Design of subsurface CO$_2$ storage

Martin Blunt

Shell Professor of Reservoir Engineering
Department of Earth Science & Engineering
Imperial College London
What to do with the CO$_2$?

IPCC Special report 2018 – limiting warming to 1.5 °C: up to 1,000Gt of CCS.
Global distribution of sedimentary basins

IPCC (2005) Special Report on Carbon Capture and Storage
Vast capacity for CO$_2$ storage globally

First generation of projects underpinned by up to 350 Gt capacity in oil and gas reservoirs

Budinis, Krevor, Mac Dowell, Brandon, Hawkes (2016) Sustainable Gas Institute White Paper
CCS exists: decades of injection & monitoring

CO2-EOR 1972, eg Scurry County, Texas, Rangeley, Weyburn ....

Sleipner: CO2 climate mitigation 1996, North Sea

10/10 No leaks

10/10 Great job
Where is CO$_2$ storage happening?

Injection into oil reservoirs dominates, 11 of 14 industrial scale projects

Revenue from EOR
Site characterisation
Infrastructure


= 1Mtpa of CO$_2$ (area of circles proportional to capacity)

* Injection currently suspended
Billions of Tons Carbon Emitted per Year

Historical emissions

Flat path

Current path = “ramp”

16 GtC/y

Eight “wedges”

Goal: In 50 years, same global emissions as today

Carbon Mitigation Initiative, Princeton University - http://cmi.princeton.edu/about/
What is a “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.

Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A “solution” to the CO₂ problem should provide at least one wedge.

Carbon Mitigation Initiative, Princeton University - http://cmi.princeton.edu/about
15 Wedge Strategies in 4 Categories

- Energy Efficiency & Conservation
- Nuclear Power
- Stabilization Triangle
- Fossil Fuel-Based Strategies
- Renewables & Biostorage

Carbon Mitigation Initiative, Princeton University - http://cmi.princeton.edu/about/
Costs of storage are low compared to the costs of capture

Recent estimates for the UK put costs at £11-20/tCO₂, much associated with capex for transport infrastructure.

Cost supply curve of transport and storage estimated for China. From Dahowski et al. (2009) Regional Opportunities for Carbon Dioxide Capture and Storage in China, PNNL-19091
Remedy for policy: Oxburgh Report 2016

There are three failures to address

1) **Expense**: create a national CCS company, who develop the first full chain capture-transport-storage infrastructure in each region. Delivery at £85/MWhr. This company is sold to investors when proven liquid operations

2) **Wider application**: CCS is essential on power, heat, transport

3) **A firm market** for storage of CO2 is created, by means of a Certificate on all producers of fossil carbon entering the UK. That carries an Obligation to store a national percentage of CO2, starting 1%, rising to 100% mid century
Critical point of CO$_2$ is 31°C and 72 atm (7.2 MPa).

CO$_2$ will be injected deep underground at supercritical conditions (depths greater than around 800 m): CO$_2$ is relatively compressible; density less than water, similar to oil; low viscosity – around 10% of that of water.

**What happens on injection?**
1. Pressure increase (fracturing, induced seismicity)
2. Buoyant movement (escape through caprock)
3. Capillary trapping (strands CO$_2$ in the pore space)
4. Dissolution (CO$_2$-rich brine sinks)
5. Reaction (forms solid carbonate)
Pressure buildup limits injection rate

Pressure buildup may lead to induced seismicity: volume added to the subsurface increases pressure and can cause fault slippage. Similar problems encountered in wastewater disposal from fracking operations in the US.

Szulczewski et al. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *PNAS.* 109, 14, 5185-5189
After injection buoyancy drives flow

IPCC (2005) Special Report on Carbon Capture and Storage
Observations at Sleipner – Norwegian North Sea

Simple flow processes can describe plume evolution

Semi-analytical models to estimate risk of migration and leakage

How does CO$_2$ move and how is it trapped – Structural, dissolution, residual trapping

Three important flow properties

Capillary pressure:
Pressure difference between phases

Relative permeability:
How fast does it move?

Residual trapping:
Limits on movement, how much is trapped
Imperial College multi-scale imaging lab

Start with the fundamentals – understand processes experimentally at the pore scale. Micron-to-metre imaging with *in situ* displacement at reservoir conditions.
Trapped CO$_2$ clusters – colour indicates size

How much is trapped and how much can be stored?

Results in sandstones (Doddington, Bentheimer and Berea).

Pentland et al., Geophysical Research Letters (2011)
Andrew et al., IJGEC, (2014)
In three-phase flow see enhanced trapping

What about storage in depleted oilfields?

Here oil spreads as a layer between water and gas and enhances trapping – more storage plus additional oil recovery.
So what is the residual saturation in relation to initial?
About 50% - So migration distances about two times emplacement.

Krevor et al. (2011) Relative permeability and trapping of CO2 and water in sandstone rocks at reservoir condition, *Water Resources Research* 48, 2, W02532
Rock heterogeneity leads to even more trapping

Krevor, Pini, Li, Benson (2011), Geophysical Research Letters GL048239
In UK rocks, less, but still significant trapping, around 40%
Where would CO$_2$ storage happen in the UK?

Offshore in the same areas of the North, Central, and Southern North Sea that have significant oil & gas

Total capacity of prioritised sites: 1.6 Gt CO$_2$

Energy Technologies Institute (2016) Progressing Development of the UK’s Strategic Carbon Dioxide Storage Resource
Injection design

Not passive injection/monitoring: Production wells to relieve pressure; Injection of brine to trap CO$_2$; Enhanced trapping in oilfields.

Shown below: 20 years of water and CO$_2$ injection followed by 2 years of water injection in realistic geology: 95% of CO$_2$ trapped after 4 years of water injection

Qi et al., IJGGC, (2009)
Overall summary

- Subsurface reservoirs provide storage potential for $\sim10^3$ Gt CO$_2$ worldwide, enough for several 25 Gt “wedges”
- Several physico-chemical processes work together to result in a stabilisation of subsurface CO$_2$ – impermeable caprocks, resistance to movement, residual trapping, dissolution into the brine.
- The movement and trapping of CO$_2$ is now well understood from both a physical perspective and a modelling perspective
- Field scale pilot projects have largely validated our understanding of how to predictively model CO$_2$ migration and trapping
- Analogue field sites demonstrate that CO$_2$ can remain stable in gaseous form in the subsurface for at least $\sim1$Ma

*Without CCS we are condemned to dangerous climate change.*
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