Stanford University

GCEP Global Climate & Energy Project

GCEP Symposium
Energy 101 Tutorials
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Carbon Capture and Sequestration (CCS) 101

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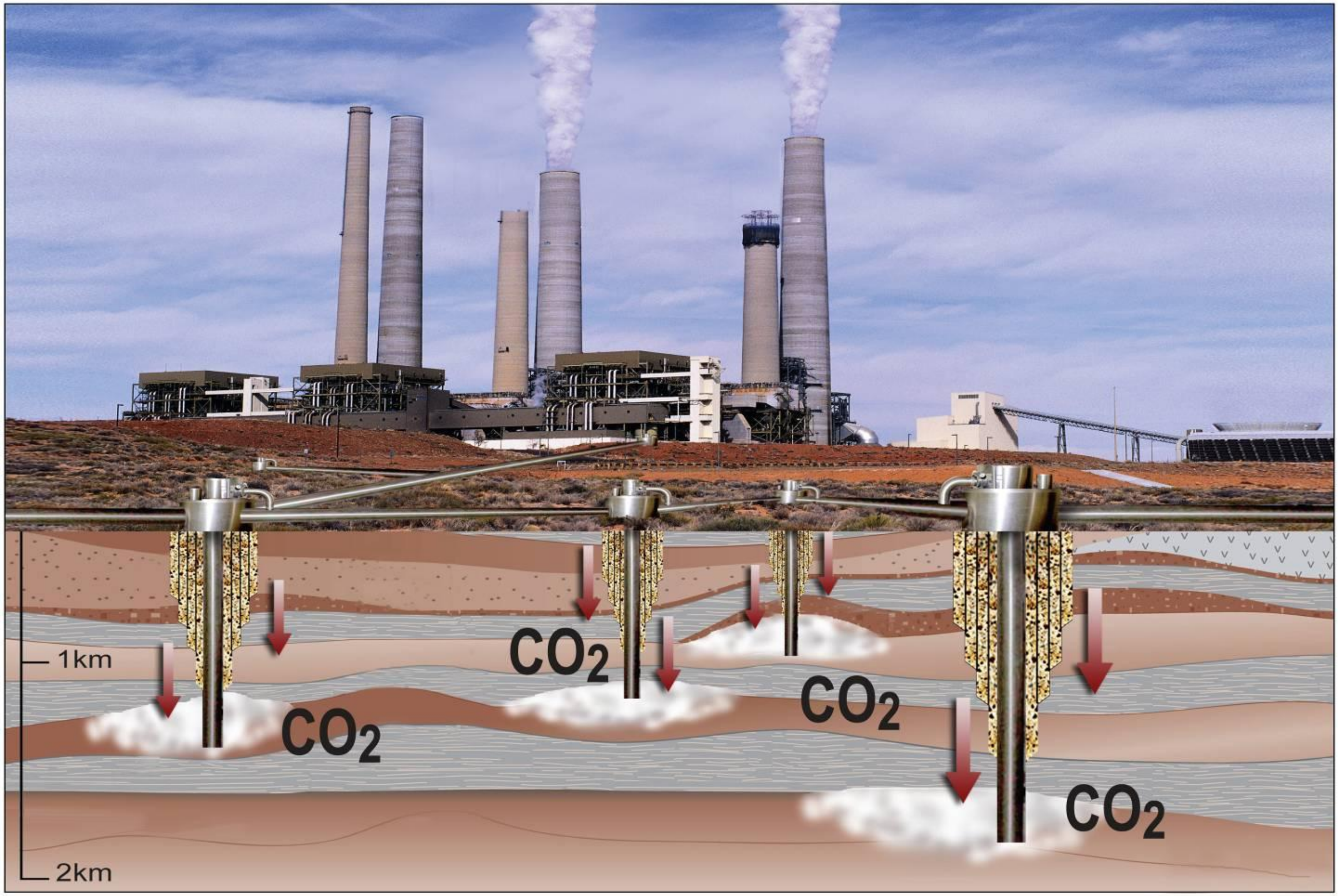
Global Challenges – Global Solutions – Global Opportunities

What is CCS?

- **CCS**: **C**arbon **C**apture and **S**equestration
  - Also, called **C**arbon **C**apture and **S**torage
  - **C**arbon **C**apture and **G**eological **S**torage (CCGS)

Sequestration: The state of being alone or being kept apart from others.
(Merriam Webster Dictionary)

Carbon Dioxide Capture and Sequestration Involves 4 Steps



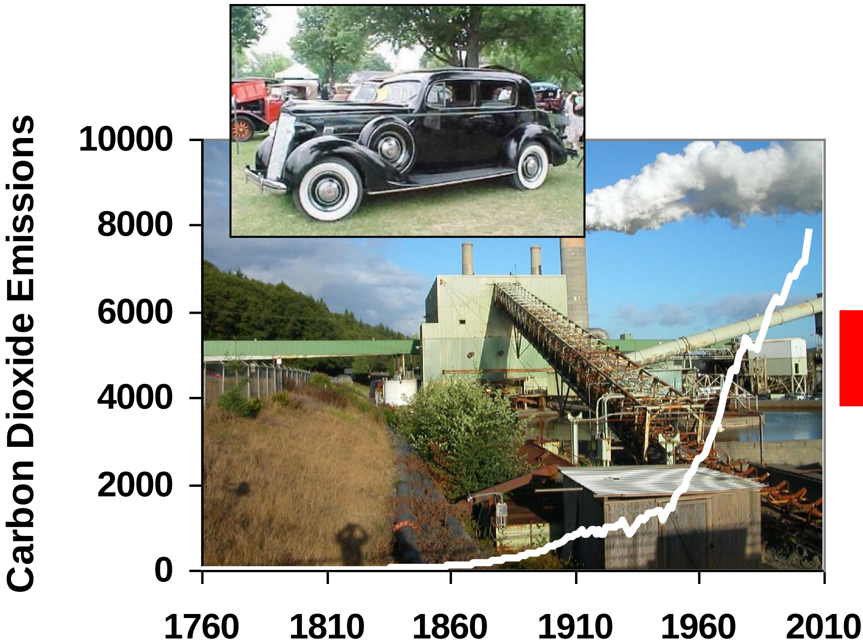
Capture → Compression → Pipeline Transport → Geological Sequestration

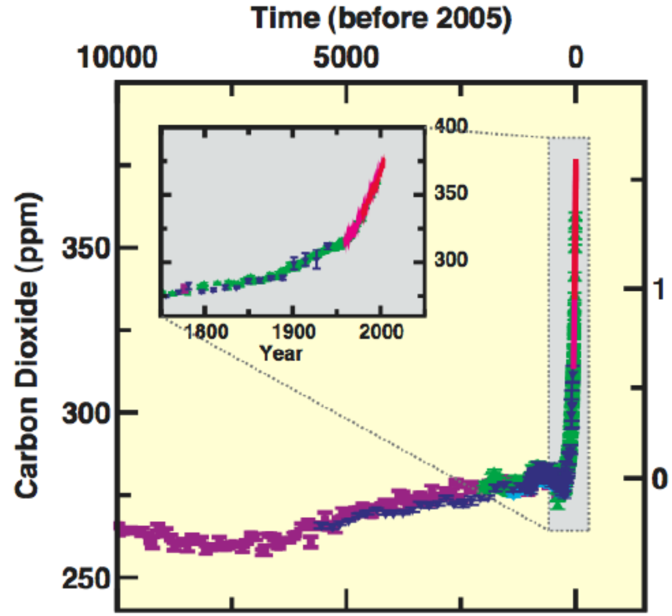
Carbon Capture and Sequestration 101: Objectives

- Familiarity with Concepts and Terminology
- The Case for Carbon Capture and Sequestration
- Technology Overview
  - Capture
  - Transportation
  - Sequestration
- Risks of CCS
- Global and N. American Potential for CCS
- Costs of CCS
- Institutional Incentive and Barriers

The Case for CCS

Carbon dioxide emissions have risen dramatically over the past two hundred years…





IPCC, 2007

… leading to the buildup of carbon dioxide in the atmosphere,
… global warming, and
… ocean acidification.

We need to reduce CO_2 emissions dramatically, beginning now.

Why CCS? Decreasing Reliance on Fossil Fuels Will Be Challenging

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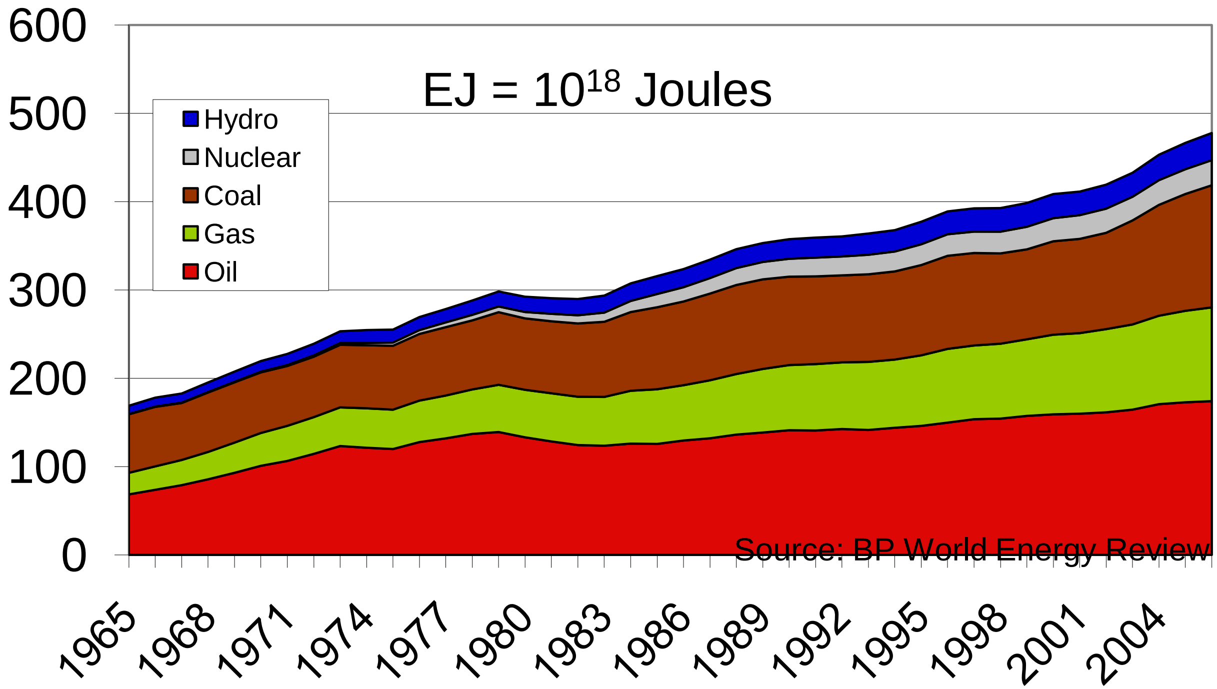
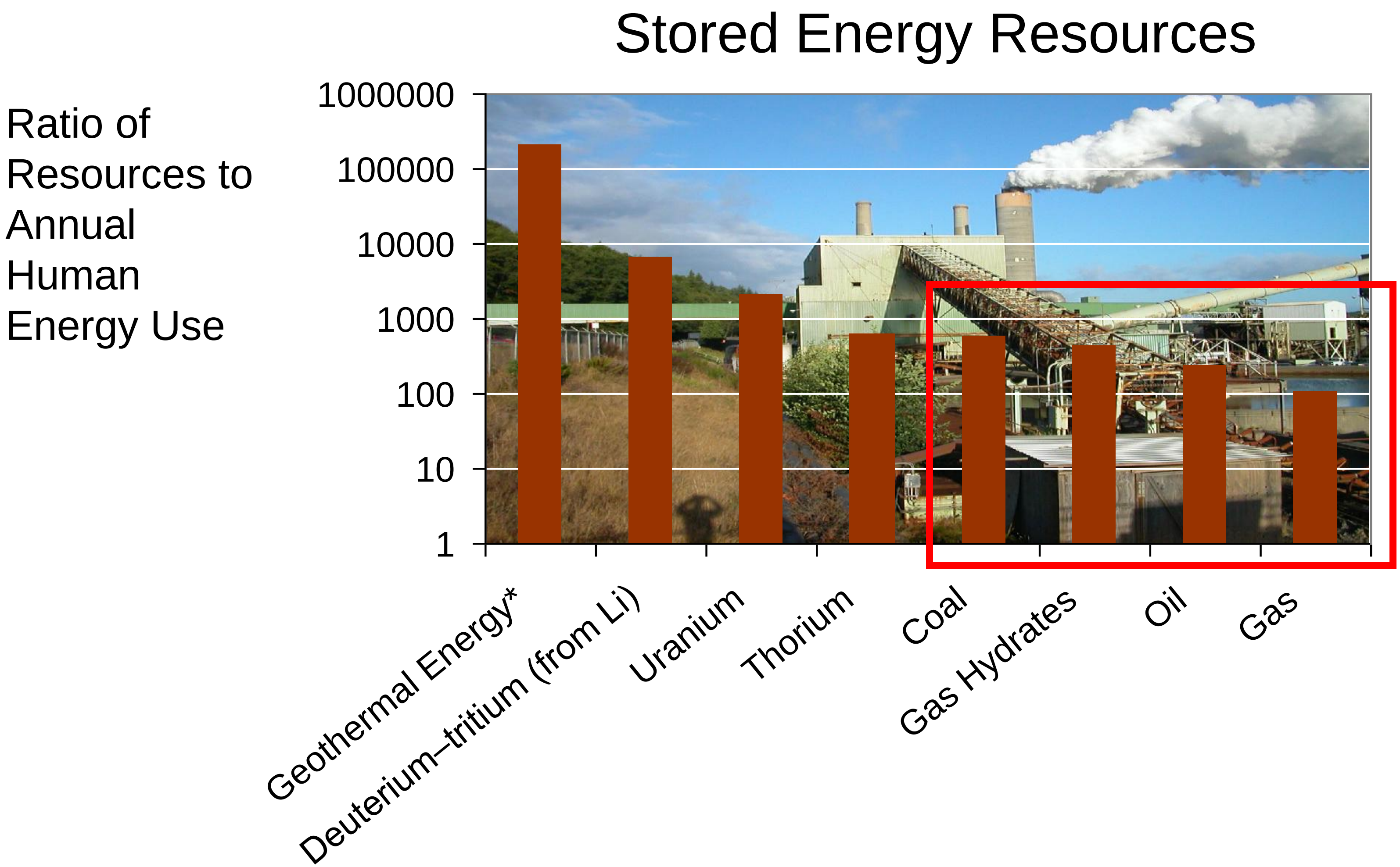
Global Energy Consumption (EJ)



- 85% of U.S. energy supply from fossil fuels
- 80% of U.S. energy supply projected by 2030
- Reductions of CO_2 and other greenhouses gases of 50 to 80% are needed by 2050
- Low carbon emission electricity options
  - Renewable energy (sun and wind)
  - Nuclear power
- Growth of these is unlikely to be fast enough to achieve needed emission reductions

Why CCS? We Are Not Running Out of Fossil Fuels.

