Status and Opportunities in CO_2 Capture, Storage and Utilization

Professor Sally M. Benson
Energy Resources Engineering Department
Director, Global Climate and Energy Project
Director, Precourt Institute for Energy
Stanford University

San Antonio, TX
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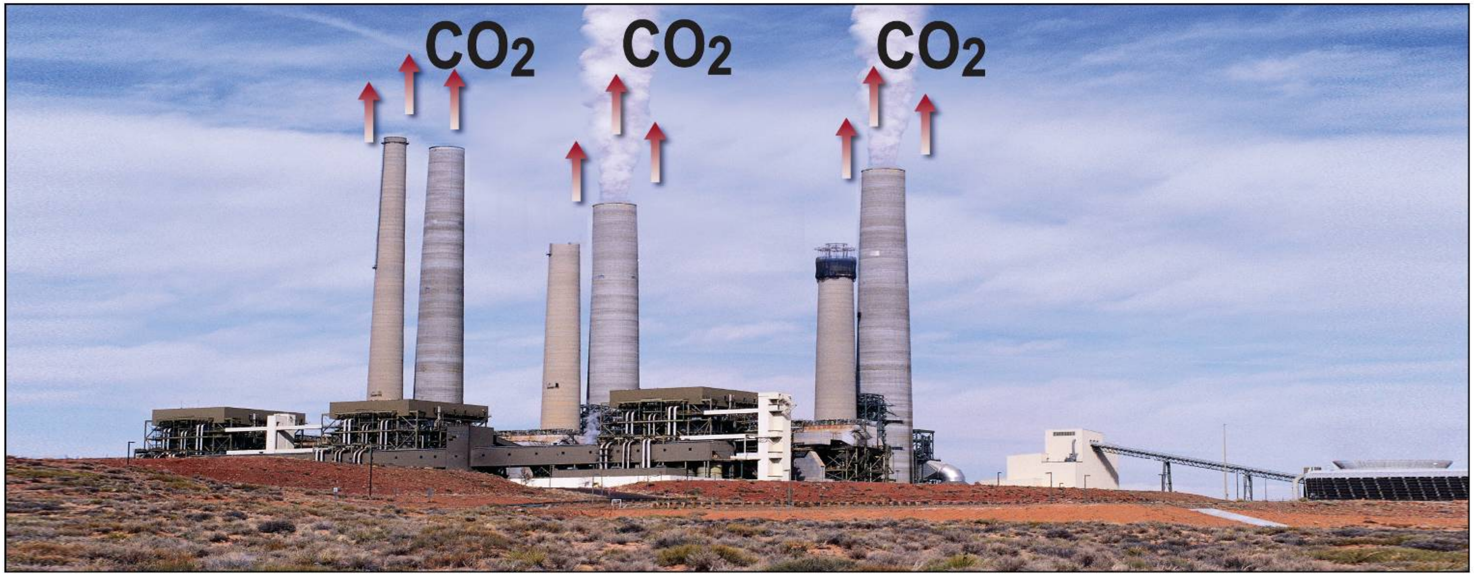
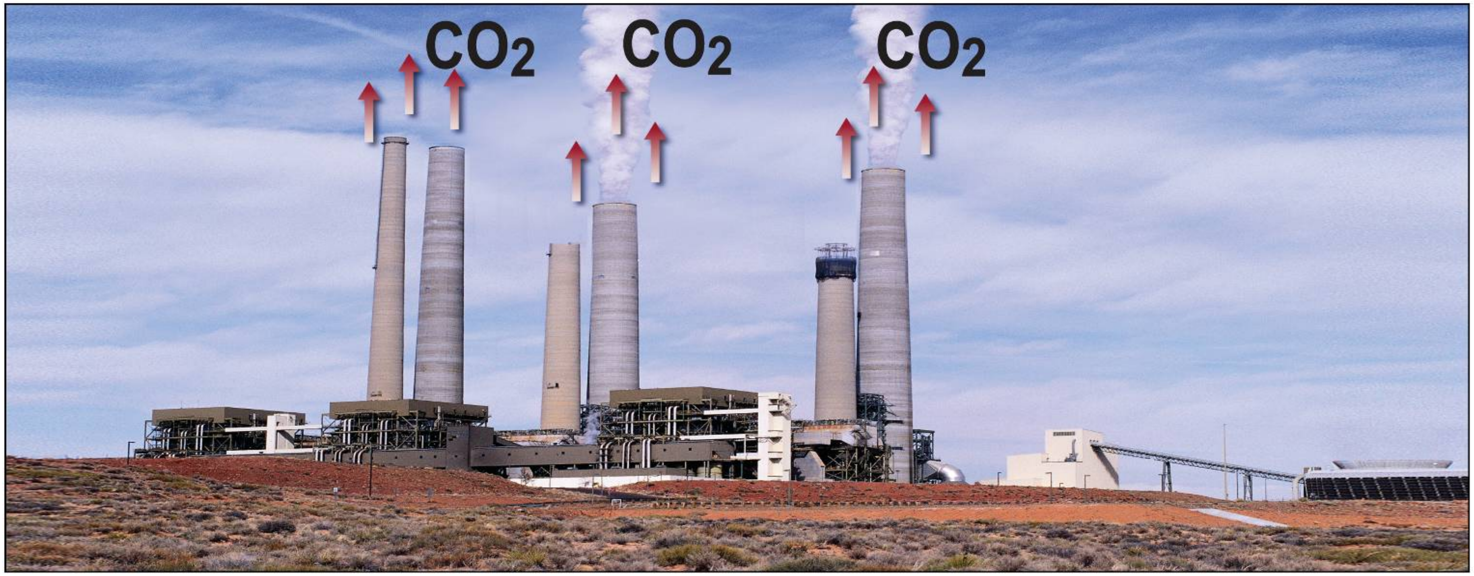
Workshop on Energy Research and Applications for Physics Students and Postdocs , APS

What is Carbon Dioxide Capture and Storage and Why is it Important?

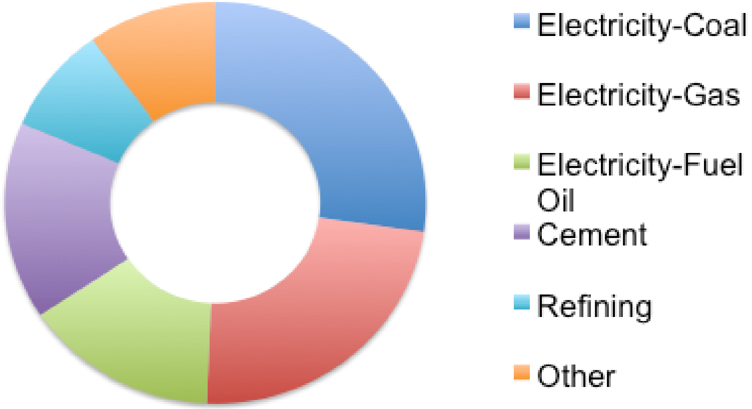


- Carbon dioxide capture and storage technology can reduce carbon dioxide emissions into the atmosphere from using fossil fuels
- More than 80% of today's energy comes from fossil fuels and a rapid transition to low carbon energy sources is difficult and expensive
- Necessary to achieve large and rapid carbon dioxide emission reductions

CCS Can Reduce Emissions from Many Sources

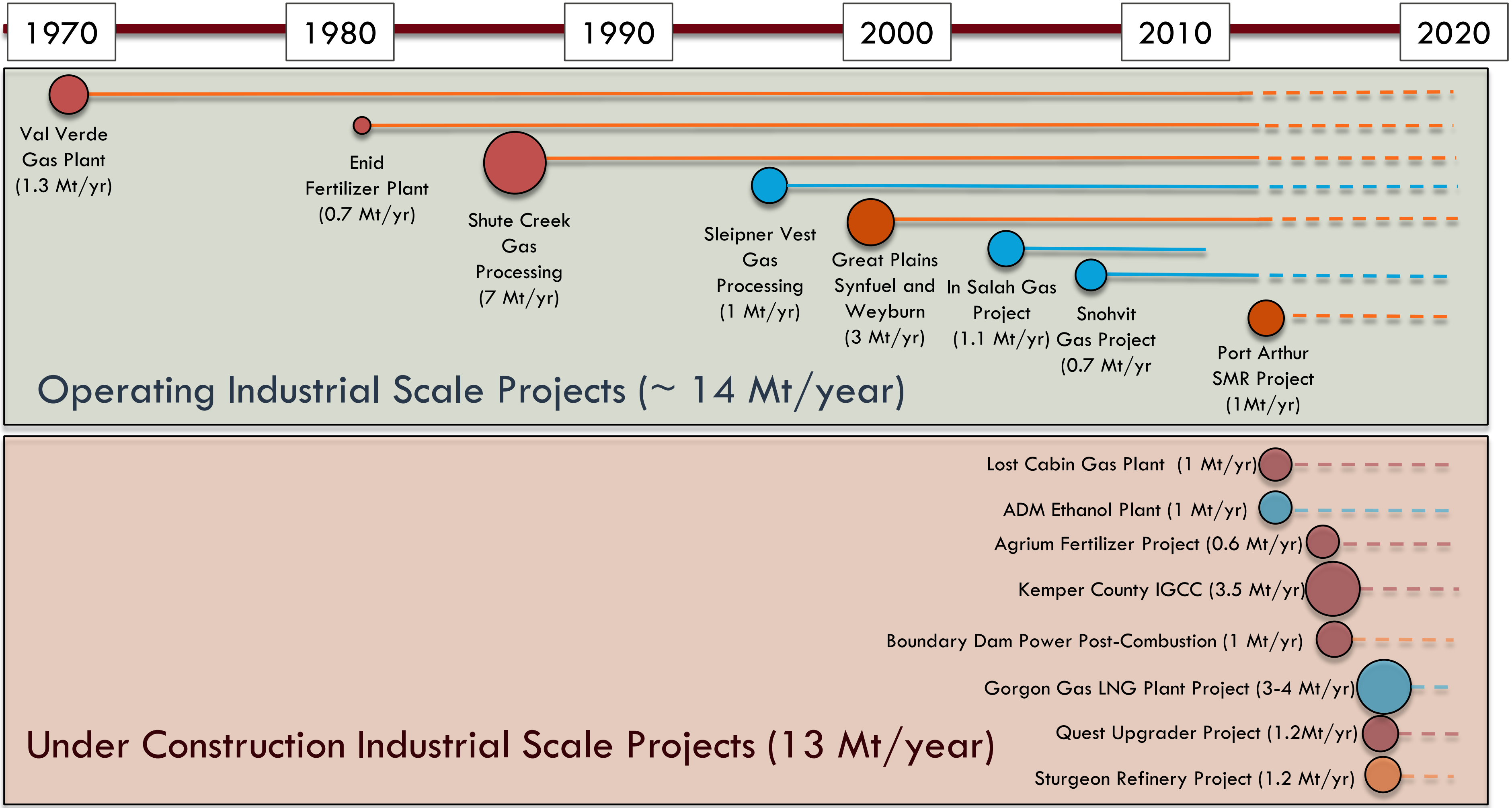


7,400 sources greater than 0.1 Mt/yr



CCS is applicable to the 60% of CO_2 emissions which come from stationary sources such as power plants, cement plants and refineries.

CCS Continues to Expand Worldwide



Val Verde Gas Plant (1.3 Mt/yr)

Enid Fertilizer Plant (0.7 Mt/yr)

Shute Creek Gas Processing (7 Mt/yr)

Sleipner Vest Gas Processing (1 Mt/yr)

Great Plains Synfuel and Weyburn (3 Mt/yr)

In Salah Gas Project (1.1 Mt/yr)

Snohvit Gas Project (0.7 Mt/yr

Port Arthur SMR Project (1Mt/yr)

Operating Industrial Scale Projects (~ 14 Mt/year)

Lost Cabin Gas Plant (1 Mt/yr)

ADM Ethanol Plant (1 Mt/yr)

Agrium Fertilizer Project (0.6 Mt/yr)

Kemper County IGCC (3.5 Mt/yr)

Boundary Dam Power Post-Combustion (1 Mt/yr)

Gorgon Gas LNG Plant Project (3-4 Mt/yr)

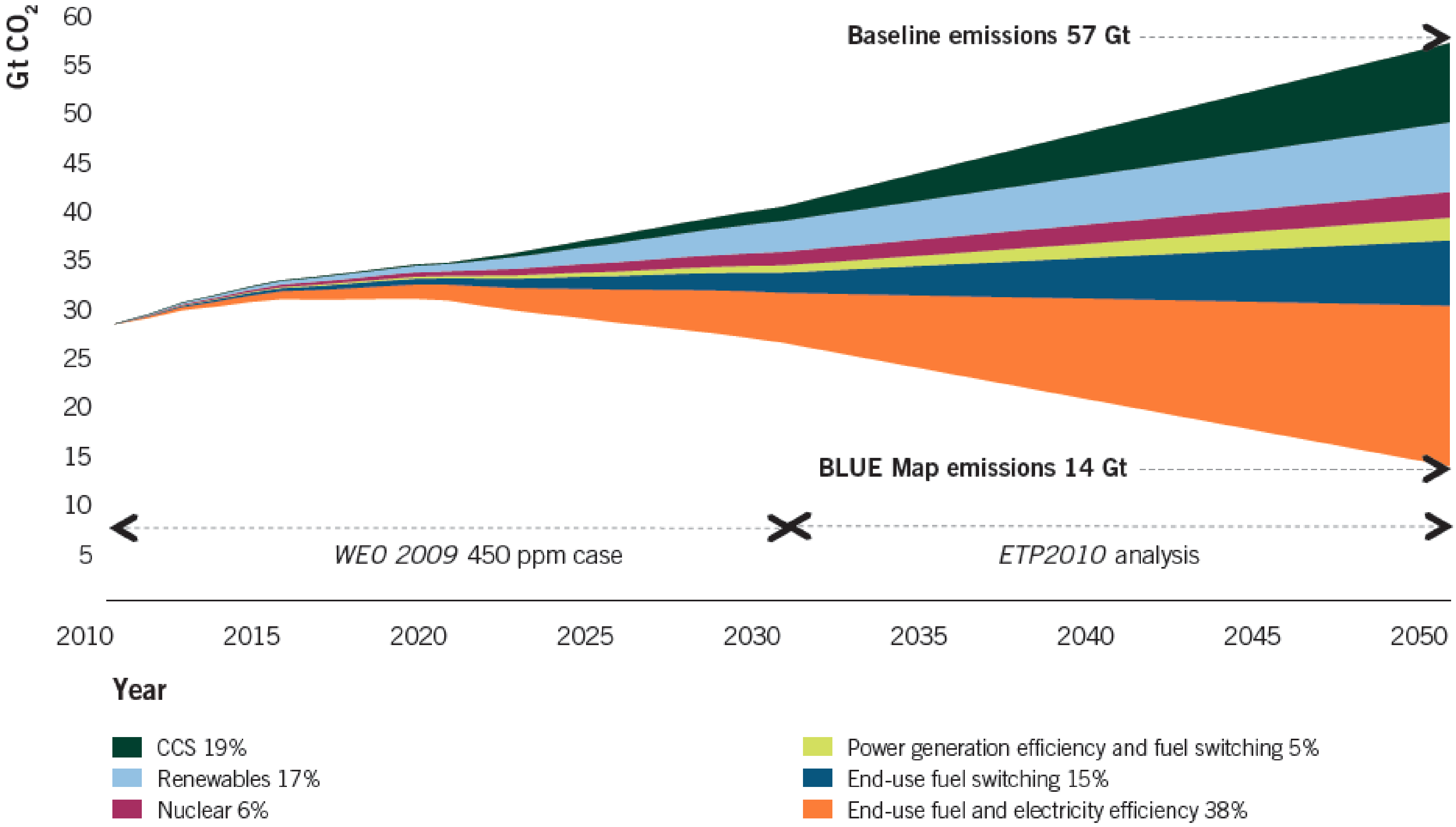
Quest Upgrader Project (1.2Mt/yr)

Sturgeon Refinery Project (1.2 Mt/yr)

Under Construction Industrial Scale Projects (13 Mt/year)

DeConninck and Benson, 2014. Annual Reviews in Energy and Environment.

