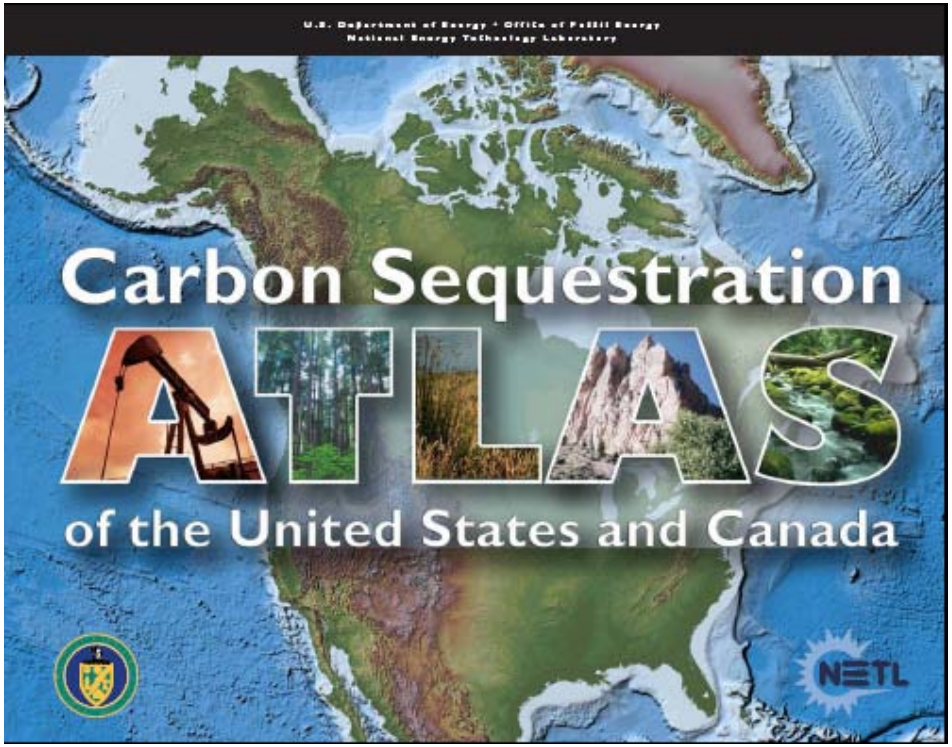
NATIONAL ENERGY TECHNOLOGY LABORATORY



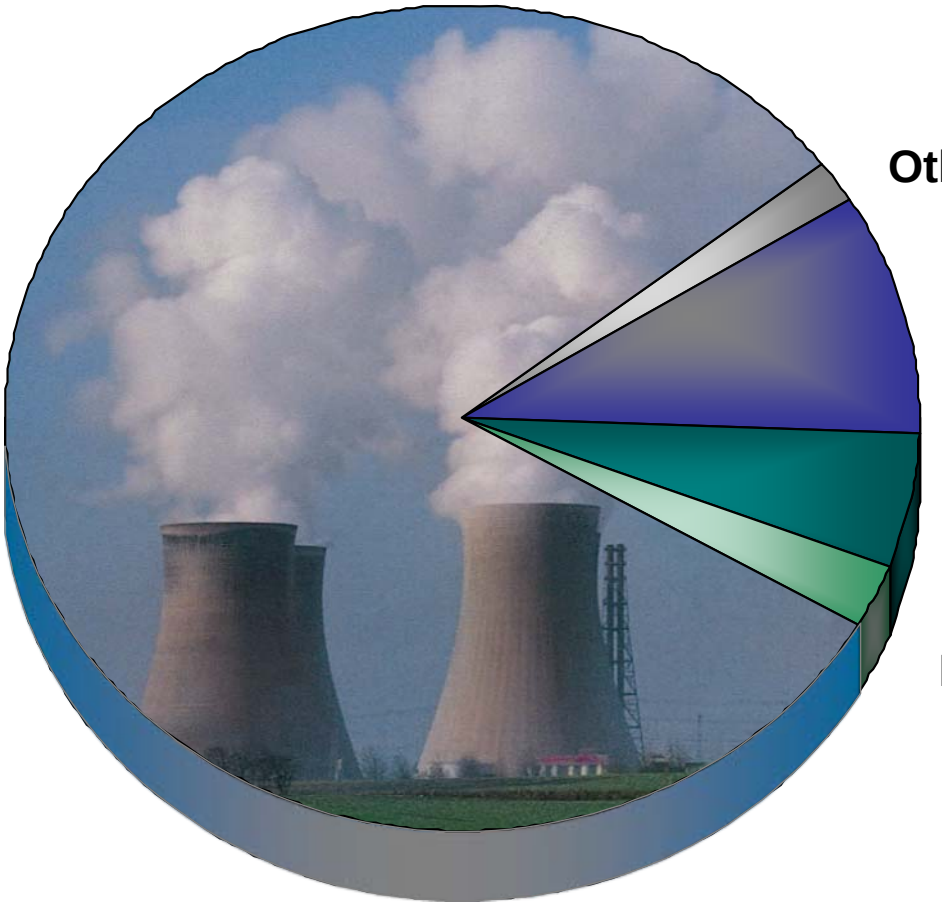
Carbon Management

Scott M. Klara
Director, Strategic Center for Coal

R&D Focus is on CO_2

United States Greenhouse Gas Emissions

(Equivalent Global Warming Basis)

