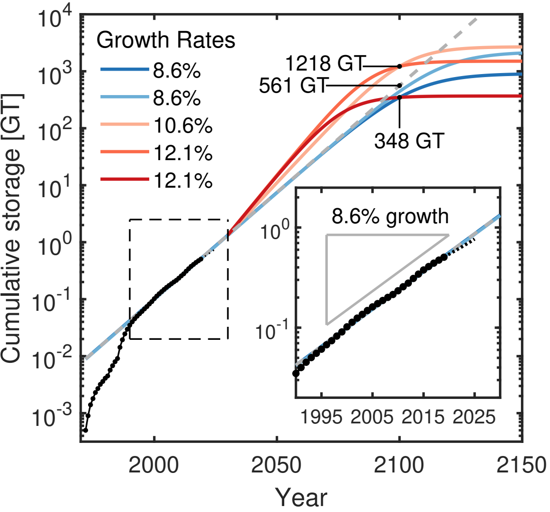
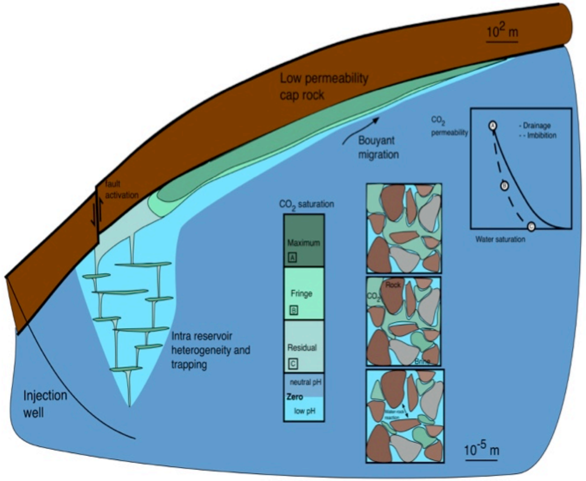
The Role of CO_2 Storage in Achieving Climate Change Targets

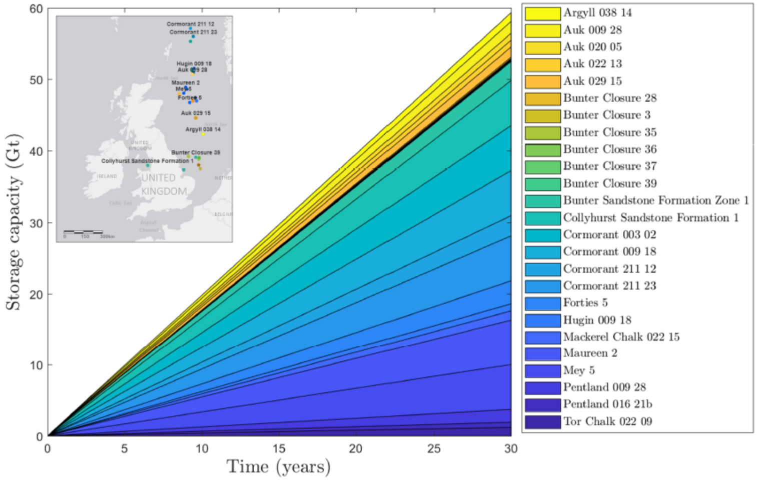
West Midlands Regional Group

Geological Society

December 3rd, 2019







Sam Krevor, Clea Kolster, Silvia De Simone, Chris Zahasky, Samuel Jackson

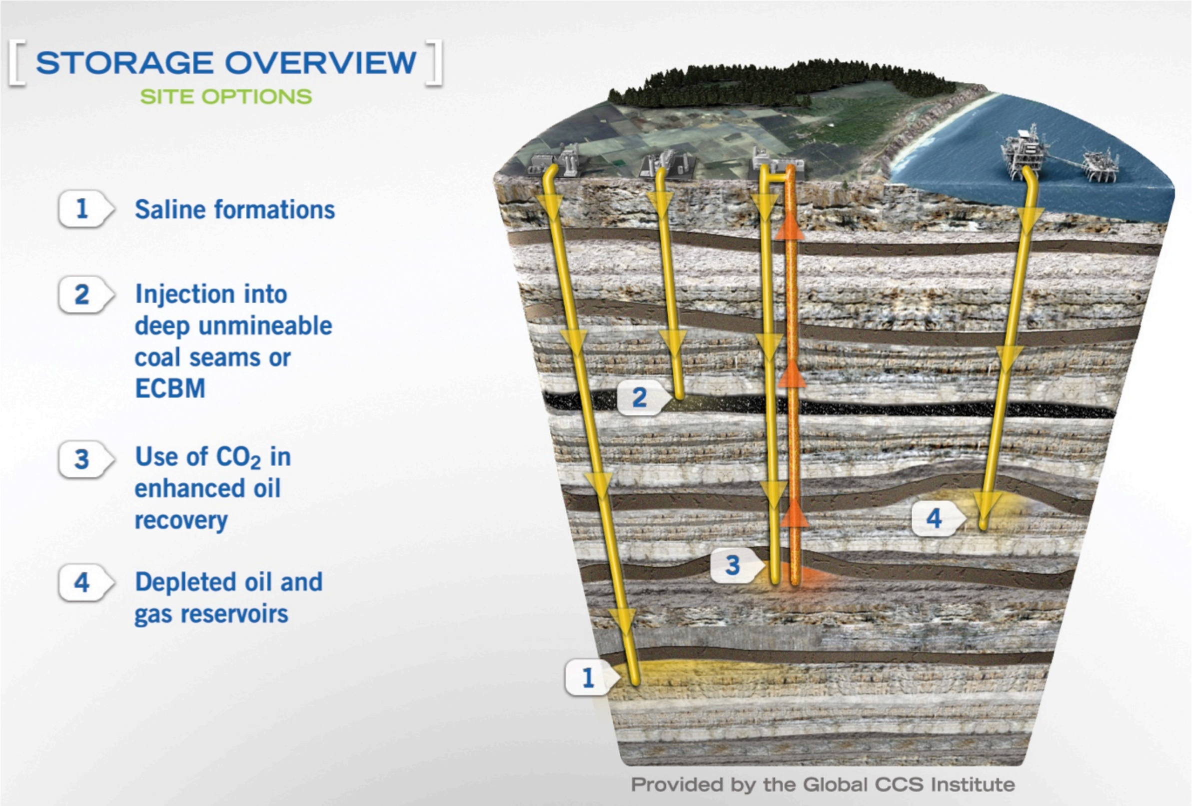
Department of Earth Science & Engineering, Imperial College London

1. Carbon Capture and Storage: What and Why

Carbon dioxide capture and geologic storage comprises:

Capture of CO_2 from an exhaust source

The injection of CO_2 into permeable subsurface (> 800m) geologic traps for fluids

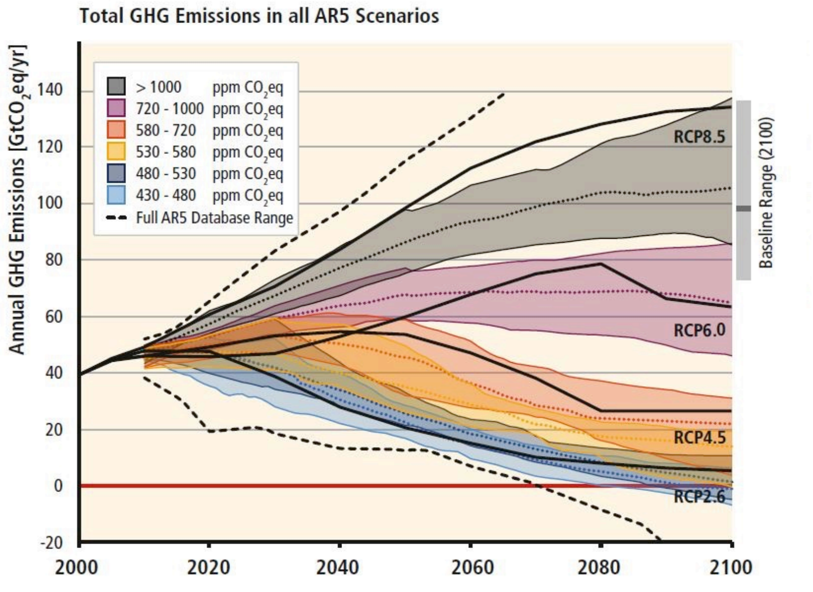


Global CCS Institute
IPCC (2005) Special Report on Carbon Capture and Sequestration

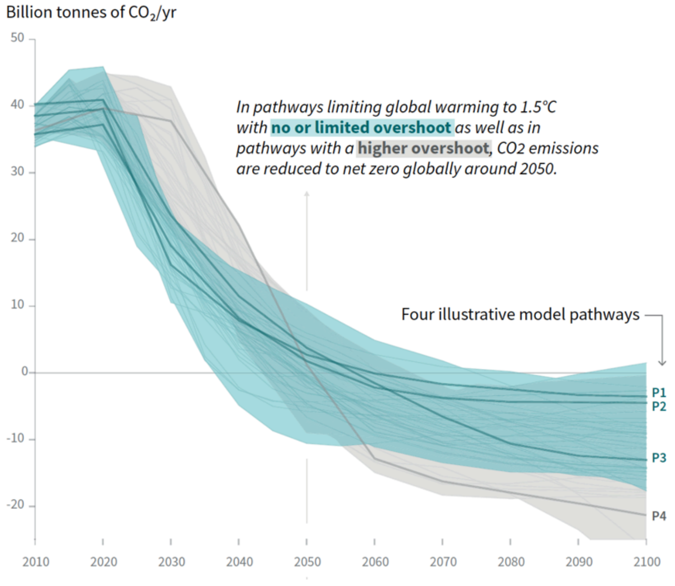
UN IPCC Synthesises Results of Integrated Assessment Models asking "How can we achieve climate change mitigation"?

Models meet emissions targets while maximising social welfare

Results compiles from > 1200 model runs



IPCC 2014 Assessment Report, < 2°C

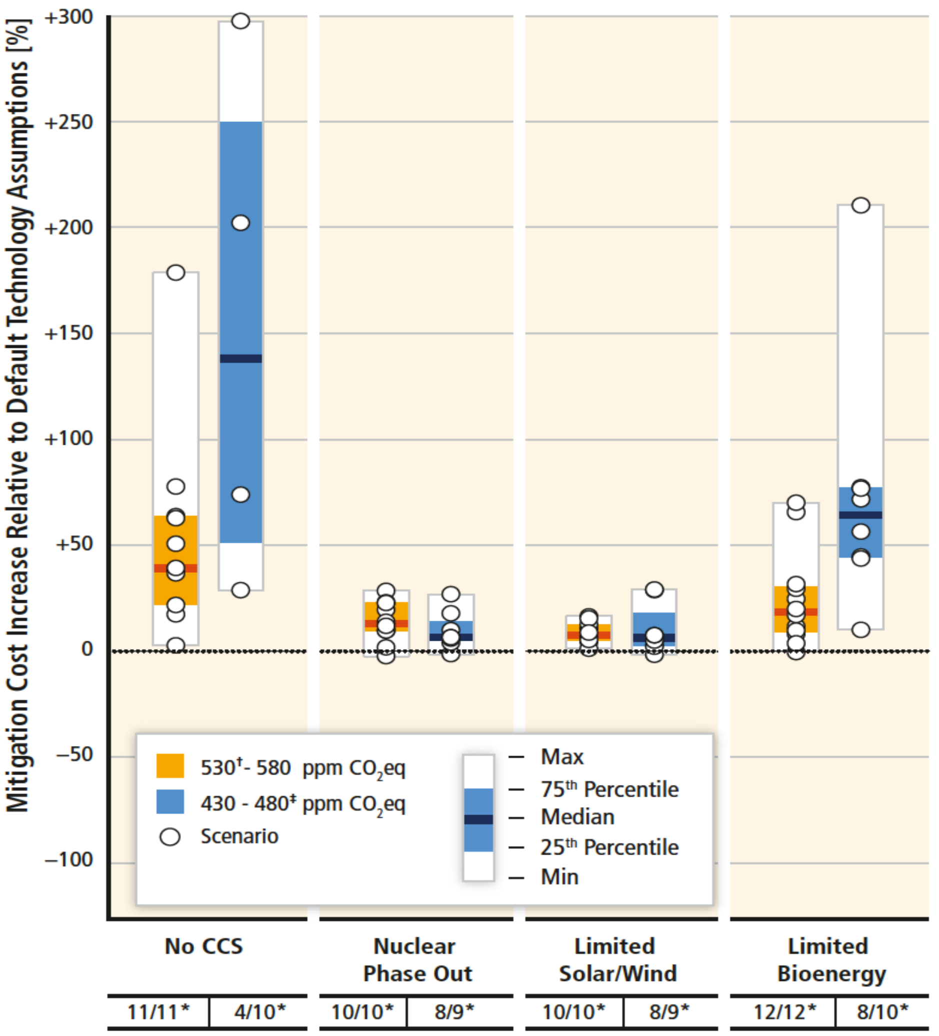


IPCC 2019 Special Report, <1.5°C

Avoiding dangerous climate change requires large scale deployment of CCS

Availability of CCS by 2030 is a leading control of mitigation costs

Most models cannot achieve 430-480 CO_2 stabilisation in the atmosphere by 2100 without CCS where nearly all can in the absence of other technological options.



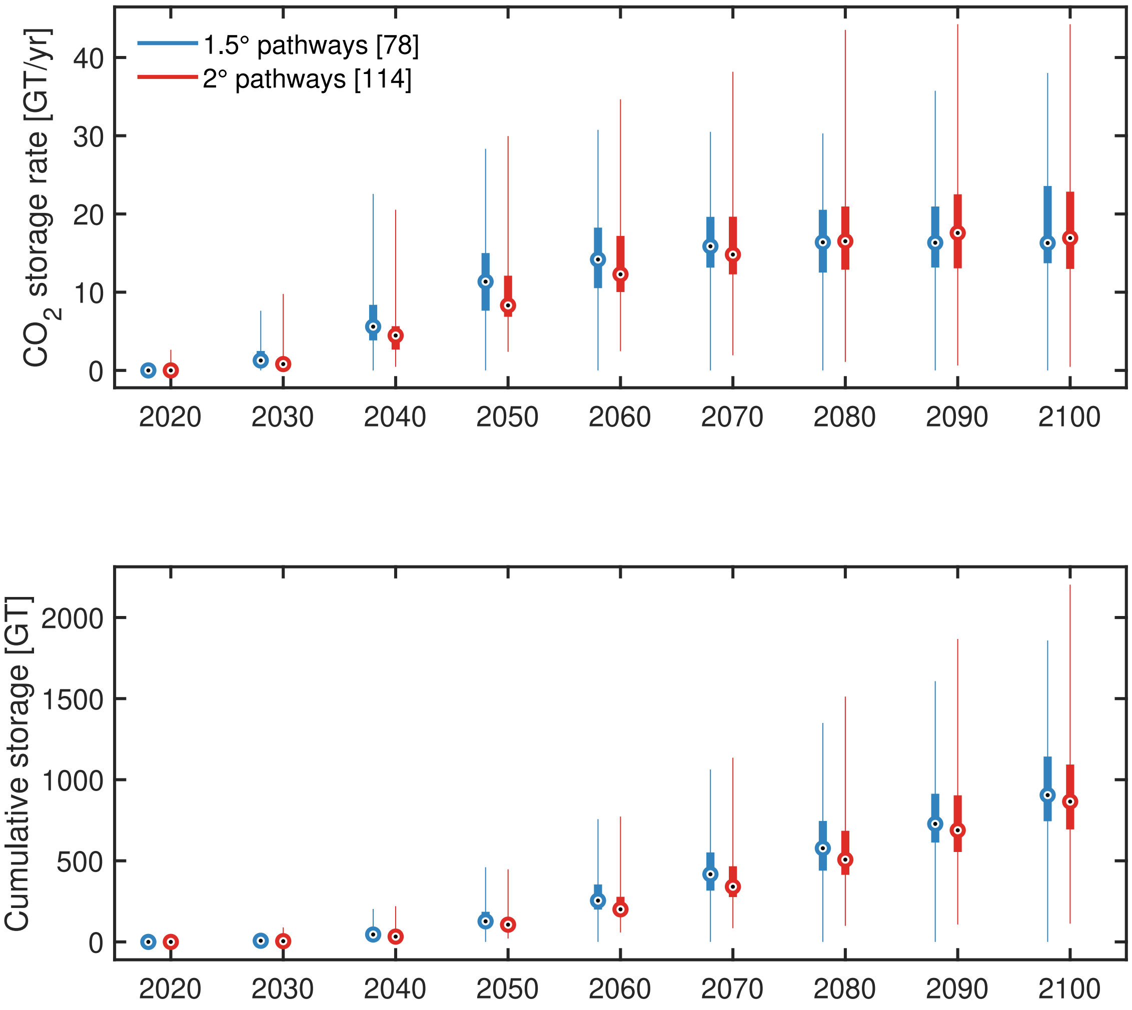
Intergovernmental Panel on Climate Change Climate Change 2014 Report – Working Group III: Mitigation of climate change