CCS Is Expected to Contribute About 20% to Needed CO_2 Emission Reductions



Source: IEA, 2010.

CCS is an Efficient Means of Large Emission Reductions

CCS with 90% capture

One 1,000 MW coal-fired power plant (~6.5 MT CO_2/year)

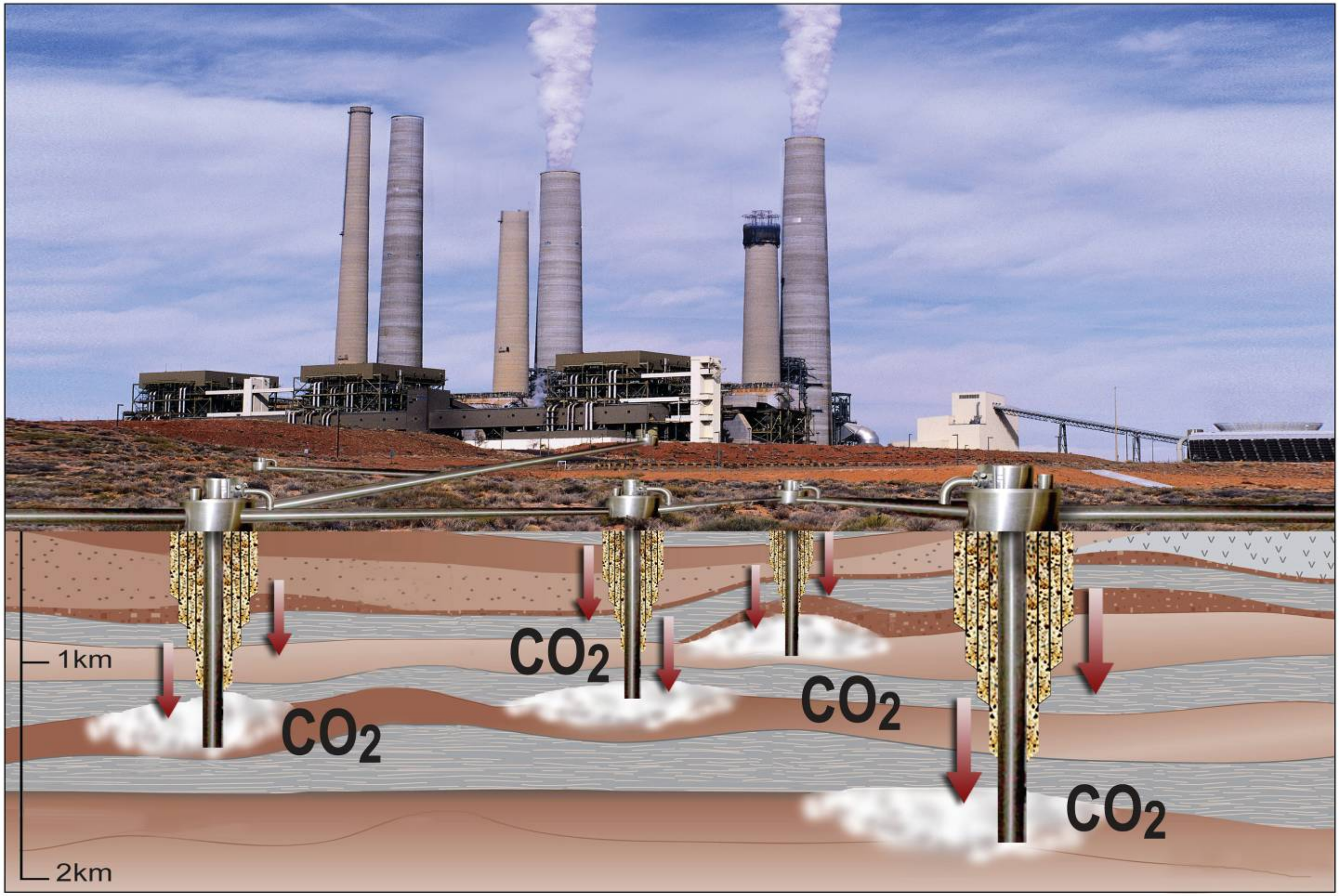
=

Increase efficiency from 25 to 50 mpg

2.8 Million Cars
(10% of California Fleet)

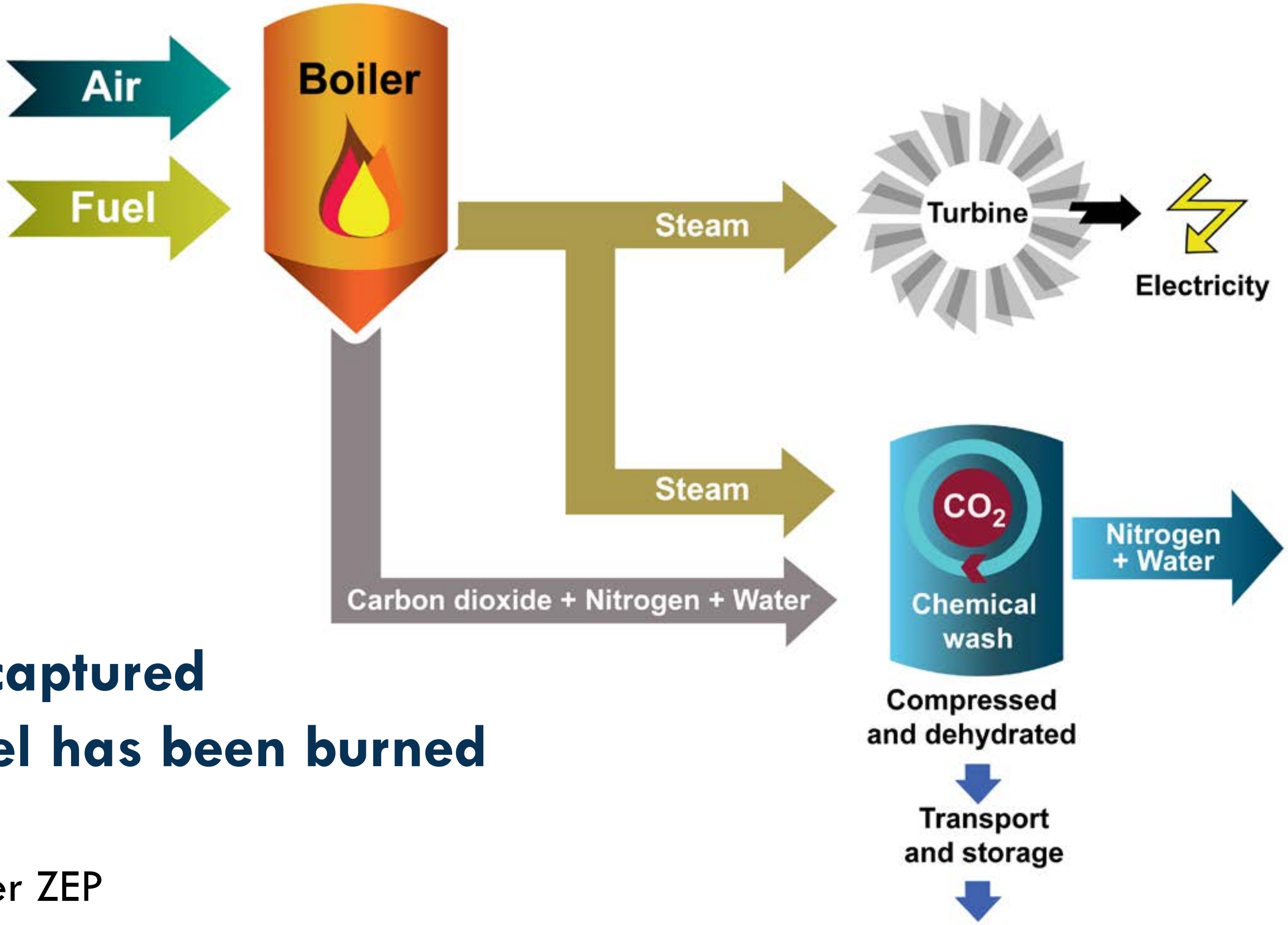
CCS dramatically reduce the number of actors needed to achieve large emission reductions.

CO_2 Capture and Storage Involves Four Steps



Capture → Compression → Pipeline Transport → Storage or Reuse

Post-Combustion Capture



CO_2 is captured after fuel has been burned

Image after ZEP

Oxy-Combustion

CO_2 is captured during combustion

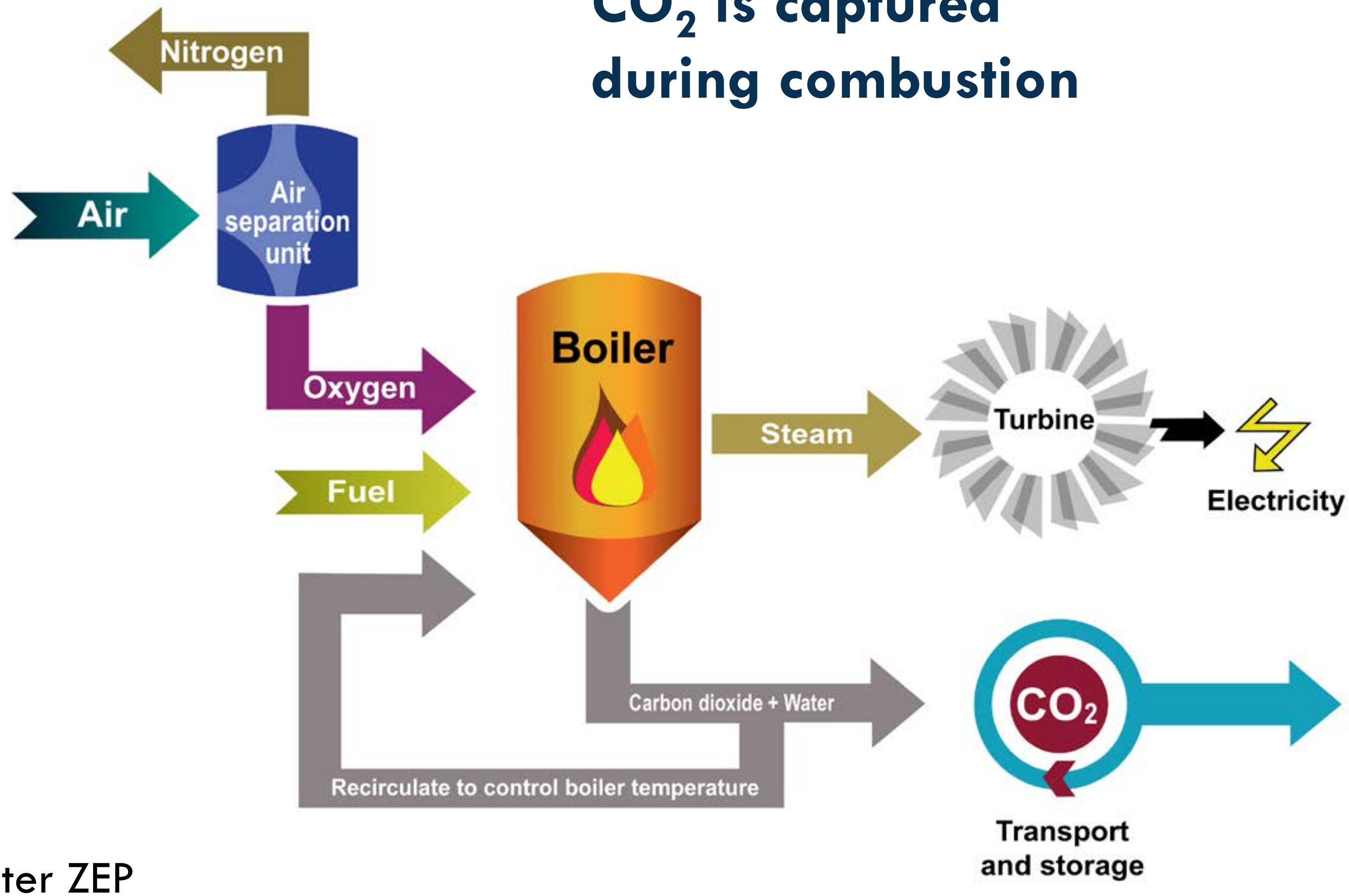
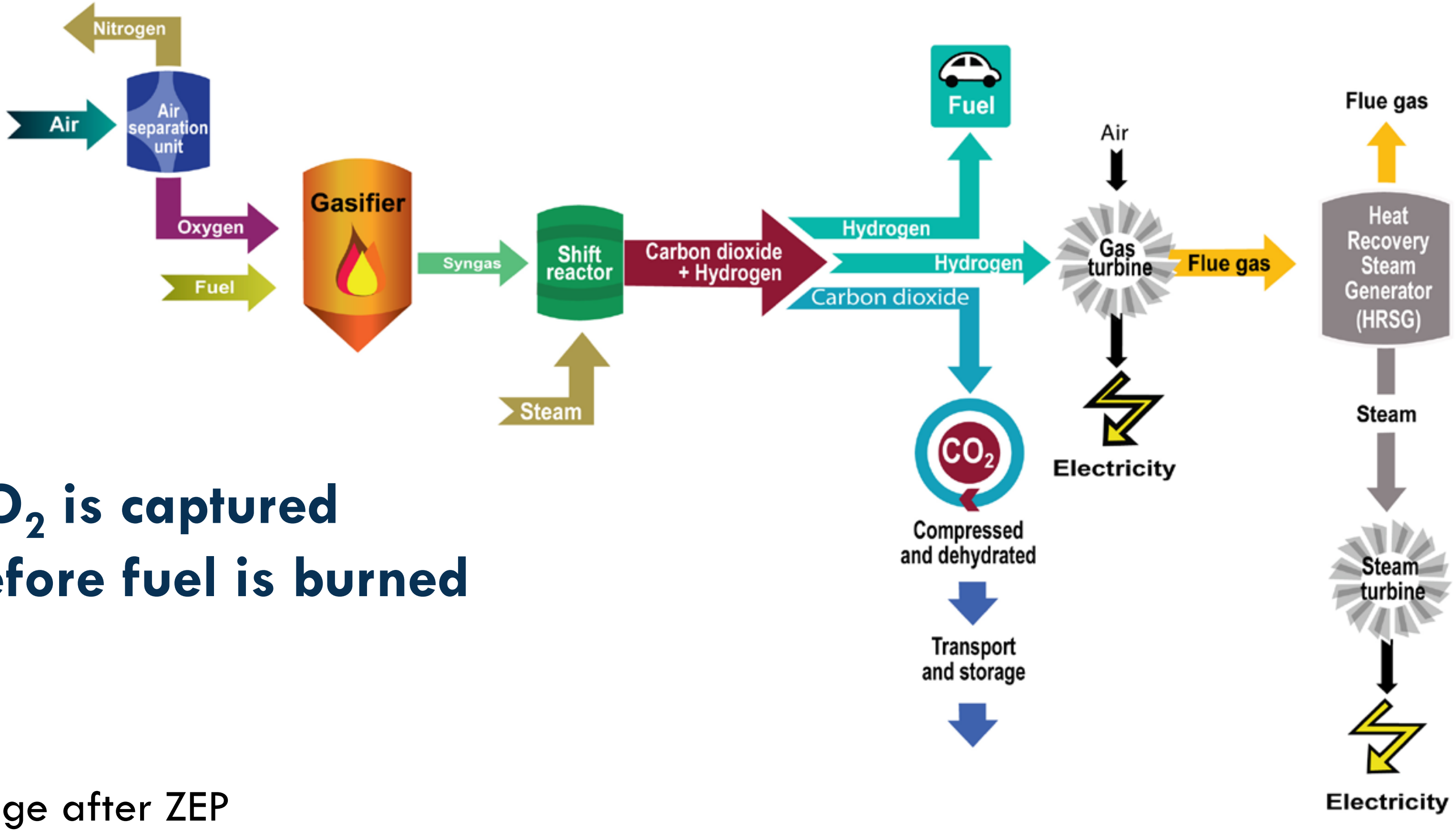