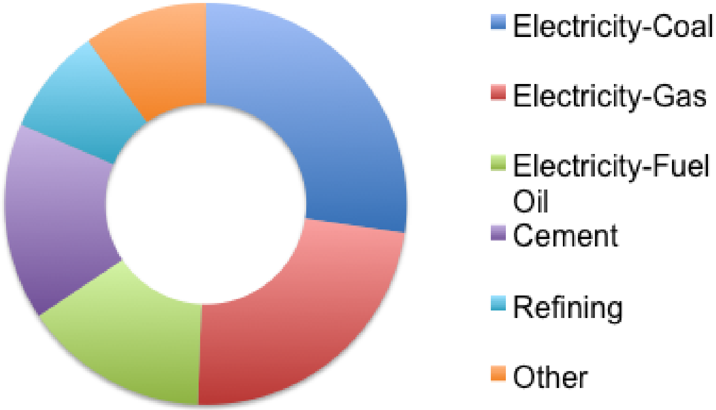


From Hermann, 2006: Quantifying Global Exergy Resources, Energy 31 (2006) 1349–1366

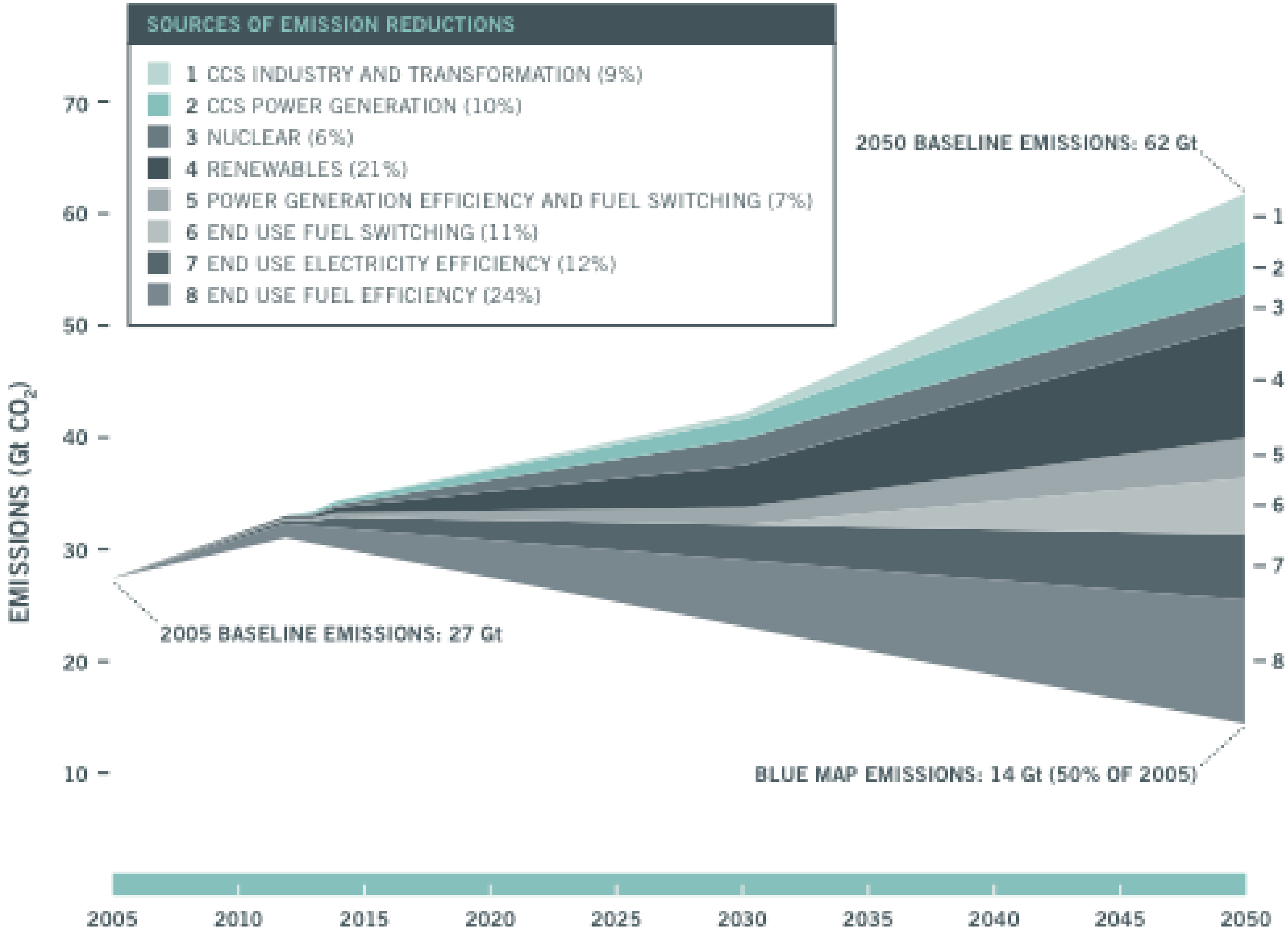
CCS Can Reduce Emissions from Many Sources

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

7,400 sources greater than 0.1 Mt/yr

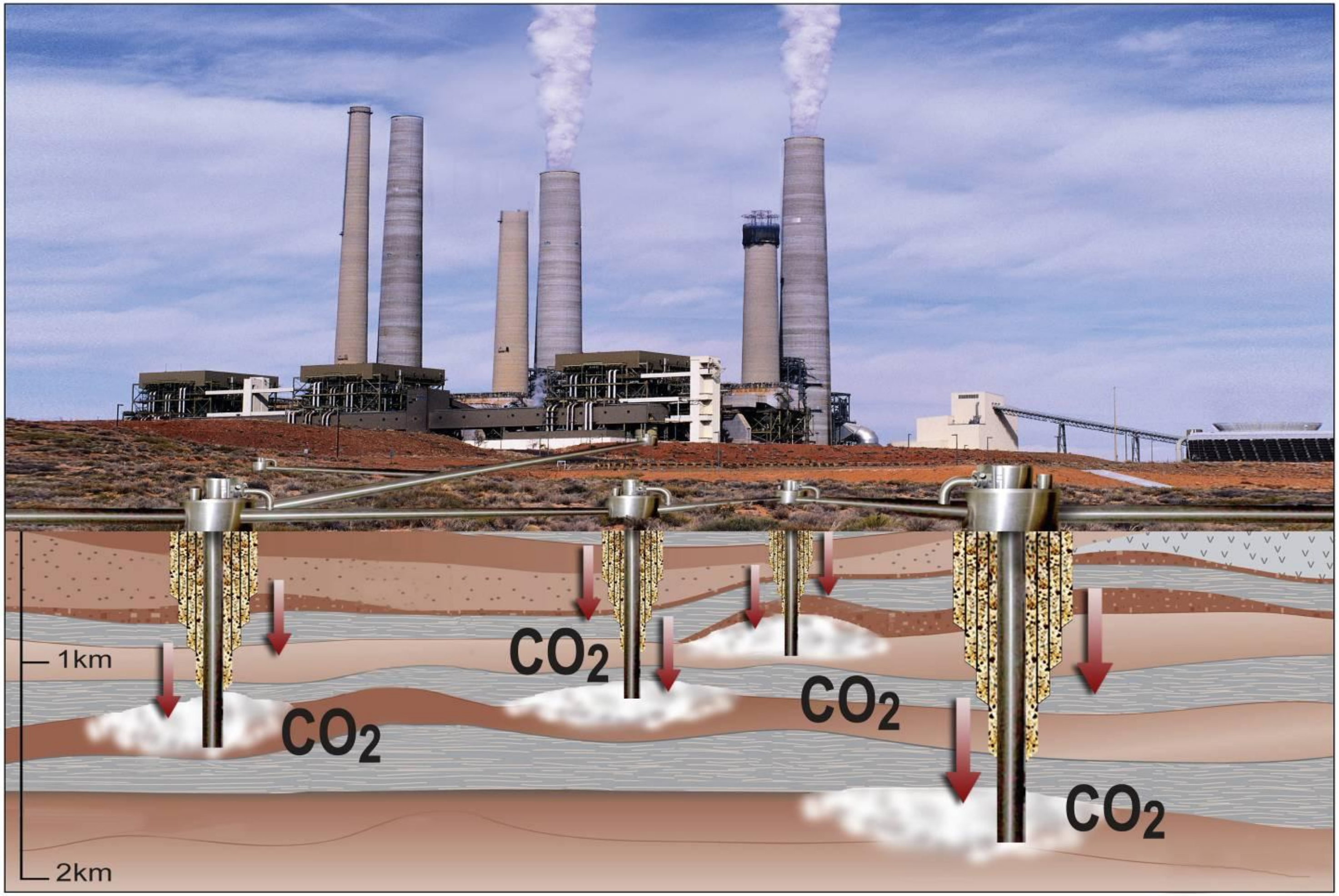


CCS Is Expected to Contribute About 20% to Needed CO_2 Emission Reduction



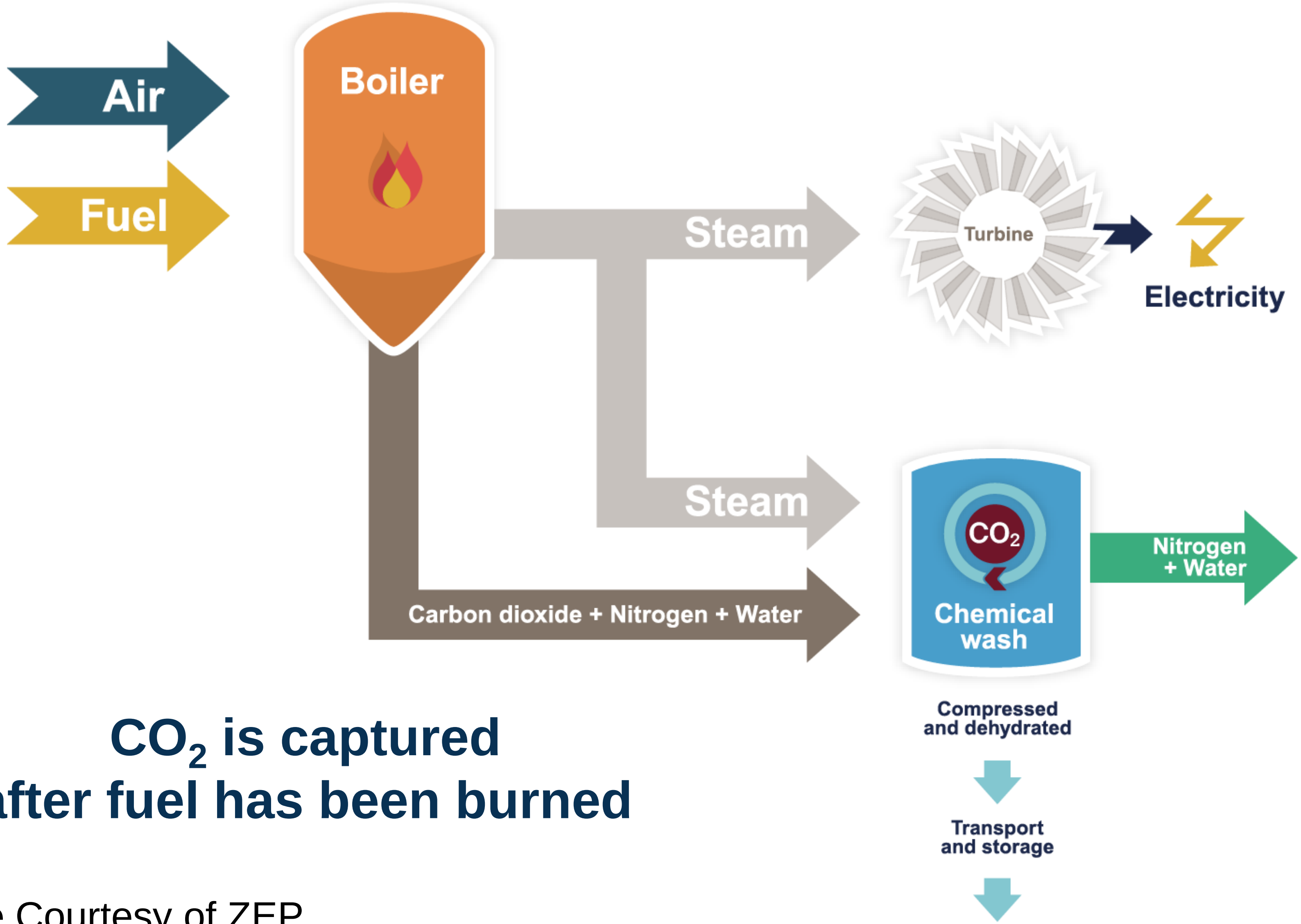
[1] **IEA BLUE MAP SCENARIO:** THIS SCENARIO IS CONSISTENT WITH STABILISING CO_2 CONCENTRATIONS AT 450PPM, WITH AN ASSOCIATED GLOBAL RISE IN TEMPERATURE OF TWO TO THREE DEGREES CELSIUS, BUT ONLY IF THE REDUCTION IN ENERGY-RELATED CO_2 EMISSIONS IS COMBINED WITH DEEP CUTS OF GREENHOUSE GAS EMISSIONS FROM NON-ENERGY SOURCES. **SOURCE:** INTERNATIONAL ENERGY AGENCY 2008, ENERGY TECHNOLOGY PERSPECTIVES: SCENARIOS AND STRATEGIES TO 2050.

