Geological Storage of CO$_2$: B) Project design and global scale-up

ETH Course on CCS and the Industry of Carbon-Based Resources
23 March 2020

Philip Ringrose
Norwegian University of Science and Technology (NTNU) and Equinor Research Centre, Trondheim, Norway
Norway CCS: Building on experience

- 23 years of operations
- Building confidence in CCS
- >24 Mt CO₂ stored
- New full-scale CCS project being developed
So how do you design a storage project?

Things you need to know:

- CO₂ supply – rates, pressures, temperatures
- Reservoir depth, water depth
- Storage site capacity
- Well design
- Site performance (plume behaviour)
- Reservoir properties
- Overburden & seal characteristics
- Regional aquifer
Sleipner CO$_2$ Injection Well Design

Key elements of the design (Hansen et al. 2005):

- Long-reach horizontal well with a sail angle of 83°
- Perforated injection interval of 38m with the top of the injection interval at 1010m TVD MSL
- High Chromium (25% Cr) stainless steel was used for the 7” injection tubing and the exposed sections of the 9 5/8” well casing.

N.B. Initial injection problems due to sand influx were solved by re-perforation of the injection interval and installation of sand and gravel packs (as shown here) and described by Hansen et al. 2005.
Injection well placement

The main choices for well placement are:

• Good reservoir quality (hence injectivity)
• Down-dip versus crestal
• Vertical or deviated
• Simple or multiple completion intervals

Some key issues are:

• Getting sufficient injectivity
• Geological heterogeneity
• Plume migration strategy
• Ensuring long-term containment

Wherever you choose to inject, basic physics tells us to expect upward migration – so injection near the base of the unit makes most sense.
Snøhvit: first and only offshore CO$_2$ pipeline

- Combines onshore capture (combined with LNG) with offshore storage project
- 150km seabed CO$_2$ transport pipeline
Small-scale CO₂ ships already exist – Yara in North Sea

1500 m³ capacity at ~20 bar and ~-20 C

Source: Yara/Norsk Hydro
CO₂ paths on phase diagram
with typical conditions for CO₂ storage operations

-56.6 °C, 5.2 bara

- Solid
- Liquid
- Vapour
- Two-phase flow
- Liquid near boiling point

Snøhvit (WH)
Sleipner (WH)
Reservoir

Big ships
Small ships

Critical point
30.98 °C
73.8 bara

Surface

Dense

Pressure (bara)

Temperature (°C)
CO$_2$ compression and cooling in PH diagram

![Diagram showing compression and cooling of CO$_2$ in a PH diagram. The diagram includes pressure and enthalpy axes, with phases V+L, L+S, V, and S indicated.](Image)

Enthalpy (kJ/kg) vs. Pressure (bara) with various points marked at different pressures and enthalpies. An isentrope line is shown, indicating the path of compression and cooling. Courtesy Gelein de Koeijer, Equinor.
$\text{CO}_2$ compression and cooling in PH diagram

![PH Diagram](image-url)
Northern Lights – Design concept

https://ccsnorway.com/

Shipping concept
- One ship per capture site
- 7,500m³ of CO₂ per ship

Pipeline design:
110km - 12 inch
Some issues for project design:
1 - Changes in impurity concentrations

Changes in impurity concentrations ...

... can change density and viscosity ...

... and change storage efficiency.
Effect of some CH$_4$ in CO$_2$

![Graph showing the effect of some CH$_4$ in CO$_2$.](image)

- Boiling line pure CO$_2$
- Hydrate pure CO$_2$
- Phase envelope 5% CH$_4$
- Hydrate 5% CH$_4$
- Typical for transport

Locations:
- Snøhvit
- Sleipner
- In Salah
- Critical point

From capture

Courtesy Gelein de Koeijer, Equinor
Issue 2 - Corrosion

Remaining \( \text{H}_2\text{O} \) (liquid), \( \text{NO}_x \) or \( \text{O}_2 \) from capture .. can lead to corrosion in pipeline .. and wells.
Corrosion example

Source: http://octane.nmt.edu/WaterQuality/corrosion/CO2.aspx
Issue 3 - Rock mechanics

- Pressures in rock formations are controlled by the rock stresses and the ability of the fluids to escape.
- Under normal conditions, the pore fluids are assumed to be in hydrostatic equilibrium.
- The rock stresses are controlled by the lithostatic or overburden stress and the tectonic stress field.
- Rock will fracture when the pore pressure exceeds a certain fracture pressure, which is controlled by the stress field and the rock properties.
The capacity controversy

• Ehlig-Economides & Economides (2010) published an analysis on “Sequestering carbon dioxide in a closed underground volume.” They concluded that:

  “… the volume of liquid or supercritical CO₂ to be disposed cannot exceed more than about 1% of pore space. [And that this] renders geologic sequestration of CO₂ a profoundly non-feasible option for the management of CO₂ emissions.”