Image after ZEP

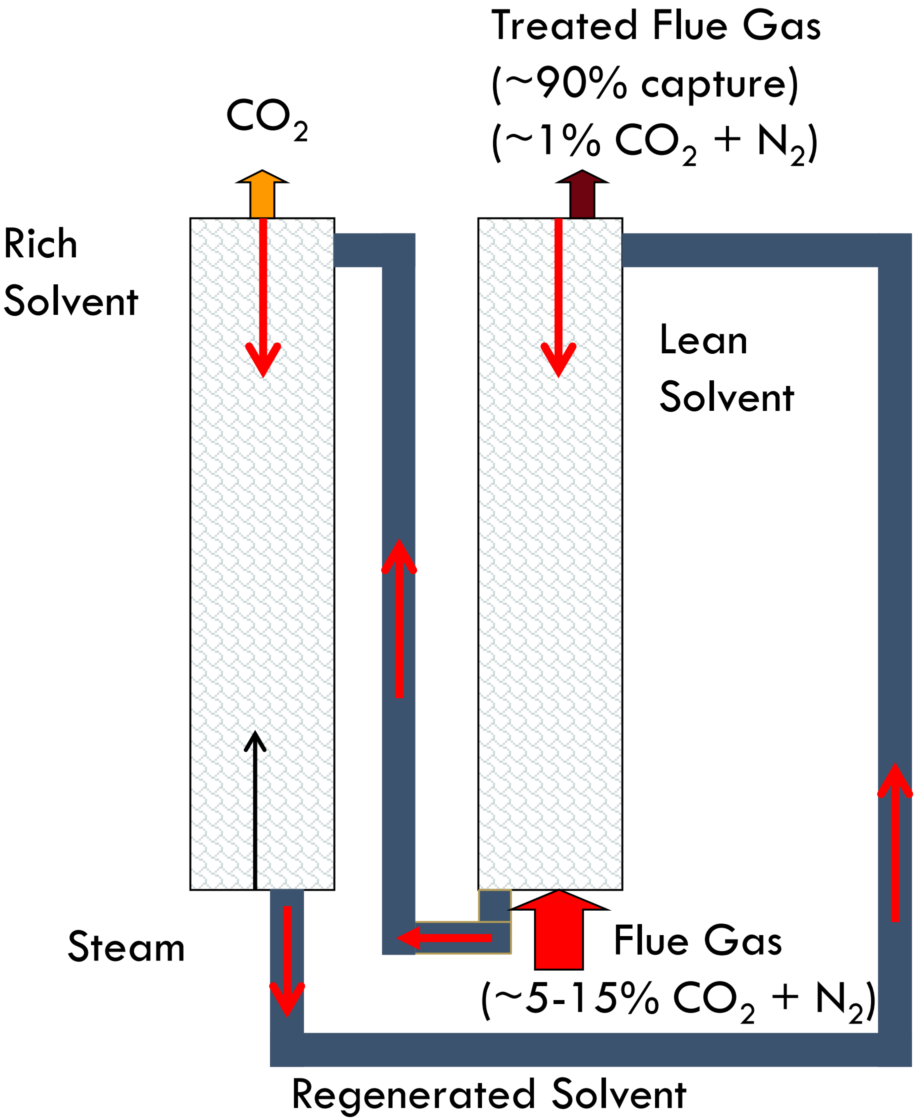
Pre-Combustion Capture

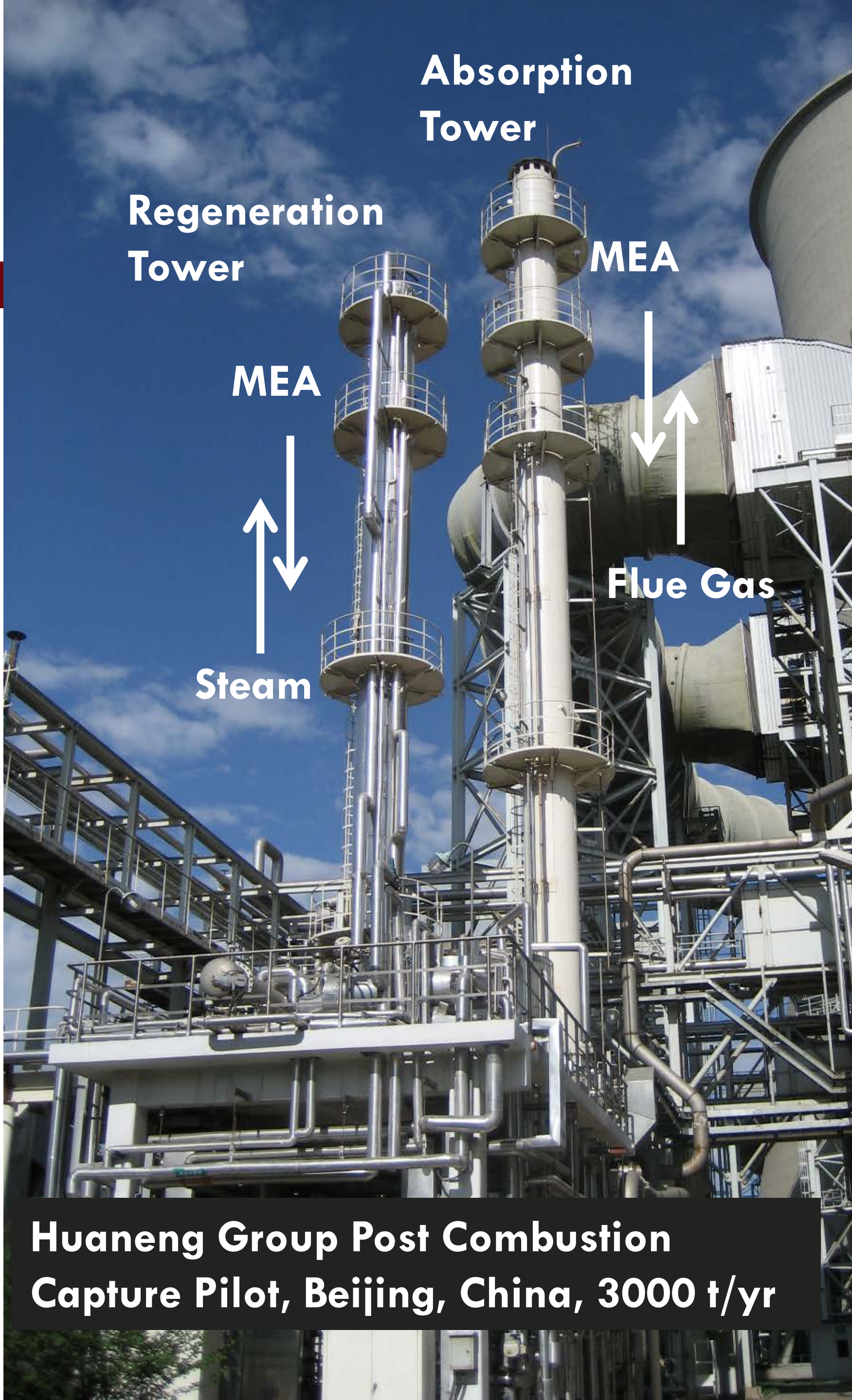


CO_2 is captured before fuel is burned

Image after ZEP

Post-Combustion Capture





Huaneng Group Post Combustion Capture Pilot, Beijing, China, 3000 t/yr

The World's First Power Plant with CO_2 Capture and Storage

Boundary Dam Project

Sasketchewan, Canada

Comparison of Capture Options

Technology	Advantages	Challenges
Post-Combustion	• Mature technology • Standard retrofit	• High energy penalty (20-30%) • High cost for capture
Pre-Combustion (IGCC)	• Lower costs than post-combustion • Lower energy penalties (10-15%) • H_2 production	• Complex chemical process • Repowering • Large capital investment
Oxygen-Combustion	• Avoid complex post-combustion separation • Potentially higher generation efficiencies	• Oxygen separation • Repowering

Cost and performance of today's capture technology

- Energy penalty: 10 to 30%
- Cost
  - \$60 to \$110/tonne CO_2 for the nth plant
  - Significantly more for the 1st plants (\$150 to \$250/tonne CO_2)
  - Cost of electricity generation: 50 to 100% increase
- Uncertain reliability
- R&D needed do develop new options and improve existing ones

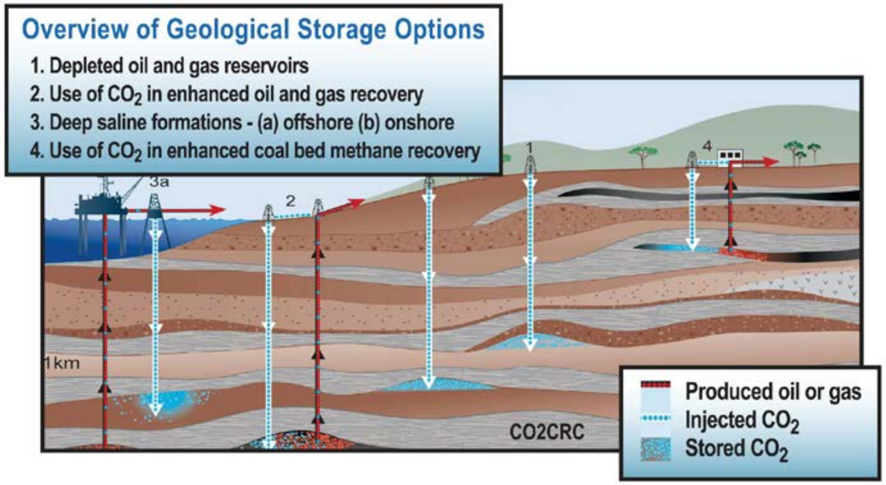
Advanced Materials and Processes for CO_2 Capture

Separation Approach	Absorption	Adsorption	Cryogenic	Membranes	Mineralization
Example Materials	Aqueous amine solutions Chilled ammonia Ionic liquids	Zeolites Metal organic frameworks (MOFs) Activated carbon	No specific material requirements	Polymer membranes Inorganic membranes	Magnesium silicates Alkalai-rich waste streams
Advantages	Numerous solvent options Rapid improvements in energy requirements achieved	Potentially lower energy requirements for regeneration	Avoid need for solvents or sorbents Lower energy requirements	Avoid regeneration energy requirements	CO_2 is converted to a solid substrate that can be reused as a building material or disposed of in surface facilities
Technological Challenges	Reducing energy for regeneration Solvent degradation	Adsorption capacity and kinetics	Solid separation and handling	Permeability Selectivity	Rate of reactions Large mass of reactants (e.g. source of Mg, Ca)

What Do You do with the CO_2 Once it's Captured?