IPCC Scenarios use a lot of CO_2 storage

10s of Gt per year by 2050

>1200 Gt stored by 2100

Not much difference in CCS use between 1.5°C and 2°C pathways

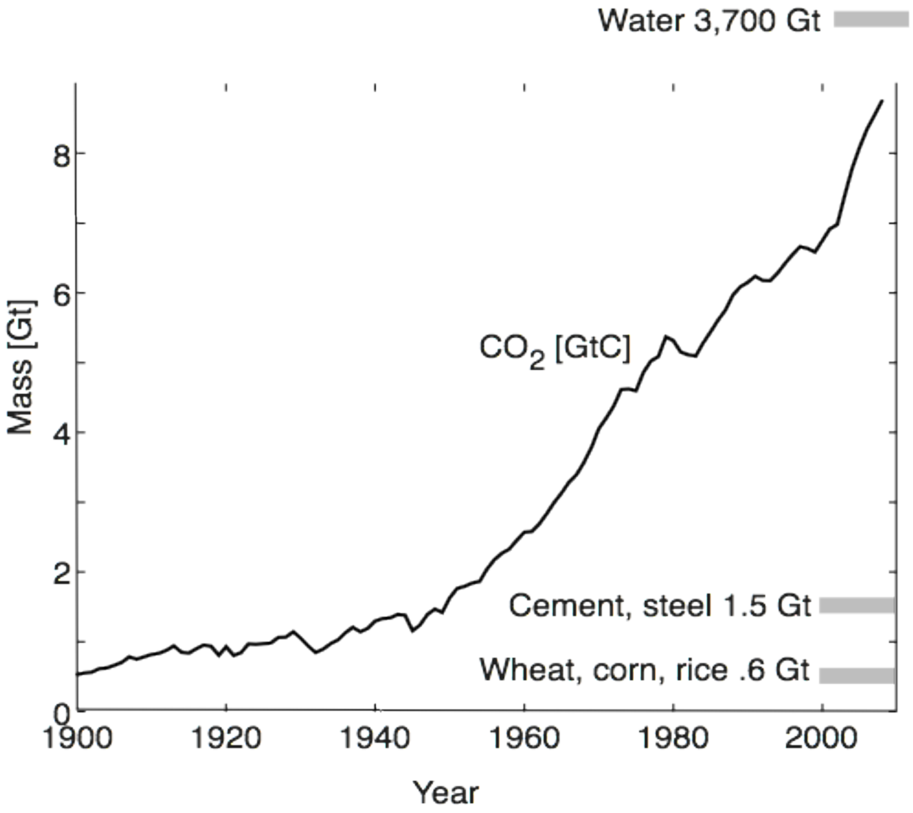


Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. Energy strategy reviews, 22, 61-81.

Zahasky and Krevor (2019), *Sub Judice*

Why not do something else with the CO_2?

Scale. The amount produced from fossil fuel consumption far exceeds any useful demand

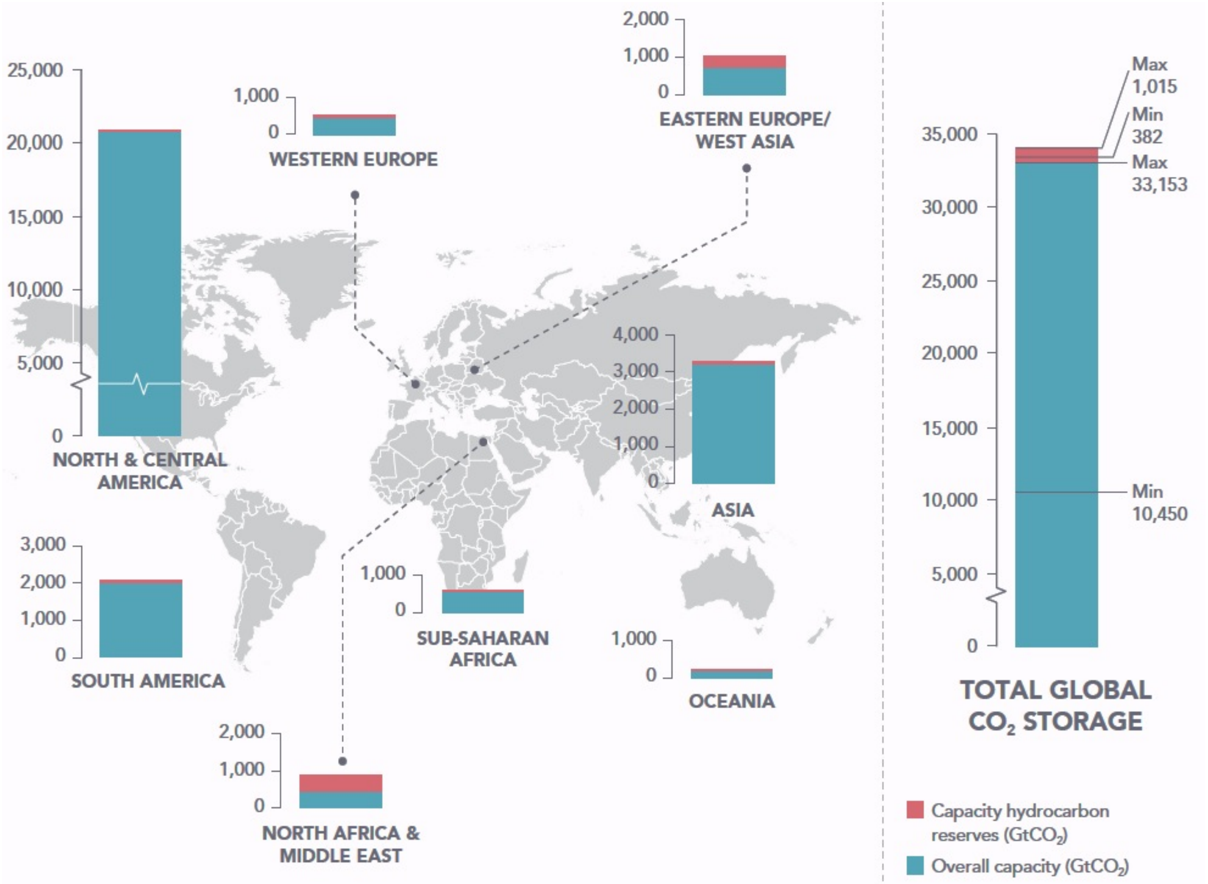


Data from: http://cdiac.ornl.gov/ftp/ndp030/global.1751_2008.ems

There is an estimated vast capacity for CO_2 storage globally

> 11,000 Gt CO_2

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

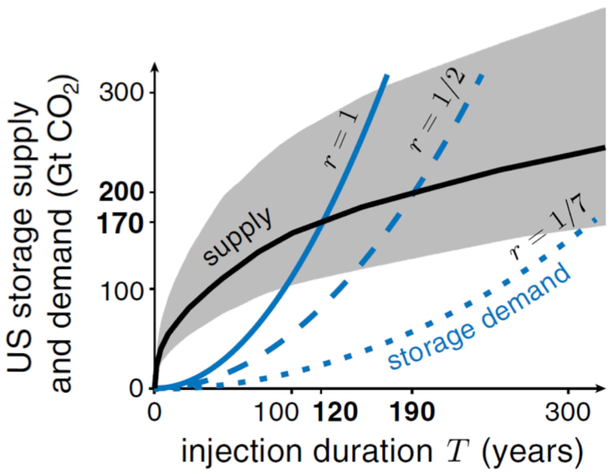


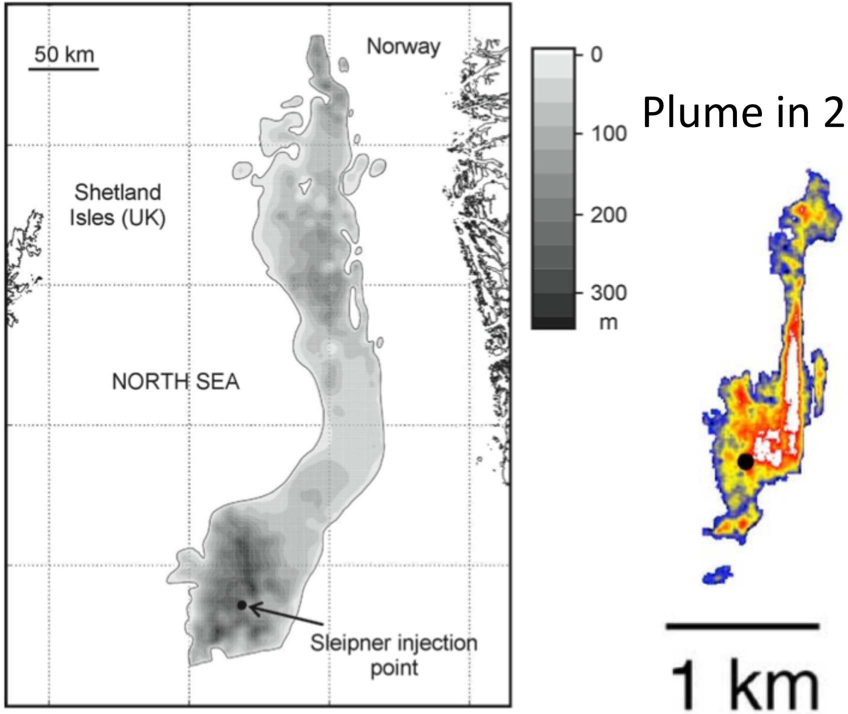
Budinis, Krevor, Mac Dowell, Brandon, Hawkes (2016)
Sustainable Gas Institute White Paper

2. Technical Limitations to Deployment

Few for the first generation of deployment

Over 50-100 year timescales pressure and plume migration create uncertainty





Szulczewski et al. (2012). Lifetime of CCS as a climate-change mitigation technology, *PNAS,* 109, 14, 5185-5189

Boait et al. (2012). Spatial and temporal evolution of injection at the Sleipner Field, North Sea, *JGR,* 117, B3

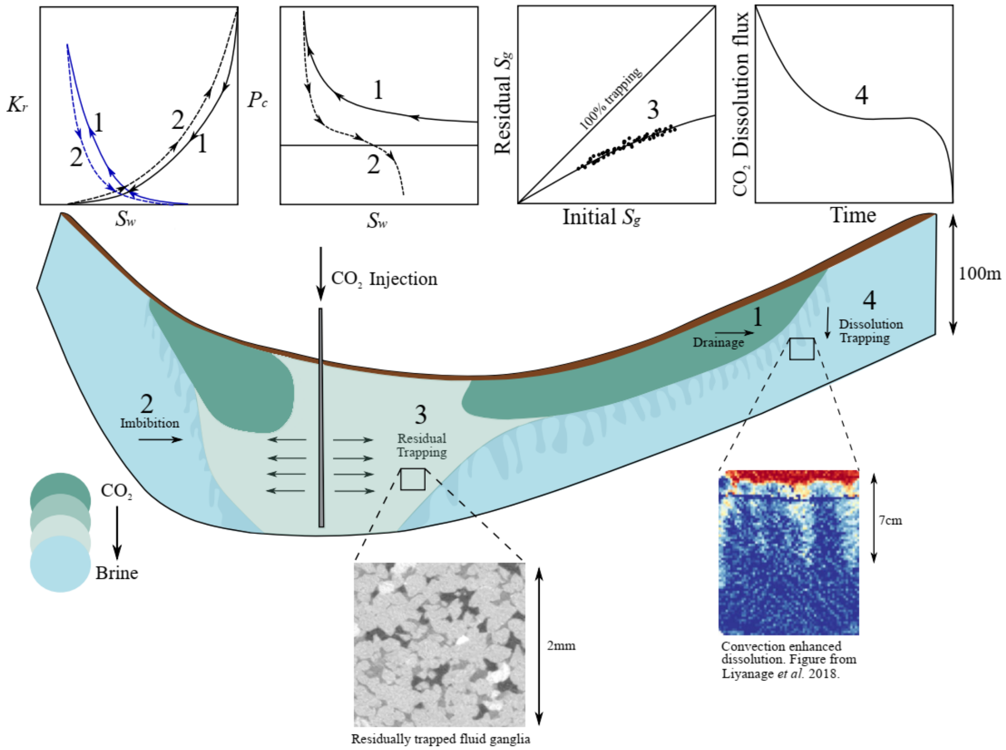
What happens to the injected CO_2?

Reservoir pressure may increase

CO_2 migrates buoyantly

It is trapped

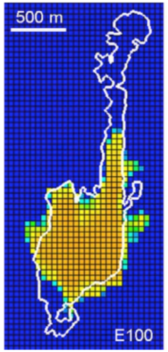
- Beneath impermeable caprocks
- In rock pores through capillary trapping
- By dissolution into reservoir brine



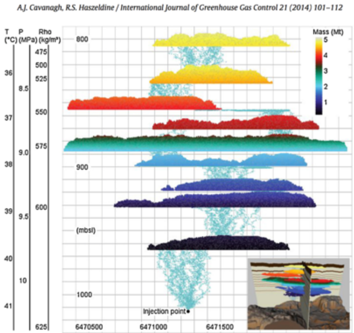
Krevor, Blunt, Benson, Pentland, Reynolds, Al-Menhali, Niu (2015) Capillary trapping for geologic carbon dioxide storage. *IJGHGT*, 40, 221-237

Unexpected plume migration often observed at large scale injection sites

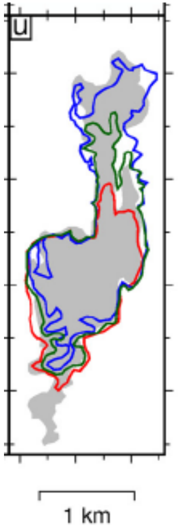
Sleipner, Norway



Williams *et al.* 2018.
DOI: 10.1016/j.ijggc.2017.11.010

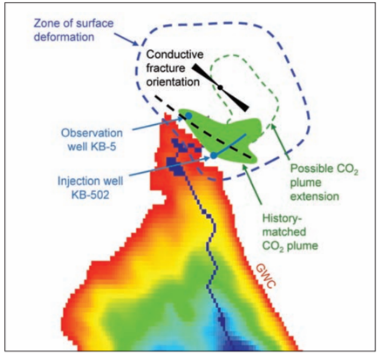


Haszeldine and Cavanagh (2014)
10.1016/j.ijggc.2013.11.017



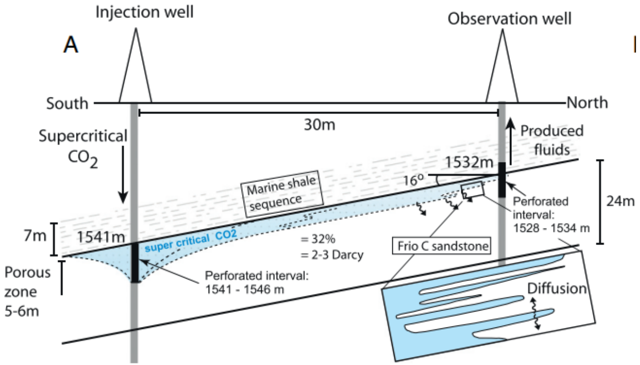
Cowton et al., (2018) DOI: 10.1016/j.epsl.2018.03.038

In Salah, Algeria



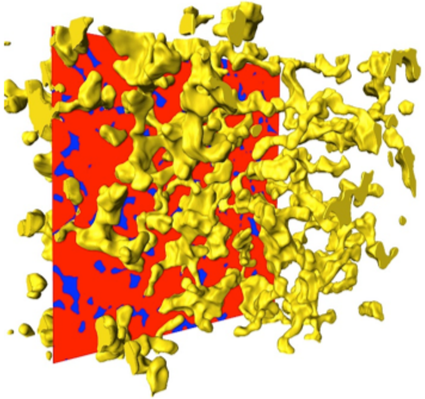
Ringrose *et al.* 2009.
First Break, 27 p 85 –89.