Technology Overview



Capture → Compression → Pipeline Transport → Geological Sequestration

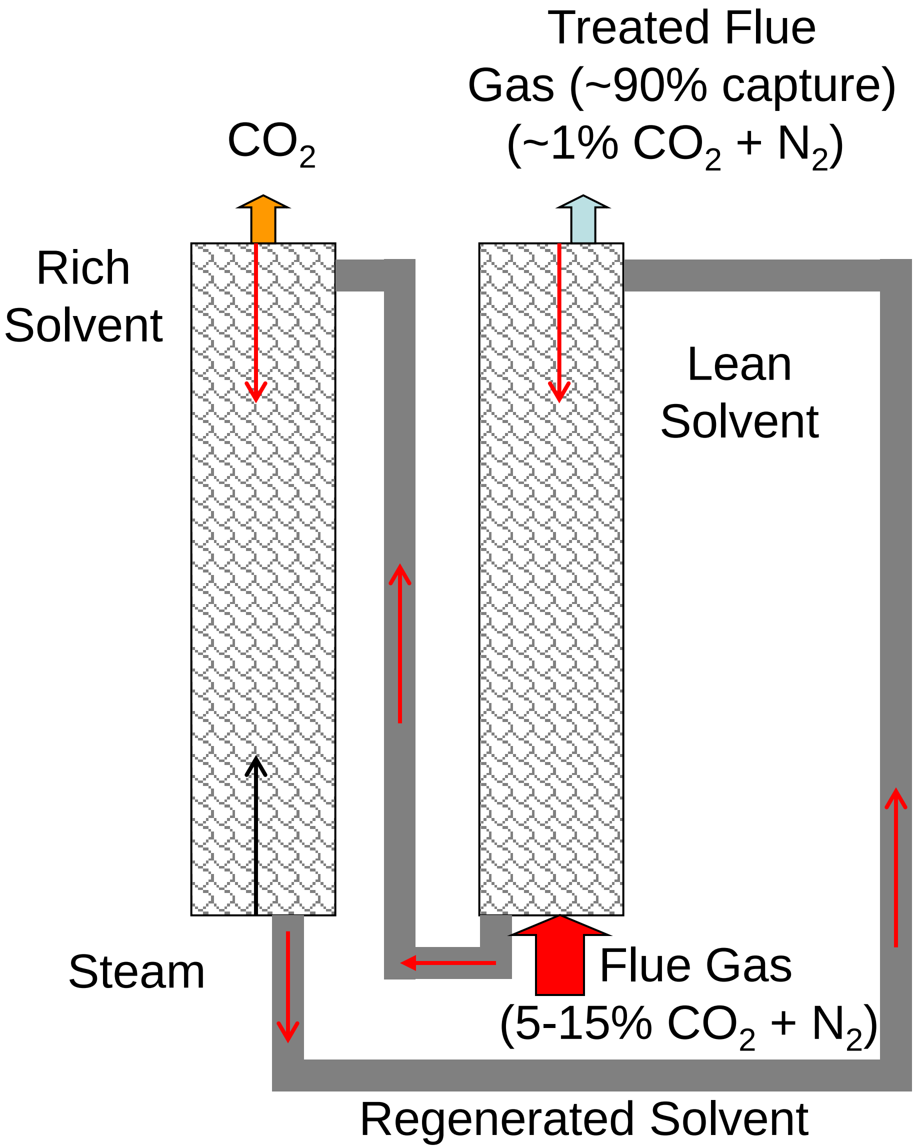
Option 1. Post-Combustion Capture

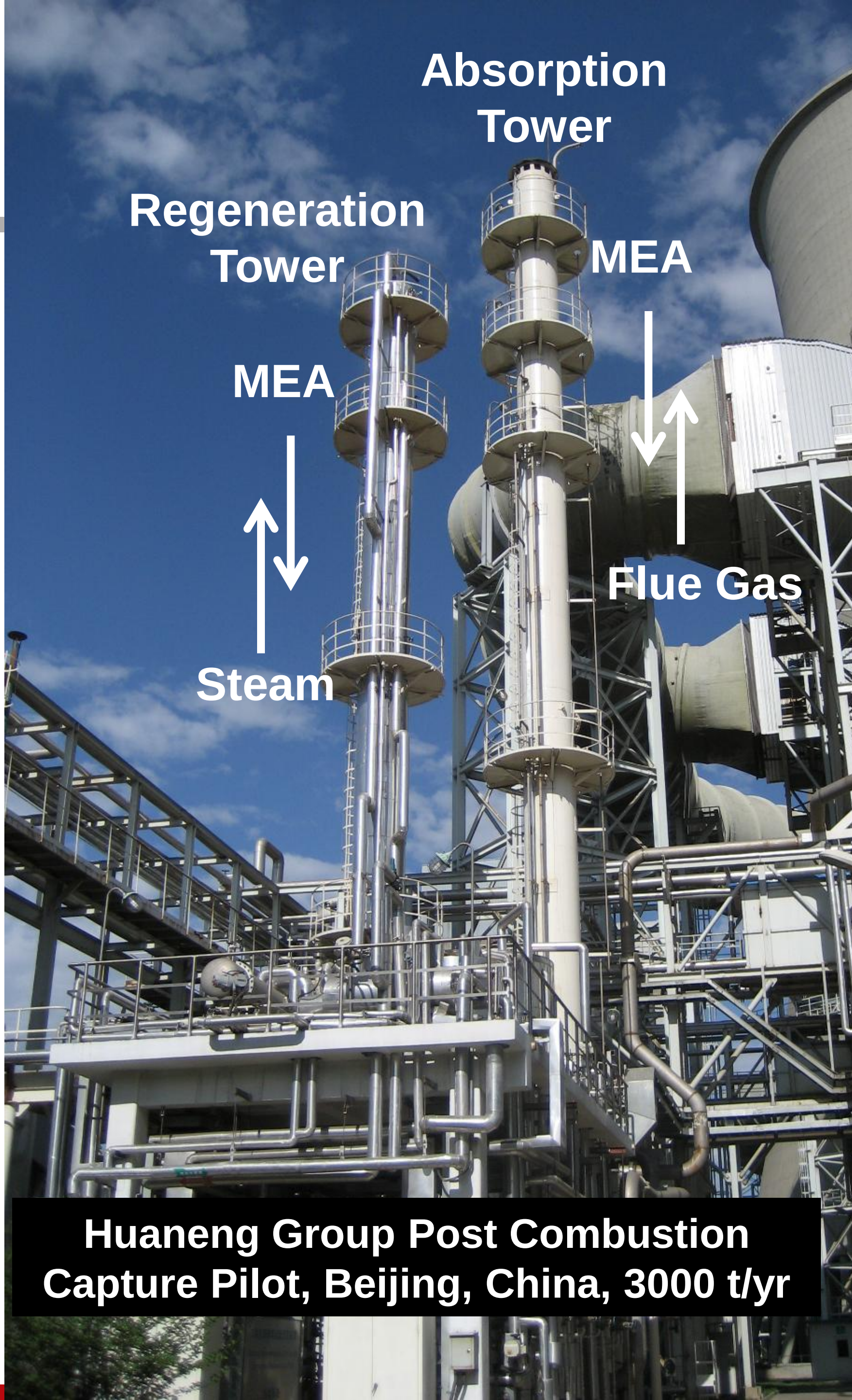


CO_2 is captured after fuel has been burned

Image Courtesy of ZEP

Post-Combustion Capture





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

Option 2. Oxy-Combustion

CO_2 is captured during fuel combustion

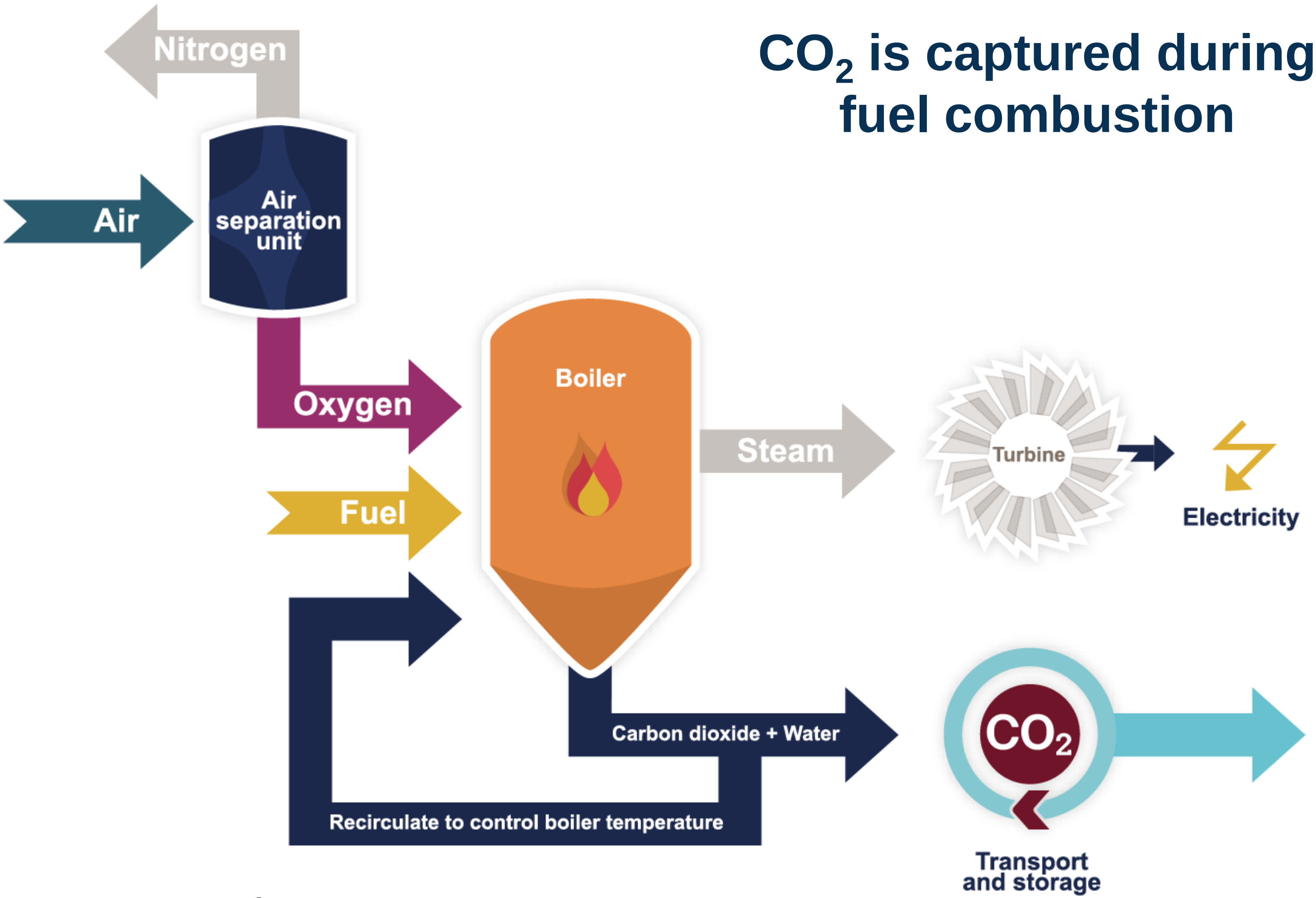
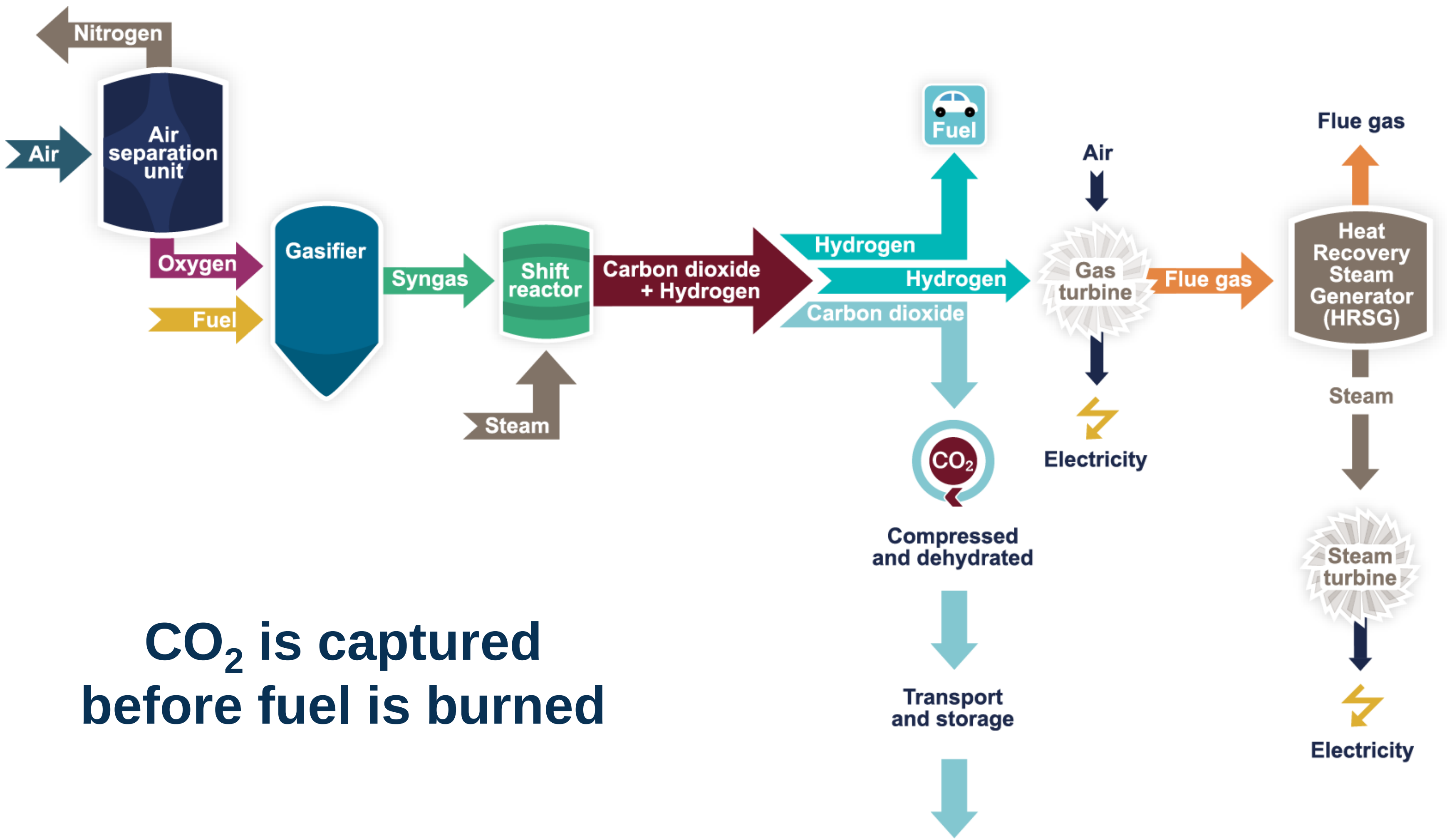