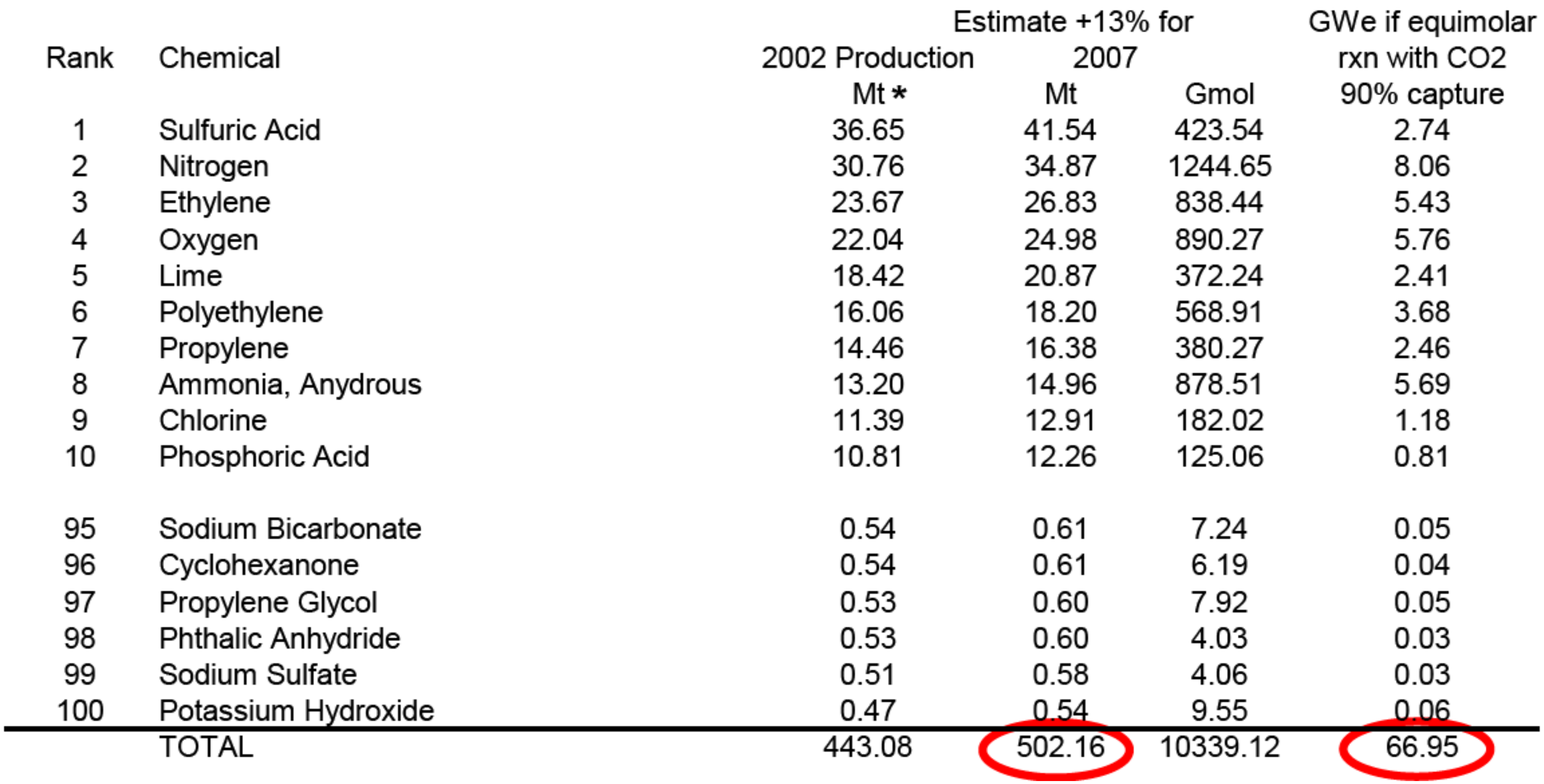
- Underground injection for sequestration or CO_2-EOR

OR



- Reuse for producing fuels, chemicals, or services

Potential for CO_2 Reuse in the Chemical Industry is Extremely Limited

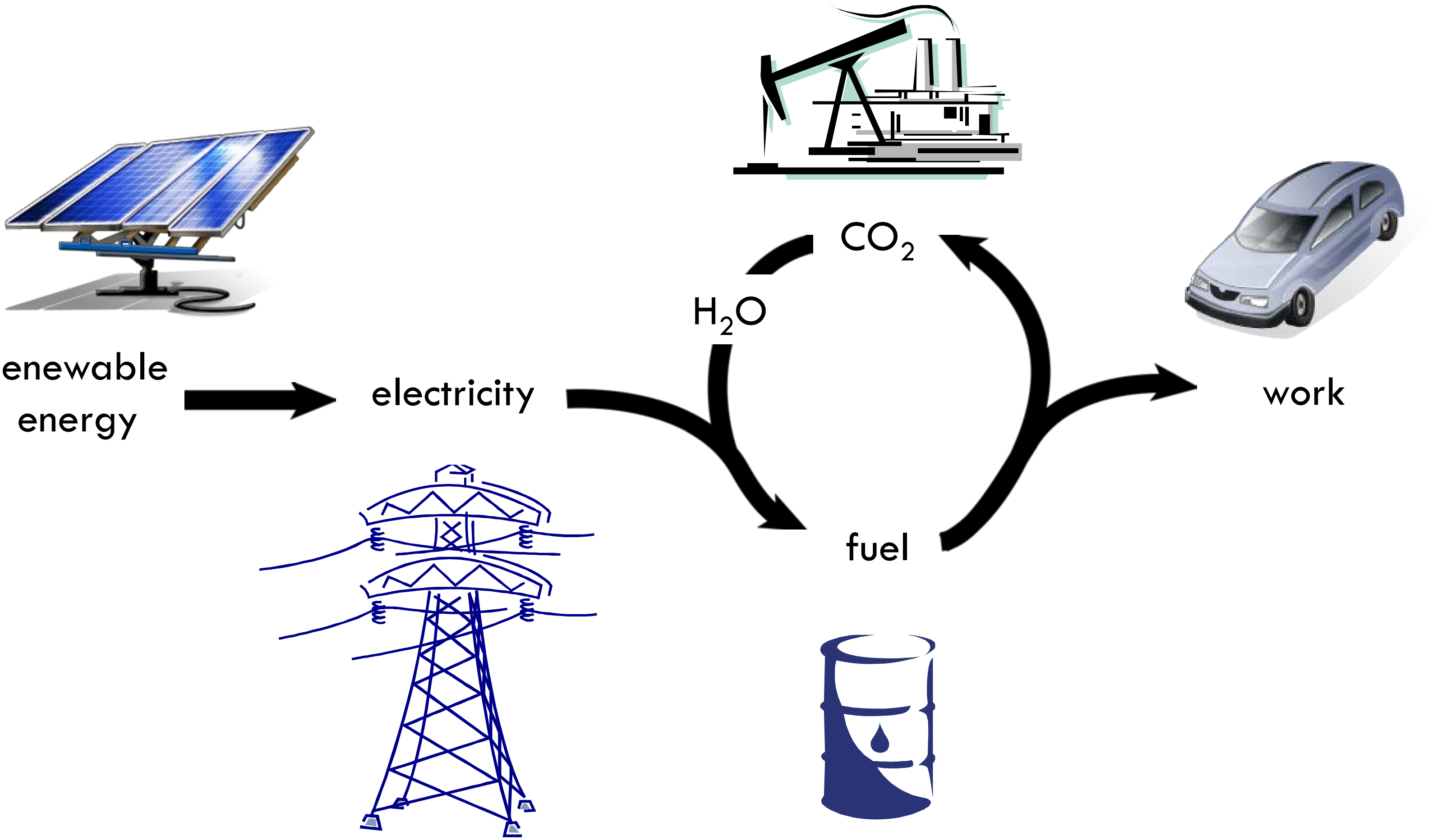


Rank	Chemical	2002 Production Mt *	Estimate +13% for 2007 Mt	Gmol	GWe if equimolar rxn with CO2 90% capture
1	Sulfuric Acid	36.65	41.54	423.54	2.74
2	Nitrogen	30.76	34.87	1244.65	8.06
3	Ethylene	23.67	26.83	838.44	5.43
4	Oxygen	22.04	24.98	890.27	5.76
5	Lime	18.42	20.87	372.24	2.41
6	Polyethylene	16.06	18.20	568.91	3.68
7	Propylene	14.46	16.38	380.27	2.46
8	Ammonia, Anydrous	13.20	14.96	878.51	5.69
9	Chlorine	11.39	12.91	182.02	1.18
10	Phosphoric Acid	10.81	12.26	125.06	0.81
95	Sodium Bicarbonate	0.54	0.61	7.24	0.05
96	Cyclohexanone	0.54	0.61	6.19	0.04
97	Propylene Glycol	0.53	0.60	7.92	0.05
98	Phthalic Anhydride	0.53	0.60	4.03	0.03
99	Sodium Sulfate	0.51	0.58	4.06	0.03
100	Potassium Hydroxide	0.47	0.54	9.55	0.06
	TOTAL	443.08	502.16	10339.12	66.95

Global top 100 chemicals produce a total of 0.5 Gt/yr; CO_2 emissions are 35 GT/yr. Therefore, opportunities for CO_2 reuse in the chemical industry are limited. Fuels are the best option for CO_2 reuse at scale.

From Abhoyjit S. Bhown, EPRI, 2009

Abiotic Renewable Fuels



renewable energy

electricity

H_2O

CO_2

fuel

work

Catalysts are the Key for CO_2 Reuse

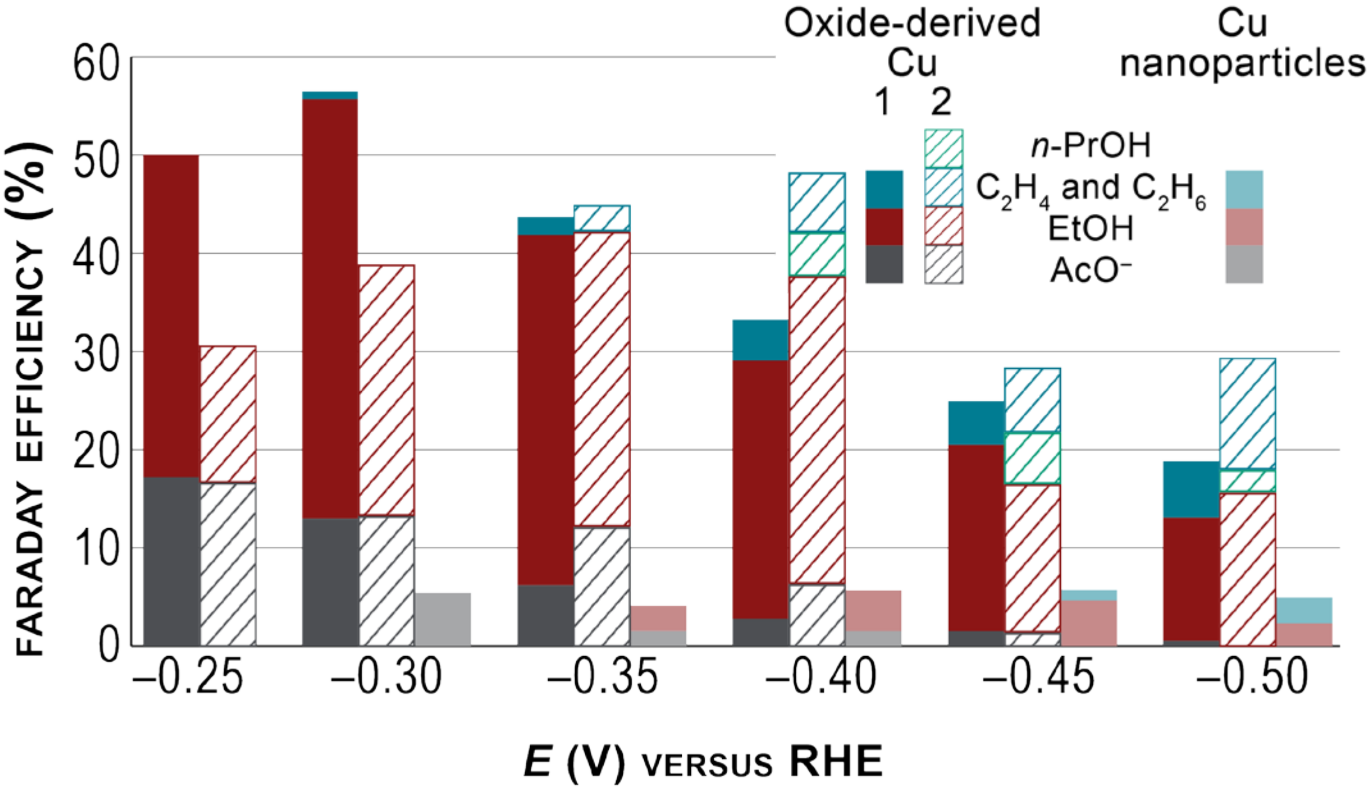
Matthew Kanan, Christina Li
Chemistry

LETTER

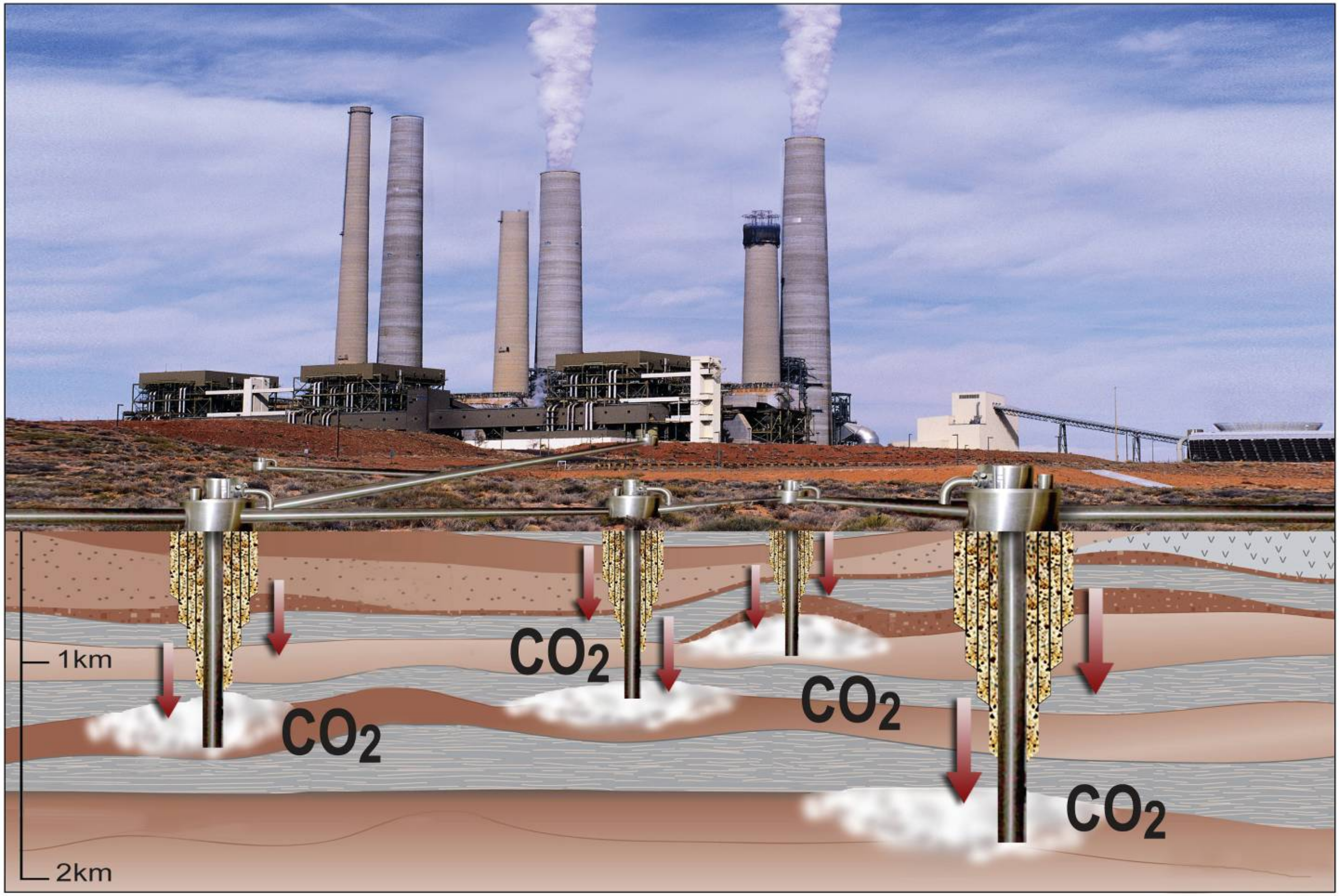
Electroreduction of carbon monoxide to liquid fuel on oxide-derived nanocrystalline copper

Nature. April 2014

- Novel copper oxide derived catalyst converts carbon monoxide (CO) to ethanol and acetate at room temperature