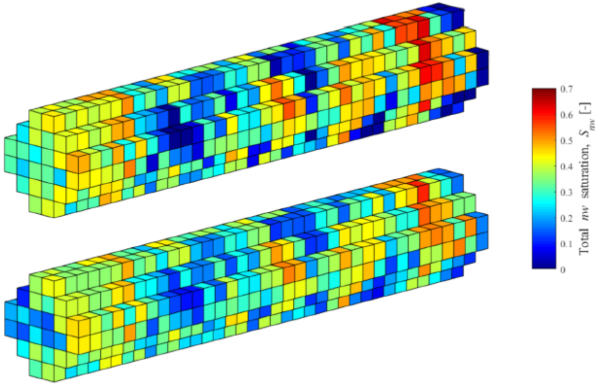
Frio, USA

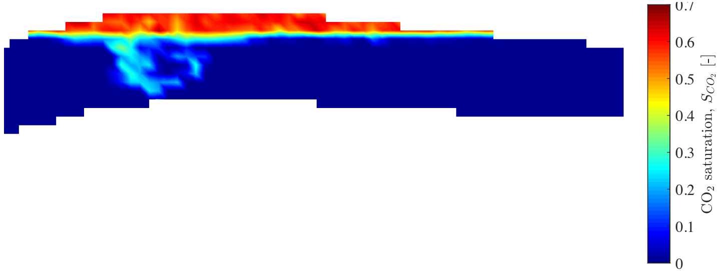


Kampman *et al.* 2014.
DOI: 10.1016/j.chemgeo.2013.11.012

Describing CO_2 flow is a multi scale issue







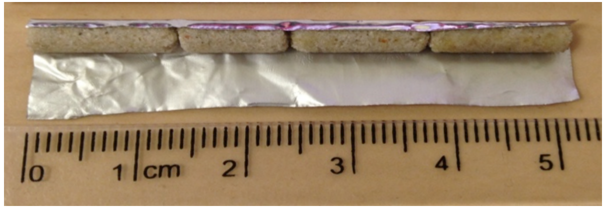
Pore
networks

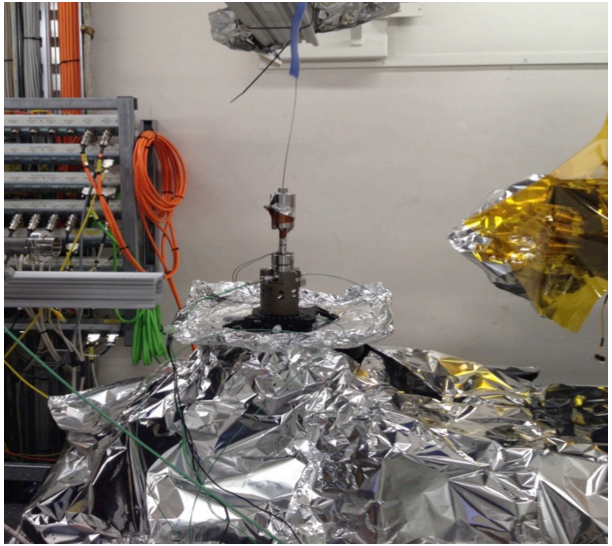
Rock core
Bunter and Captain
Sandstones

Storage site
Captain
sandstone

10^{-3} 10^{-1} 10^{3} m

Steady state, co-injection of N_2 and brine into a Bentheimer sandstone rock core, 5mm diameter, 12mm length

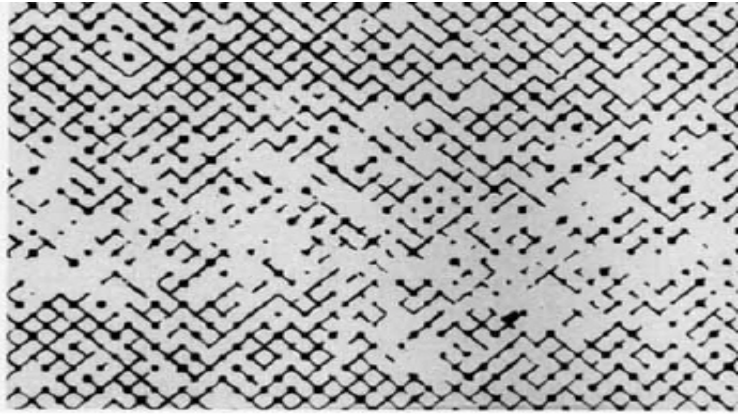




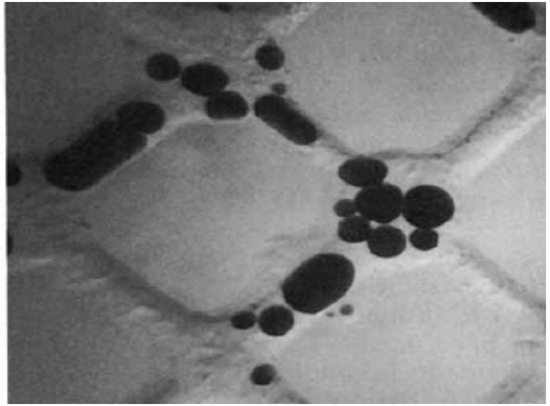
Conceptual picture for Darcy's law: Connected paths

$$\mathbf{q} = -\frac{kk_r}{\mu}\nabla(P - gz)$$

~5 000 μm



~100 μm

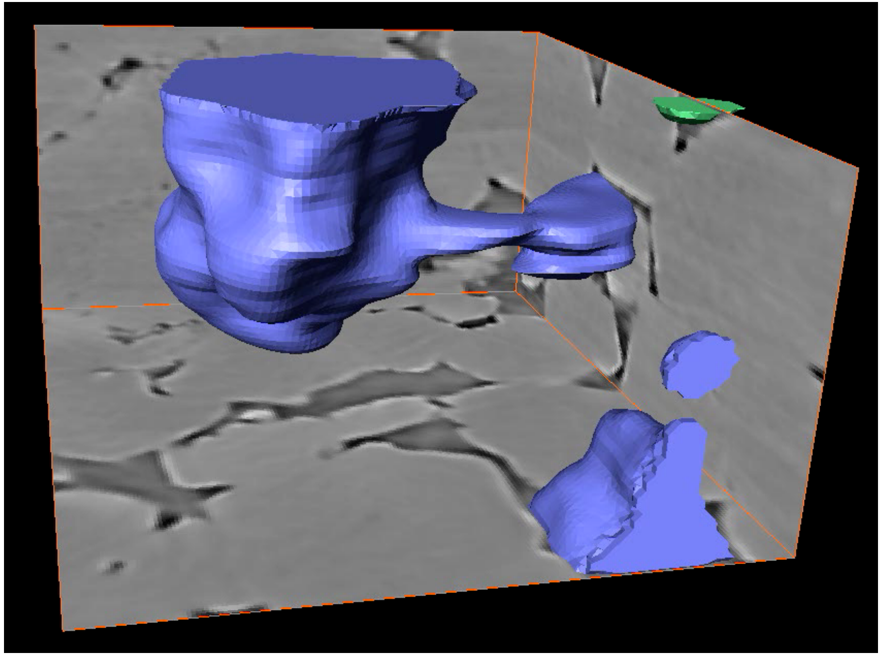


< 10^{-6} > 10^{-3}

$$Ca_i = \mu_i q_i / \gamma$$

Avraam, Payatakes (1995) Flow regimes and relative permeabilities during steady-state two-phase flow in porous media, *J. Fluid Mech.*, 293, 207-236

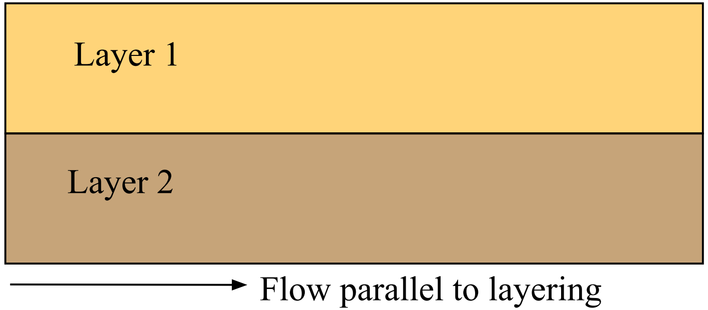
There is constant breakage and reformulation of connected paths along pore networks at low capillary number



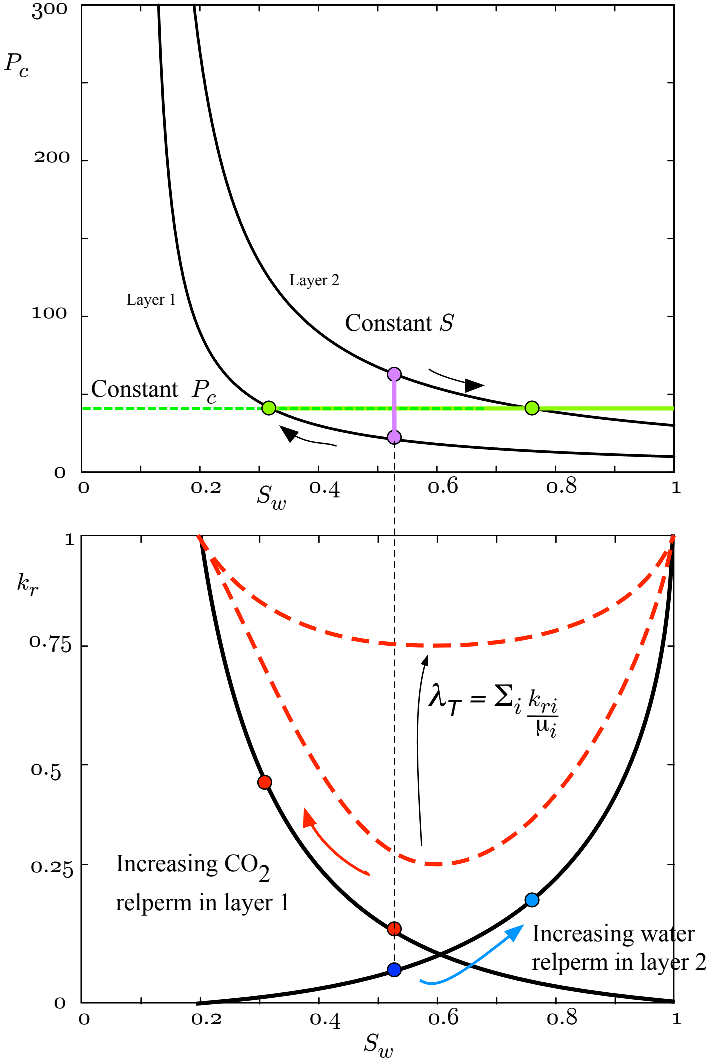
Nitrogen visualised flowing through the pores during co-injection with water. Each frame ~45s Field of view ~ 1 mm^3. Flow from left to right

Reynolds, C. A., Menke, H., Andrew, M., Blunt, M. J., & Krevor, S. (2017). Proceedings of the National Academy of Sciences, 114(31), 8187-8192.

At cm-scales heterogeneities can lead to large variations in saturation, and impacts on relative permeability



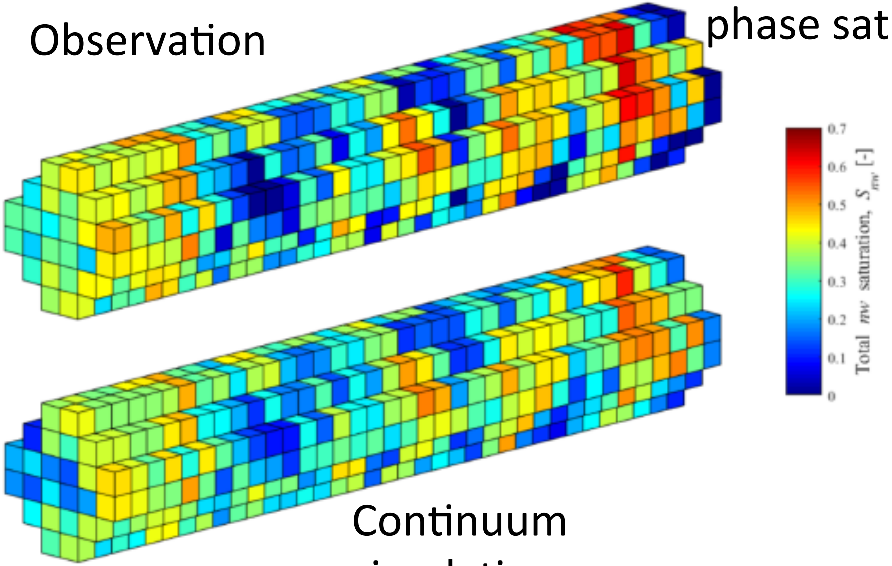
$$K_x = \sum_{1}^{n} \frac{K_i d_i}{d}$$



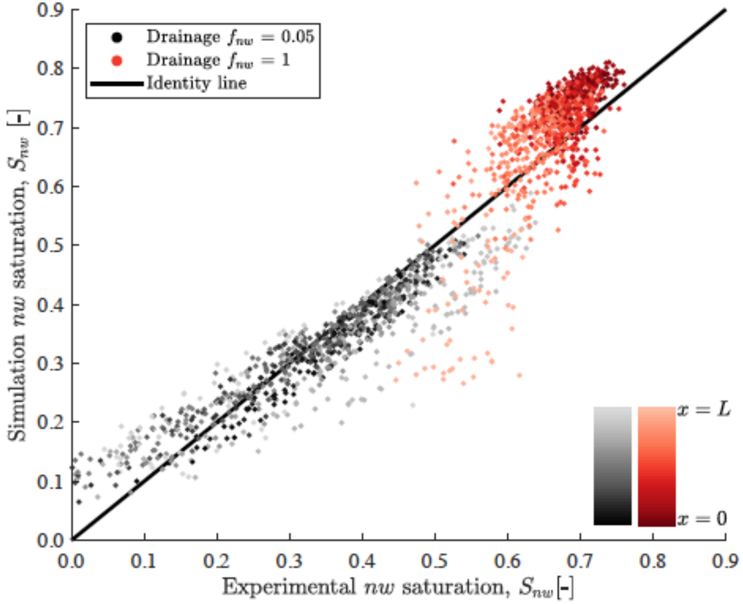
We can construct numerical models with multiphase flow heterogeneity from the data – the first step in upscaling

Observation

Non wetting phase saturation



Continuum simulation



Jackson, S., Lin, Q., & Krevor, S. (2019). *Sub Judice*, Pre print: https://eartharxiv.org/2aejr/
Data https://dx.doi.org/10.5285/4483646c-6e21-4927-a2bf-60f9648e6dec

We characterised cm-scale heterogeneity on a 60m interval of the Captain Sandstone

Planned injection site for (discontinued) Peterhead CCS project, aim to store ≈ 20Mt CO_2.