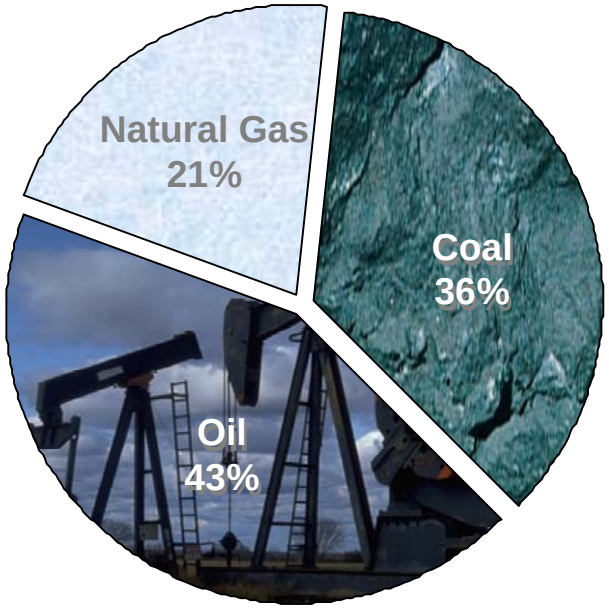


"EIA Emissions of Greenhouse Gases in the U.S.: 2000"

R&D Focus is on Coal & Electricity

United States CO2 Emissions

36% Emissions From Coal



39% Emissions From Electricity

Annual CO_2 Emissions Extremely Large

Emissions	Total Release in the U.S., short tons per year
Mercury	120
Sulfur Dioxide (SO_2)	15,000
Municipal solid waste	230,000,000
Carbon Dioxide (CO_2)	6,300,000,000

Data sources: Mercury - EPA National Emissions Inventory (1999 data); SO_2 - EPA air trends (2002 data); MSW - EPA OSWER fact sheet (2001 data); CO_2 - EIA AEO 2004 (2002 data)

Technological Carbon Management Options

Reduce Carbon Intensity

- Renewables
- Nuclear
- Fuel Switching

Improve Efficiency

- Demand Side
- Supply Side

Sequester Carbon

- Capture & Store
- Enhance Natural Sinks

All options needed to:

- Affordably meet energy demand
- Address environmental objectives

What is Carbon Sequestration?

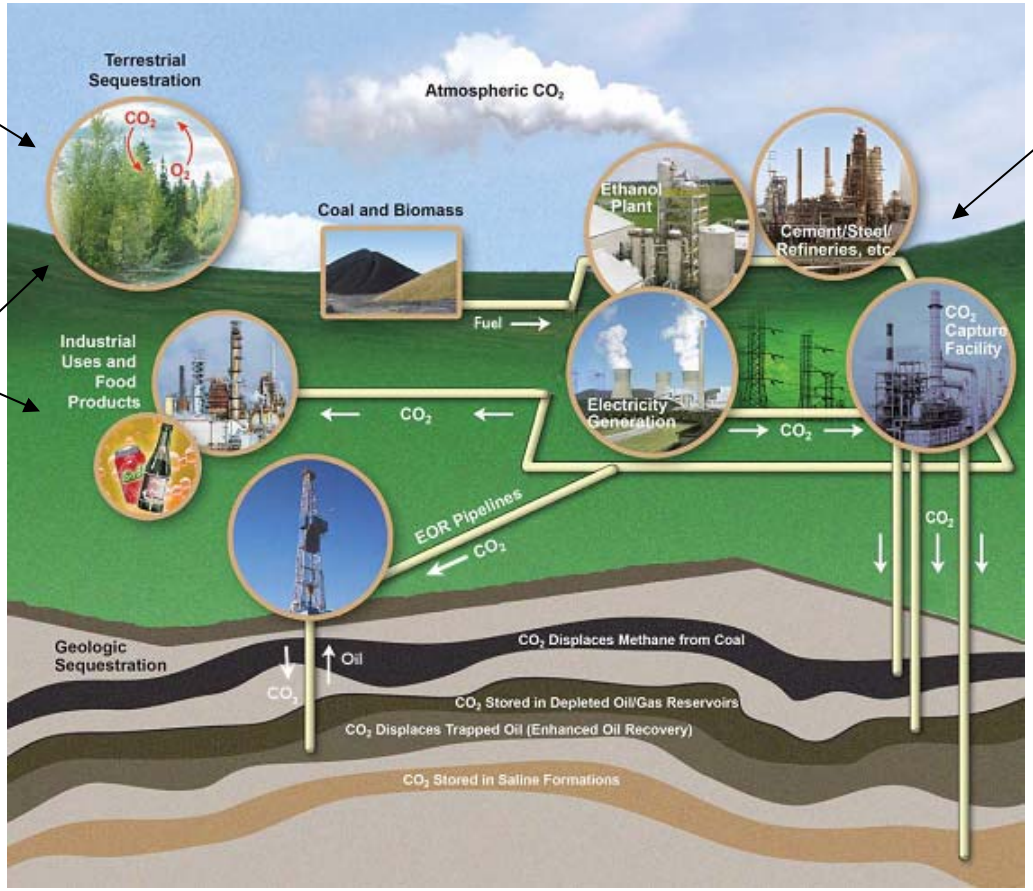
Capture and storage of CO_2 and other Greenhouse Gases that would otherwise be emitted to the atmosphere