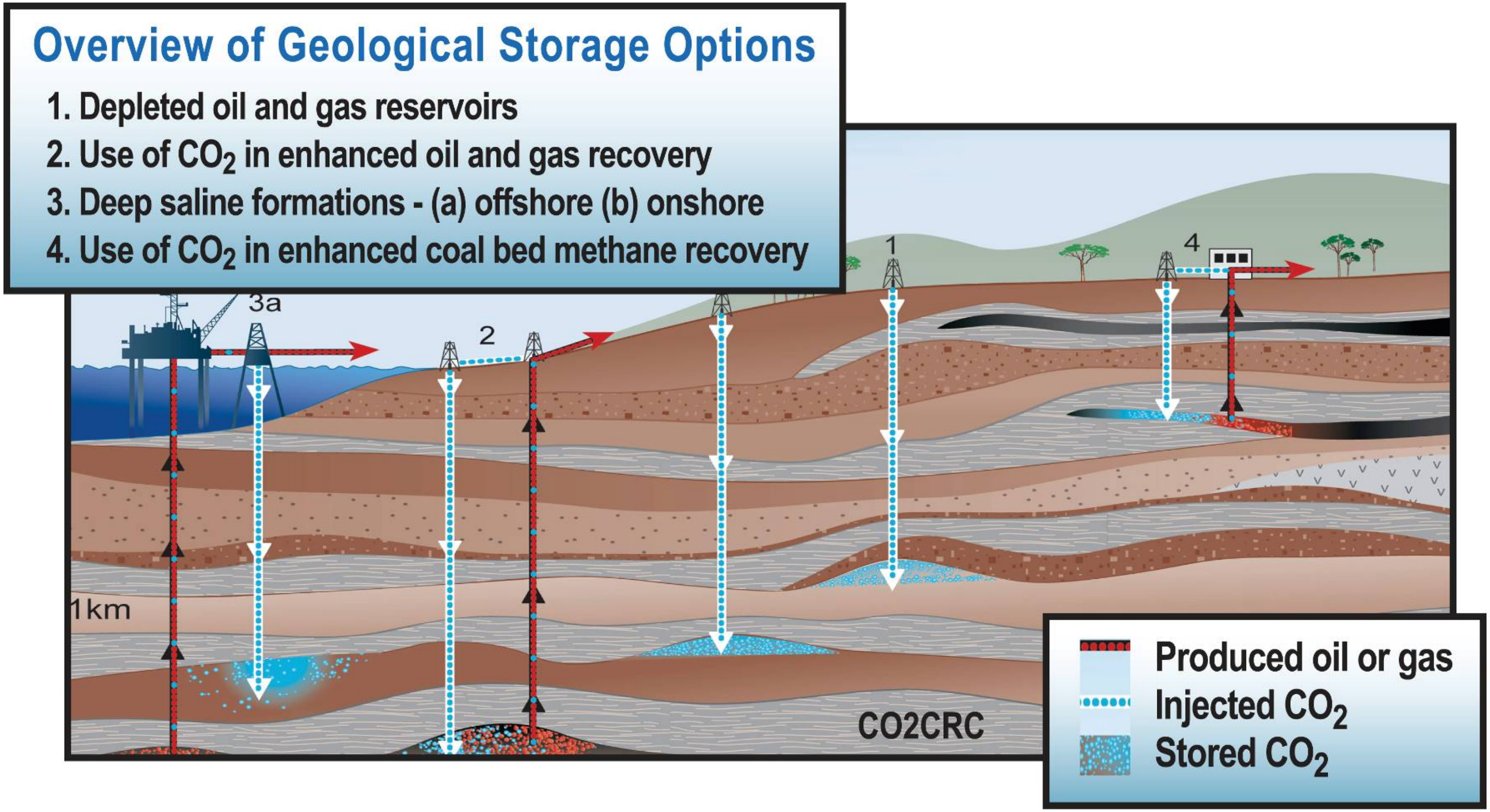


CO_2 Capture and Storage Involves Four Steps



Capture → Compression → Pipeline Transport → Storage or Reuse

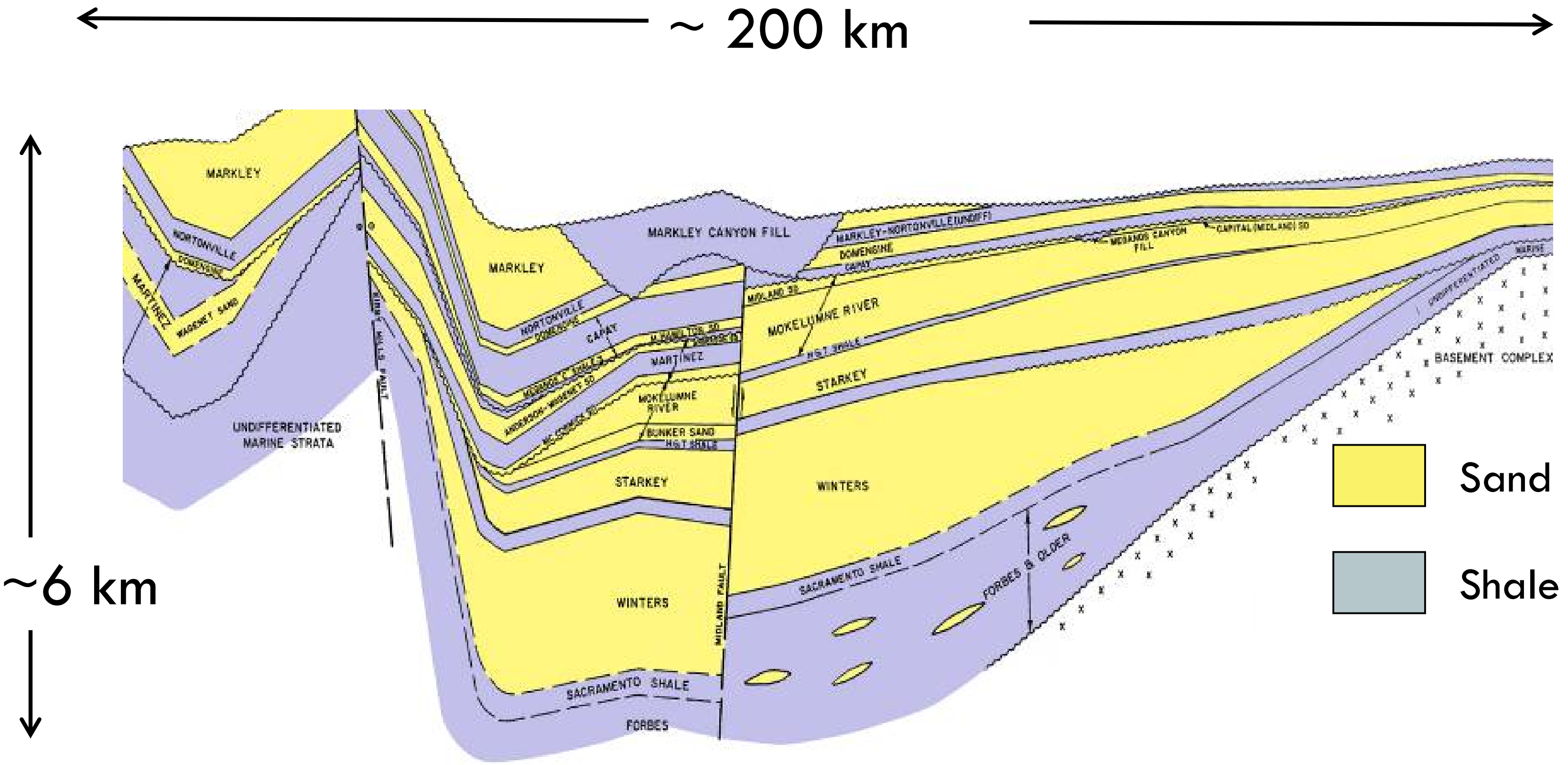
Options for Geological Storage



Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO_2 in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO_2 in enhanced coal bed methane recovery

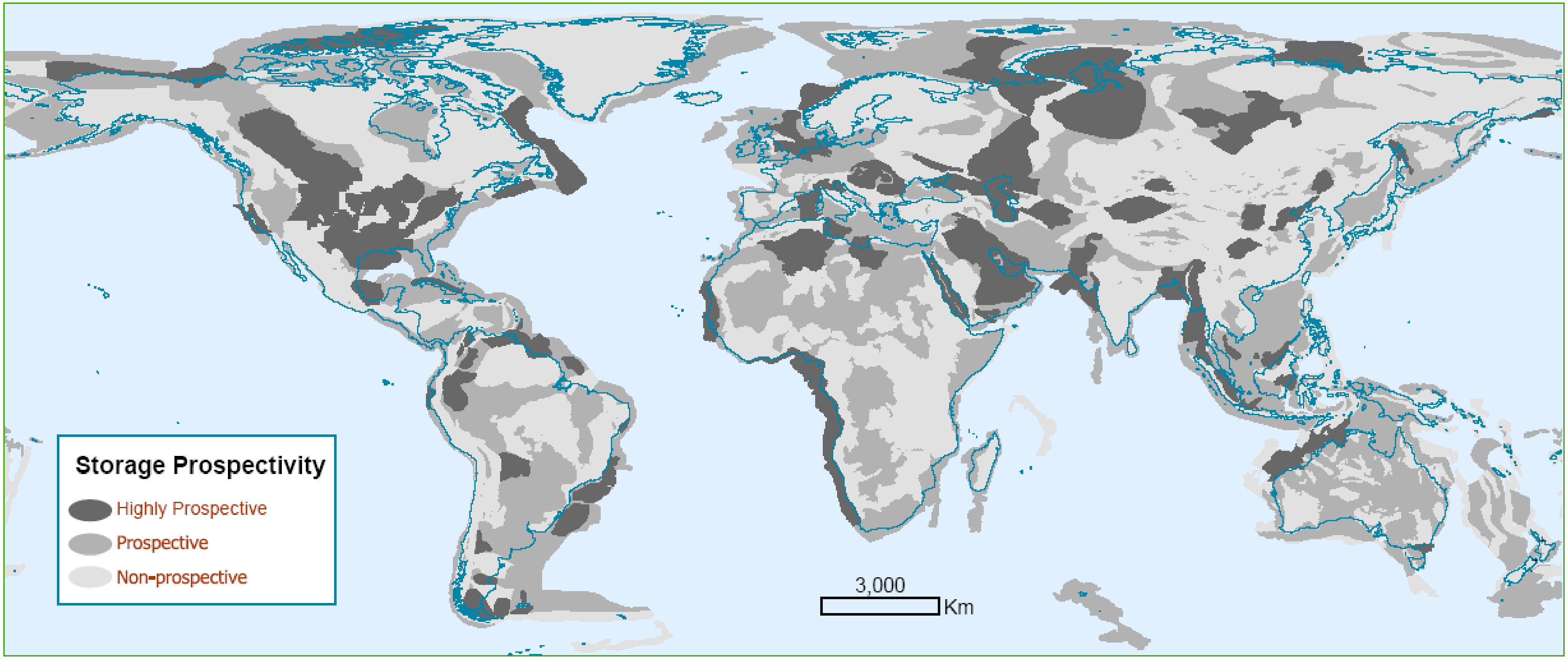
Cross Section of Typical Sedimentary Basin



Northern California Sedimentary Basin

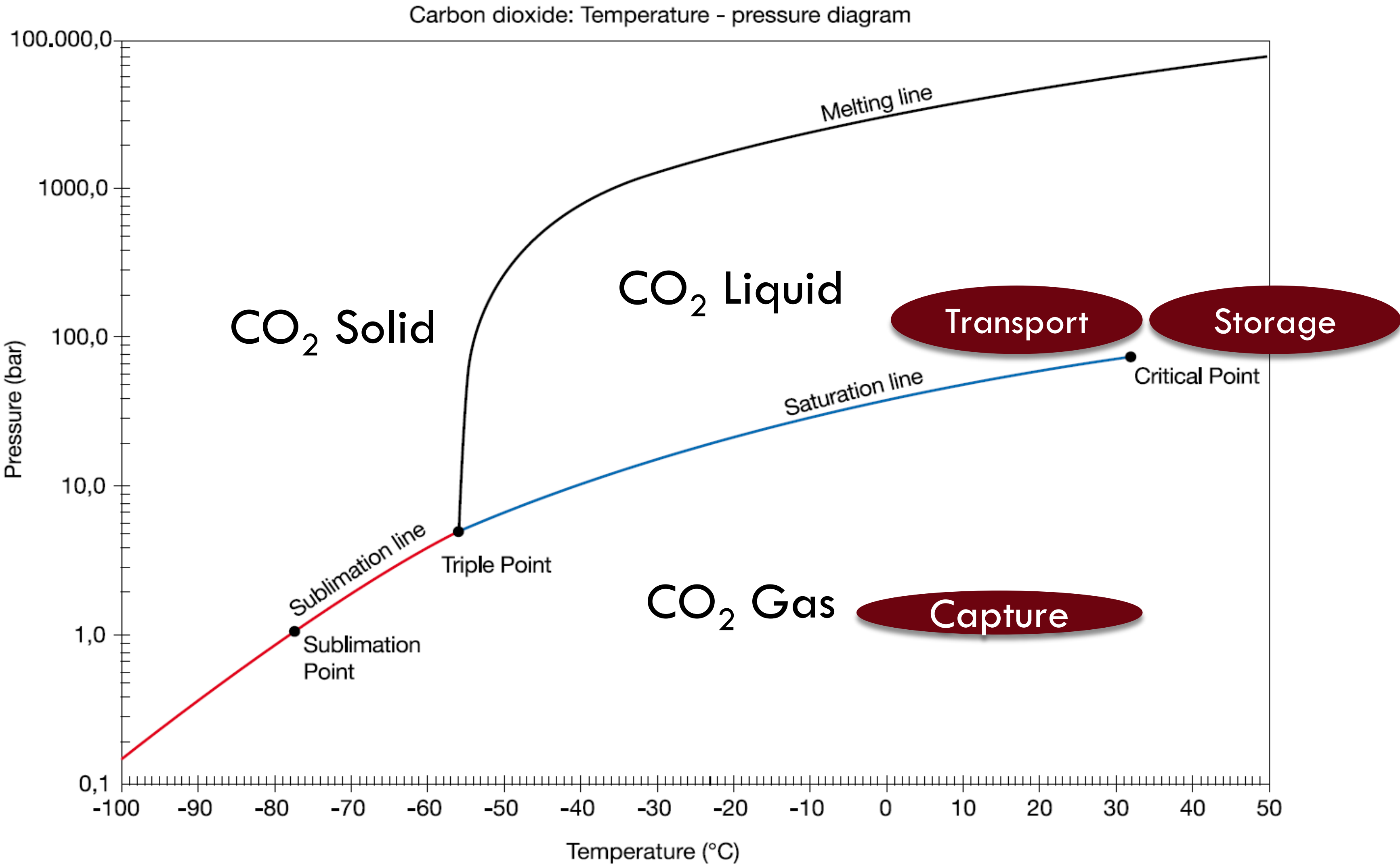
Example of a sedimentary basin with alternating layers of coarse and fine textured sedimentary rocks.