Figure from: Shell U.K., Peterhead CCS project. Document # PCCS-05-PT-ZR-3323-00002

Jackson, S., & Krevor, S. (2019). *Sub Judice*

We characterised cm-scale heterogeneity on a 60m interval of the Captain Sandstone

Storage unit - Captain D, lower Cretaceous Sandstone, 100m thick. Sample of 48 rock core plugs from depth 2950m – 3050m

Typical North Sea Sandstone:

- Poorly consolidated
- High permeability
- Thin mudstone layers

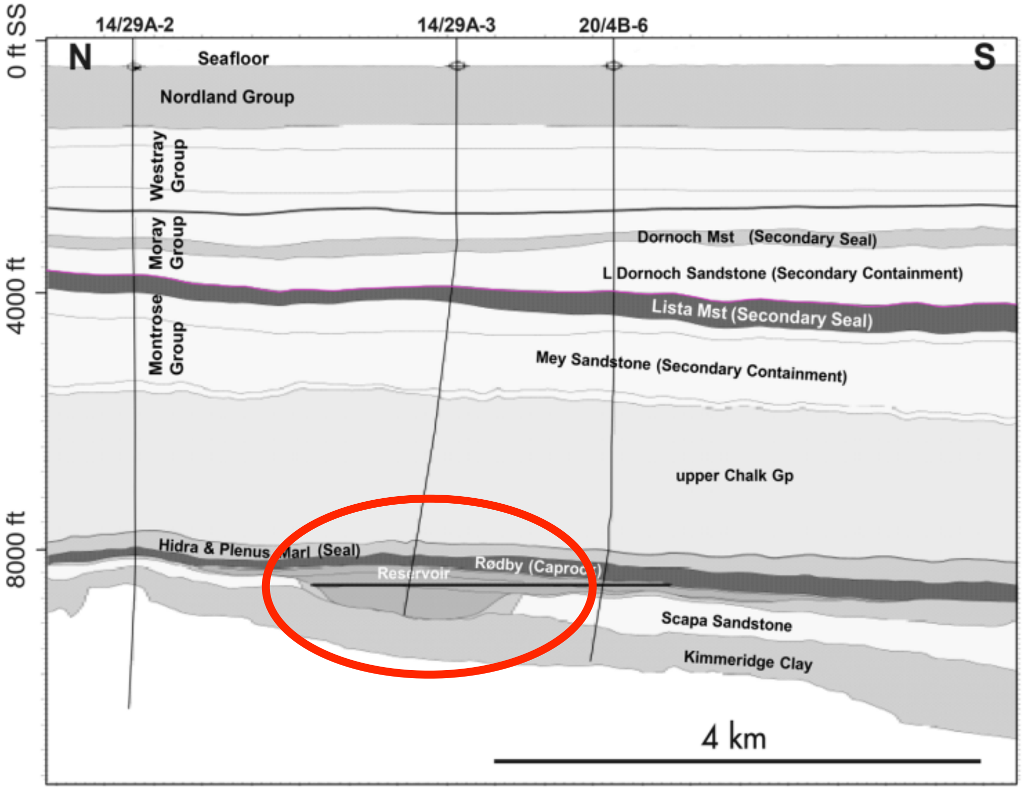
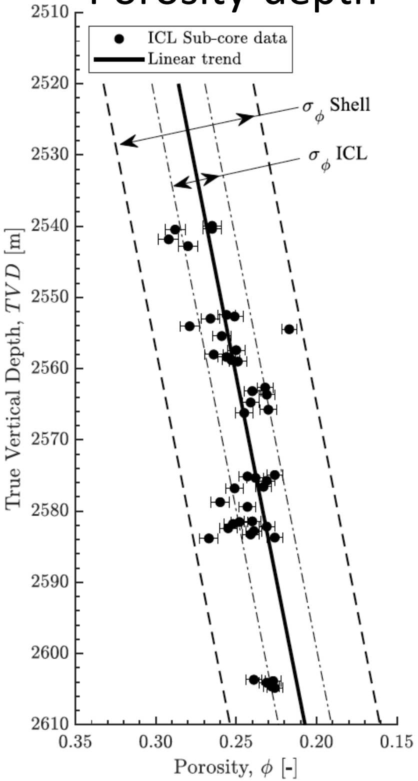


Figure from: Marshall *et al.* 2017. DOI: 10.1144/PGC8.18

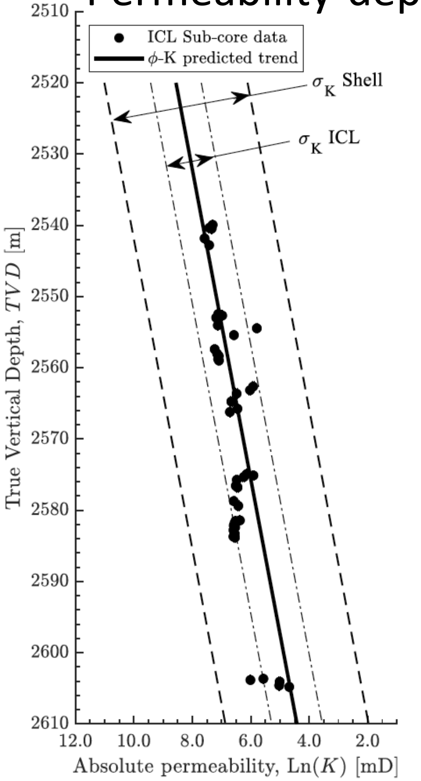
Exhaustive sample characterisation

> 40 rock cores characterised to develop a "ground truth" for modelling the Captain Sandstone

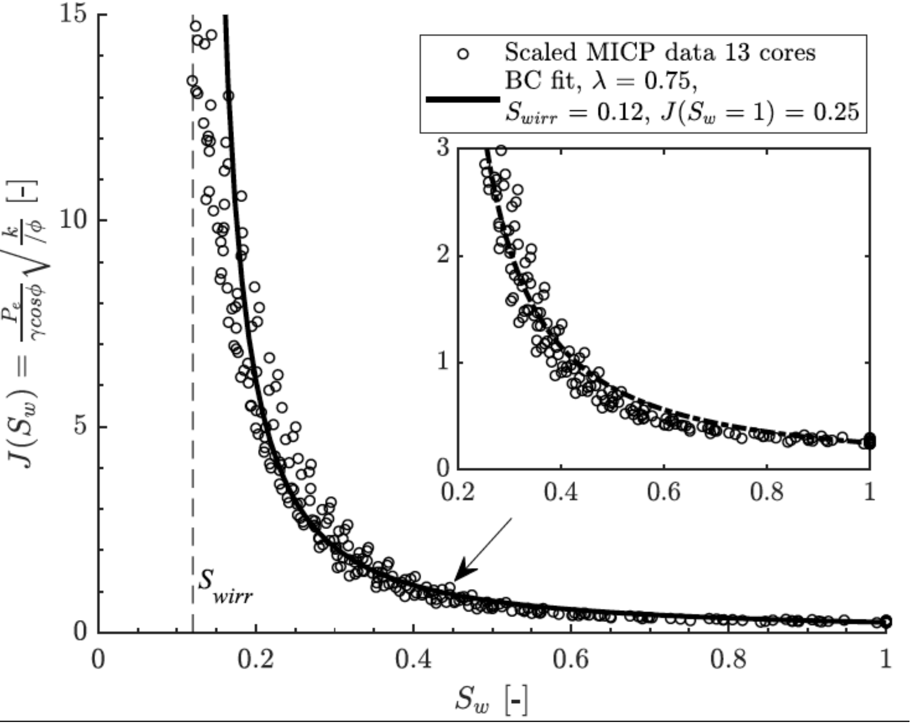
Porosity-depth



Permeability-depth

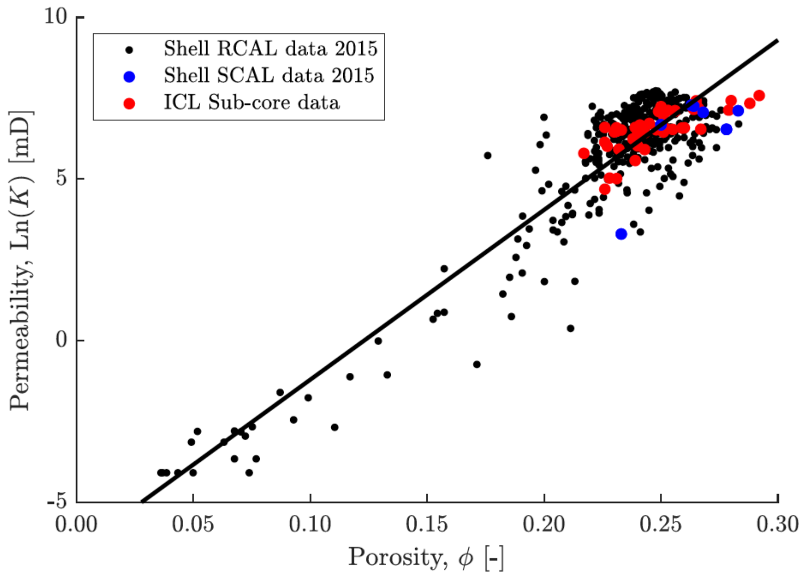


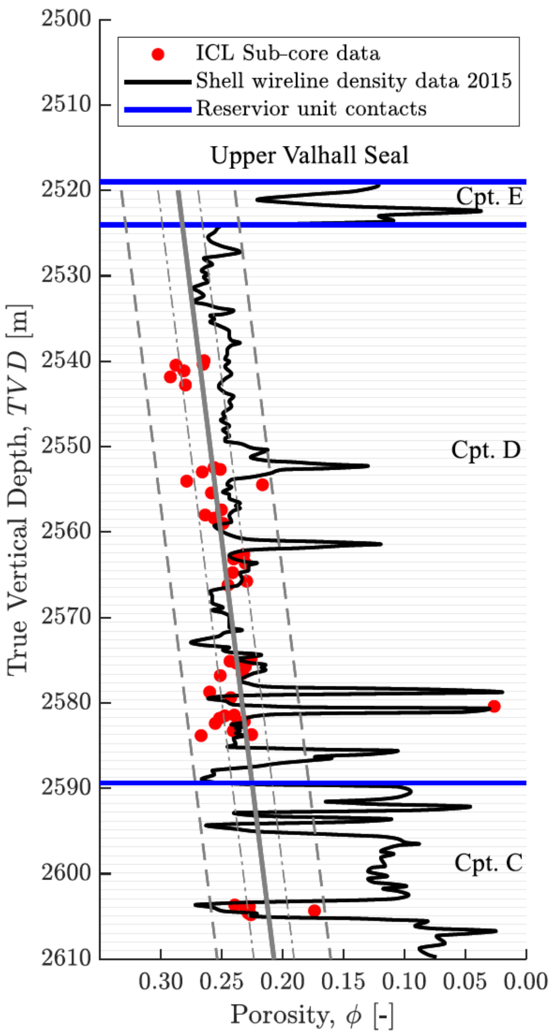
Capillary pressure characteristics



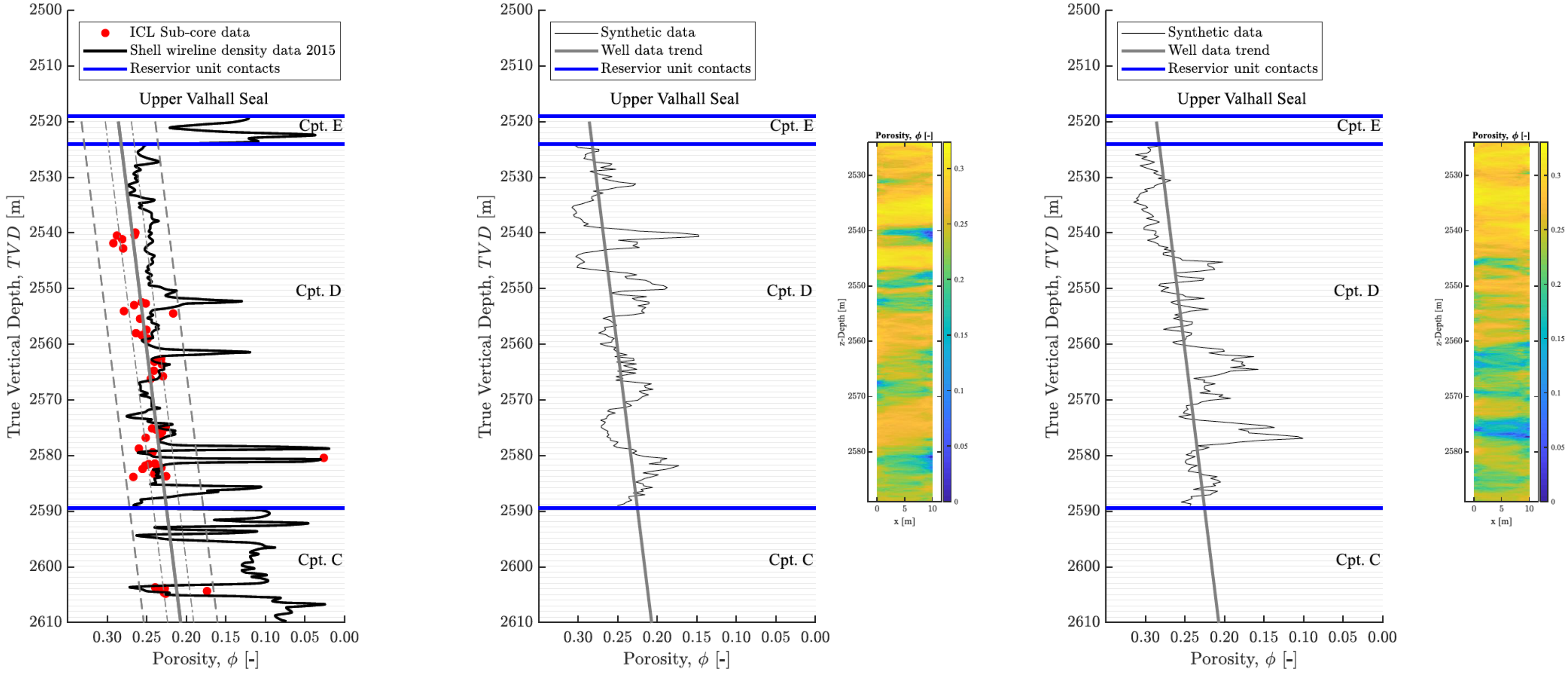
Benchmark against well logging

Consistency with industry measurements of single phase flow properties – porosity and permeability – provides confidence in our measured dataset



