gas sector, policy makers in governments and environmental organizations, and scientists and engineers in industry.

The Intergovernmental Panel on Climate Change (IPCC) was established jointly by the World Meteorological Organization and the United Nations Environment Programme (UNEP). The Panel provides authoritative international assessment of scientific information on climate change. This report was produced by the IPCC on the invitation of the United Nations Framework Convention on Climate Change.


2005
In Swedish conditions
..going into the methods in depth..

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Editors: Niemi, Auli, Bear, Jacob, Bensabat, Jacob (Eds.)

Thank you for your attention!

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