Prospectivity for Storage Around the World



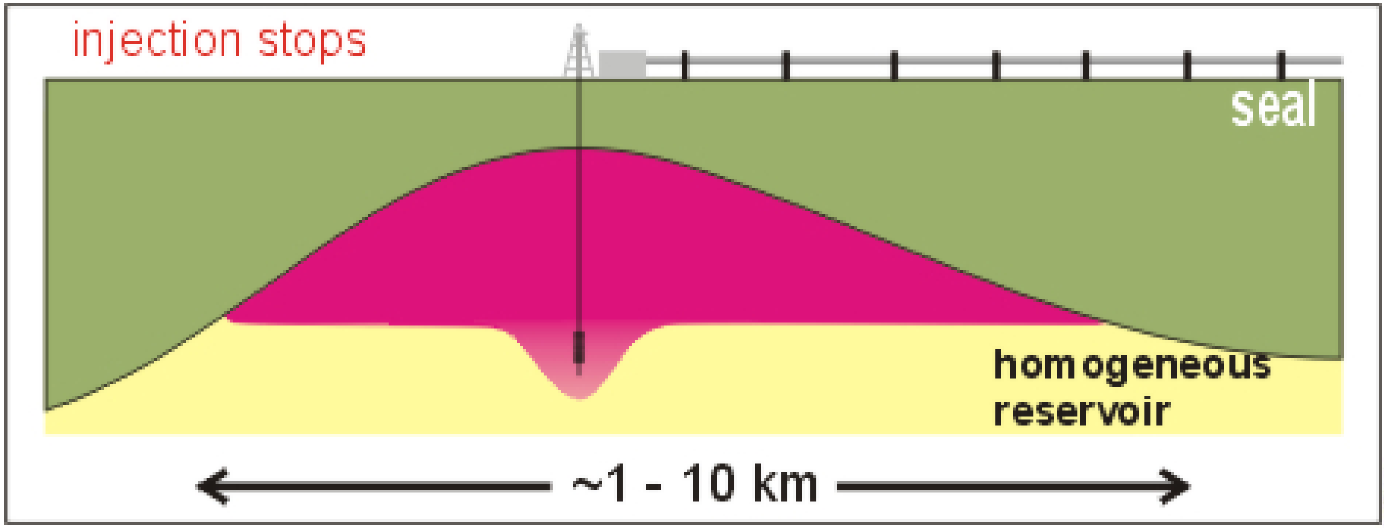
From Bradshaw and Dance 2005

Phases of CO_2 for the CCS System



Basic Concept of Geological Storage of CO_2

- Injected at depths of 1 km or deeper into with tiny pore spaces
- Primary trapping
    - Beneath seals of low permeability rocks



Courtesy of John Bradshaw

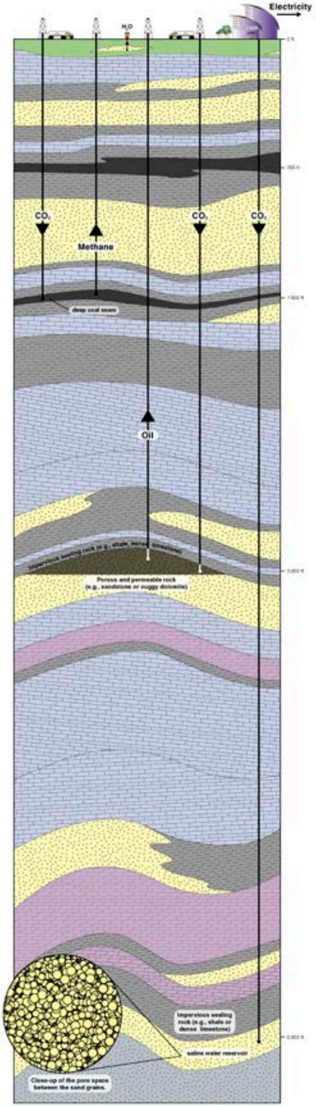
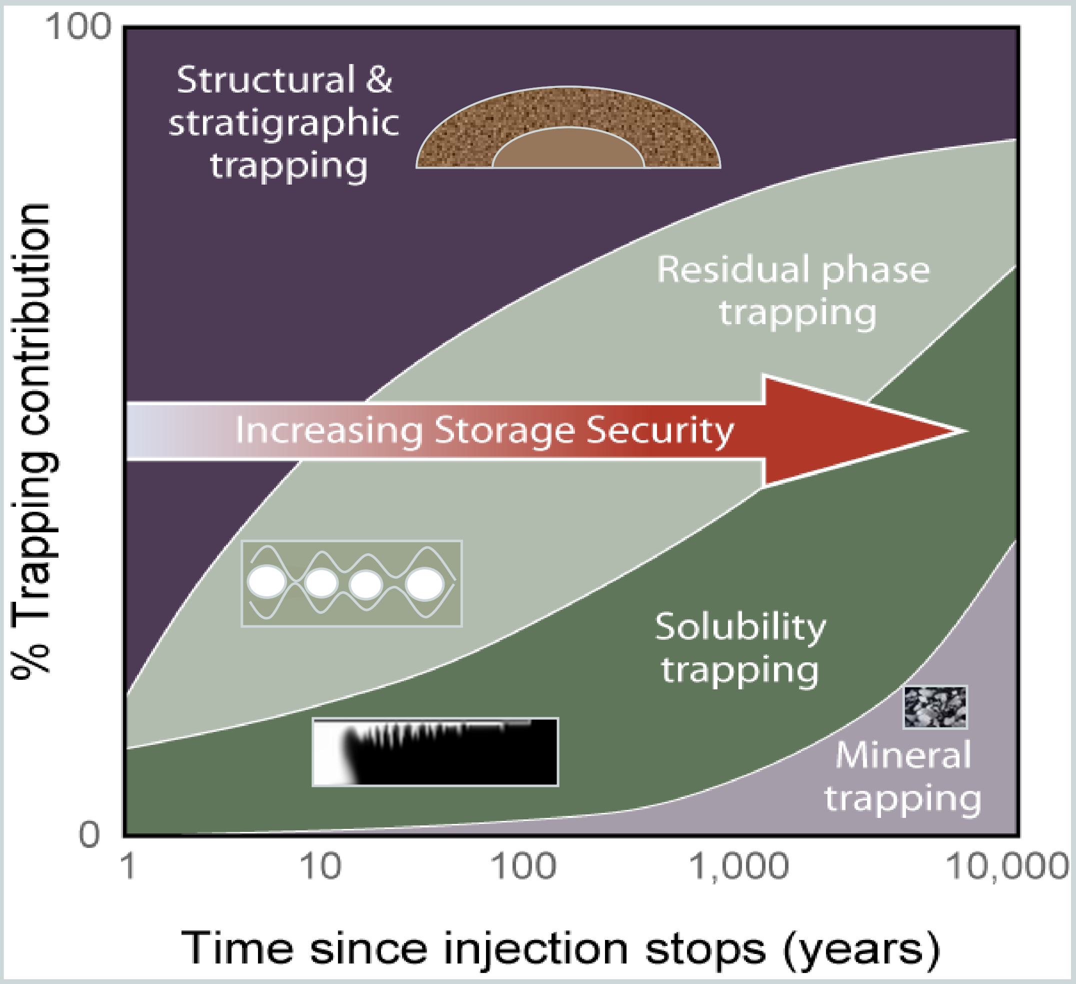


Image courtesy of ISGS and MGSC

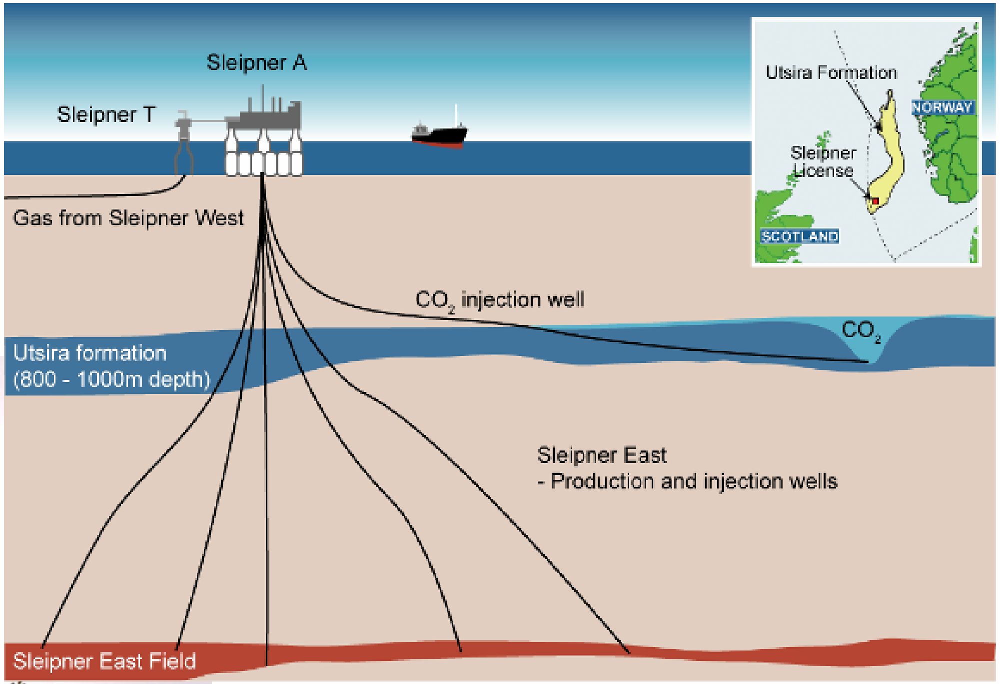
Secondary Trapping Mechanisms Increase Over Time

- Solubility trapping
  - CO_2 dissolves in water
- Residual gas trapping
  - CO_2 is trapped by capillary forces
- Mineral trapping
  - CO_2 converts to solid minerals
- Adsorption trapping
  - CO_2 adsorbs to coal