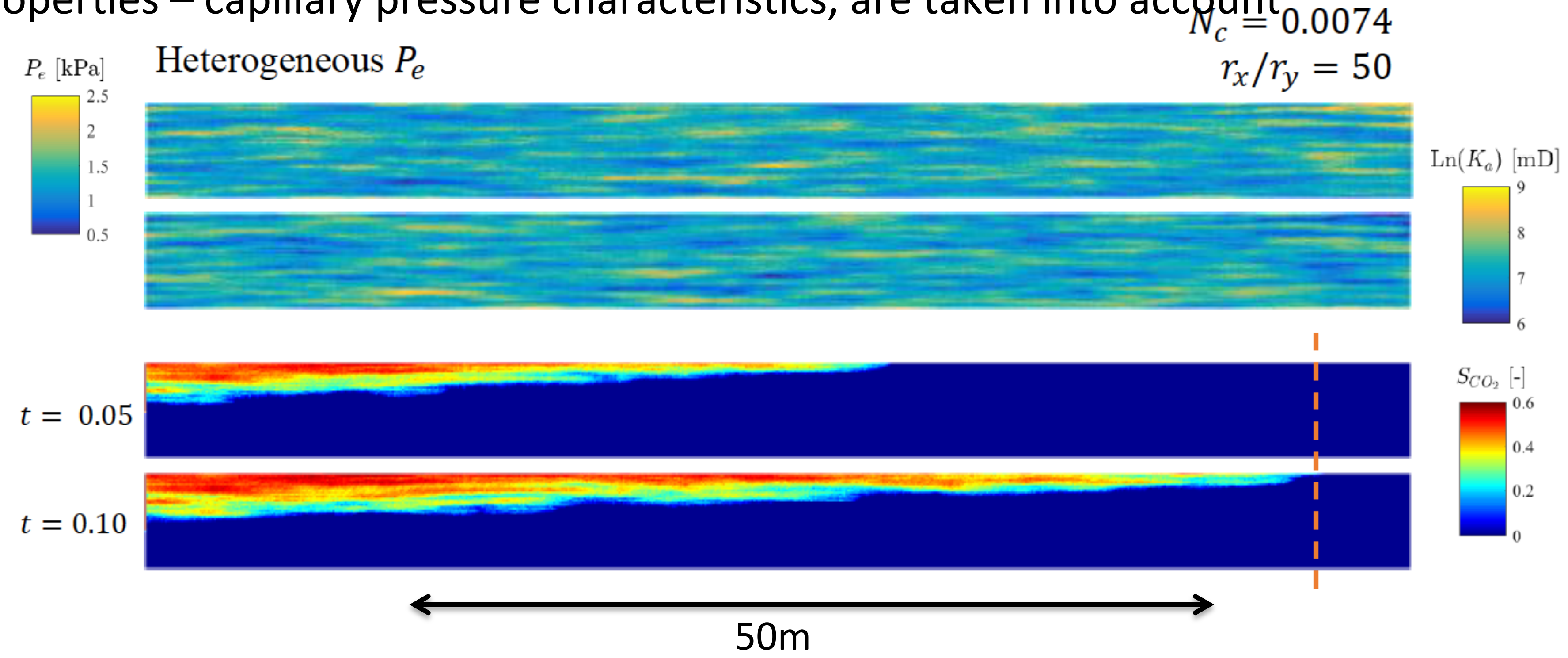


We generate synthetic realisations of the reservoir at cm-scale resolution

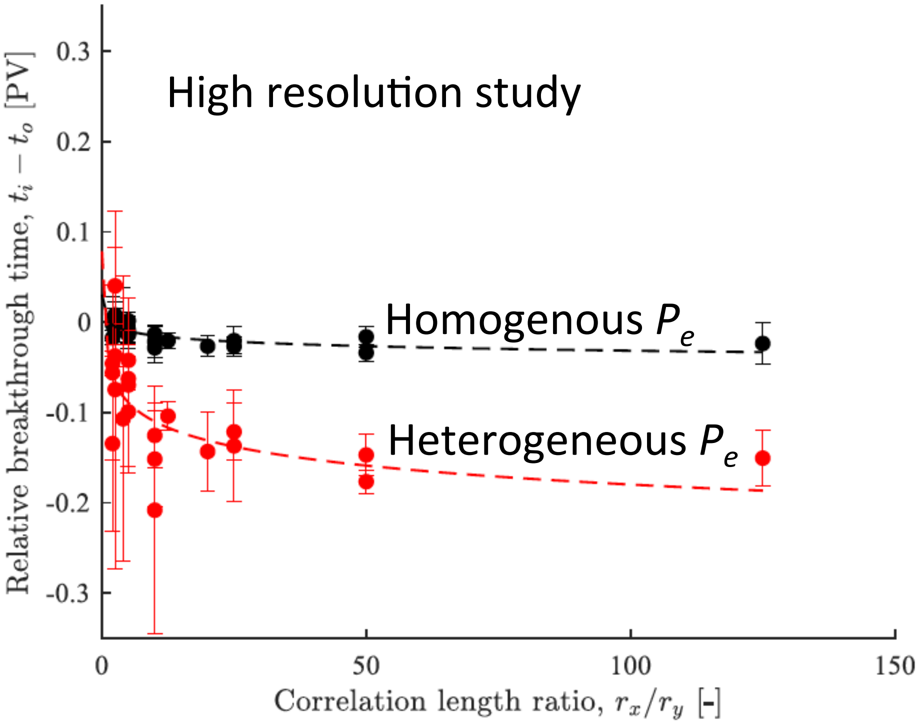


Centimetre-scale layered heterogeneity significantly increases plume migration rate

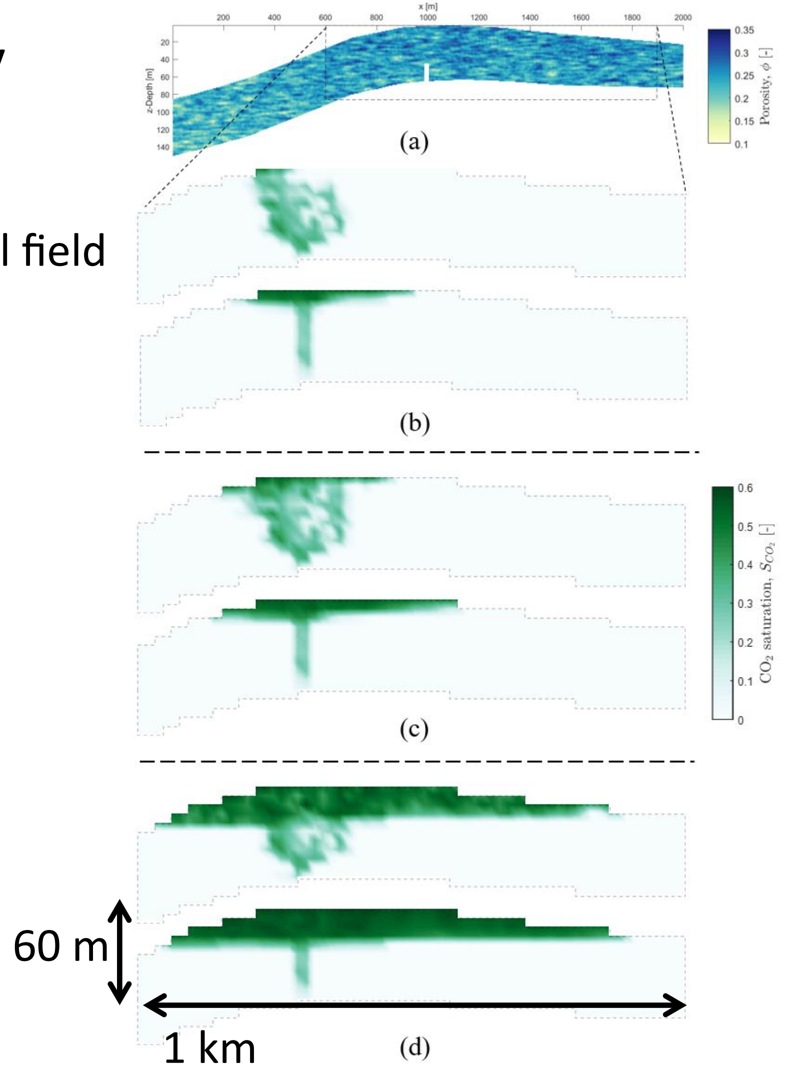
The effect is only present if heterogeneity in the multiphase flow properties – capillary pressure characteristics, are taken into account



Centimetre-scale layered heterogeneity controls field scale plume migration

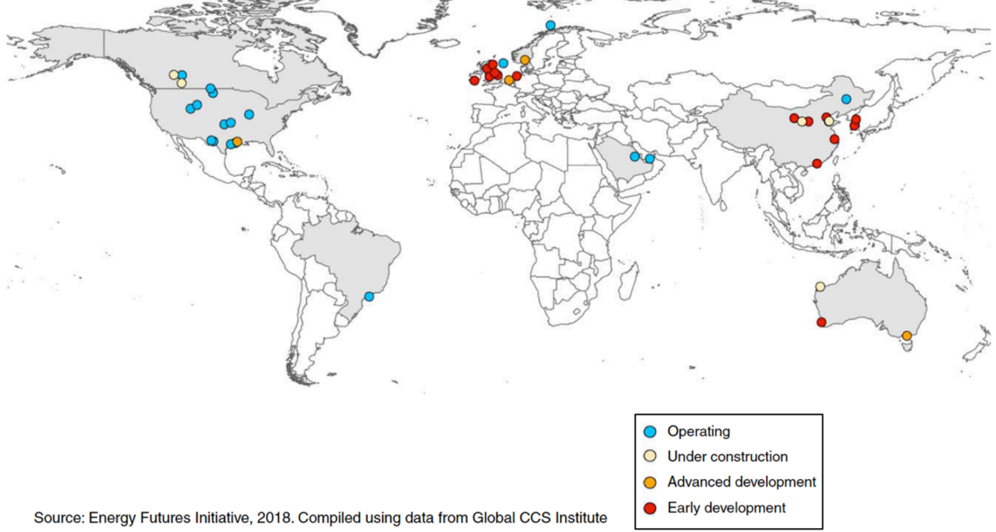


Full field



3. Incentives to Deployment

Currently a limited number of industrial projects around the world ~35 Mtpa capacity

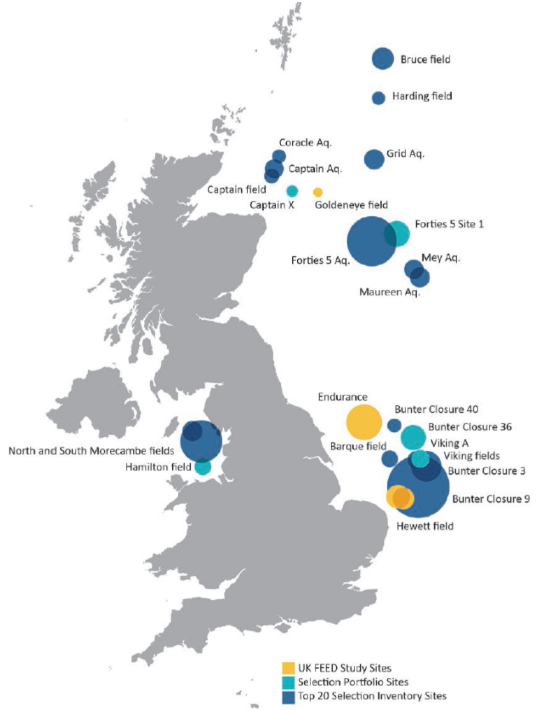


Source: Energy Futures Initiative, 2018. Compiled using data from Global CCS Institute

Orr Jr, F. M. (2018). Carbon Capture, Utilization, and Storage: An Update. SPE Journal, 23(06), 2-444.

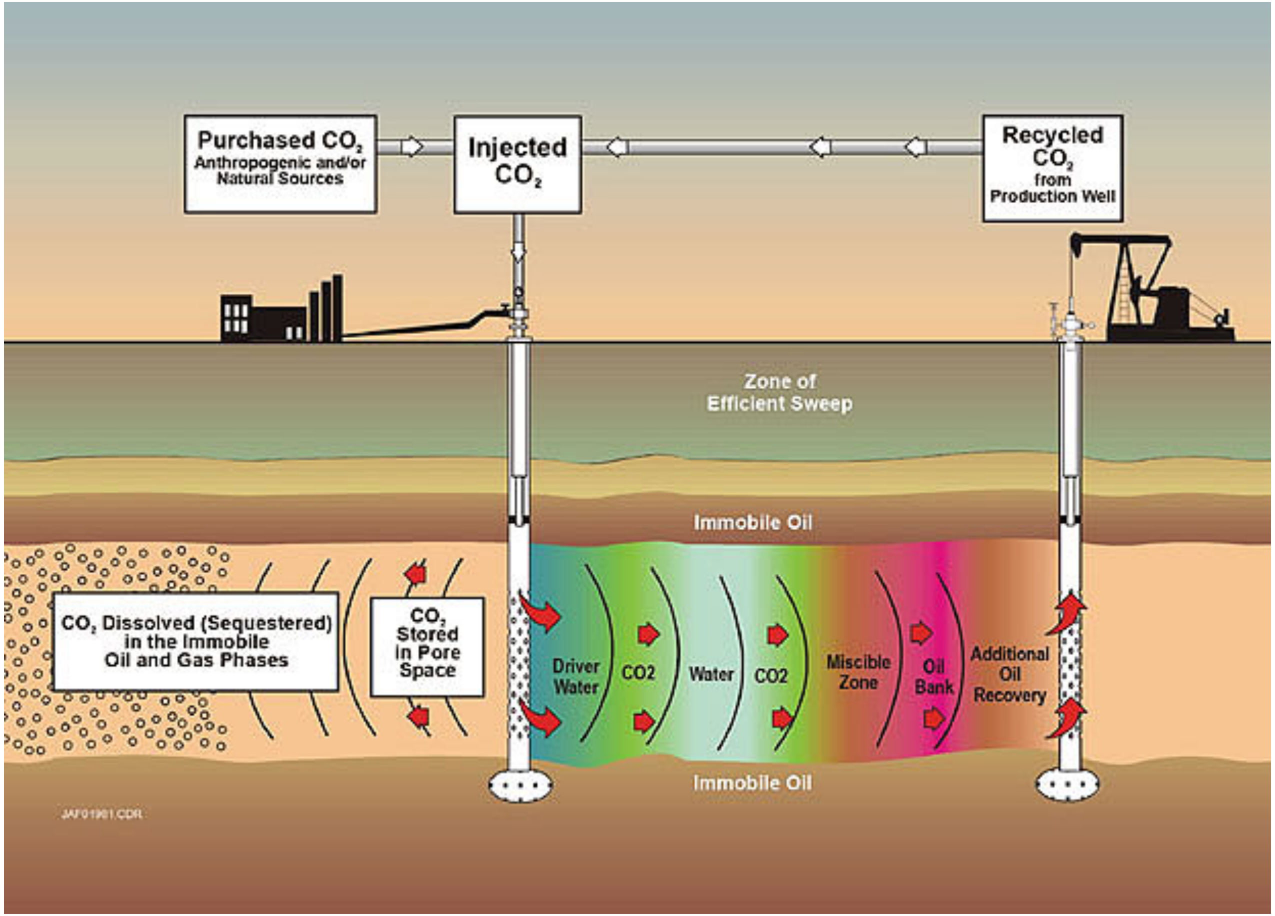
Nowhere in the UK, but lots of activity

See: https://www.gov.uk/guidance/uk-carbon-capture-and-storage-government-funding-and-support



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

Enhanced Oil Recovery currently drives commerciality



Advanced Resources International and Melzer Consulting, Optimization of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects, prepared for UK Department of Energy & Climate Change, November 2010.

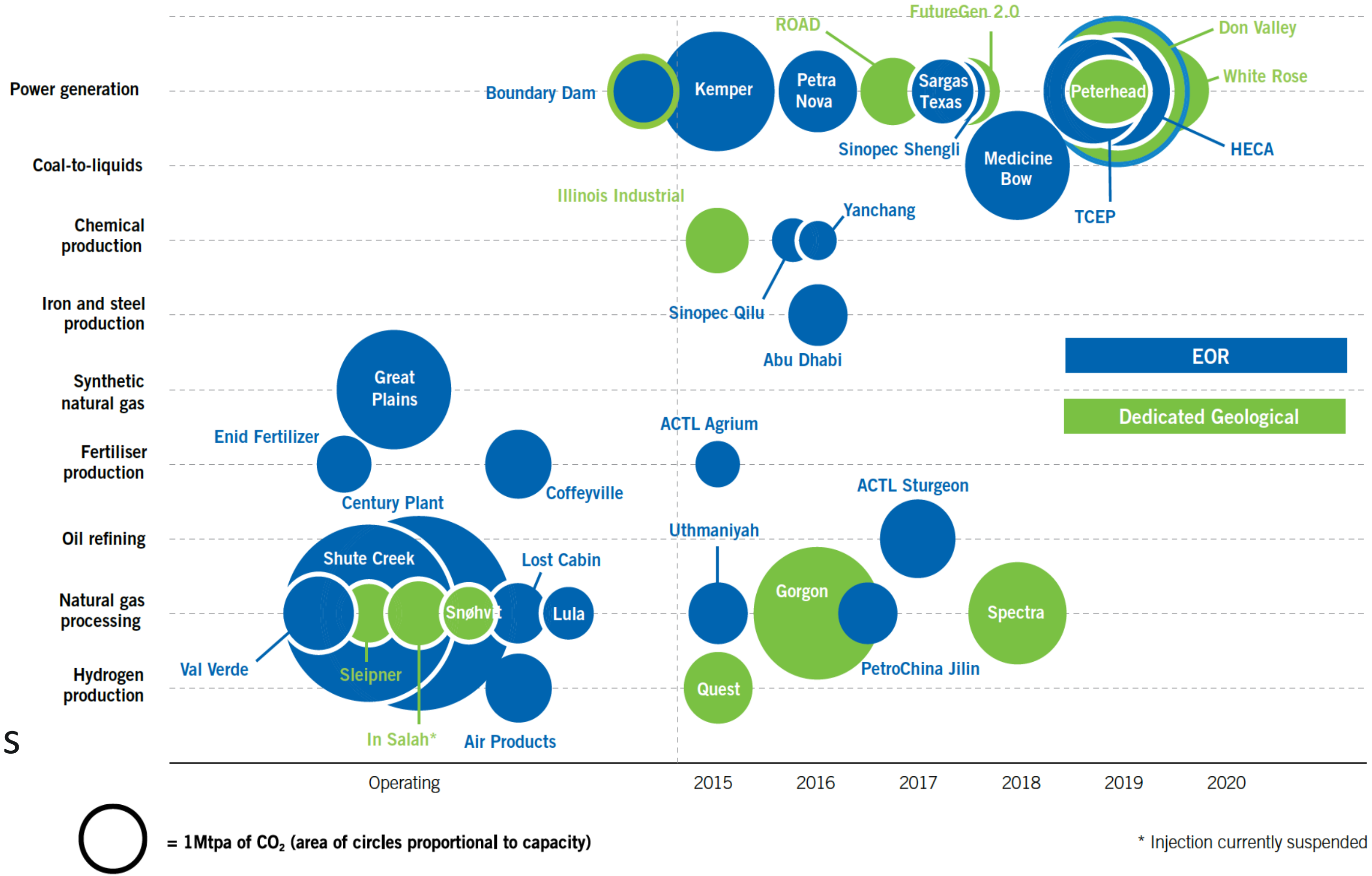
EOR incentivizes 11 of 14 industrial scale projects

Revenue from EOR

Site characterisation

Infrastructure

Question: How strong of an incentive is EOR?