Image Courtesy of ZEP

Option 3. Pre-Combustion Capture



CO_2 is captured before fuel is burned

Image Courtesy of ZEP

Comparison of Capture Options

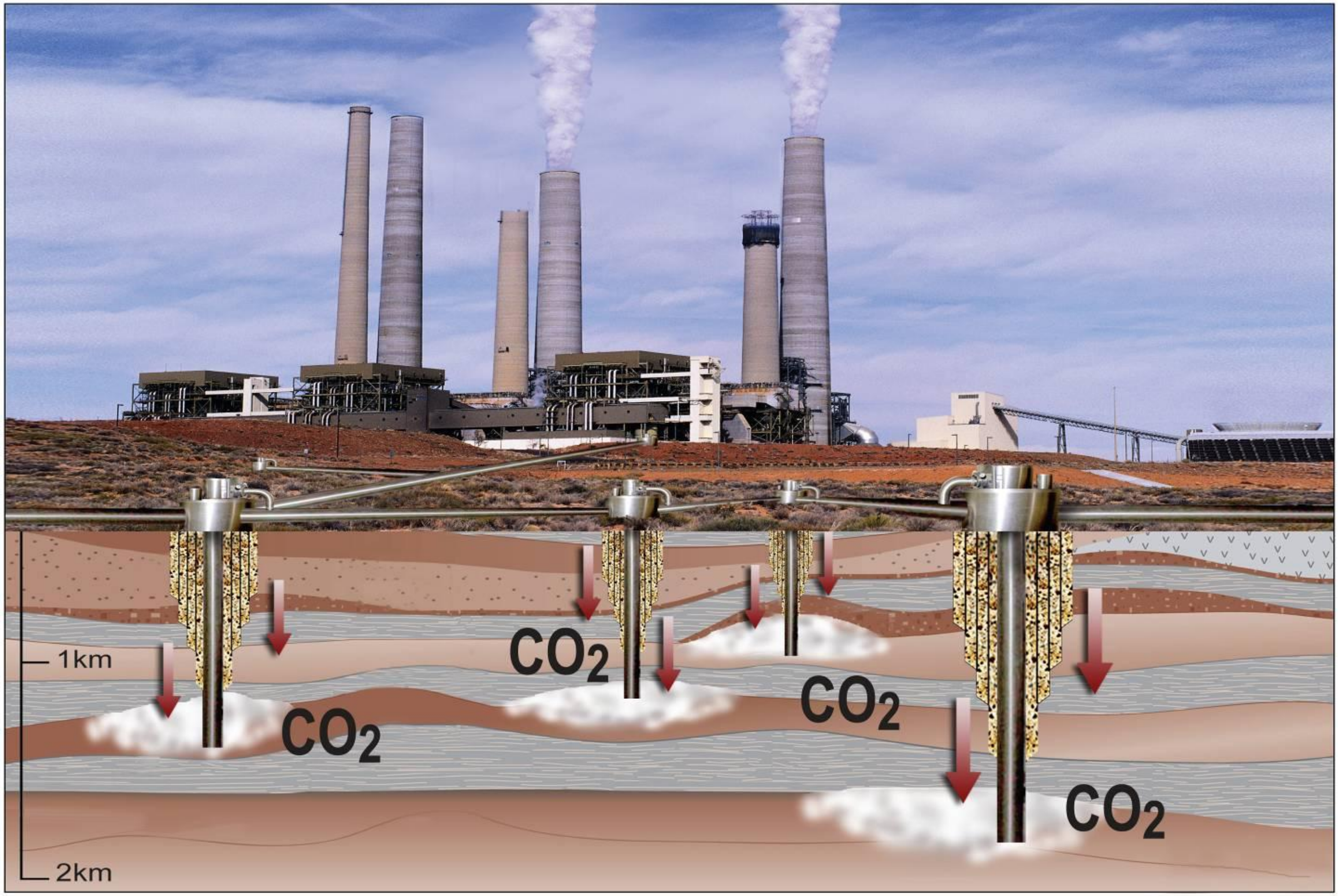
Technology	Advantages	Challenges
Post-Combustion	• Mature technology • Standard retrofit	• High energy penalty (~30%) • High cost for capture
Pre-Combustion (IGCC)	• Lower costs than post-combustion • Lower energy penalties (10-15%) • H_2 production	• Complex chemical process • Repowering • Large capital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

Technology Overview

Capture → **Compression** → **Pipeline Transport** → **Geological Sequestration**

- Compression of CO_2 to a liquid state (about 100 bars)
  - Compression is a mature technology
- Transport of liquid CO_2 in pipelines
  - Pipeline transport is a mature technology with over 2,000 miles of pipelines in the U.S.

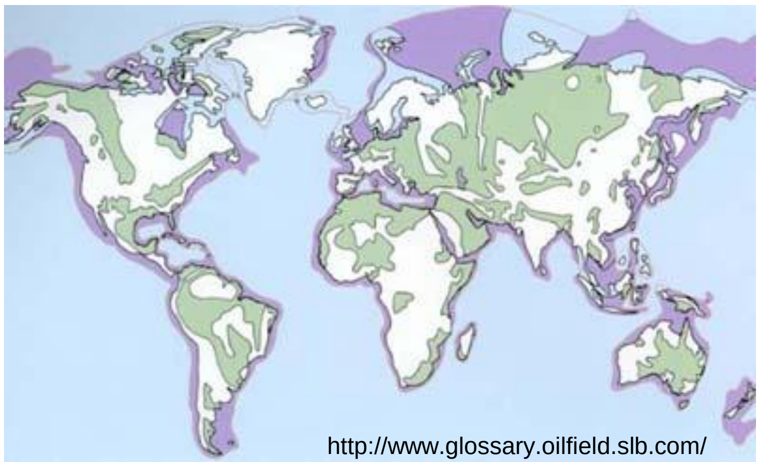
Technology Overview



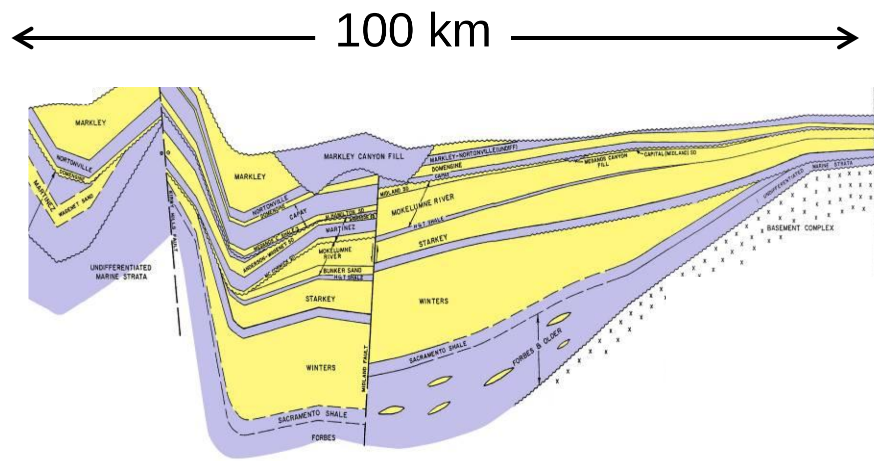
Capture → **Compression** → **Pipeline Transport** → **Geological Sequestration**

What Types of Rock Formations are Suitable for Geological Storage?

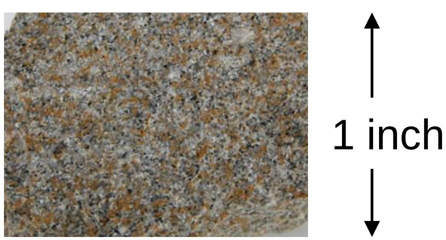
Rocks in deep sedimentary basins are suitable for CO_2 storage.



Map showing world-wide sedimentary basins



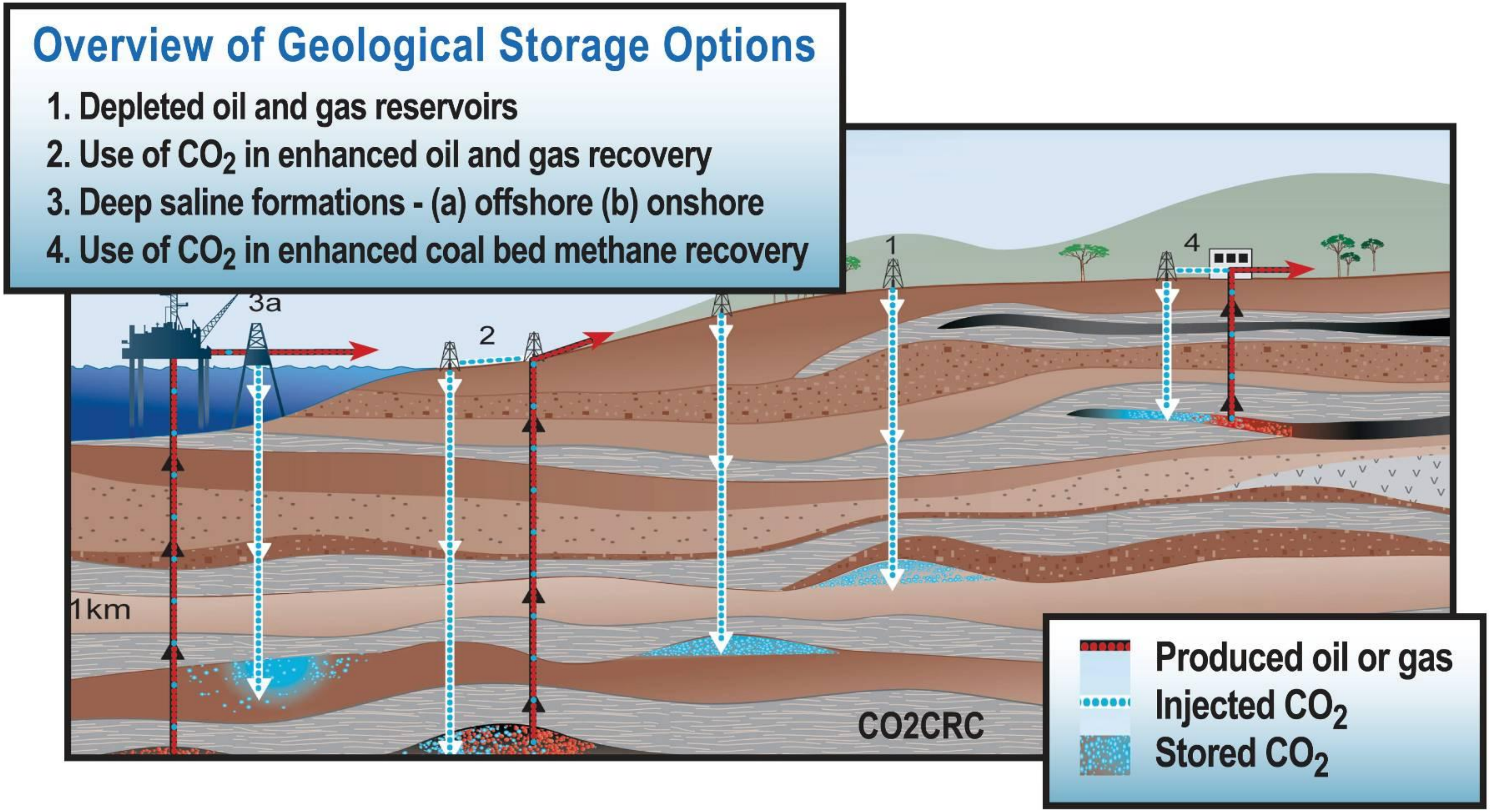
Northern California Sedimentary Basin



Sandstone

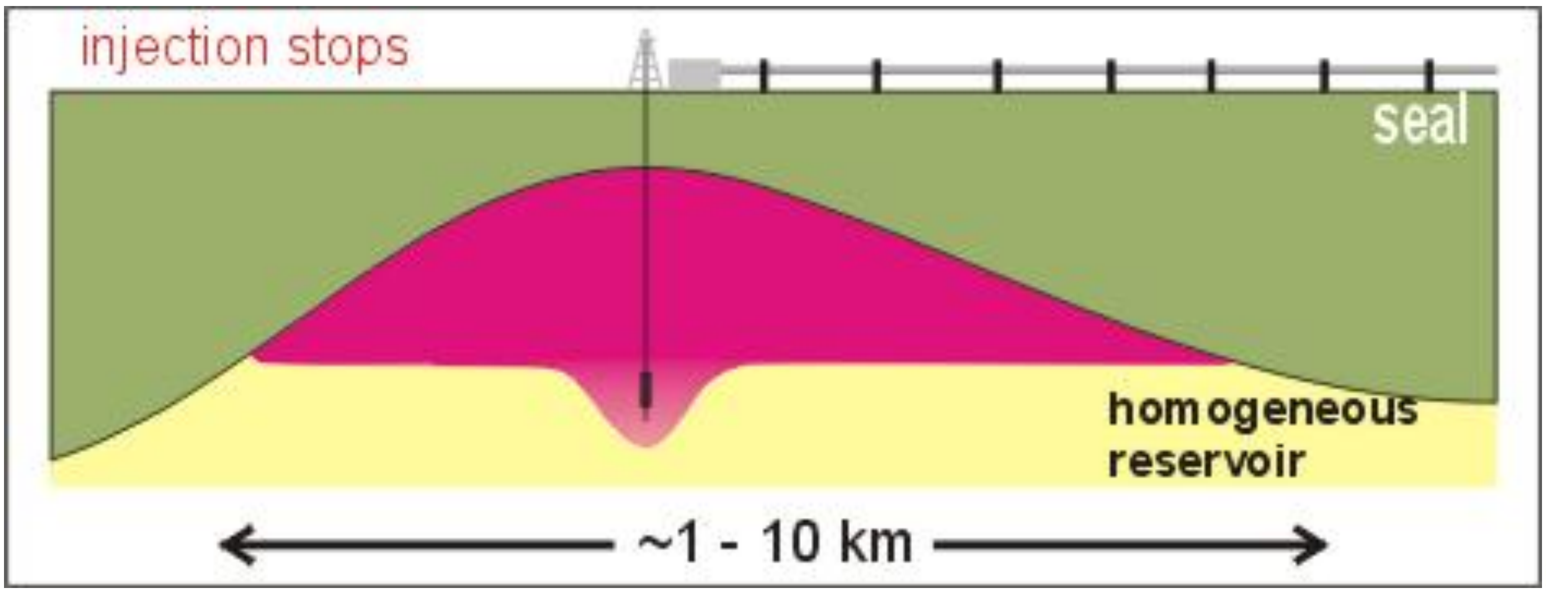
Example of a sedimentary basin with alternating layers of sandstone and shale.