• This study argued that the maximum storage efficiency value, ε, was 1% – significantly lower than the values used by CO₂ storage capacity estimation studies.

• There was a strong reaction to the E&E (2010) paper, e.g. from Cavanagh et al. (2010) who argued that:

  ➢ the E&E analysis of open systems was flawed
  ➢ the E&E closed-system model was based on an incorrect conceptual model
  ➢ study used an overly simplistic mathematical analysis
  ➢ and that large-scale geological CO₂ storage is feasible.
Is there enough room for CO\textsubscript{2} storage?

Most people agree that you cannot inject very much fluid into a “confined box.”

There are three important limiting factors:

1. The size of the box (the storage unit)
2. The properties of the box boundaries (faults and shale sealing units)
3. The ability of the box to absorb increased pressure (rock and fluid compressibility).

Zhou et al. (2008) concluded that:

- Storage efficiency is \(~0.5\%\) for closed systems
- But that a semi-closed system with a seal permeability of \(10^{-17} \text{ m}^2\) (0.01 md) or greater behaves essentially as open system with respect to pressure buildup (due to brine leakage).

Sketch of open, closed or semi-closed systems, from Zhou et al. (2008)
Issue 4 - The earthquake controversy

In 2012, Zoback and Gorelick created a stir by stating that:

There is a high probability that earthquakes will be triggered by injection of large volumes of CO₂ into the brittle rocks commonly found in continental interiors.

[And that]..., in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

- Their main argument was that the Earth’s crust is critically stressed and that fluid injection in deep wells can trigger earthquakes when injection increases the pore pressure close to potentially active faults.
- They also accept that individual projects (like Sleipner) can be executed safely, and mainly argued that it is large-scale CCS cannot be done safely.
Earthquakes and CO$_2$

There were many responses to the Z&G (2012) statement, most notably Vilarrasa and Carrera (2015), who argued that: “Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO$_2$ could leak”

They presented four main arguments supporting their case:

i. Sedimentary basins are not normally critically stressed

ii. Highest injection pressures occur at the start and can be controlled

iii. Capillary forces retain CO$_2$ while allowing water to dissipate

iv. CO$_2$ gradually dissolves in the brine phase

Data and models of friction coefficients from Vilarrasa & Carrera (2015), PNAS
Geomechanics overview

- Need to separate expected mechanical response from unwanted effects

From Rutqvist (2012)
Seismicity observed in CO$_2$ injection projects

At Weyburn (Verdon et al. 2013), the long field history led to complicated pattern of micro-seismicity:

- Most events related to production wells and during shut-in of CO$_2$ injection well.

Weyburn micro-seismic monitoring (Verdon et al., 2013) showing geophones (gray triangles), injection wells (purple lines), and production wells (black lines). Events are colored by occurrence time: before CO$_2$ injection (yellow), during the initial injection stages (dark blue), during a period of elevated injection (green), during the second phase of monitoring (light blue), and after injection well shut-in September 2010 (red).

Legend:
- SATELLITE GEODESY
- SURFACE UPLIFT
- BEDDING PARALLEL SLIP
- WELLBORE FAILURE
- REACTIVATION
- FAULT REACTIVATION
- MICROSEISMIC MONITORING
- INFLATION OF RESERVOIR
- BOREHOLE TILT METER
Issue 5) Could it leak out?

1. A lot of public concern around the topic of possible leakage:
   - Based on evidence or rumours?

2. Many natural stores of CO₂ in volcanically active regions of the world:
   - Bravo Dome in New Mexico contains 1.6 Gigatons of CO₂ which has been there for approximately 1.3 million years (Sathaye et al. 2014; PNAS)

3. Humans (especially the Romans!) have been living alongside natural CO₂ vents for 1000’s of years

4. Study of a 400-thousand-year-old leaky fault in a CO₂ volcanic region (Paradox Basin Utah) shows a maximum leakage rate of ~870 t/yr (Burnside et al. 2013; Geology, 41, 471-474)
   - at the Crystal Geyser tourist spot!