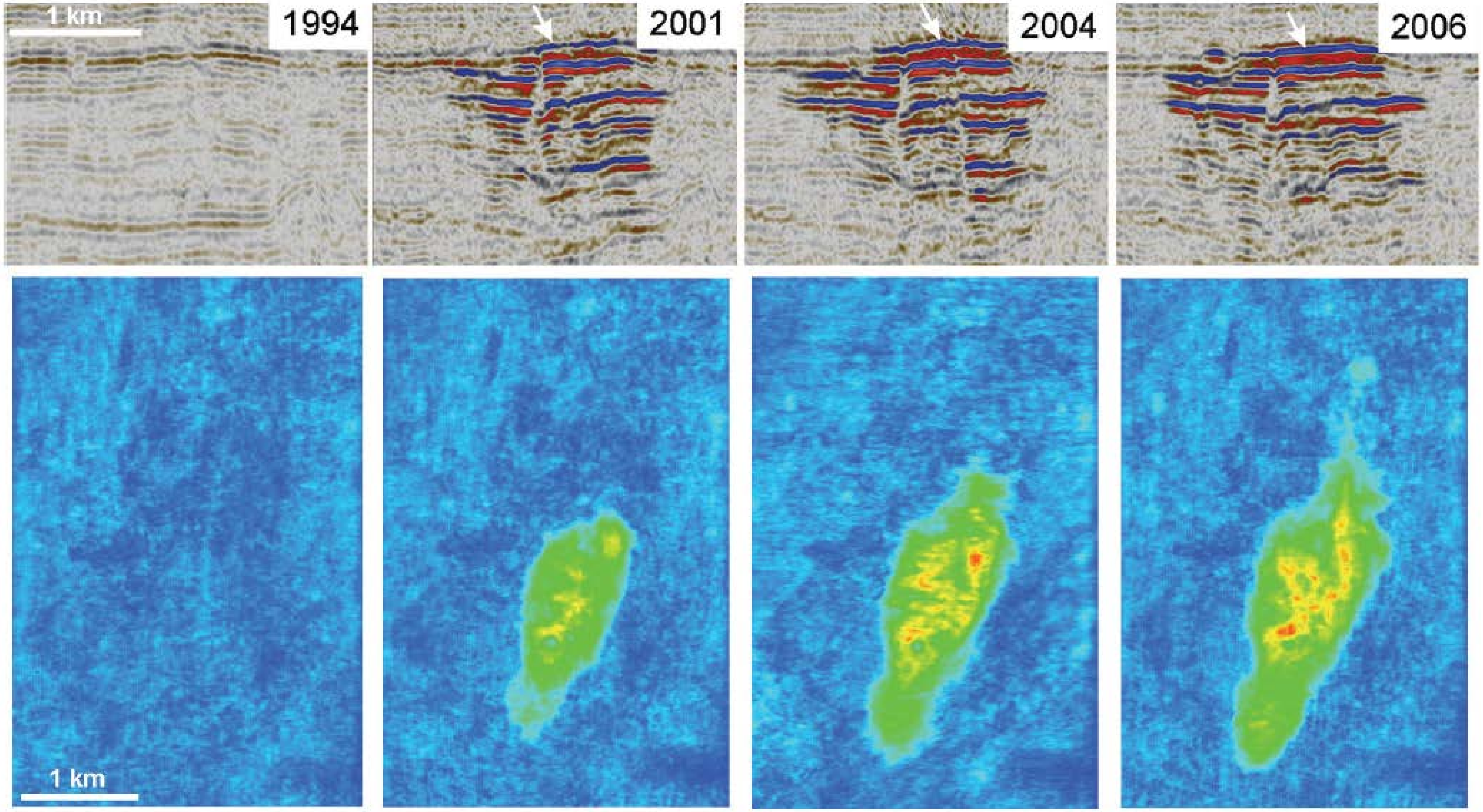
Sleipner Project, North Sea

- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring



Courtesy *Statoil*

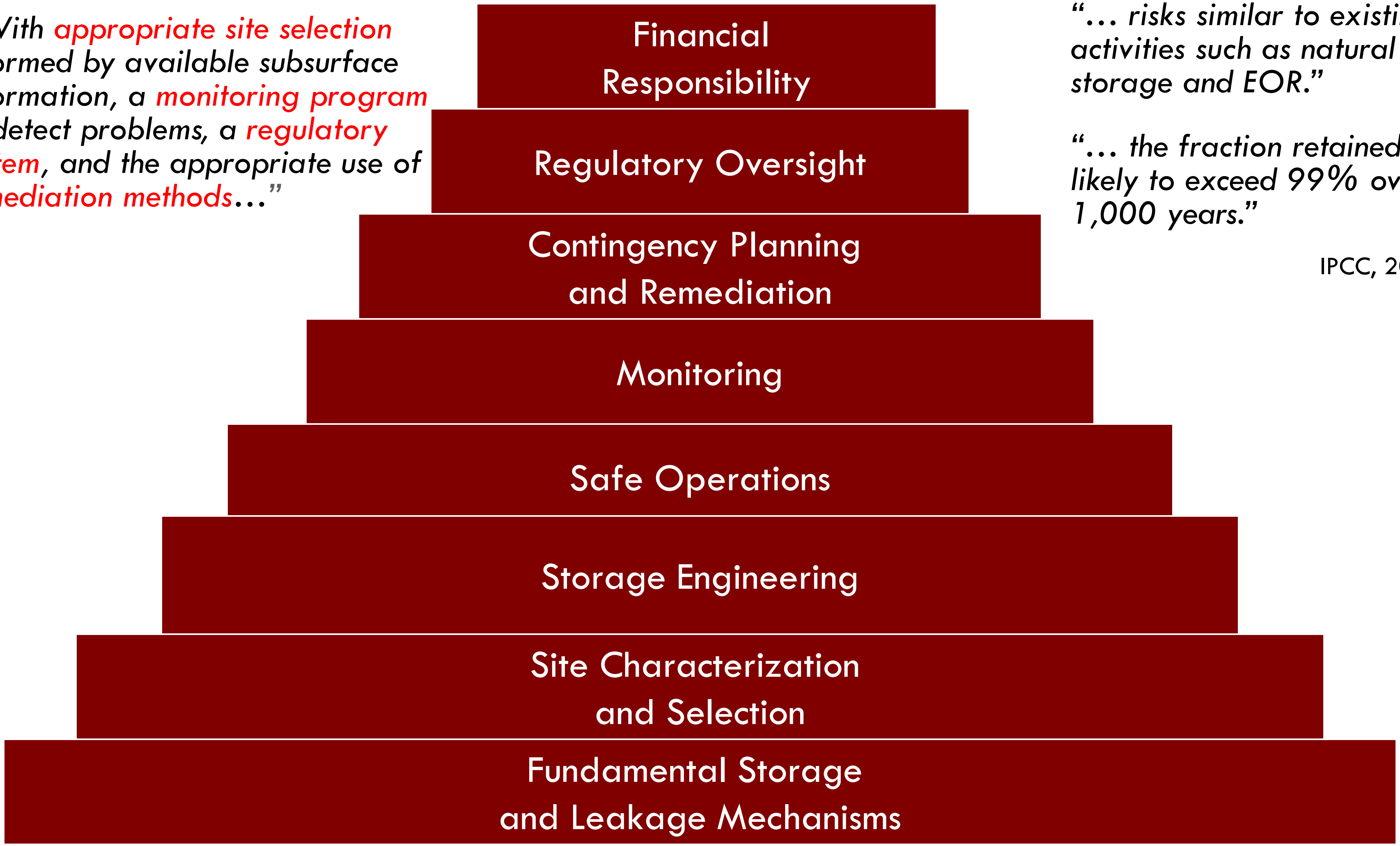
Seismic Monitoring Data From Sleipner, Norway



From Chadwick et al., GHGT-9, 2008.

Key Elements of a Geological Storage Safety and Security Strategy

" With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods…"



Financial Responsibility

Regulatory Oversight

Contingency Planning and Remediation

Monitoring

Safe Operations

Storage Engineering

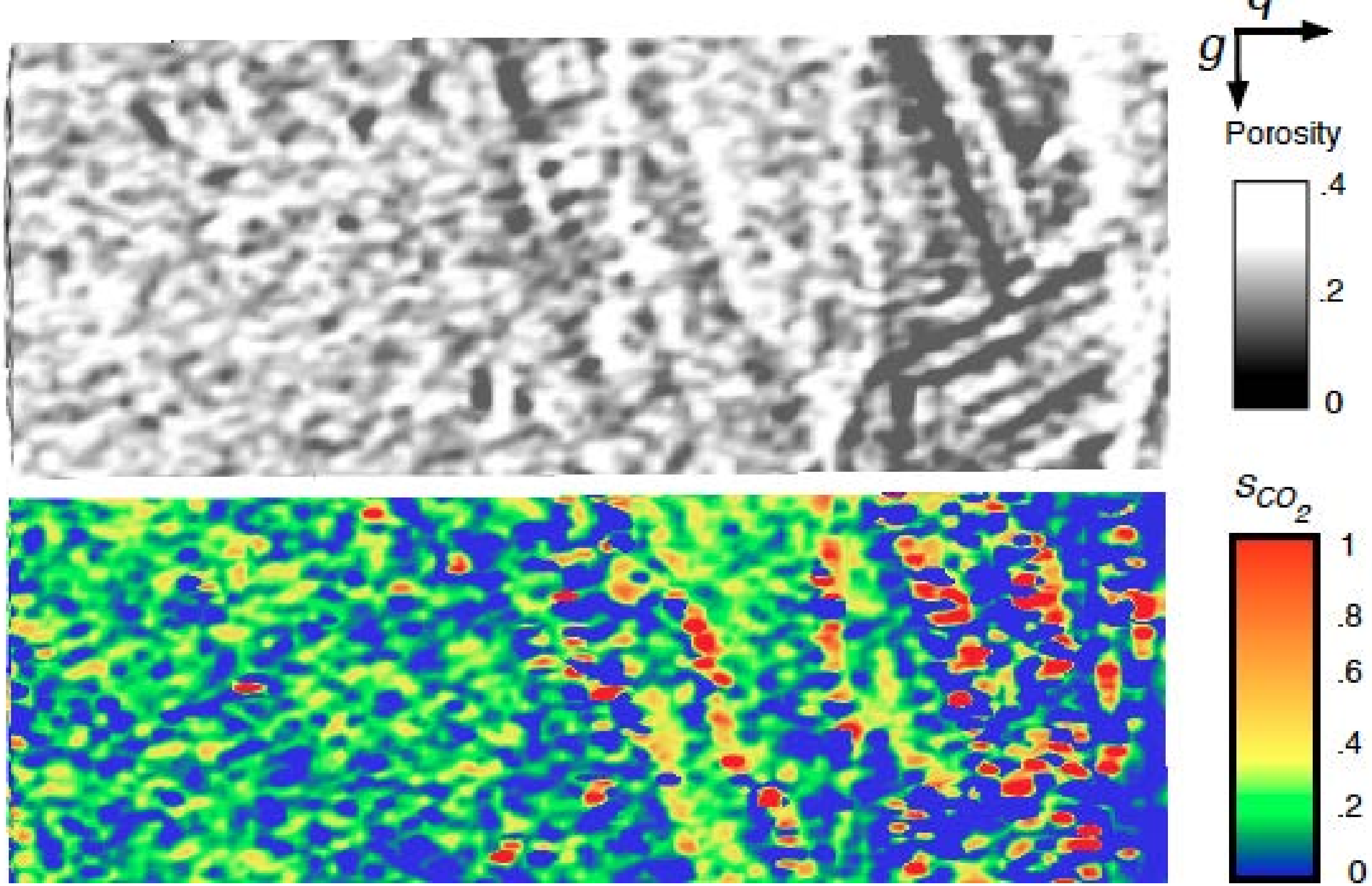
Site Characterization and Selection

Fundamental Storage and Leakage Mechanisms

"… risks similar to existing activities such as natural gas storage and EOR."

"… the fraction retained is likely to exceed 99% over 1,000 years."

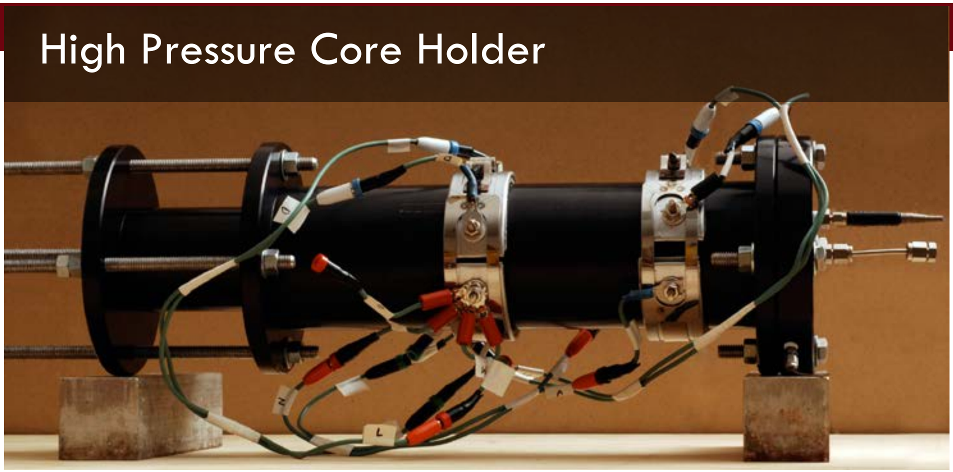
IPCC, 2005



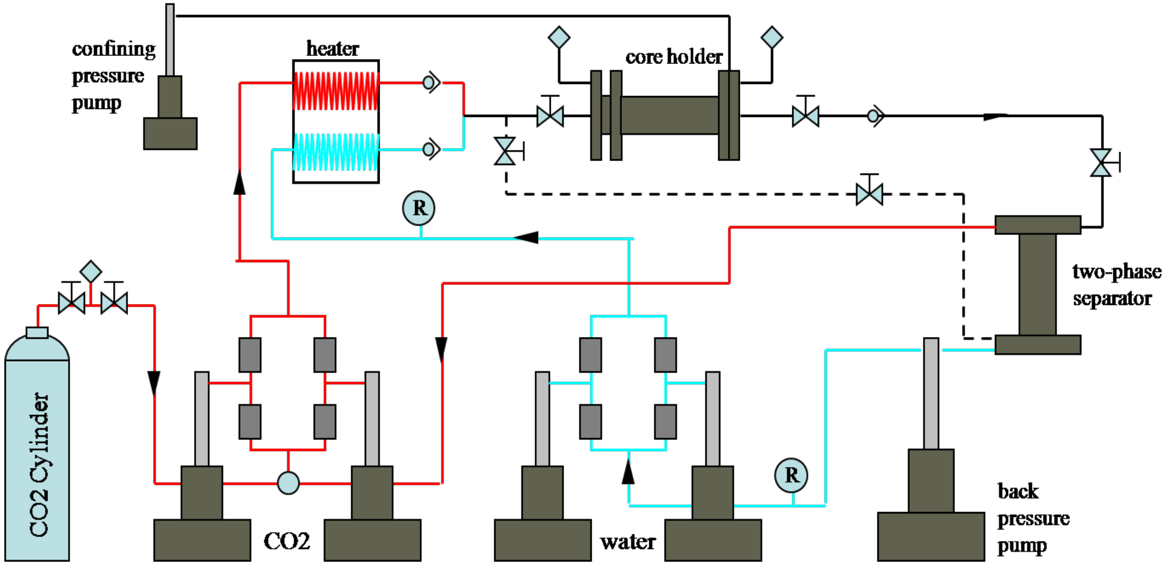
Influence of Heterogeneity on CO_2 Storage