Options for Geological Storage



Basic Concept of Geological Sequestration of CO_2

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



Courtesy of John Bradshaw

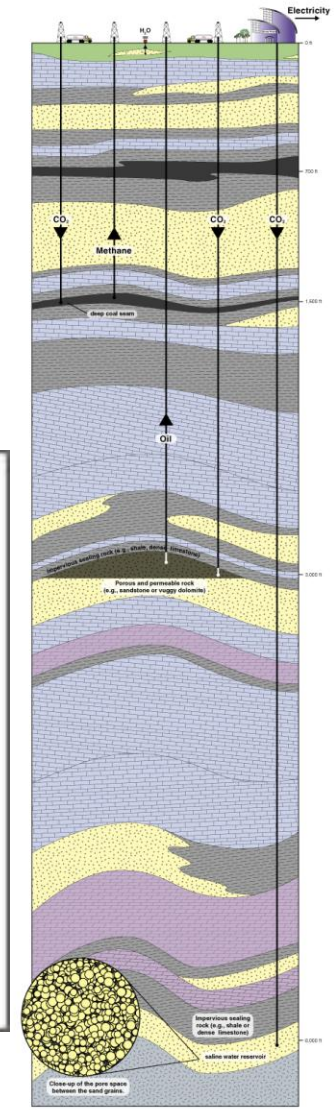


Image courtesy of ISGS and MGSC

X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

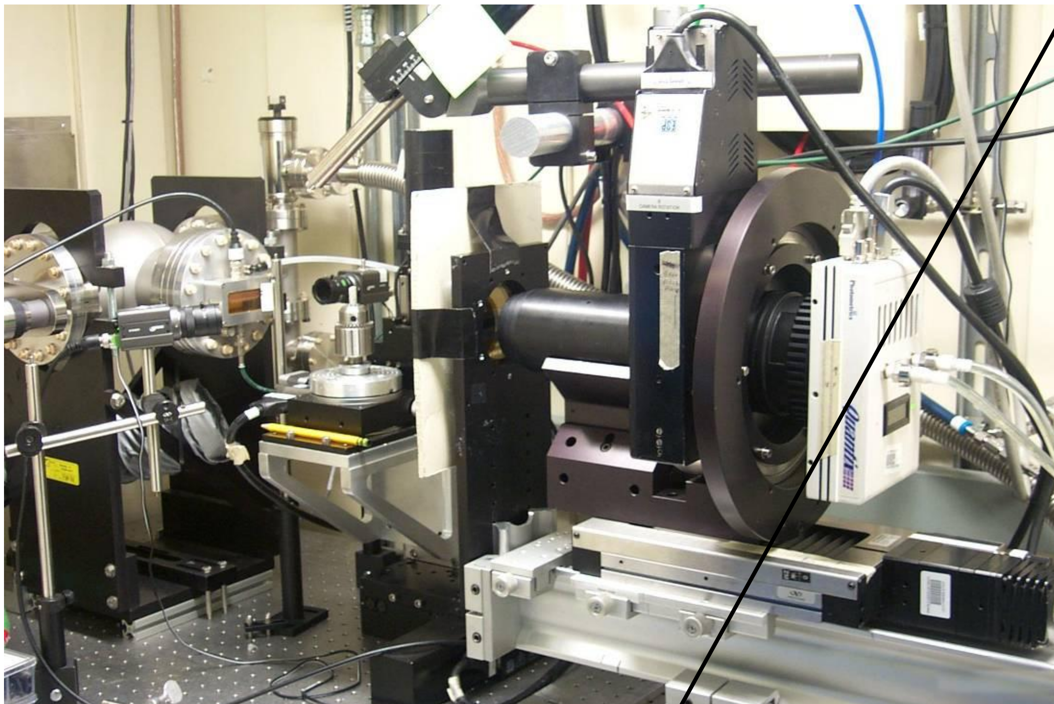
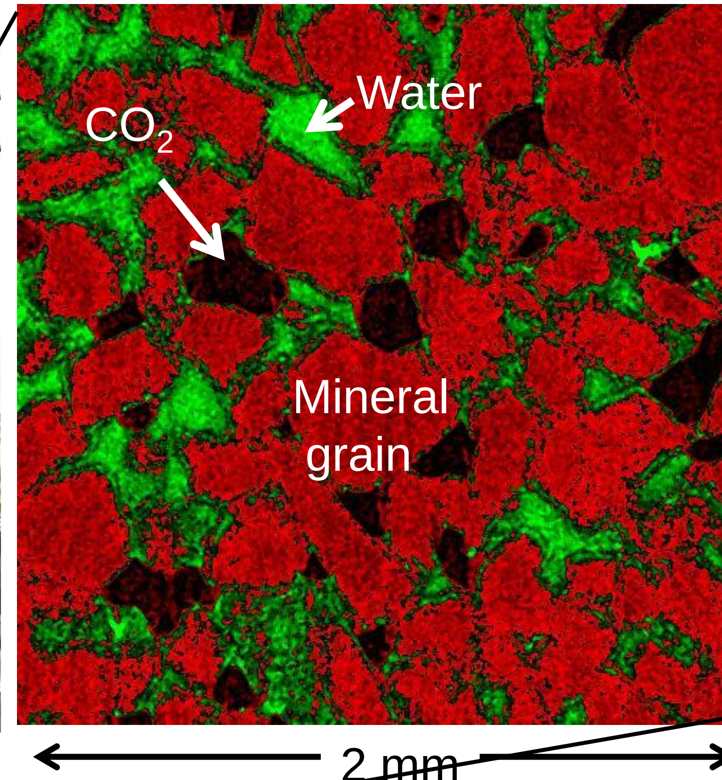
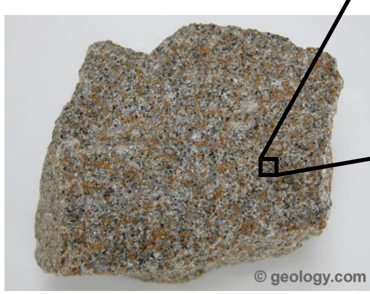


Image of Rock with CO_2

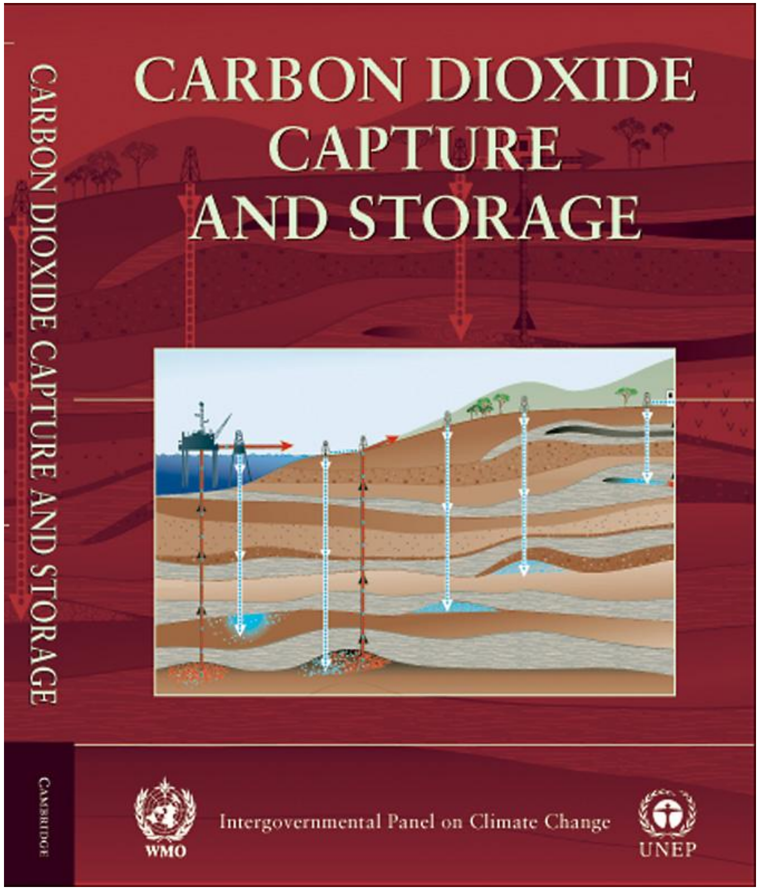




Expert Opinion about Storage Safety and Security

" Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely** to exceed 99% over 1,000 years."*

" 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 to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas."

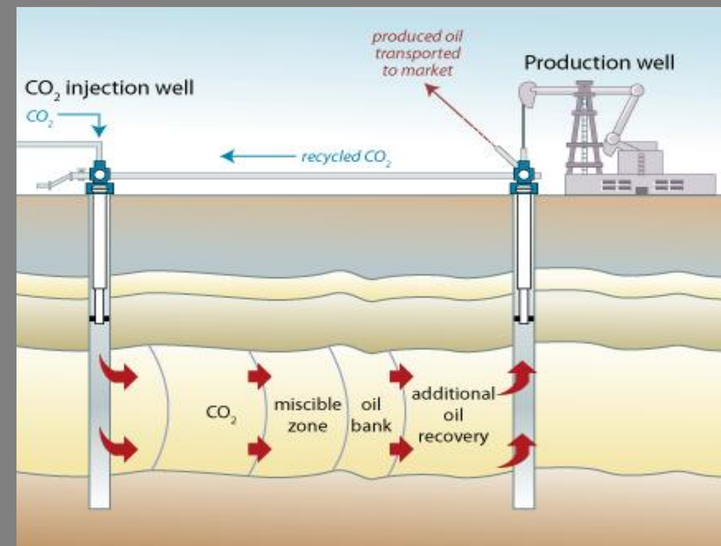


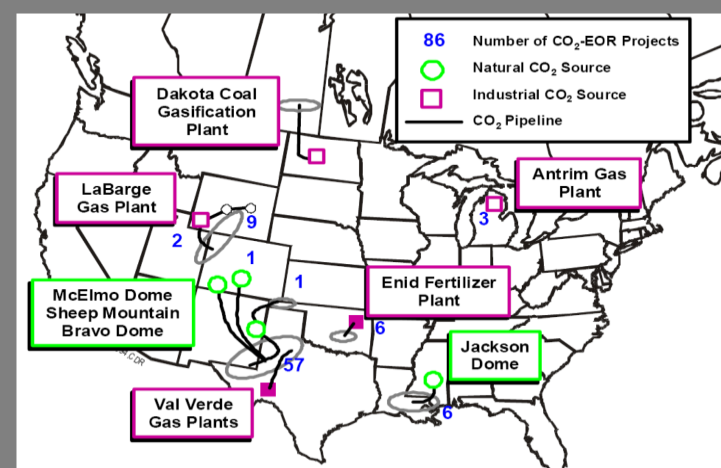
* "Very likely" is a probability between 90 and 99%.

** Likely is a probability between 66 and 90%.

Evidence to Support these Conclusions

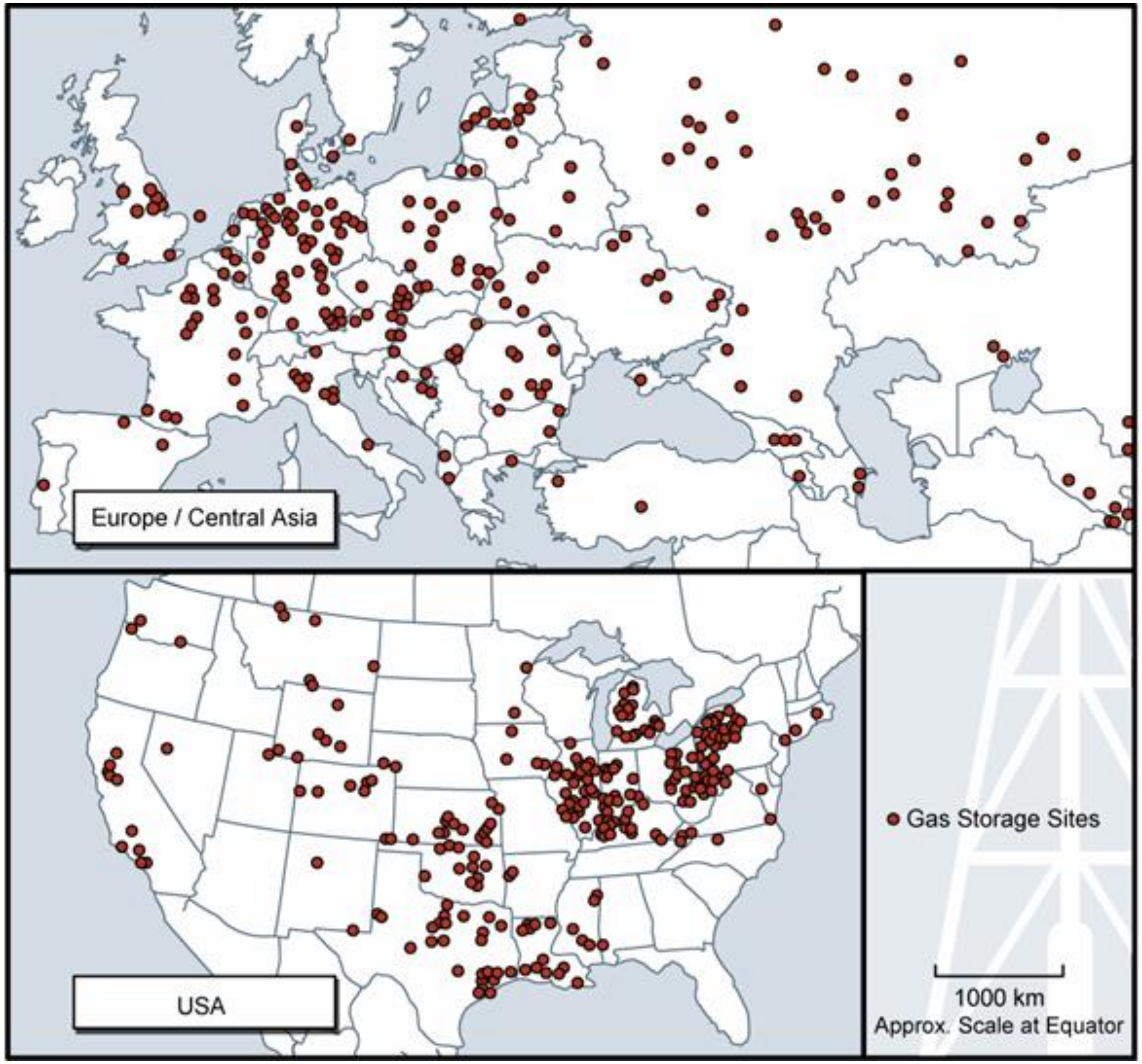
- Natural geological analogs
  - Oil and gas reservoirs
  - CO_2 reservoirs
- Performance of industrial analogs
  - 40 years experience with CO_2 EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 30+ years of cumulative performance of actual CO_2 storage projects
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004
  - Snovhit, Norway, 2008





~40 Mt/yr are injected for CO_2-EOR

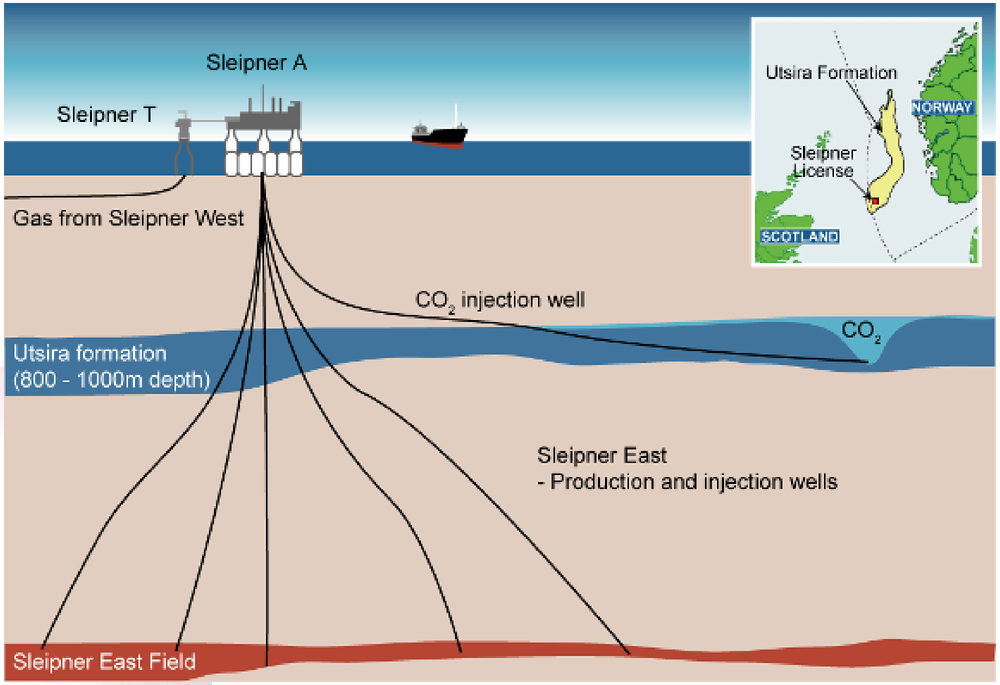
Natural Gas Storage



- Seasonal storage to meet winter demands for natural gas
- Storage formations
  - Depleted oil and gas reservoirs
  - Aquifers
  - Caverns