Terrestrial Capture

CO_2 absorbed from air

Terrestrial Storage

Trees, grasses, soils



Point Source Capture

Power Plants

Ethanol Plants

Cement, Steel, Refineries

Natural Gas Processing

Value Added Options

- **EOR**
- **ECBM**
- **Carbon Recycling**

Geologic Storage

- ***saline formations***
- ***depleted oil/gas***
- ***unmineable coal***
- ***other: basalts, shales***

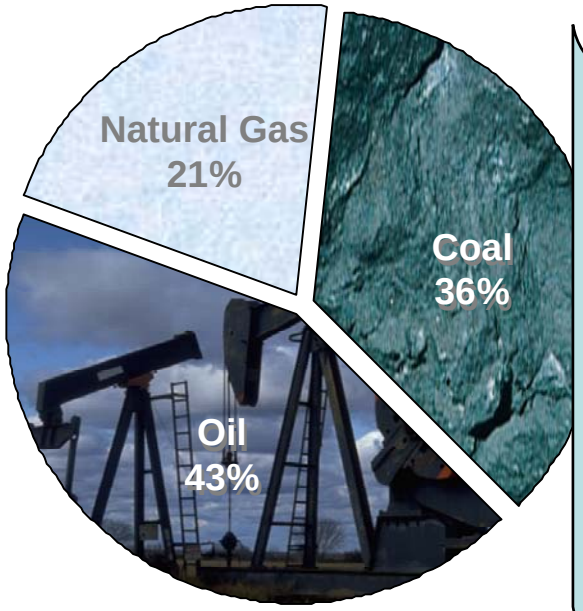
Requirements for Sequestration

- **Environmentally acceptable**
  - No legacy for future generations
  - Respect existing ecosystems
- **Safe**
  - No sudden large-scale CO_2 discharges
- **Verifiable**
  - Ability to verify amount of CO_2 sequestered
- **Economically viable**

CCS – It's Not Just About Coal !!!