Global CCS Institute (2014) The global status of CCS 2014

Model of Iterative Investment in CCS with CO_2-EOR

MIICE

Developed a geographically neutral detailed iterative economic model in MATLAB with assumption based inputs

INPUTS

- CO_2 supply
- Oil fields suitable for CO_2-EOR
- CO_2 -EOR production profiles
- Capital & Operating Cost of CCS + CO_2-EOR
- Economic climate

***NPV Analysis for each plausible 30-year CCS with CO_2-EOR project**

OUTPUTS

- Installed capacity of CCS
- Cost of CO_2 Captured
- CO_2 Stored
- Oil Produced
- FOAK* to NOAK* cost reduction

*FOAK = First of a Kind
*NOAK = Nth of a Kind

*NPV = Net Present Value of the sum of discounted cash flows
→ Takes into account time value of money & risk of investment

Kolster, C., Masnadi, M. S., Krevor, S., Mac Dowell, N., & Brandt, A. R. (2017). CO_2 enhanced oil recovery: a catalyst for gigatonne-scale carbon capture and storage deployment?. Energy & Environmental Science, 10(12), 2594-2608.

Soure code available at:
https://zenodo.org/record/1098243#.Xa3dJZNKj6A

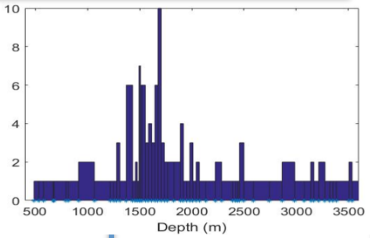
Model of Iterative Investment in CCS with CO_2-EOR
MIICE

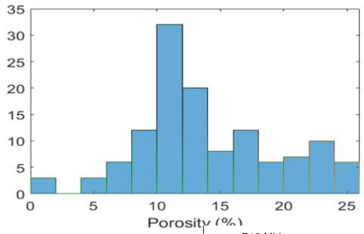
Year

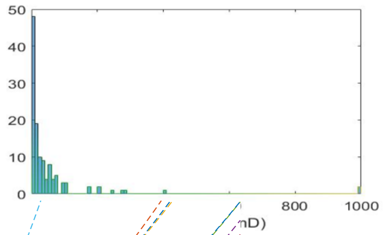
Pool **of 1000** potential oil field EOR projects based on current data representing global potential

Potential Oil Field k + Production profile

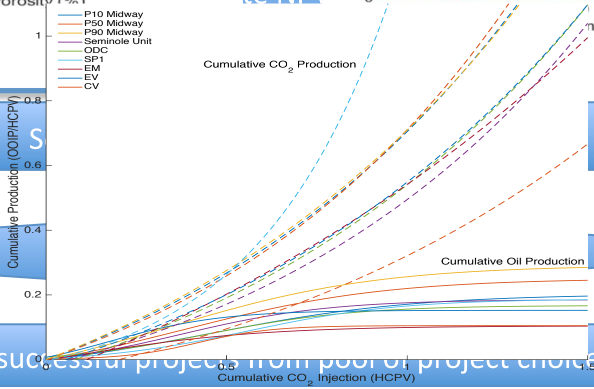
Updated Price signals: New Oil Price, New CO_2 tax, learning achieved







Choose to build CCS plant capturing 1, 2, 3, or 4 $MtCO_2$/ year and oil field management will depend on how much CO_2 needs to be injected

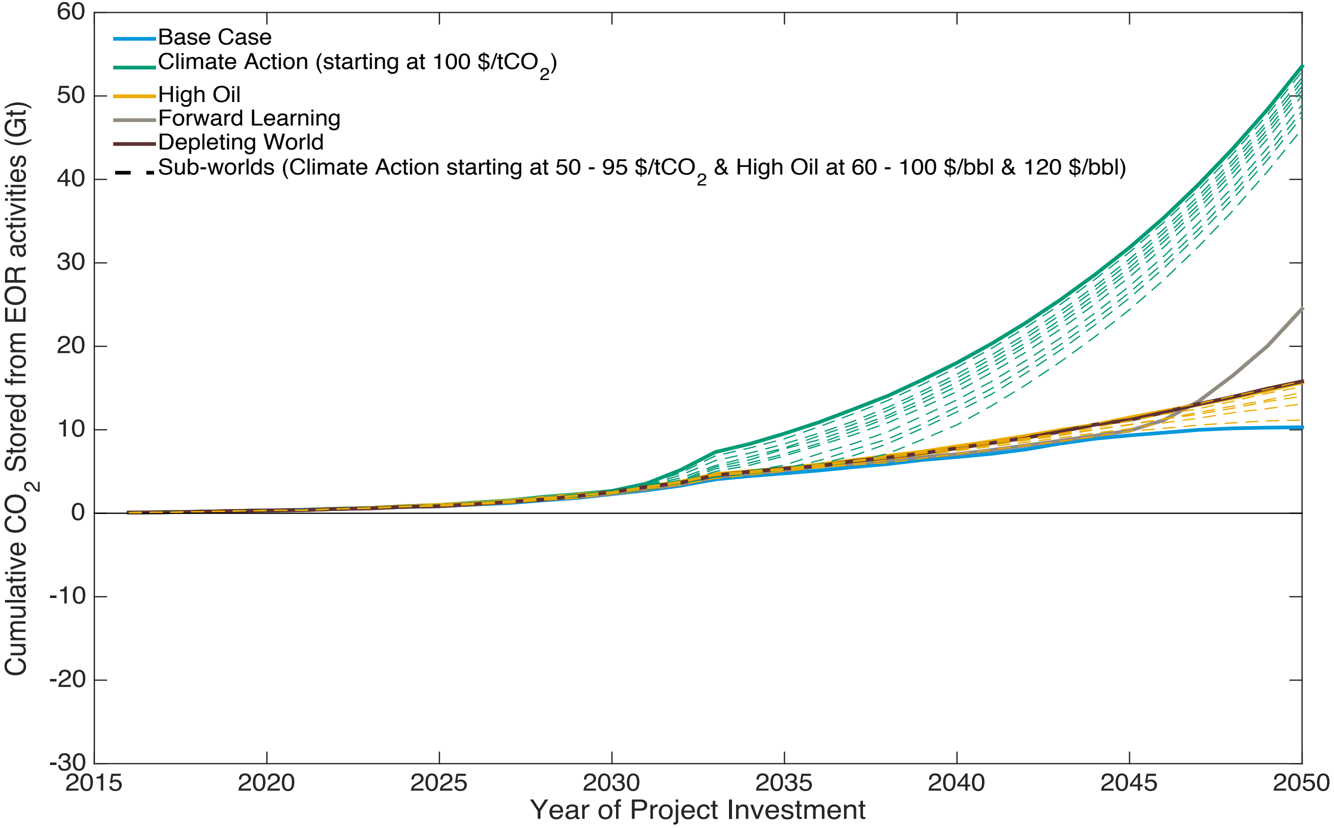


Eliminate successful projects from pool of project choices

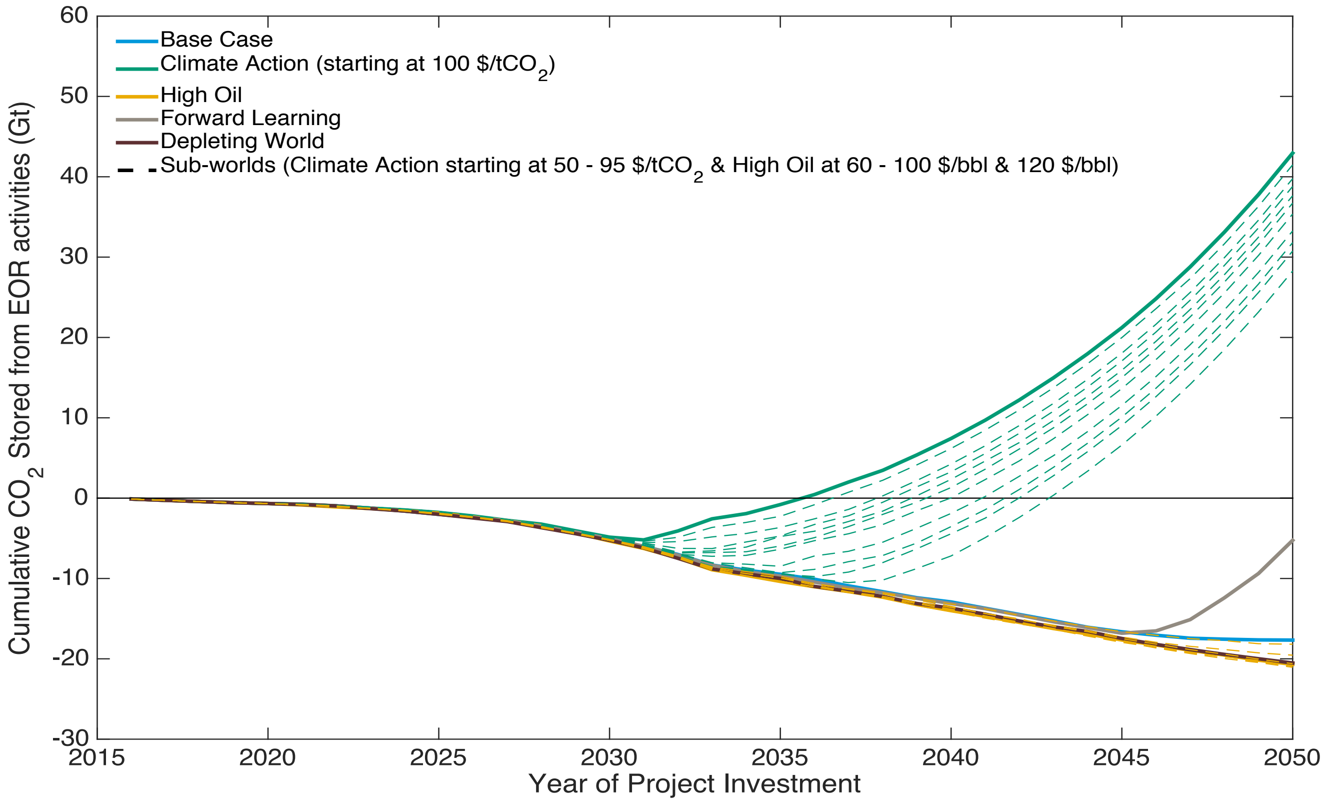
Five Scenarios exploring oil price, CO_2 tax, rates of price growth and learning

Scenario Name	Price of Oil in 2016 \$/bbl	Tax/credit on CO_2 in 2016 \$/tCO2	Tax rate increase \$/tCO_2/yr	Learning rate	Oil price growth rate
Base Case	55	25	+1\$	10%	No growth (only inflation)
Climate Action	55	**100**	**+2\$**	10%	No growth
High Oil	**110**	25	+1\$	10%	No growth
Forward Learning	55	25	+1\$	**14%**	No growth
Depleting Resources	55	25	+1\$	10%	**2%/year**

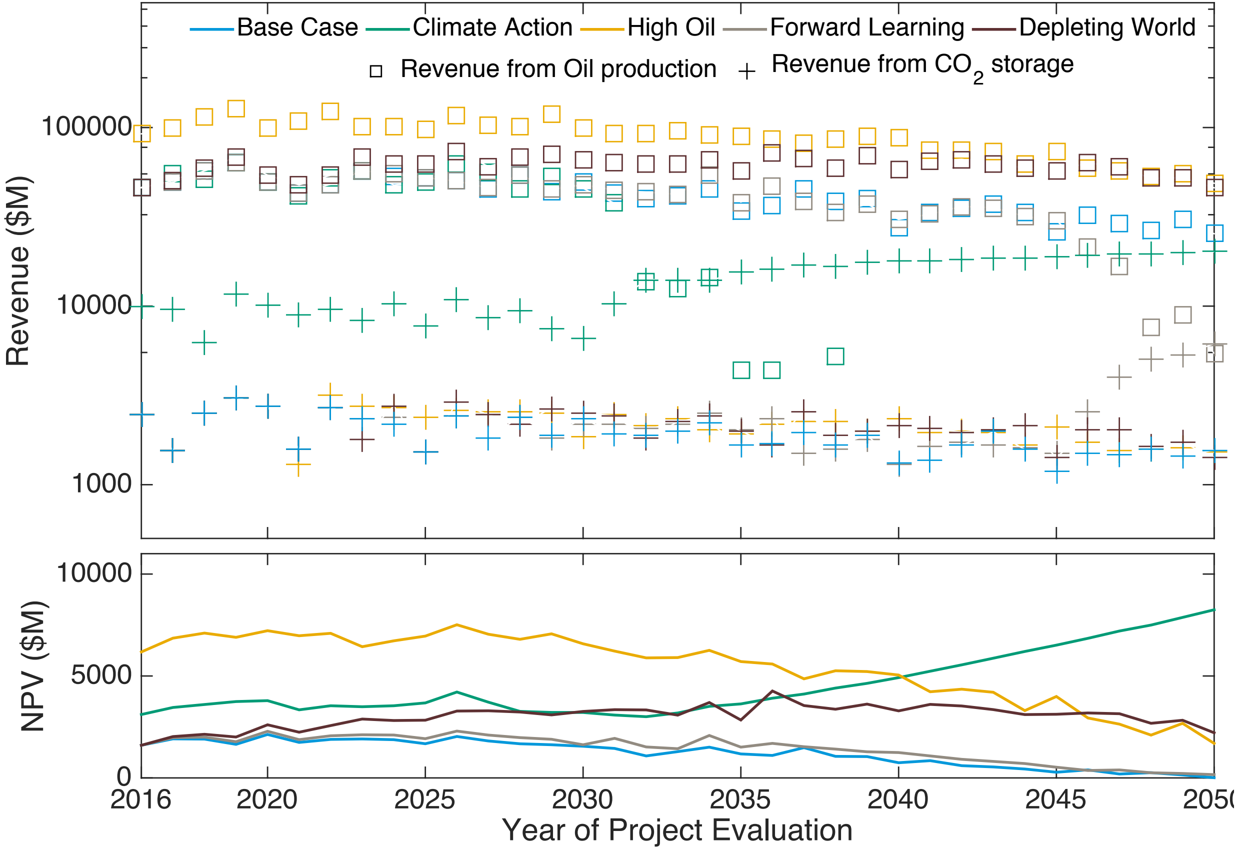
Not accounting for oil consumption, more CO_2 is stored when revenues from CO_2 storage are high



Including emissions from end-use crude oil produced, only very high CO_2 revenue leads to net CO_2 removed from the atmosphere