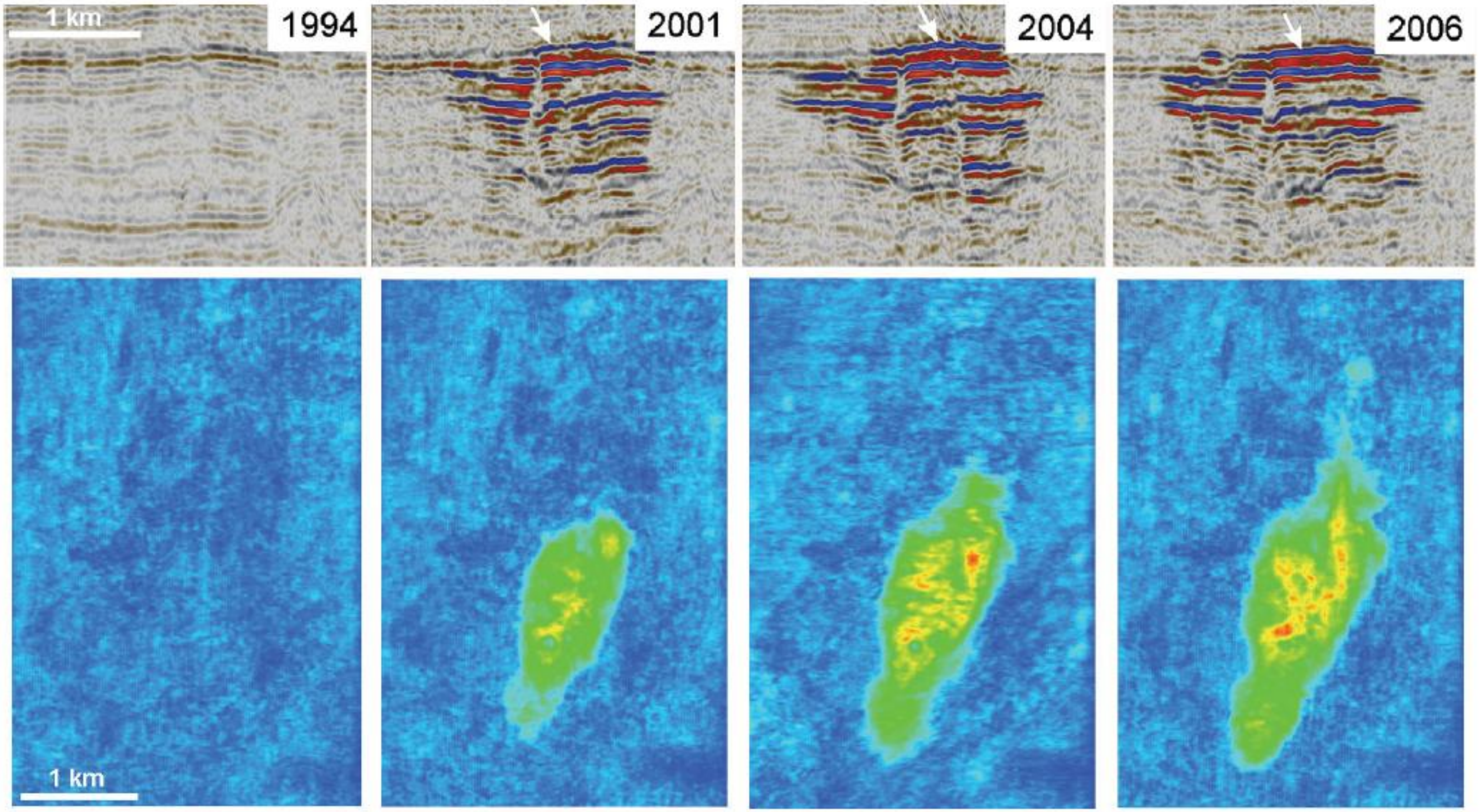
Sleipner Project, North Sea

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



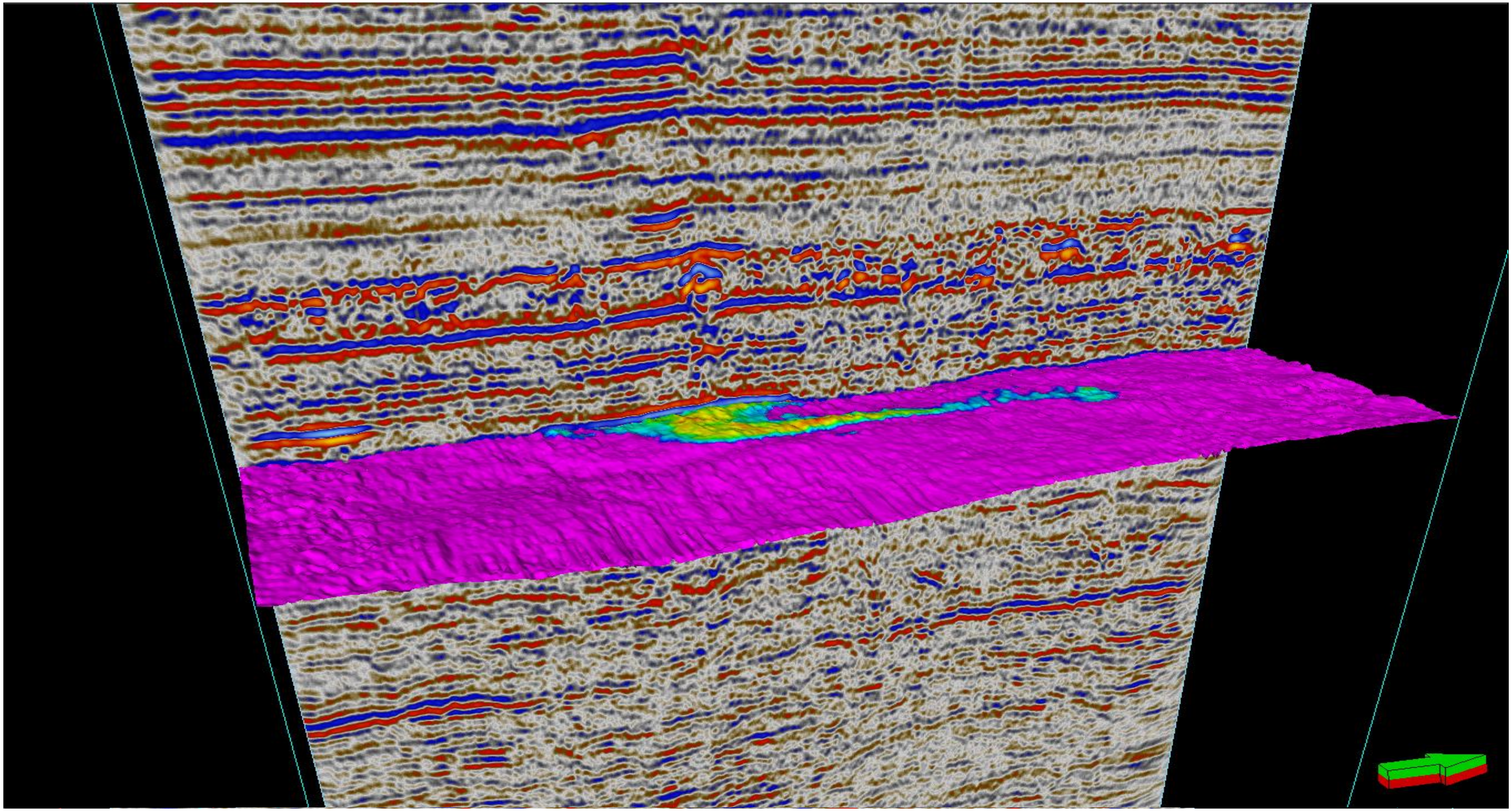
Courtesy *Statoil*

Seismic Monitoring Data from Sleipner



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

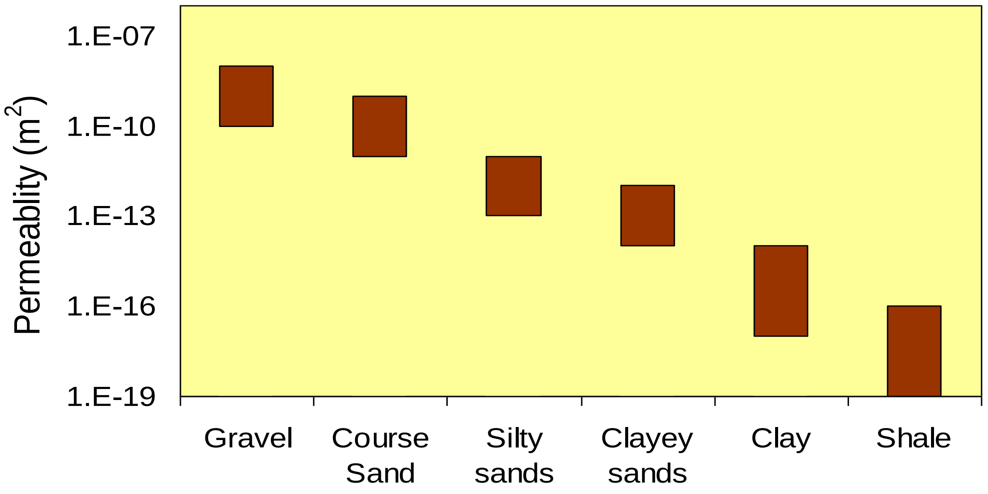
Plume and topmost layer 2001 - 2006

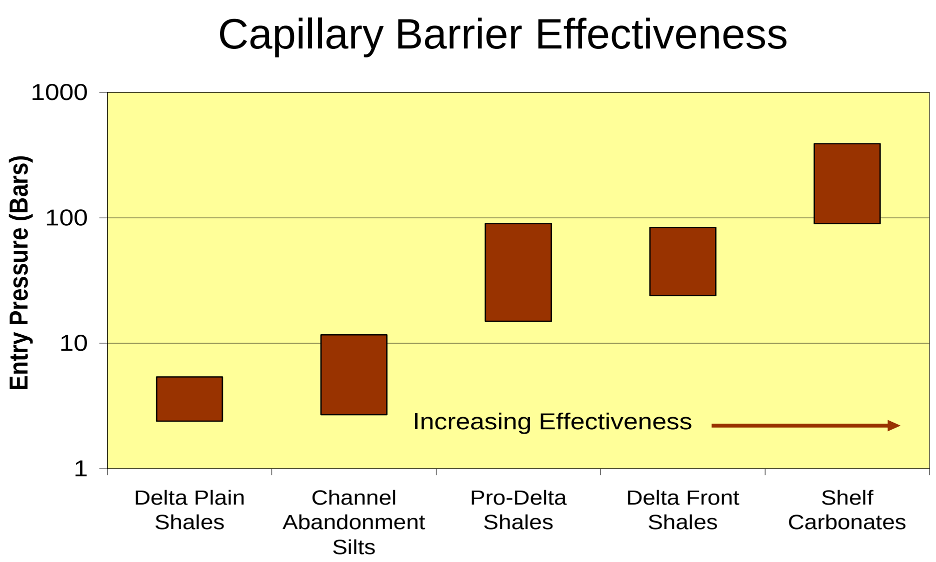


From Andy Chadwick, BGS, 2010

Seal Rocks and Trapping Mechanisms

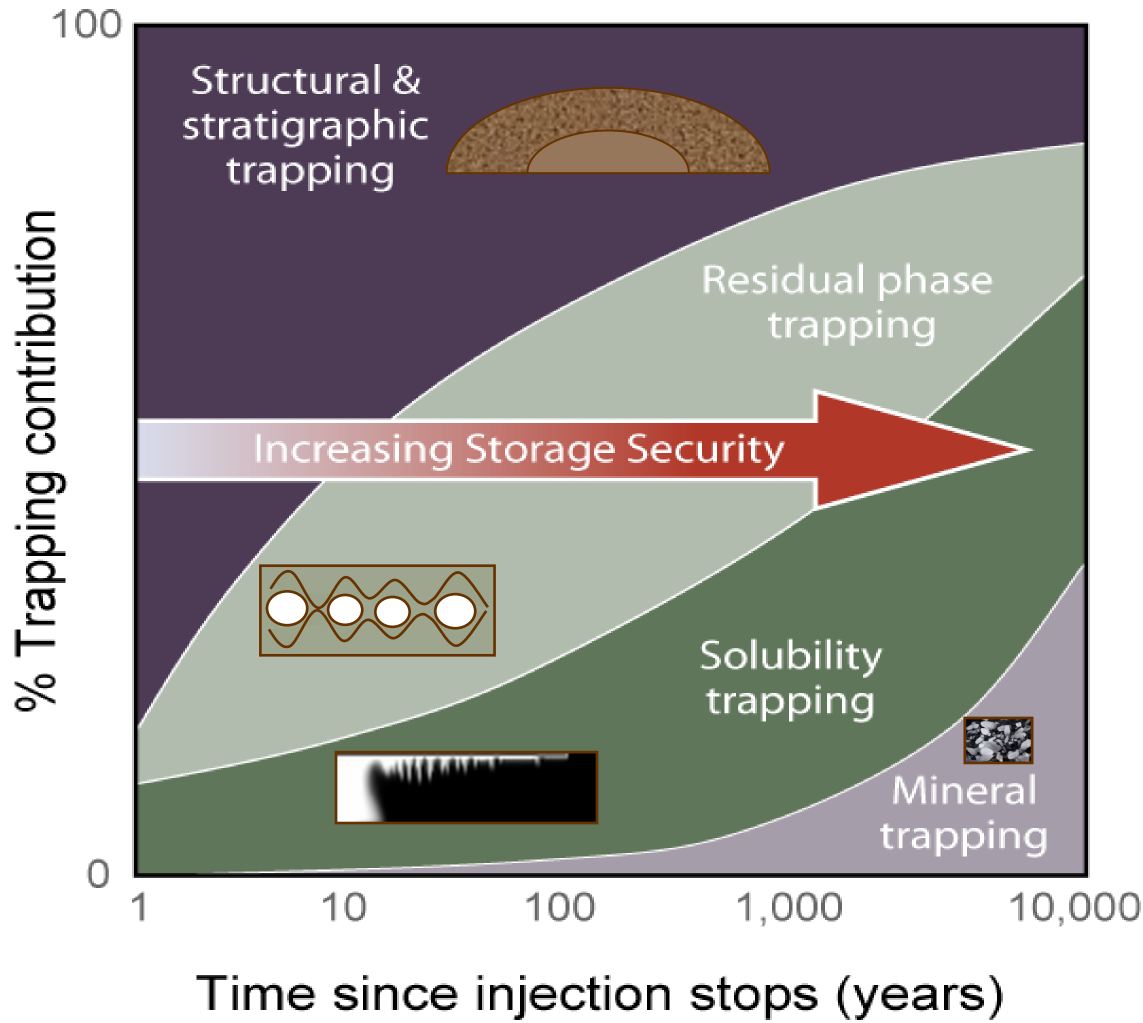
- Seal rock geology
  - Shale
  - Clay
  - Carbonates
- Two trapping mechanisms
  - Permeability barriers to CO_2 migration
  - Capillary barriers to CO_2 migration