United States CO_2 Emissions

Emissions By Fuel Type



Natural Gas Power Plants

Natural Gas Processing

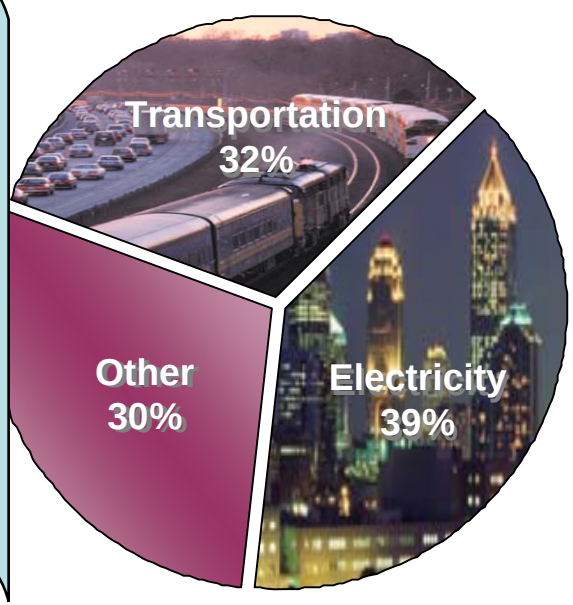
Ethanol Plants

Cement Production

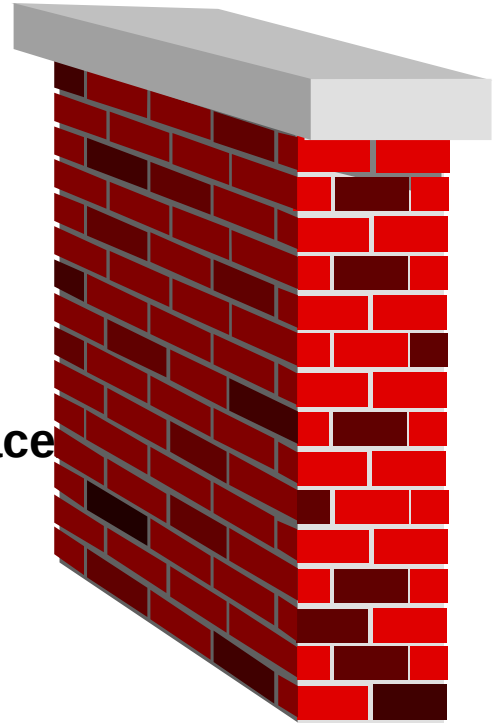
Refineries

Etc….

Emissions By Sector



Key Challenges to CCS

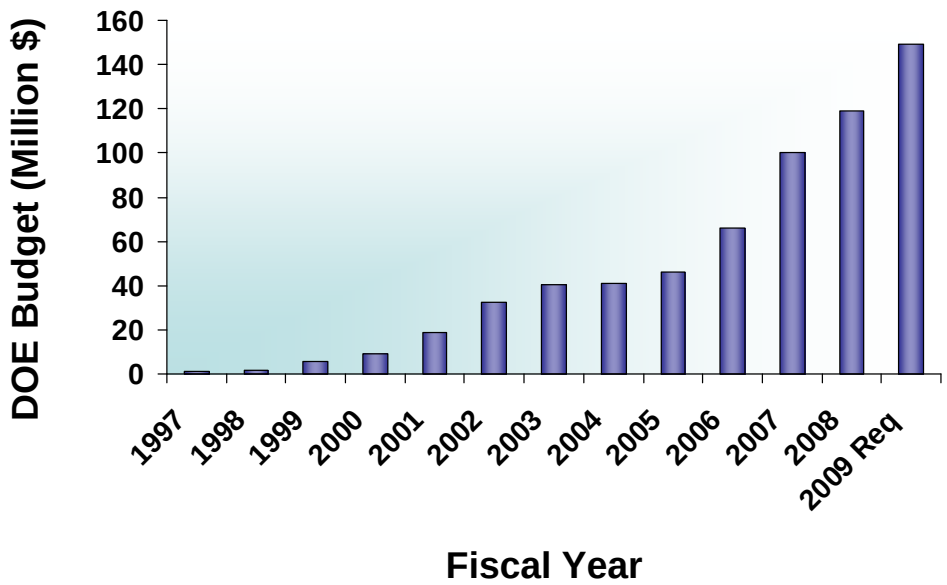


- Cost of CCS
- Sufficient Storage Capacity
- Permanence
- Best Practices
- Regulatory Framework
- Permitting
- Liability
- Ownership – pore space
- Infrastructure
- Public Acceptance
- Human Capital Resources

CCS Goals

- **Deliver technologies & best practices that validate Carbon Capture and Storage (CCS):**
  - 90% CO_2 capture
  - 99% storage permanence
  - < 10% increase in COE (pre-combustion capt
  - < 35% increase in COE (post- and oxy-combustion)
  - +/- 30% storage capacity