Core-Flood Visualization Lab

X-Ray CT Imaging



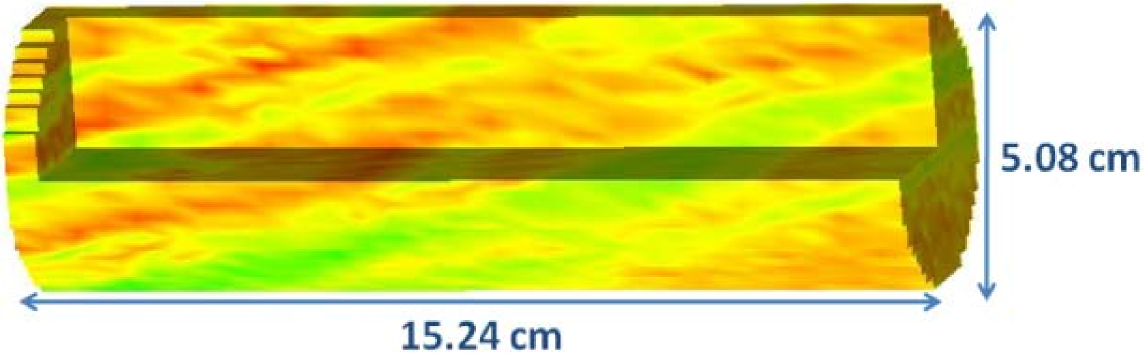
High Pressure Core Holder



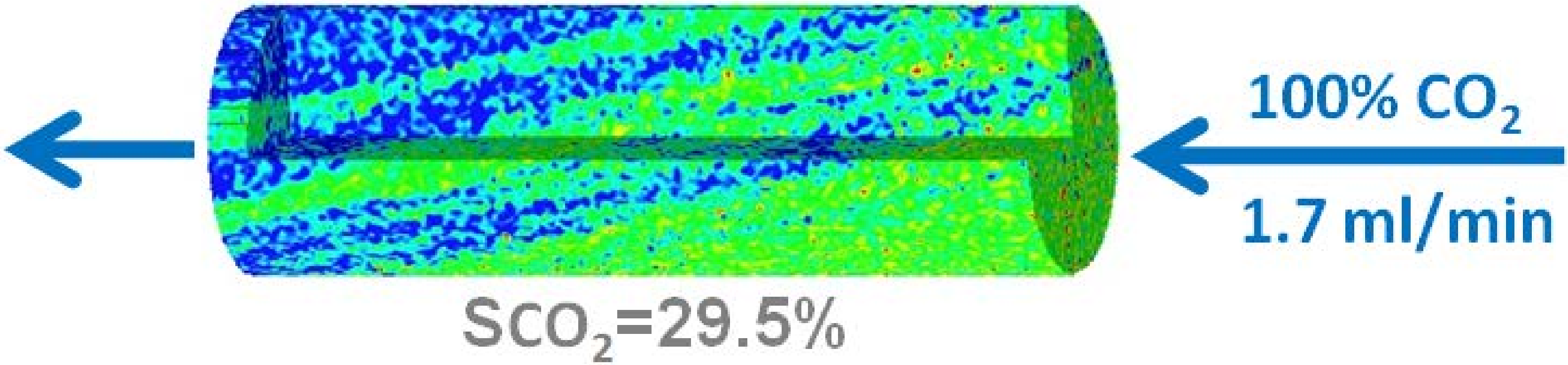
Continuous Flow Core-Flooding Apparatus

CO_2 Saturations are Highly Variable

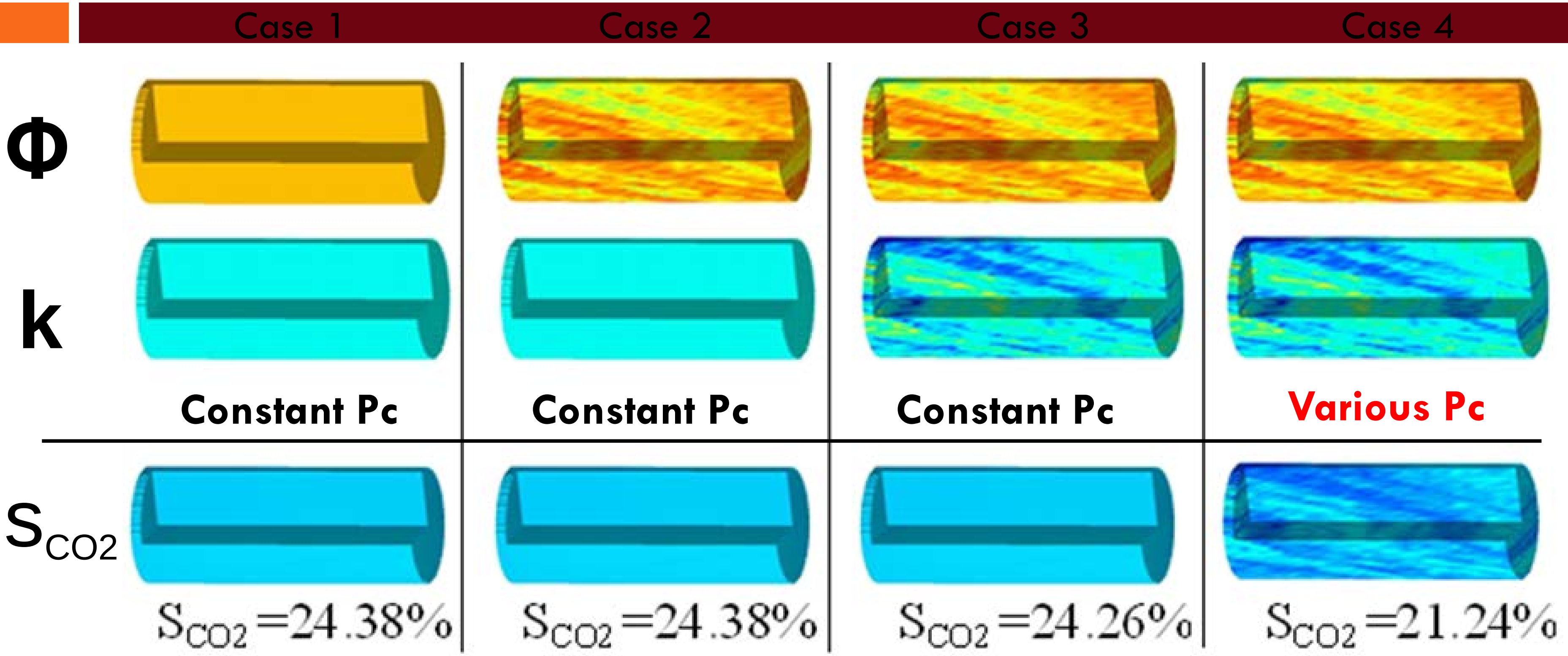
Porosity



Saturation Distribution



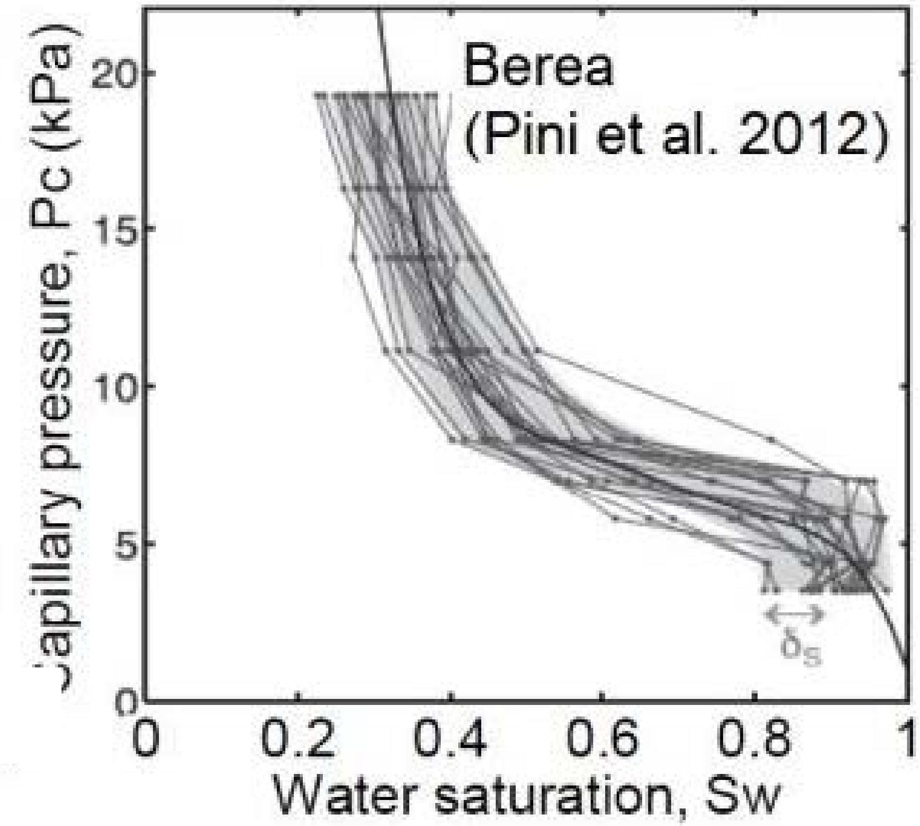
Capillary Pressure Curve Heterogeneity Causes CO_2 Saturation Variations



Unique capillary pressure curves are needed to create spatial variations in CO_2 saturation.

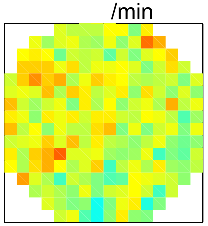
C-W Kuo, J-C Perrin, and S. M. Benson, 2011. Simulation studies of effect of flow rate and small scale heterogeneity on multiphase flow of CO_2 and brine. Energy Procedia 4 (2011) 4516–4523.

Direct Measurement of Capillary Heterogeneity



35 ml/min

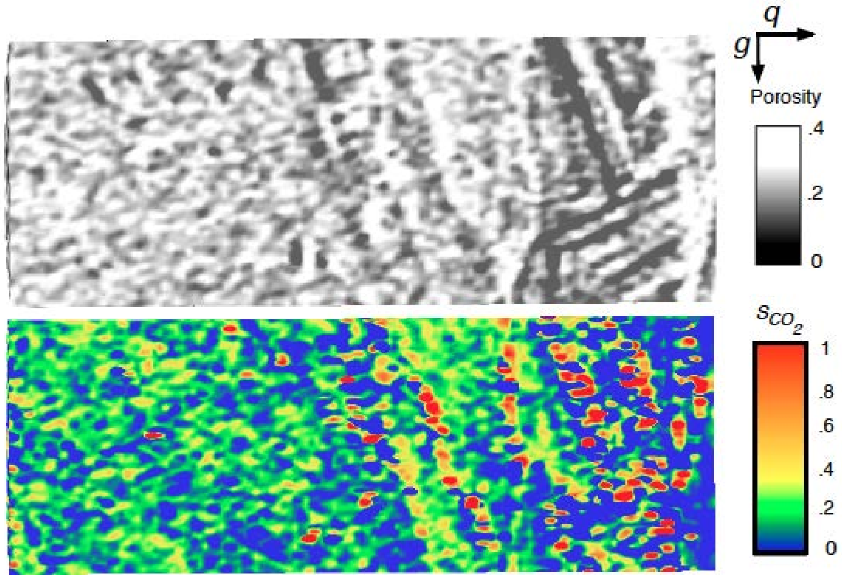
25 ml/min



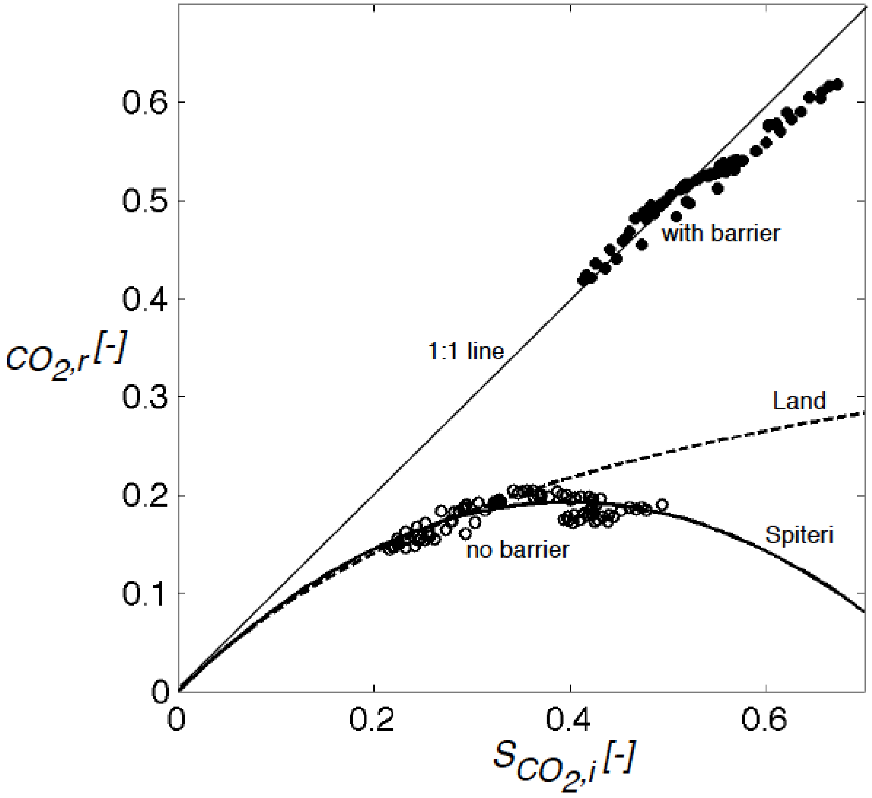
R. Pini, S.C. R. Krevor, and S. M. Benson, 2012. Capillary pressure and heterogeneity for the CO_2/water system in sandstone rocks at reservoir conditions, Advances in Water Resources 38 (2012) 48–59.

Local Capillary Heterogeneity Leads to Increased Trapping

Mt. Simon Sandstone Rock Showing Bedding Planes



Saturation Distribution Showing CO_2 Trapping Before the Barrier



Krevor, S. C. M., R. Pini, B. Li and S. M. Benson, Capillary heterogeneity trapping of CO2 in a sandstone rock at reservoir conditions, GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L15401, 5 PP., 2011. doi:10.1029/2011GL048239

X-Ray microtomography showing droplets of CO_2 in the rock (ALS, LBNL)

Micro-tomography Beamline

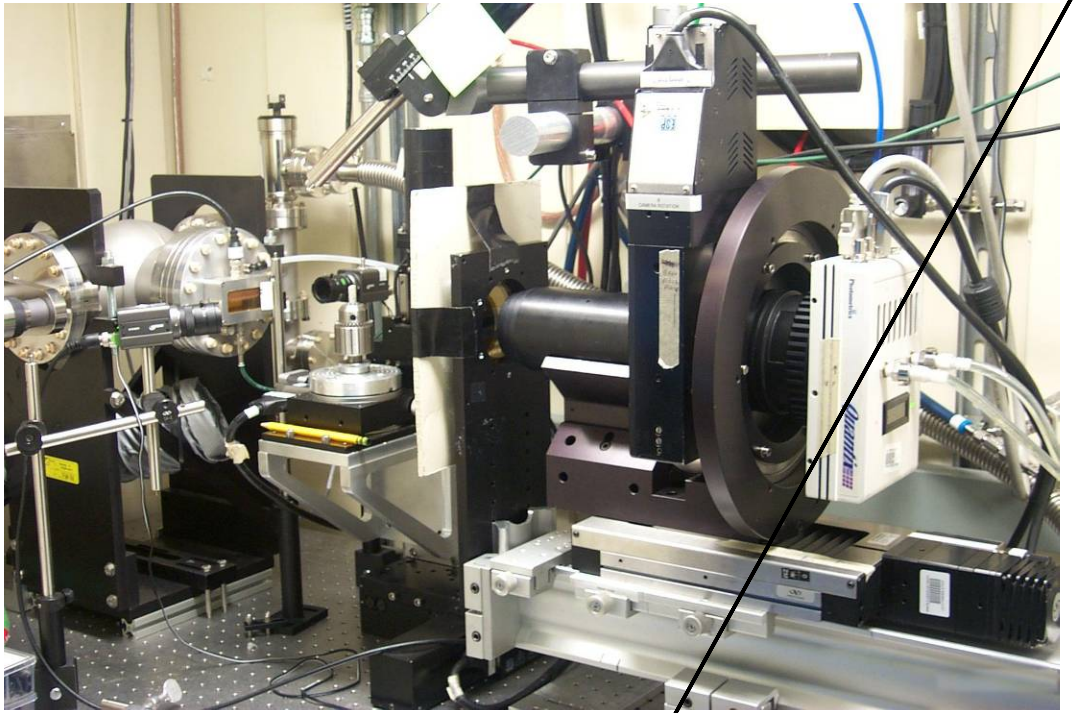
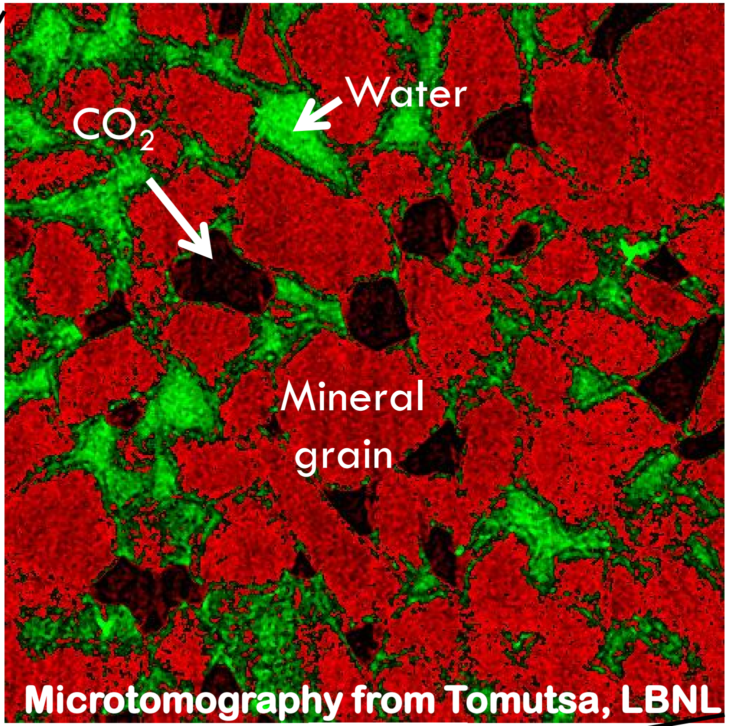


Image of Rock with CO_2



Microtomography from Tomutsa, LBNL

© geology.com

Resolution ~ 5 μm

Critical Issues for CCS

- Gain practical experience with power generation with CO_2 capture and storage
  - Reliability and operating costs
- Lower the cost of capture by 50% or more
  - Current technology estimated to cost 3-6 cents per kWh
- Increase confidence in storage safety and security
  - CO_2 retention and groundwater impacts
  - Induced seismicity?
- Sustain R&D
  - New capture technologies
  - Storage security, site characterization, and monitoring
- Favorable policy environment