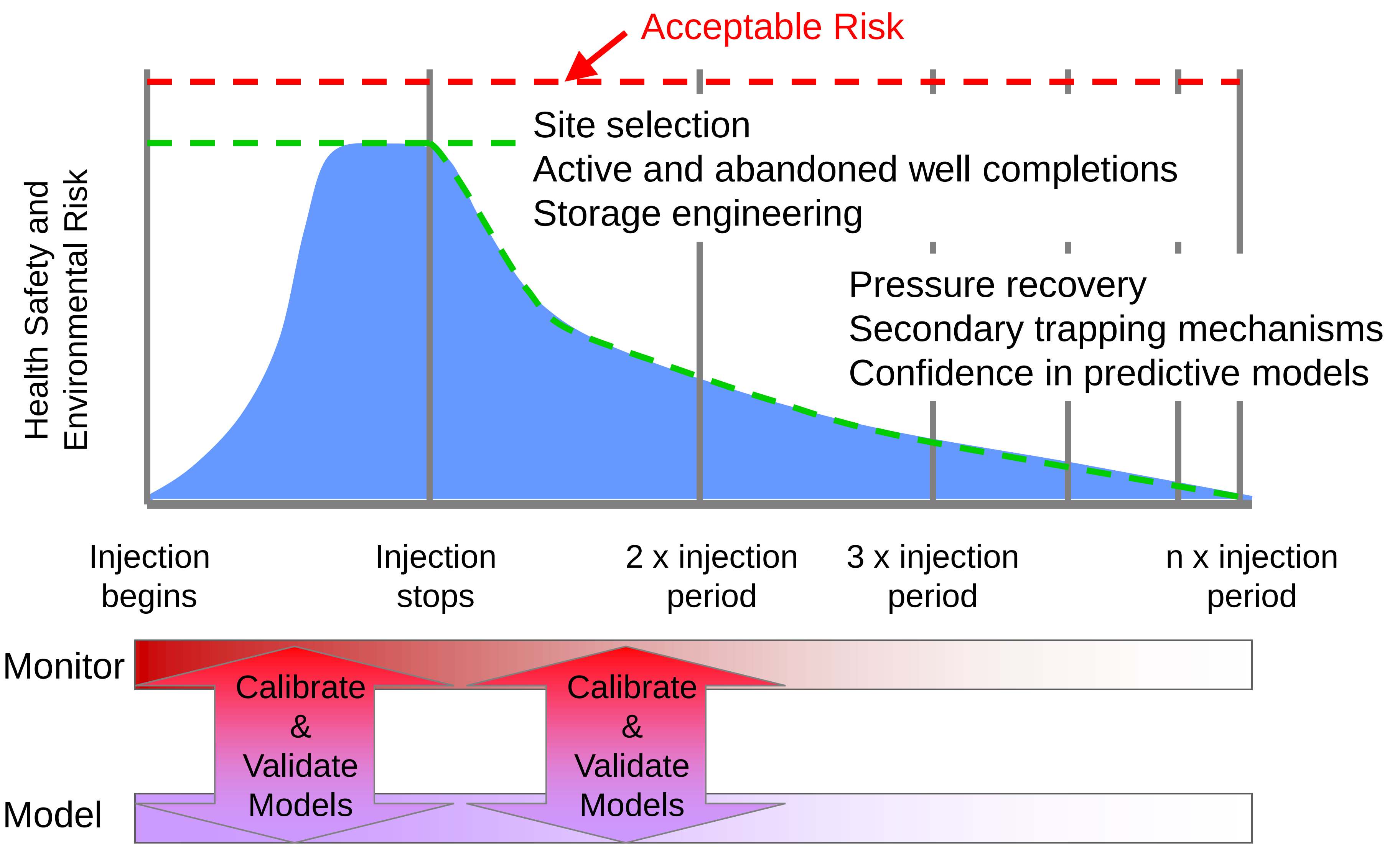


Secondary Trapping Mechanisms Increase Over Time

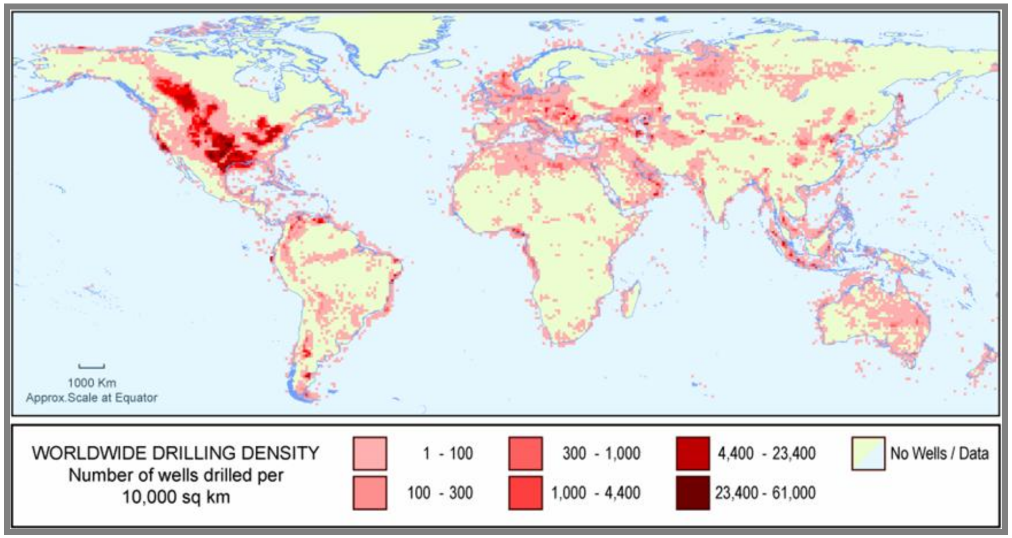
- Solubility trapping
  - CO_2 dissolves in water
- Residual gas trapping
  - CO_2 is trapped by capillary forces
- Mineral trapping
  - CO_2 converts to solid minerals
- Adsorption trapping
  - CO_2 adsorbs to coal



Risk Management



What Could Go Wrong?



Potential Release Pathways

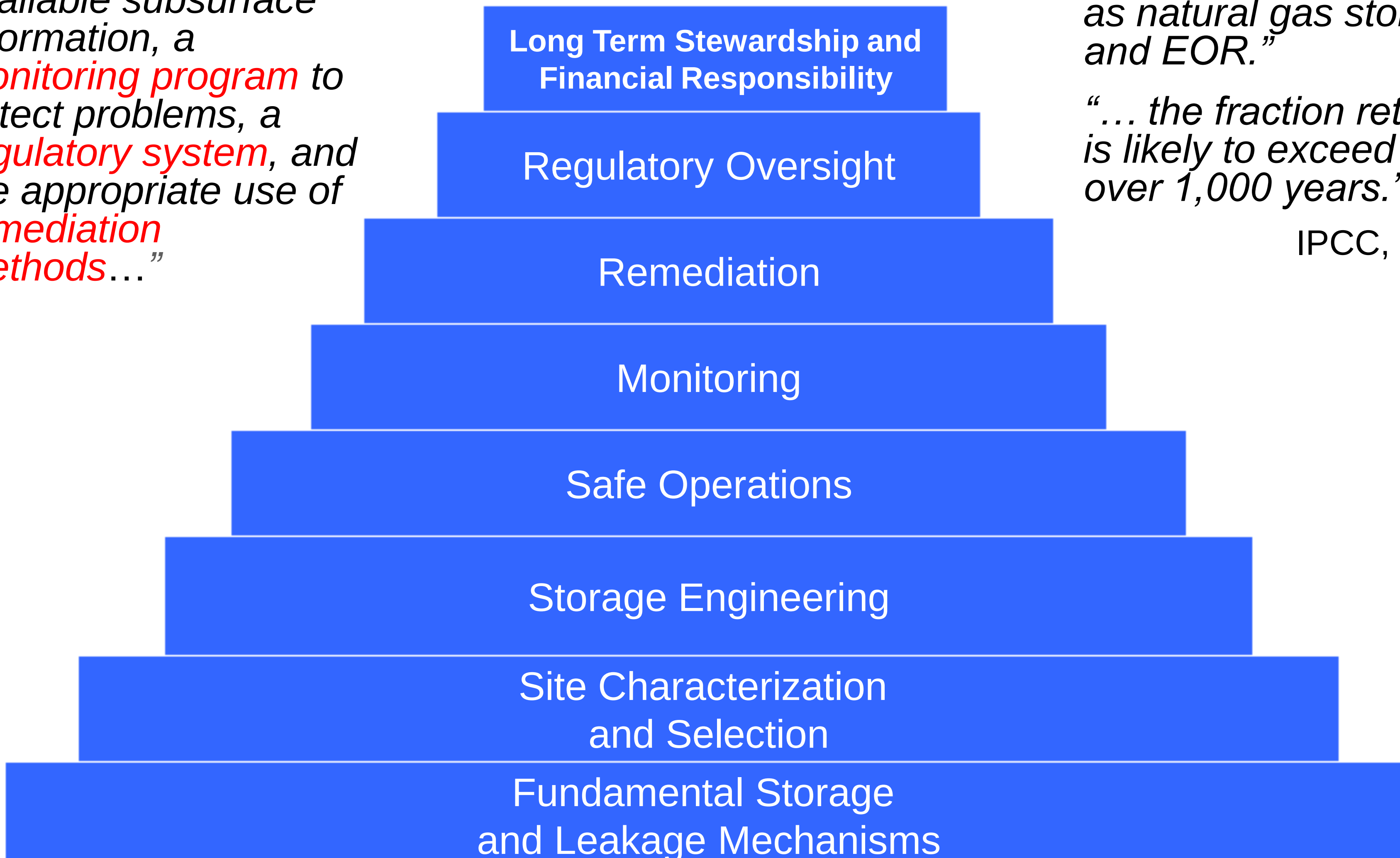
- Well leakage (injection and abandoned wells)
- Poor site characterization (undetected faults)
- Excessive pressure buildup damages seal

Potential Consequences

1. Worker safety
2. Groundwater quality degradation
3. Resource damage
4. Ecosystem degradation
5. Public safety
6. Structural damage
7. Release to atmosphere

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…"



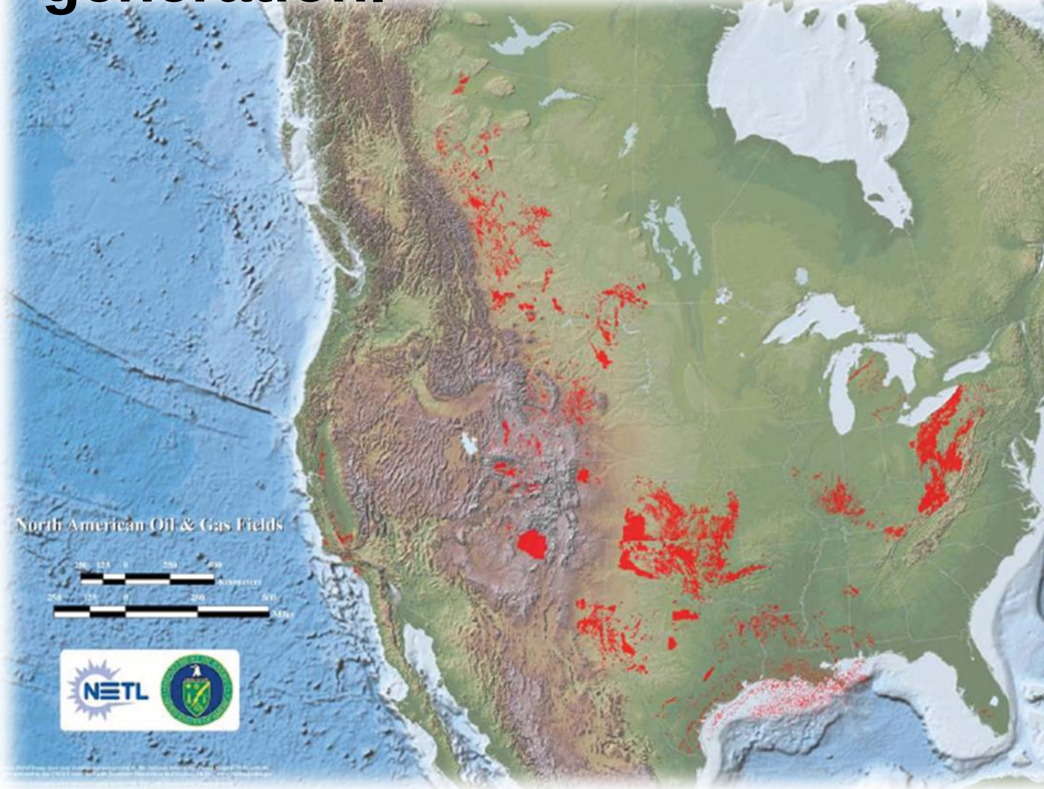
"… risks similar to existing activities such as natural gas storage and EOR."

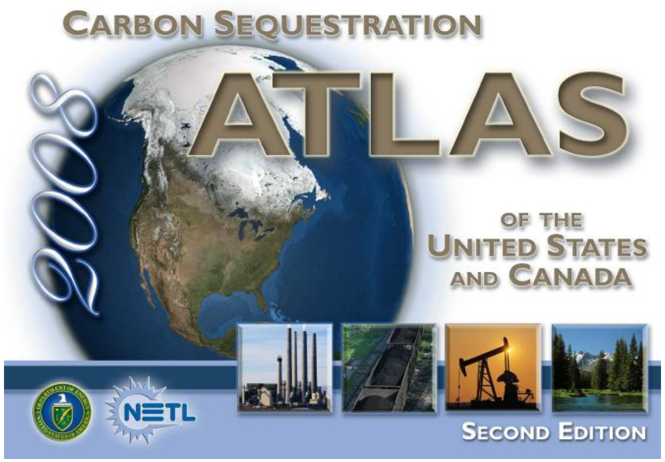
"… the fraction retained is likely to exceed 99% over 1,000 years."

IPCC, 2005

Storage Resources in Oil and Gas Reservoirs

Oil and gas reservoirs could potentially store about 60 years of current emissions from power generation.