Sequestration Program Statistics FY2008

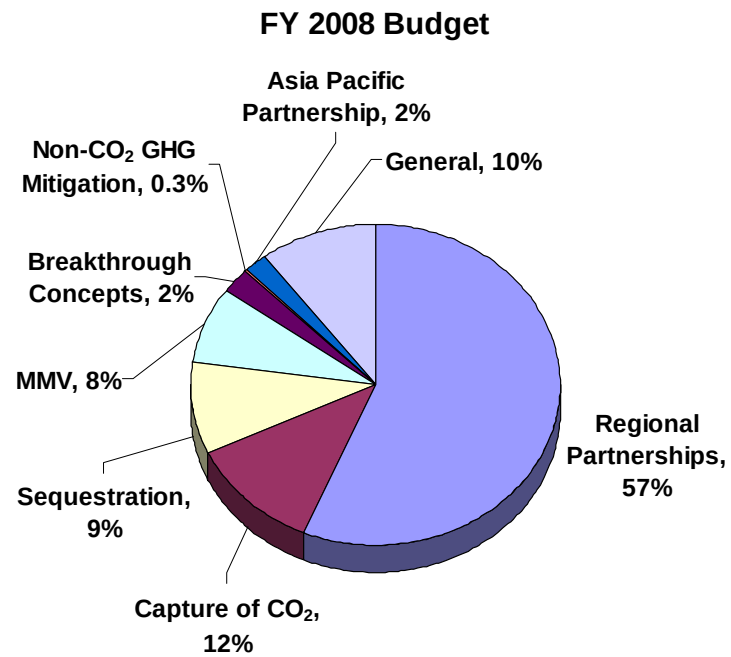


Strong industry support

~ 39% cost share on projects

Federal Investment to Date

~ $481 Million

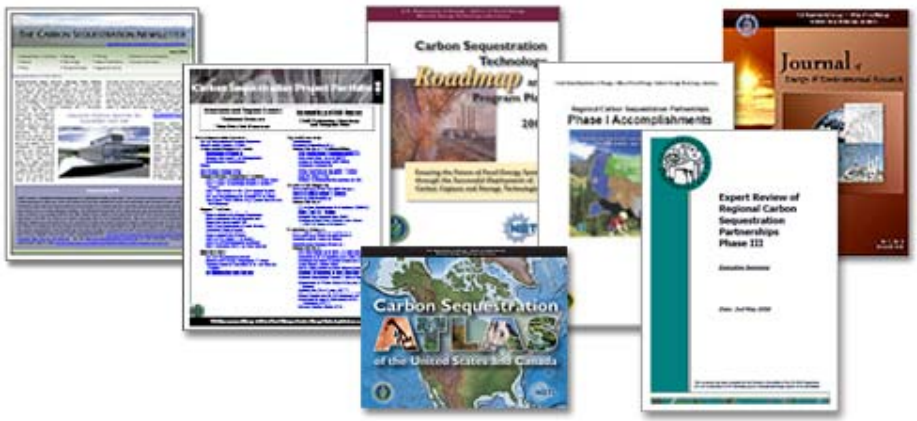


Diverse research portfolio

~ 70 Active R&D Projects

Program Highlights

- **IEA GHG International Review of the Regional Partnership large scale field tests – March 2008**
  - RCSP was recognized as most significant program in the world today



- APEX Awards recognizing publication excellence
  - **Carbon Sequestration Atlas of the United States and Canada**

The Challenge:

Sufficient Storage Capacity ?

The Direction:

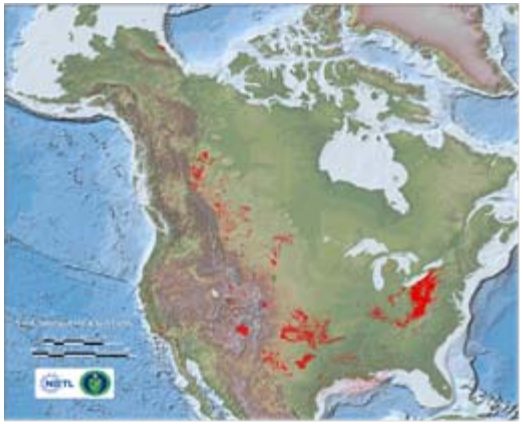
- **Validate Storage Capacity to +/- 30% Accuracy**
- **Validate Ability to Capture > 90% CO_2**

How Much CO_2 Are We Talking About?

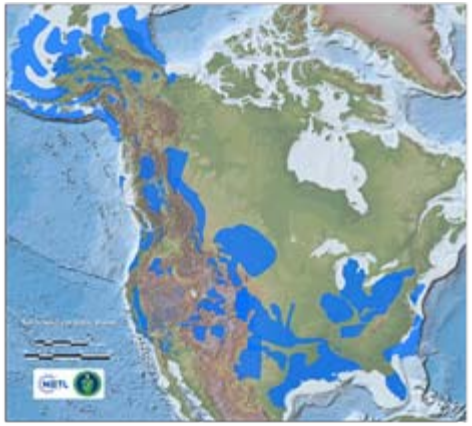
- **1 million metric tons of CO_2:**
  - Every year would fill a volume of 32 million cubic feet
  - *Close to the volume of the Empire State Building*
- **U.S. emits roughly 6 billion tons (gigatons) of CO_2 per year**
  - Under an EIA reference case scenario cumulative CO_2 emissions 2004-2100 are expected to be 1 trillion tons
  - *Enough to fill Lake Erie with liquid CO2 almost twice*

National Atlas Highlights

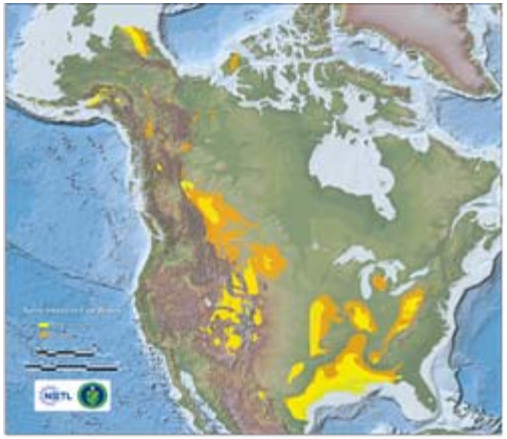
U.S. Emissions ~ 6 GT CO_2/yr all sources