Revenues from CO_2 Storage struggle to overcome revenue from oil production



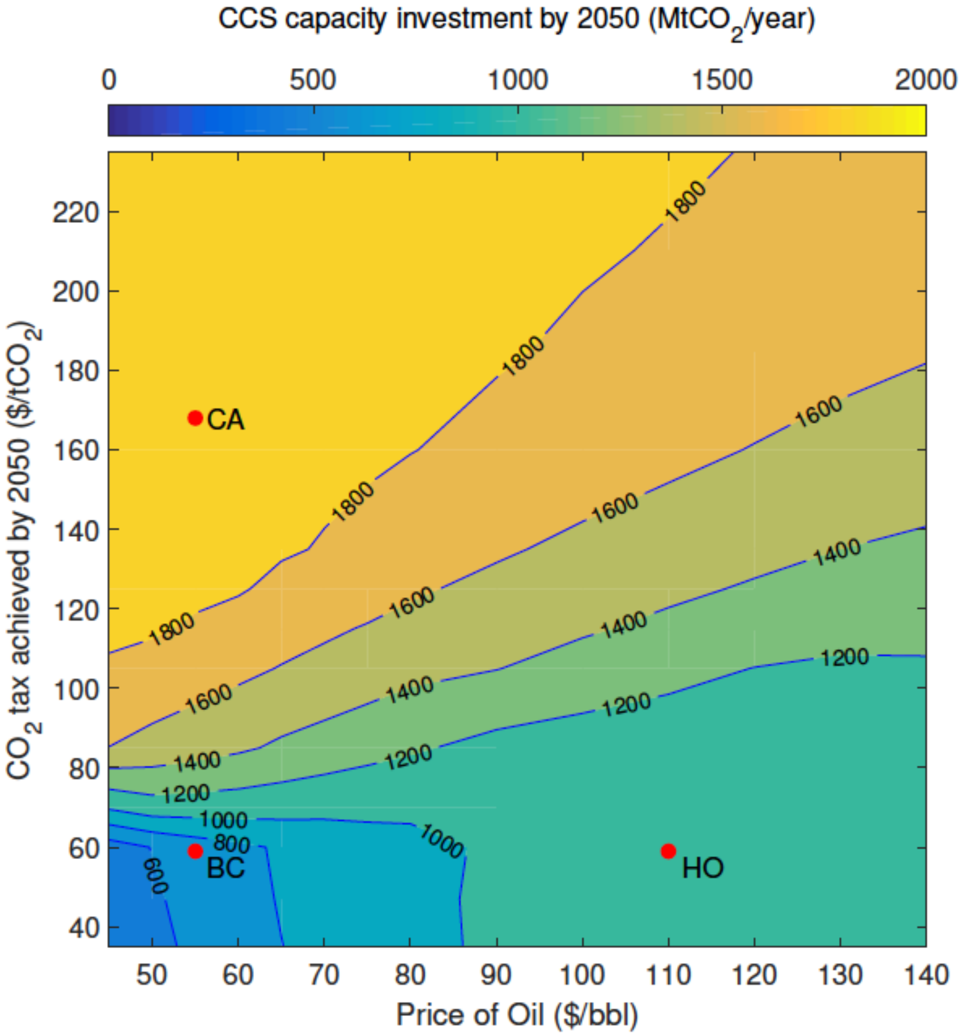
Why is it not happening more?

Costs and weak incentives

For storage deployment > 1Gt CO_2/year by 2050, need either

> $85/barrel of oil

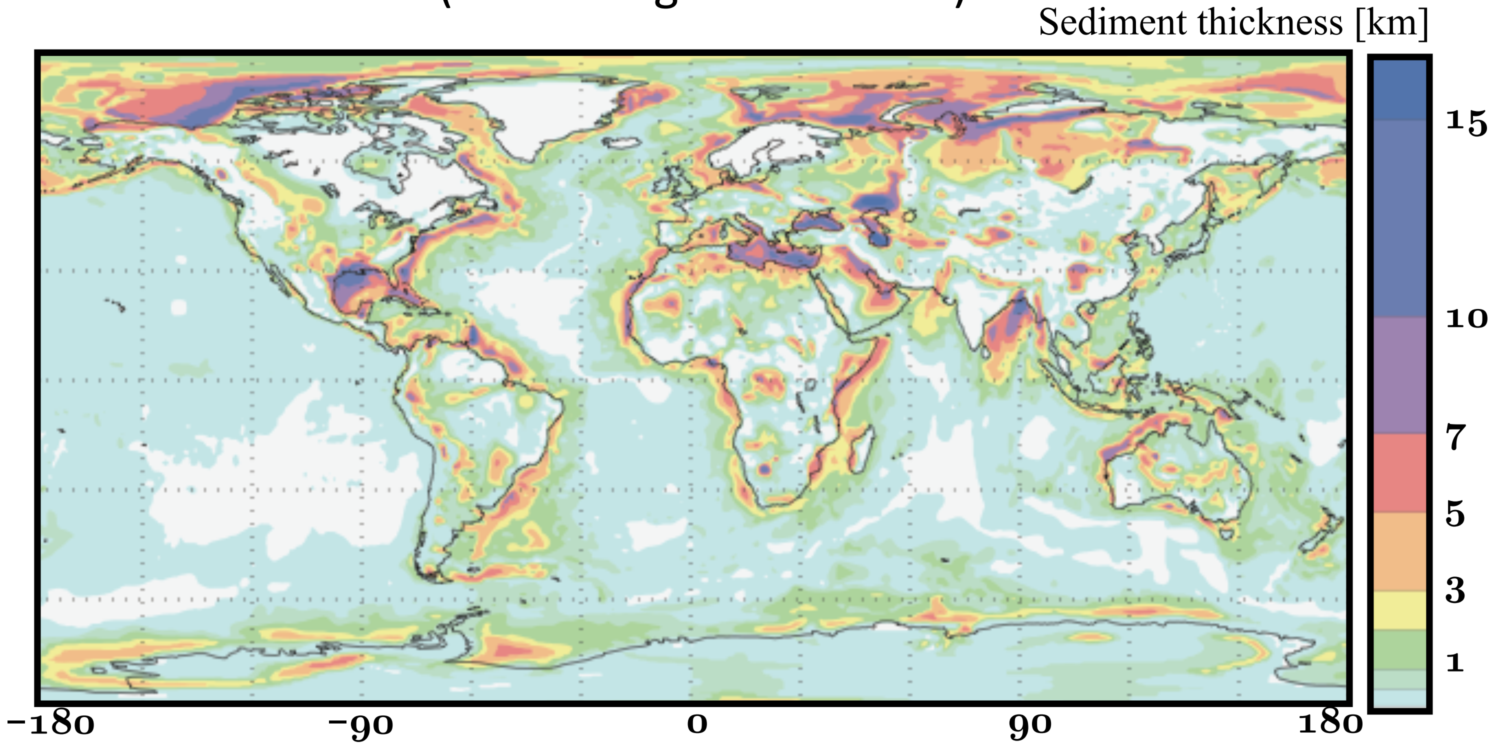
> $65/ton CO_2 tax



Kolster, C., Masnadi, M. S., Krevor, S., Mac Dowell, N., & Brandt, A. R. (2017). CO_2 enhanced oil recovery: a catalyst for gigatonne-scale carbon capture and storage deployment?. Energy & Environmental Science, 10(12), 2594-2608.

4. Storage Resource

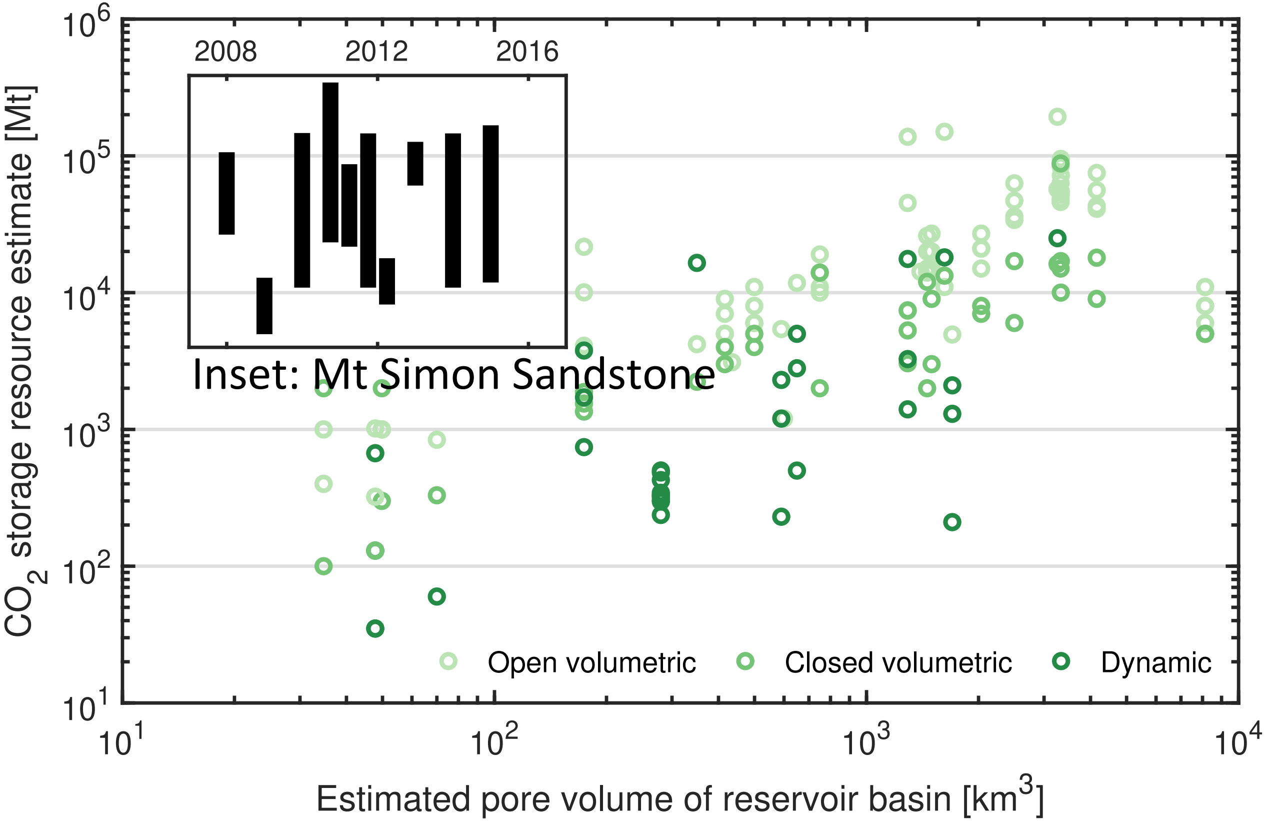
Storage reservoirs are found in sedimentary basins
(like oil & gas reservoirs)



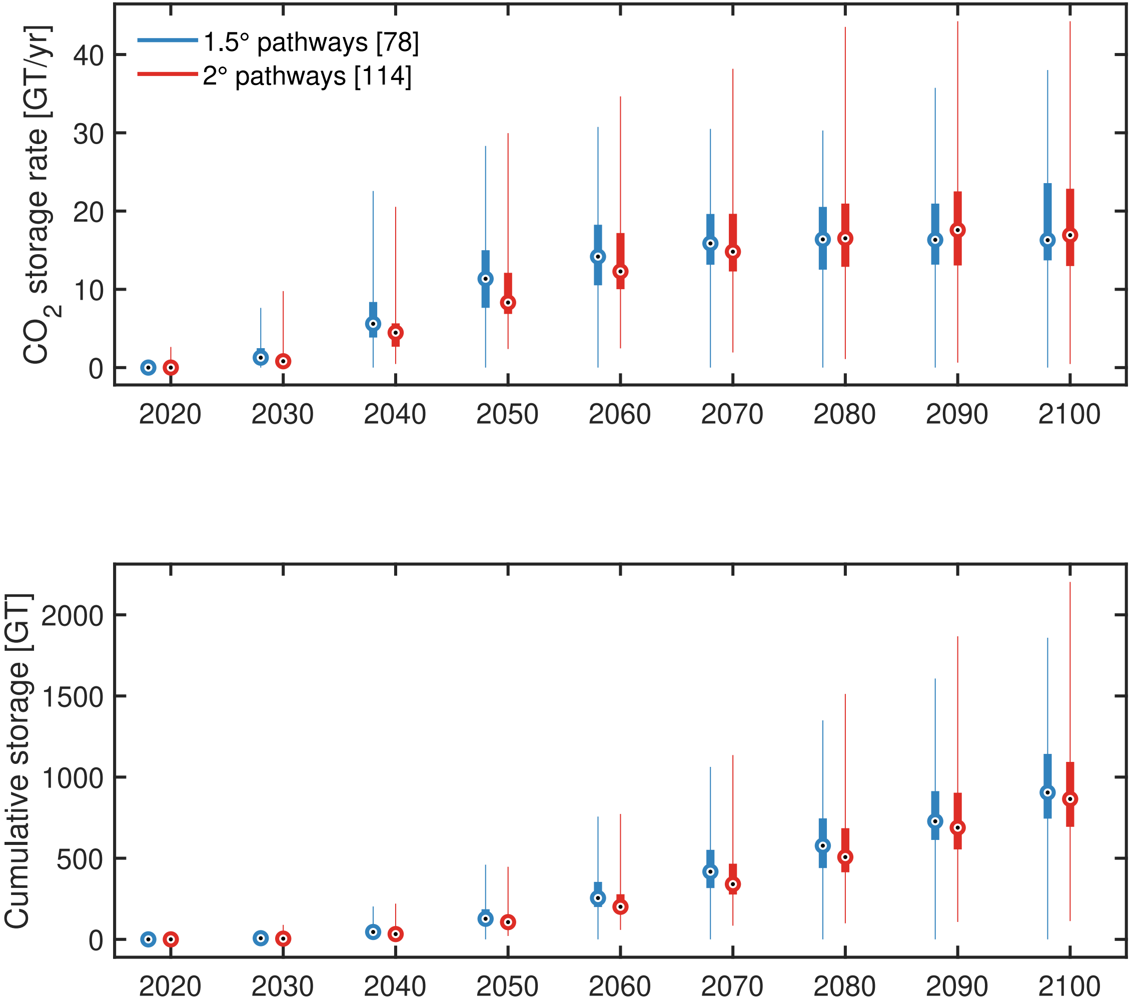
Laske, G., & Masters, G. (1997). A Global Digital Map of
Sediment Thickness. EOS Trans. AGU, 78, F483

Geologically based estimates of storage resource are uncertain

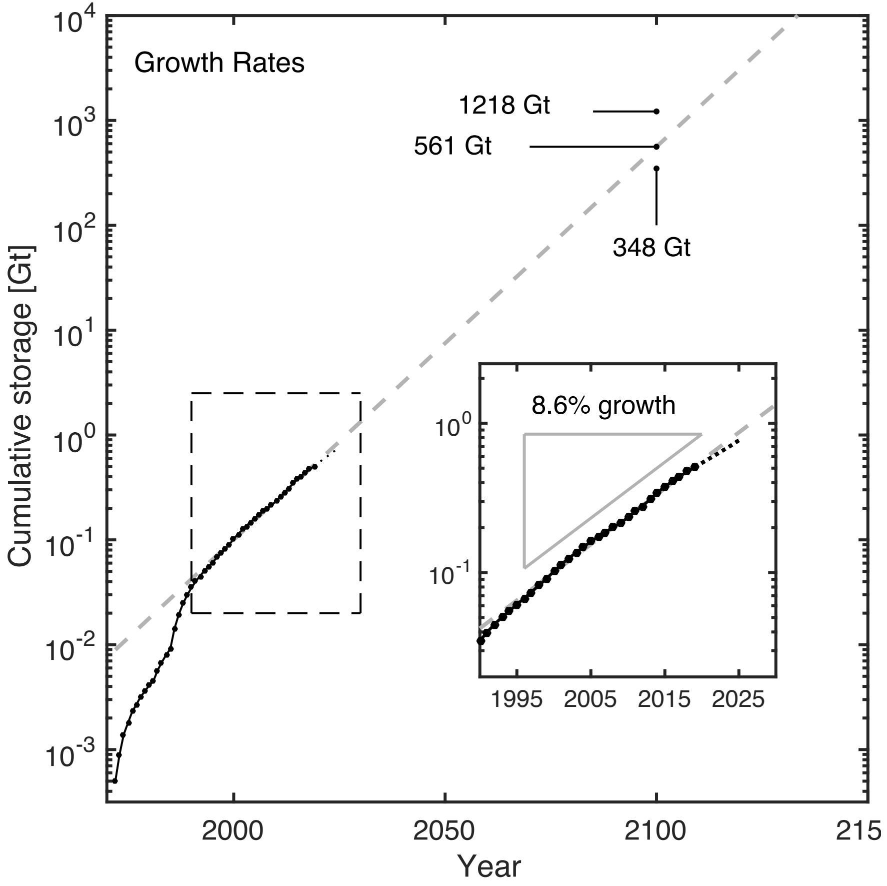
Accurate resource assessment depends on a history of resource use