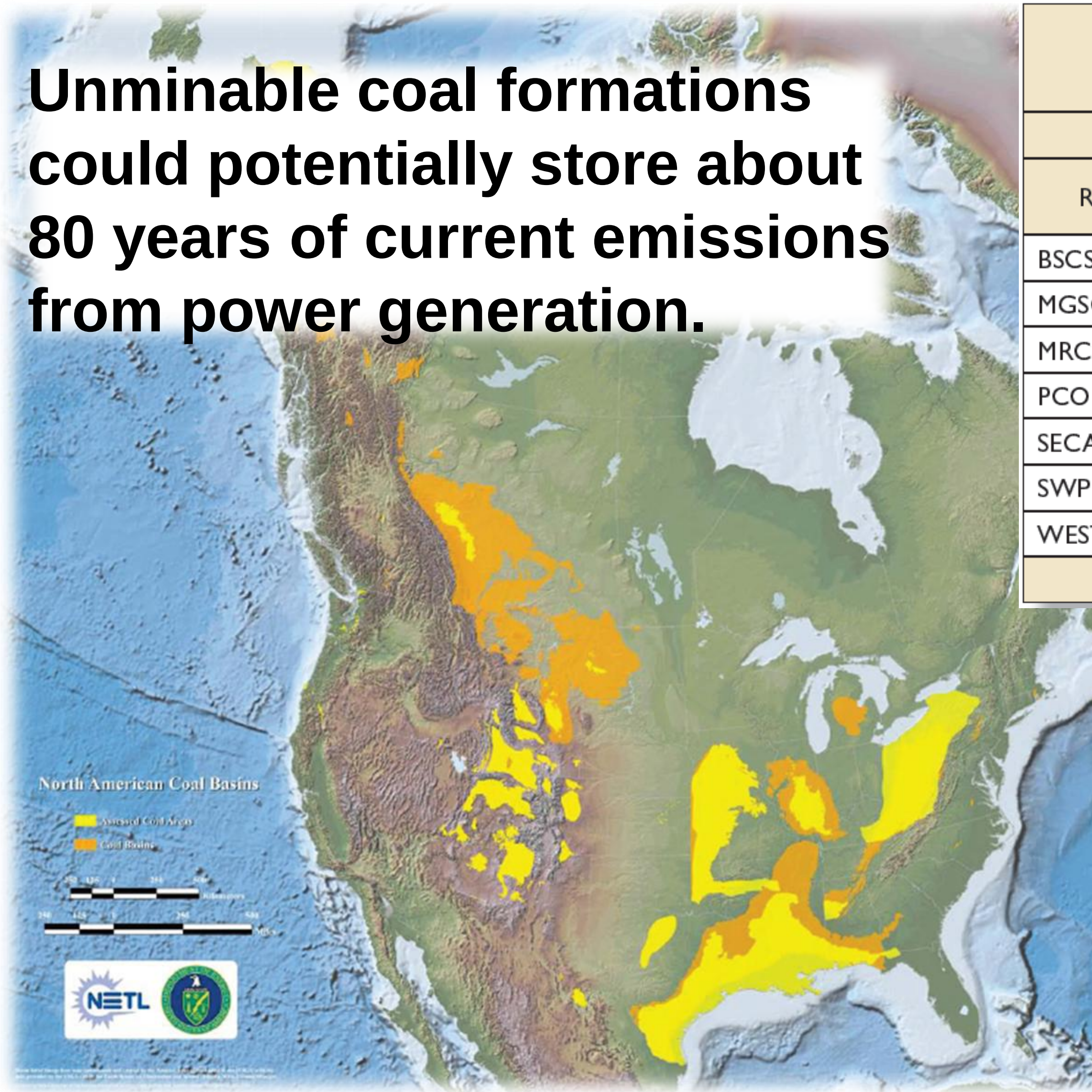




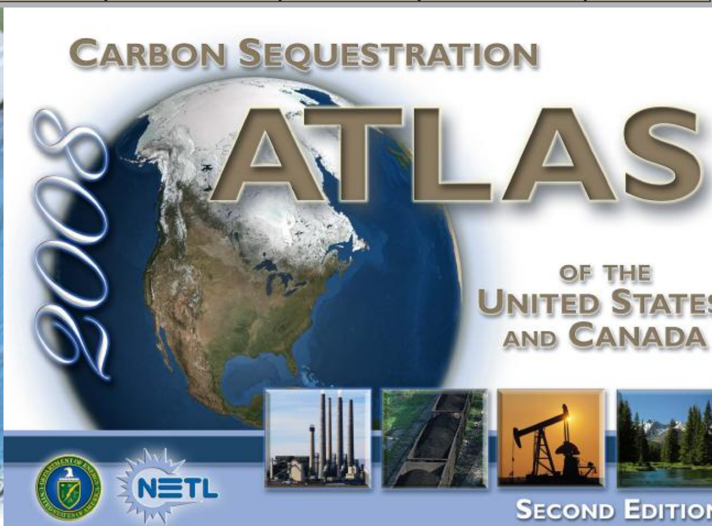
CO$_2$ Resource Estimates by Regional Carbon Sequestration Partnership for Oil and Gas Reservoirs		
RCSP	Billion Metric Tons	Billion Tons
BSCSP	1.5	1.6
MGSC	0.4	0.4
MRCSP	8.4	9.3
PCORP	24.1	26.5
SECARB	27.1	29.9
SWP	62.3	68.7
WESTCARB	5.8	6.4
TOTAL	129.6	142.9

Storage Resources in Coal Beds

Unminable coal formations could potentially store about 80 years of current emissions from power generation.



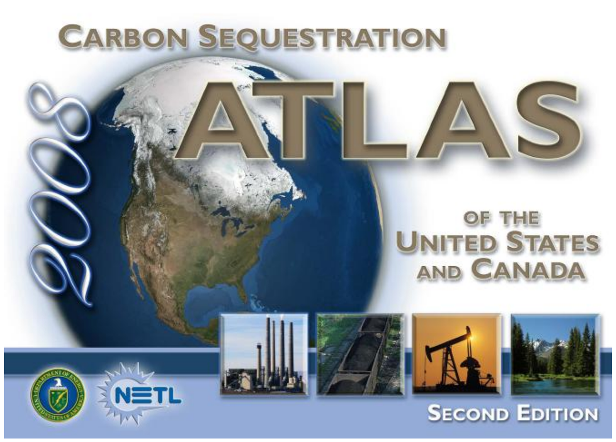
CO_2 Resource Estimates by Regional Carbon Sequestration Partnership for Unmineable Coal Seams				
	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	12.1	13.3	12.1	13.3
MGSC	1.7	1.8	2.4	2.6
MRCSP	0.8	0.9	0.8	0.9
PCORP	10.7	11.8	10.7	11.8
SECARB	57.8	63.7	82.8	91.3
SWP	0.7	0.8	1.8	2.0
WESTCARB	86.8	95.7	86.8	95.7
TOTAL	170.6	188.0	197.3	217.5



Saline Aquifers

Saline aquifers could potentially store more than 1,000 years of current emissions from power production.

CO$_2$ Resource Estimates by Regional Carbon Sequestration Partnership for Saline Formations				
	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	460.9	508.0	1,831.5	2018.9
MGSC	29.2	32.1	116.6	128.6
MRCSP	117.8	129.8	117.8	129.8
PCORP	185.6	204.6	185.6	204.6
SECARB	2,274.6	2,507.3	9,098.4	10029.3
SWP	10.7	11.8	42.6	47.0
WESTCARB	204.9	225.9	817.3	900.9
TOTAL	3,283.6	3,619.5	12,209.8	13459.0



Global Sequestration Capacity Estimates

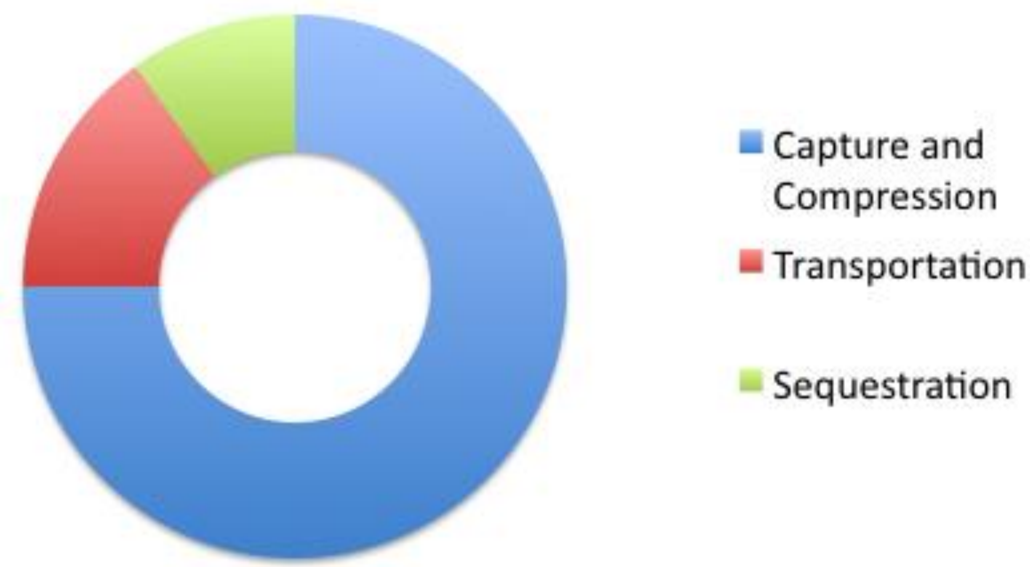
Region	Estimated Storage Capacity (billion tons of CO2)				Source	Note
	Depleted Oil and Gas Reservoirs	Saline Aquifers	Coal Seams	TOTAL		
North America	143	3600-13000	187-217	3930-13360	1	
Latin America	89	30.3	2	NA	14	1*
Brazil	NA	2000	0.2	2000.2	2	
Australia	19.6	28.1	11.3	59	3, 4	2*
Japan	0	1.9-146	0.1	2-146.1	5, 6, 14	
Centrally Planned Asia and China (CPA)	9.7-21	110-360	10	1445 -3,080	7, 8, 9, 17	3*
Other Pacific Asia (PAS)	56-188	NA	NA	56-188	11, 12	4*
South Asia (SAS)	6.5-7.4	NA	0.36-0.39	6.86-7.79	12	5*
Former Soviet Union (FSU)	177	NA	NA	177	13	6*
Subsaharan Africa	36.6	34.6	7.6	48.3	14	7*
Middle East & North Africa	439.5	9.7	0	449.2	14	
Europe	20.22-30	95.72-350	1.08-1.5	117-381	15, 16	8*
World	996 - 1,150	5,900 - 16,000	210 - 240			9*

From KM13 GEA, 2010.

Global Distribution of Commercial, Pilot and Demonstration Projects

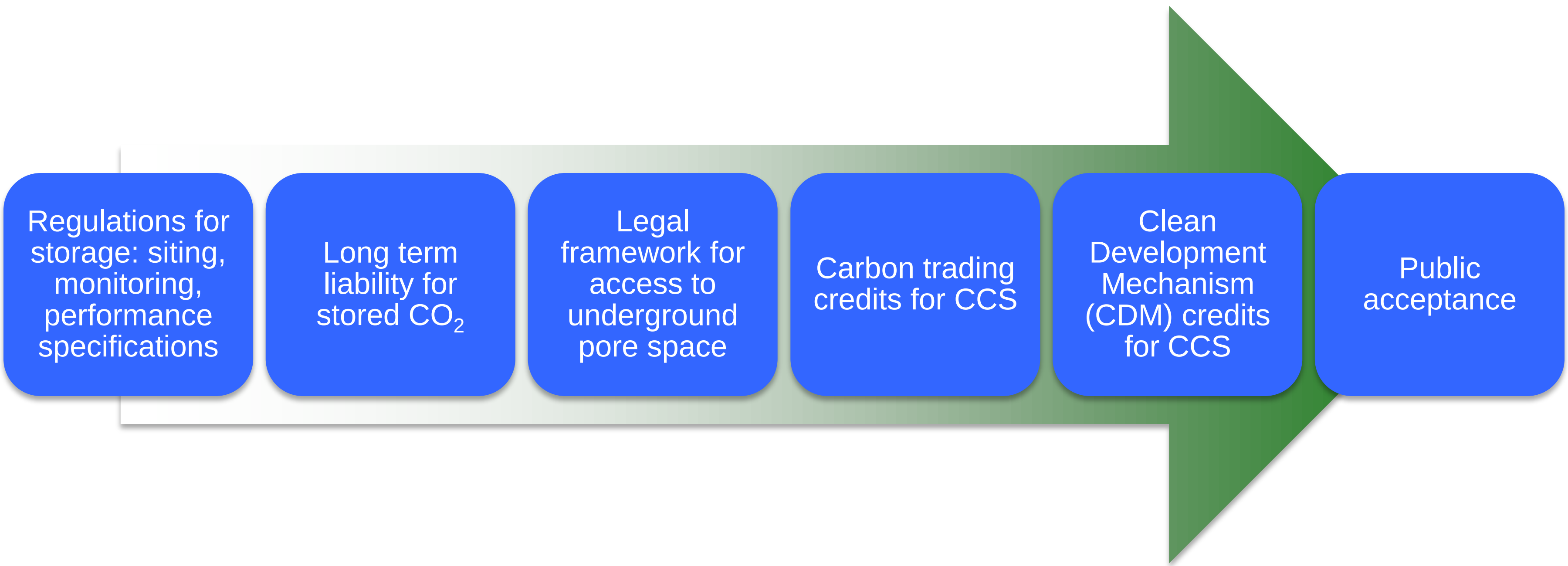
Cost of CCS

- Complex to assess costs, depending on baseline, technology choices, site specific considerations
- Increase the cost of electricity generation by 50 to 100%



Distribution of costs for a typical CCS project.

Institutional and Social Issues



None is likely to be a show stopper, but all require effort to resolve.

Maturity of CCS Technology

- Are we ready for CCS?

Oil and gas reservoirs

Saline aquifers

Coalbeds

State-of-the-art is well developed, scientific understanding is excellent and engineering methods are mature

Sufficient knowledge is available but practical experience is lacking, economics may be sub-optimal, scientific understanding is good

Demonstration projects are needed to advance the state-of-the art for commercial scale projects, scientific understanding is limited

Pilot projects are needed to provide proof-of-concept, scientific understanding is immature

Concluding Remarks

- CCS is an important part of solving the global warming problem
- Progress on CCS proceeding on all fronts
  - Industrial-scale projects
  - Demonstration plants
  - Research and development
- Technology is sufficiently mature for commercial projects with CO_2-EOR and for large scale demonstration projects in saline aquifers
- Research is needed to support deployment at scale
  - Capture: Lower the cost and increase reliability
  - Sequestration: Increase confidence in storage permanence
- Institutional issues and incentives need to be addressed to support widespread deployment

Additional Reading and Resources

- Metz et al., 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press.
- S. M. Benson and D. R. Cole (2008), CO_2 Sequestration in Deep Sedimentary Formations, *ELEMENTS*, Vol, 4, pp. 325-331, DOI: 10.2113/gselements.4.5.325.
- S.M. Benson, and T. Surles (2006) Carbon Dioxide Capture and Storage: An Overview with Emphasis on Capture and Storage in Deep Geological Formations, The Proceedings Special Issue, Institute of Electrical and Electronics Engineers (IEEE), Vol. 94, No 10, October 2006, DOI 10.1109/PROC.2006.883716.
- Global Carbon Capture and Storage Institute: http://www.globalccsinstitute.com/
- IEA Greenhouse Gas Programme: http://www.ieaghg.org/index.php?/20091218110/what-is-css.html