Oil and Gas Fields



Saline Formations



Unmineable Coal Seams

North American CO_2 Storage Potential (Giga Tons)

Conservative Resource Assessment

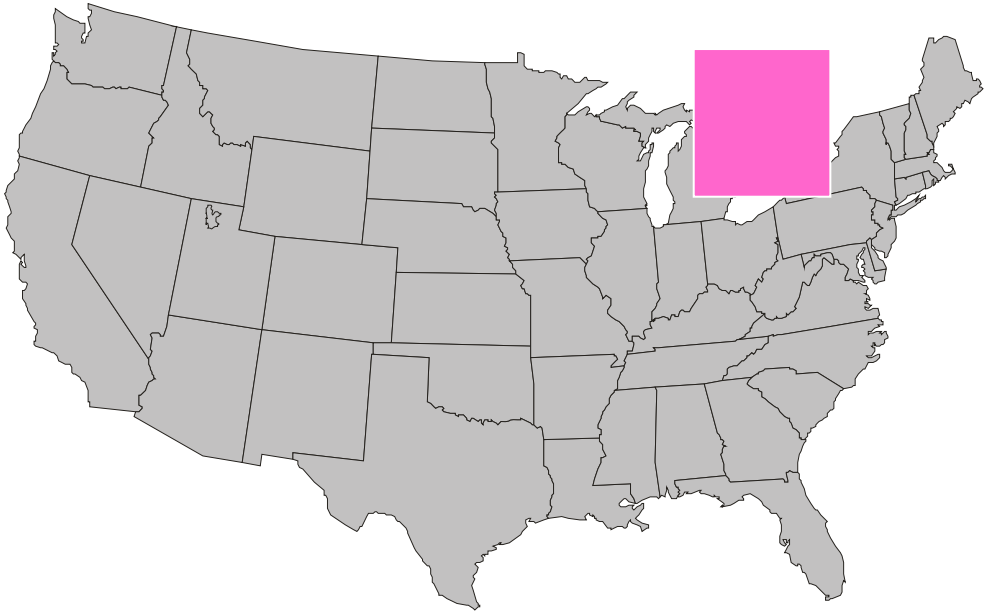
Sink Type	Low	High
Saline Formations	969	3,223
Unmineable Coal Seams	70	97
Oil and Gas Fields	82	83

Hundreds of Years of Storage Potential

Available for download at http://www.netl.doe.gov/publications/carbon_seq/refshelf.html

CO_2 Storage Very Large But Within the Capability of U.S. Geologic Storage Capacity

Stabilization Thru 2100



- **Would fill Lake Erie twice**

This is equal to:

- **5% of the land mass of the contiguous U.S.**

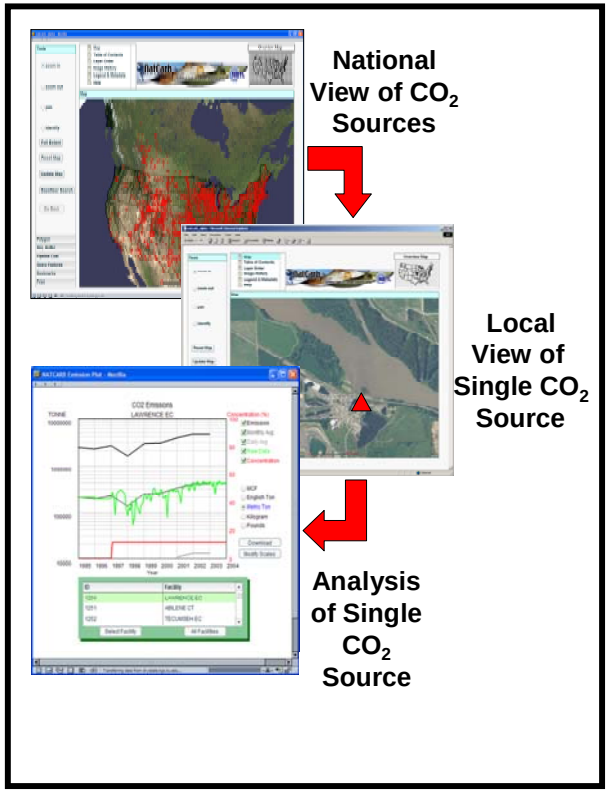
Assume CO2 capture and geosequestration represents 40% of the total GHG emissions reduction need in 2100 (up from 30% in 2050) 200 x 109 tons CO2 / 1.32 x106 tons CO2 / sq. mile = 150,000 square miles