Pathways in the IPCC consistent with limiting warming to less than 2°C require very large scales of CO_2 injection globally

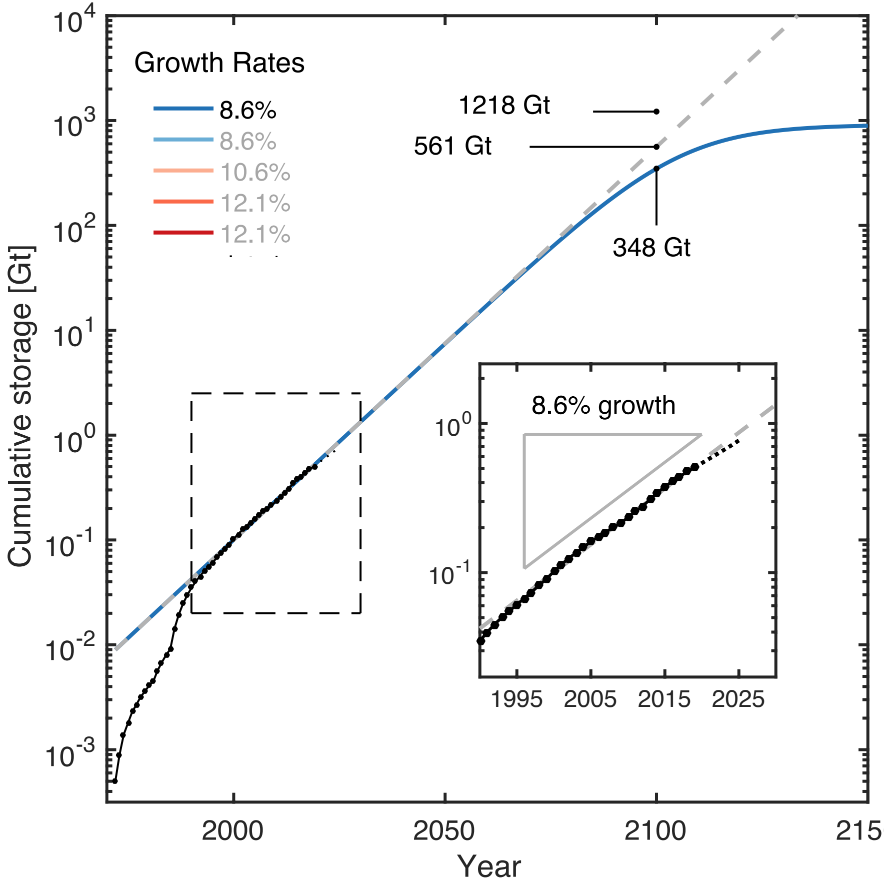


Current exponential growth of storage rates: 8.6%, sufficient to meet some <2°C pathways

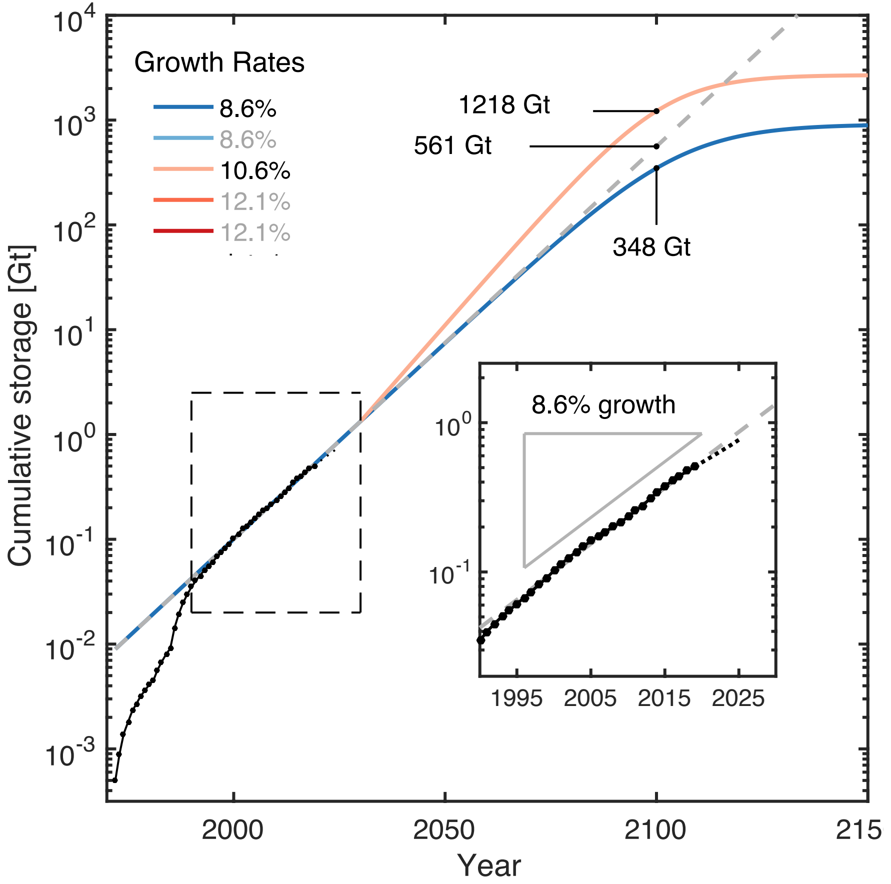


Logistic growth models: an initial exponential phase followed by a slowing of growth, e.g., due to emerging resource limitation constraints

There are realistic growth pathways to meet the lowest storage demand scenario, P2, in the IPCC 1.5°C report

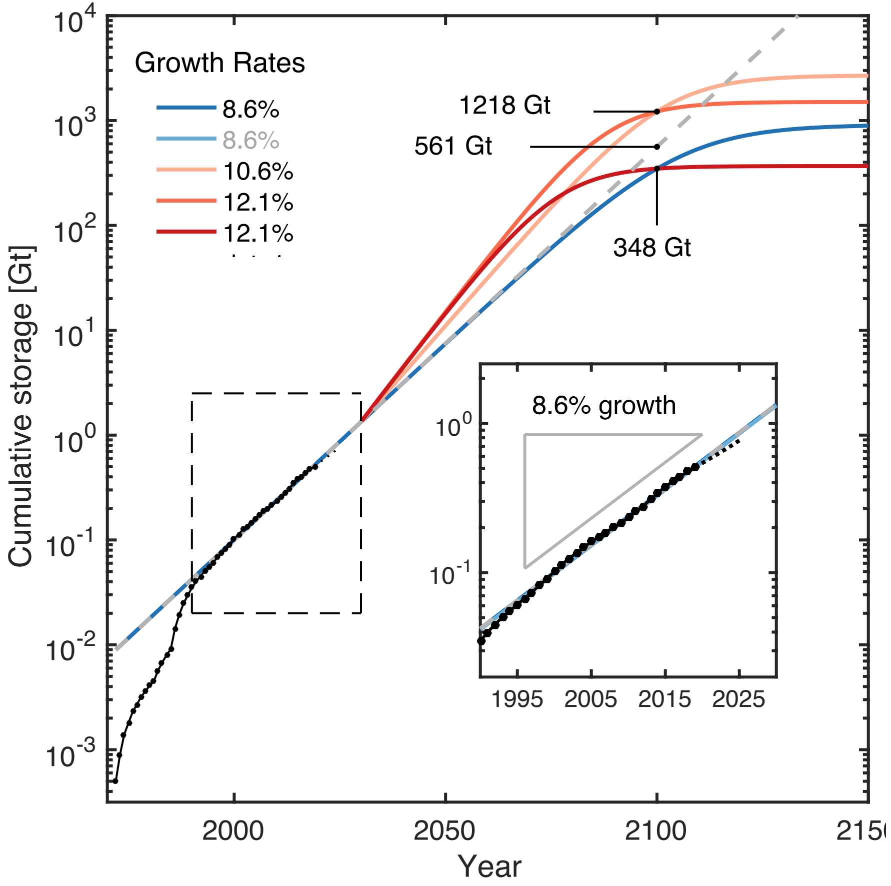


Higher and sustained growth rates are needed to hit median storage demand targets



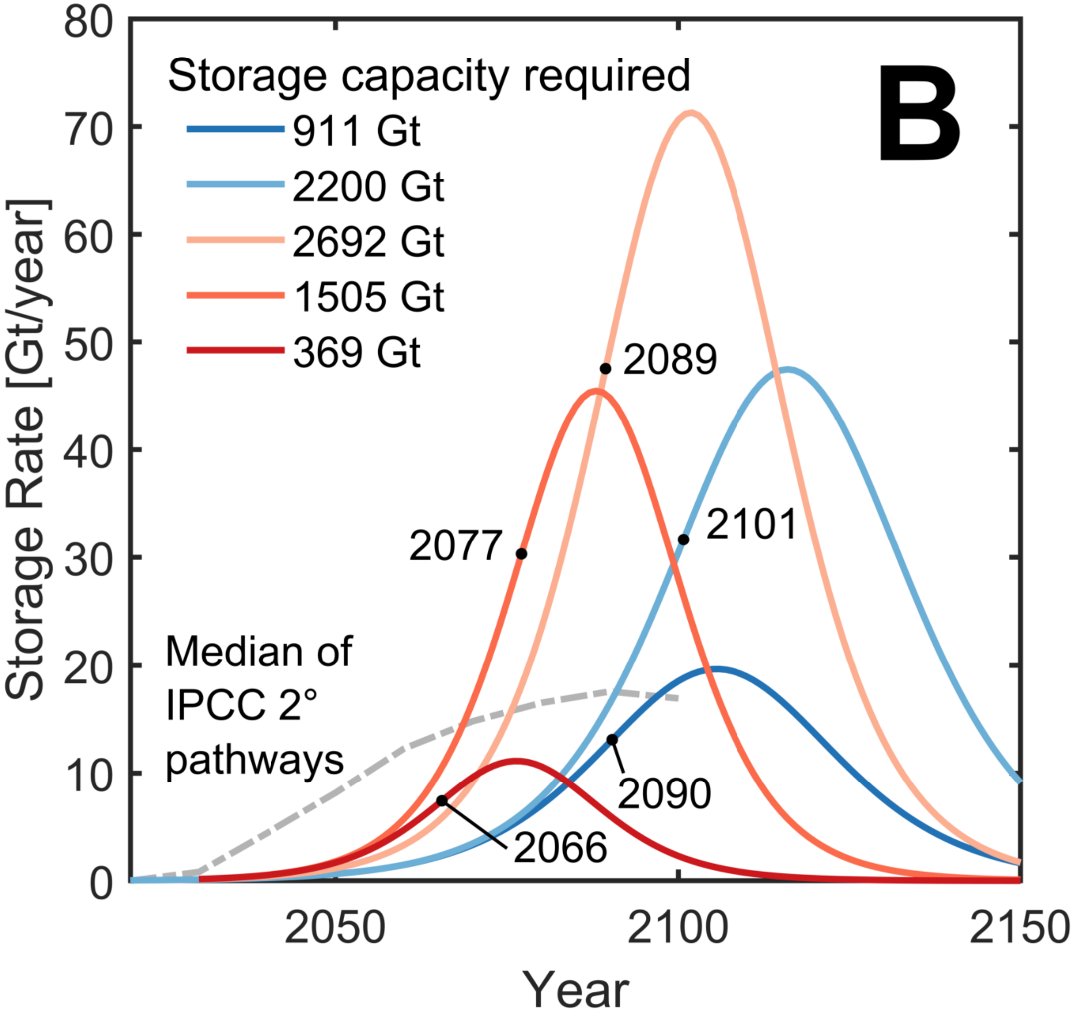
Even higher rates of growth achieved early, allow targets to be met with an early slow down in growth, e.g., due to resource limitations

Sigmoidal resource limited growth exhibits exponential growth for a maximum of ~20% of the storage resource



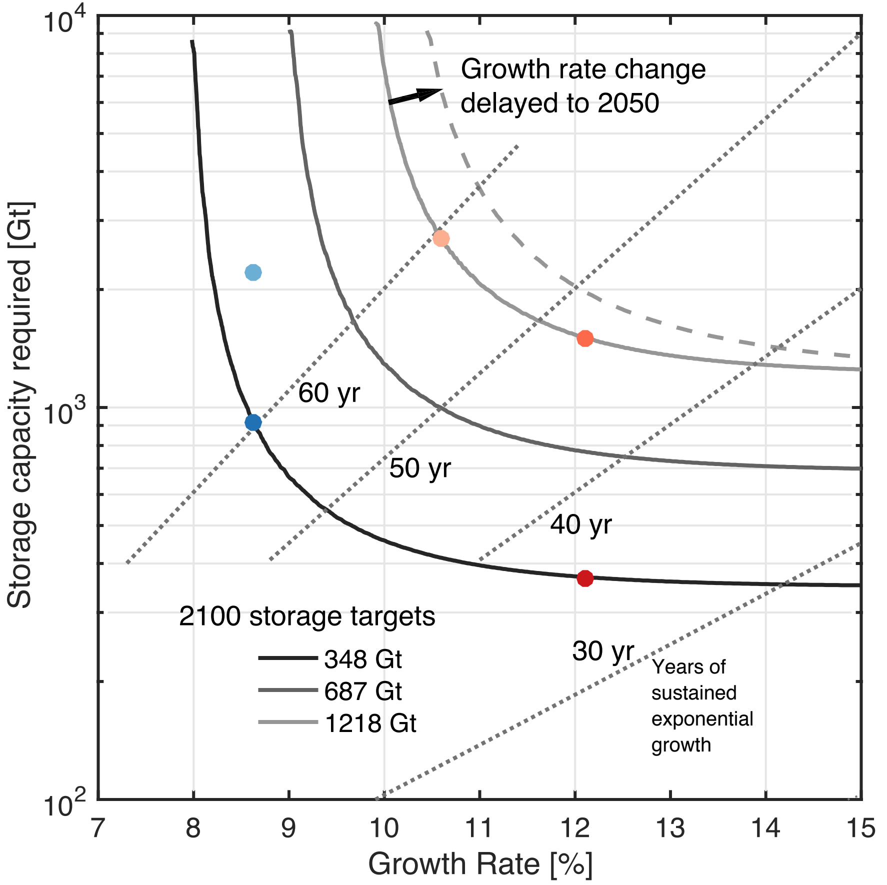
Thus, IPCC targets point to minimum* requirements for both growth rates and global storage resource

*minimum, or conservative, because resource depletion is often asymmetric



Meeting the highest 2100 storage target, 1218 Gt, implies a maximum requirement of 2700 Gt global storage capacity

Creating certainty around storage resources up to 2700 Gt would indicate we have sufficient storage to meet long term demand



Zahasky, C., Krevor, S. (2019). *Sub Judice*

Some takeaways

- CO_2 storage is central to meeting climate change targets
- Important ongoing technical issues include plume migration prediction and subsurface pressurisation
- Enhanced oil recovery is a strong incentive for CO_2 storage in the USA and implications for meeting climate change targets must be assessed
- Growth is currently on track for low end demand scenarios, ~400 Gt stored by 2100
- High confidence in capacity for low end demand scenarios, larger targets are less certain but not impossible

Acknowledgements:

UKCCS RESEARCH CENTRE
NERC SCIENCE OF THE ENVIRONMENT
Accelerating CCS Technologies
ELEGANCY