“Jenn couldn’t resist playing in the geyser. They don’t let you do this in Yellowstone!”
Travel blog from www.rvoutoftheratrace.com/My%20Albums/Utah%20Sep%202008/slides/Jenn%20playing%20in%20Crystal%20Geyser.html
Communicating storage effectiveness

Five arguments for storage safety

1. Climate protection
2. Physical basis
3. Operational experience
4. Geophysical monitoring
5. Regulatory compliance

(Furre et al. 2019, First Break 37, 83-89)

Laboratory demonstration of capillary seal - using an aquarium tank, air and a food sieve

https://www.youtube.com/watch?v=8-dXwakvmsI
Ongoing work on storage risks

In support of the Northern Lights project and for future storage scale up, Equinor and many partners are working on:

• Fault mapping from seismic
• Fault Seal and fault permeability
• Pressure communication
• 3D geological modelling
• Geomechanics and strain
• Micro-seismic monitoring
• Flow simulation

Long Wu et al (2019), EAGE Fault & Top Seal Conference
Back to the big questions?

- Is large-scale CCS at all realistic? If so, what would it take to actually deploy it?

Global distribution and thickness of sediment accumulations on continental margins, with largest oilfields and main river systems (Ringrose & Meckel, 2019)
Ringrose & Meckel (2019) paper on feasibility of global offshore storage

Propose that initial and final pressure per well can be used to estimate capacity

**Generic ‘basin ΔP’ approach:**

Integration of the injectivity equation over the project lifetime:

\[ V_{project} = I_c \left( p_{well} - p_{init} + \int_{i}^{f} A p_D(t_D) \right) + F_b \]

where,

- \( V_{project} \) = estimated volume stored
- \( I_c \) = injectivity
- \( p_{well} \) = injection well pressure
- \( p_{init} \) = initial reservoir pressure
- \( A p_D(t_D) \) = characteristic pressure function
- \( F_b \) = volume flux boundary condition
We also need to know well delivery rates

- CO₂ injection well data set (60 years of injection from 9 wells)

A. All CO₂ injection wells

B. Offshore wells only

4 scenarios modelled to illustrate the range of expected behaviours

Shallow open
Medium confined
Deep open
Deep confined

Statistics used for global basin forecasts:
- P90 = 0.33 Mt/year
- P50 = 0.70 Mt/year
- P10 = 1.06 Mt/year
Application of $\Delta P$ method to global developments

- Projected growth of CO$_2$ injection wells based on historical hydrocarbon well developments.
- Concept captures industrial maturation phases for global CO$_2$ storage.
- Uncertainty range based on bounds (P10 - P90) from empirical injection rates.

**Main finding:**
We will need ~12,000 CO$_2$ injection wells by 2050 to achieve 2DS goal.

---

![Graph showing the number of active CO$_2$ injection wells and cumulative CO$_2$ injected over time.](image-url)
Main findings: Global scale-up

Using historical well development trajectories transposed into a future CO₂ injection industry, we can infer that:

• A single ‘Gulf-of-Mexico well development’ CO₂ injection model could achieve the 7 Gtpa storage by 2043 and 12 Gtpa by 2050. Cumulative storage in 2050 would be 116 Gt.

• Alternatively, five ‘Norway offshore well development’ models could achieve the 7 Gtpa storage by 2050. Cumulative storage in 2050 would be 73 Gt.

• Cumulative storage of >100 Gt by 2050 is most efficiently achieved with 5-7 regions pursuing a Norwegian-scale offshore well development model:
  − Resources are equitably distributed and would likely occur in multiple offshore basins close to the main locations of onshore capture

It will only take a fraction of the historic worldwide offshore petroleum well development rate to achieve the global requirements for geological storage of captured CO₂ under the 2DS scenario.
A practical pathway for global CO$_2$ storage

- Let’s assume we have five continental clusters around the planet
- What would the build-out rate look like?

Next 10 years: about 200 wells per cluster

By 2040: about 1000 wells per cluster
Summary

1. Reviewed main elements in CO₂ storage project design:
   - Building on operational experience
   - Identifying some key issues and questions

2. Proposed an approach to quantify a pathway for global scale-up:
   - Number of wells needed under the 2DS scenario is only a fraction of the historic worldwide petroleum well development rate
   - CO₂ storage is best achieved with a limited number of dedicated storage hubs/clusters
Main supporting references