Technology Must Show Ability for Significant Capture

- **To stabilize emissions, future emission reductions likely to be quite large**
- **Off the shelf capture technologies can already achieve greater than 90% capture of the CO_2 that it "sees"**
- **Emerging technologies must be at least that good**
- **90% capture capability does NOT imply 90% capture requirement !!!**

National Carbon Sequestration Database and Geographical Information System (NATCARB)

- **Relational database and geographic information system (GIS) that integrates carbon sequestration data from the RCSPs and various other sources**
- **Provides a National view of the carbon sequestration potential in the U.S. and Canada**
- **Decision Support Tools**
- **Outreach tool**
  - Web-site gets 600+ unique visitors every month from around the world



CO_2 Sources

www.natcarb.org

The Challenge:

Cost of CCS ?

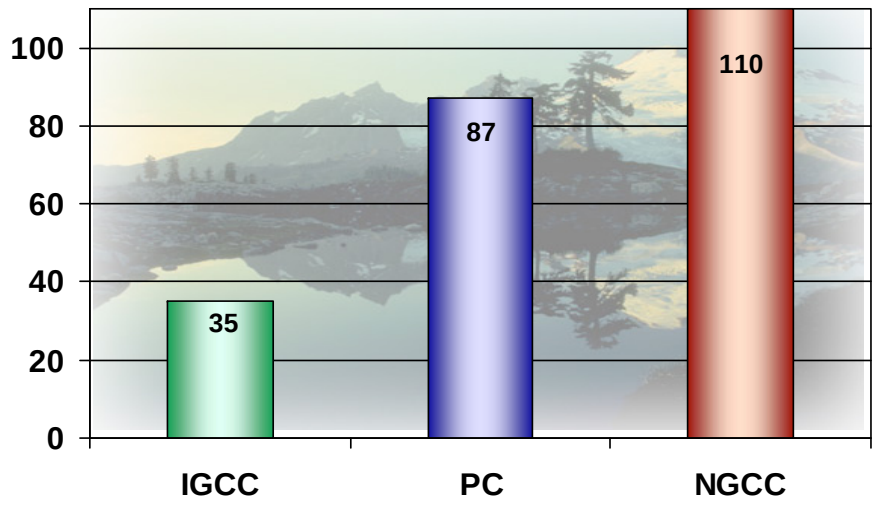
The Direction:

- < 10% increase in COE (pre-combustion capture)
- < 35% increase in COE (post- and oxy-combustion)

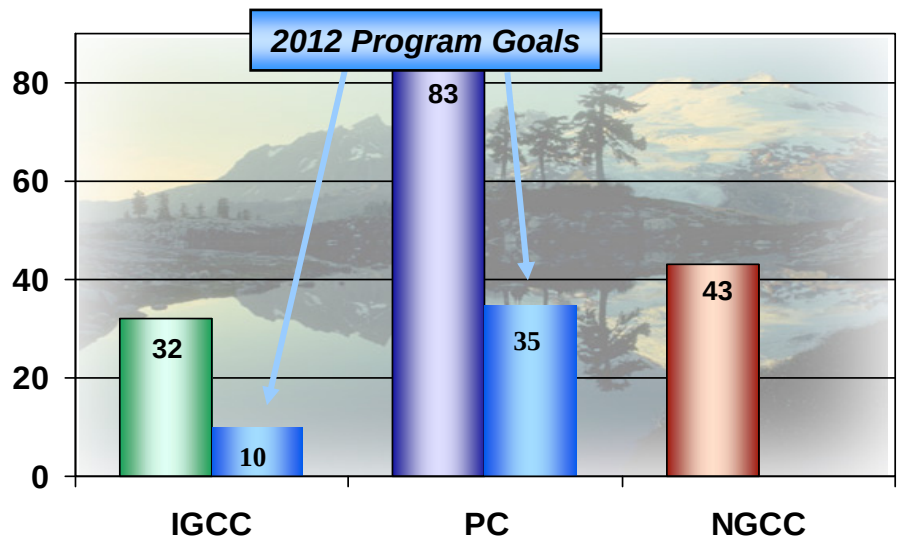
CCS Is Expensive !

- **5–30% parasitic energy loss**
- **35–110% increase in capital cost**
- **30–80% increase in cost of electricity**

Effect of CO_2 Capture on Capital Cost
(% Increase Resulting From CO_2 Capture)



Effect of CO_2 Capture on Cost of Electricity
(% Increase Resulting From CO_2 Capture)



Source: *Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity.*

Scale-Up Is An Issue

Laboratory Scale

- 0.1 ft^3 Reactor Volume
- 0.27 scf per minute

Technically Possible?

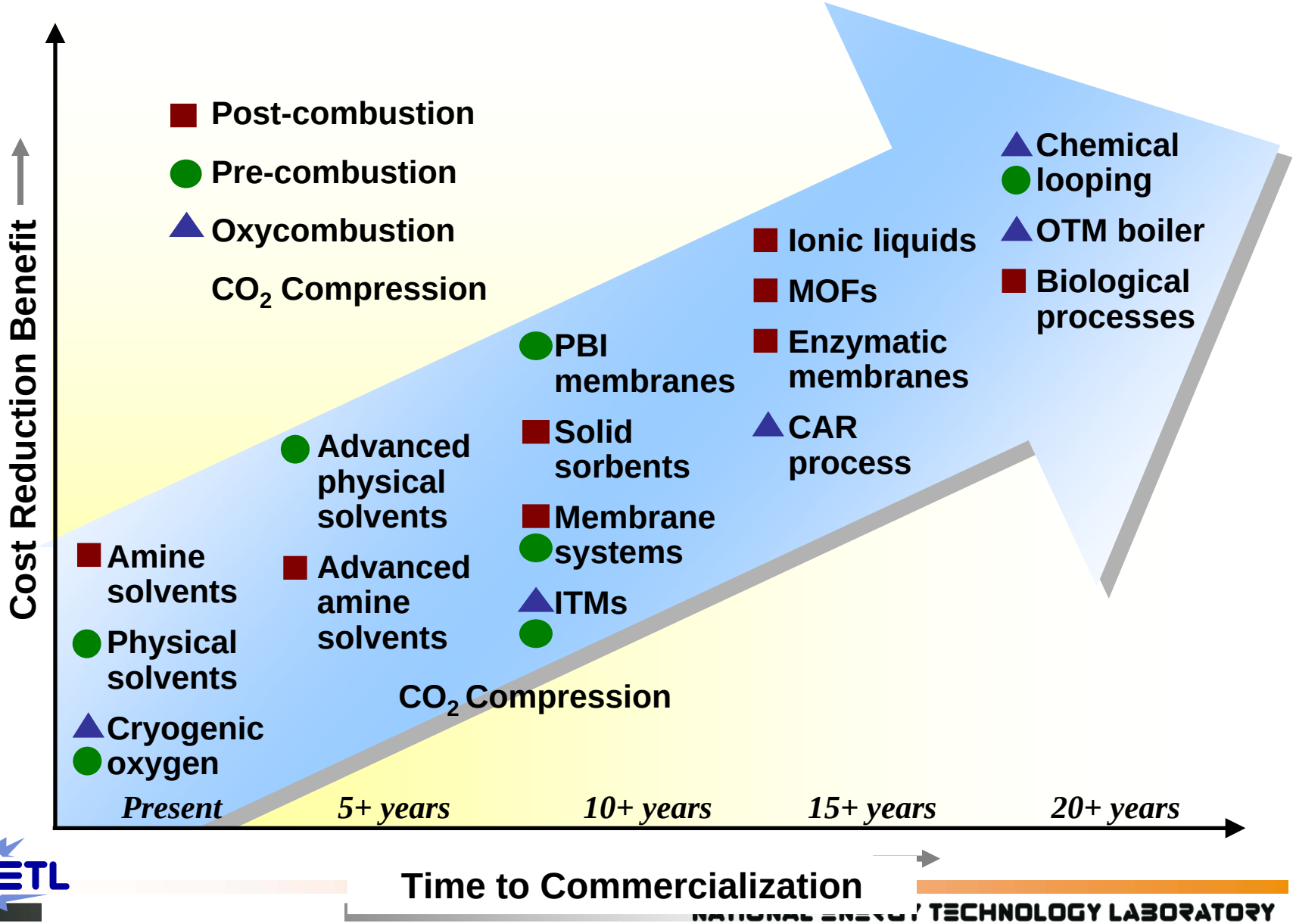
Scale-up

Economically Feasible?

500 MW Commercial Power Plant

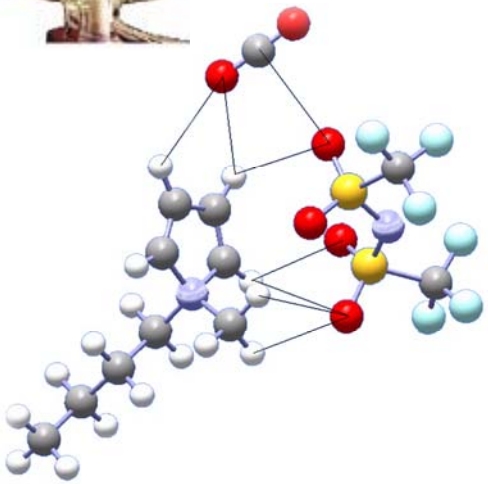
- 57,000 ft^3 Reactor Volume
- 1,800,000 scf per minute

Technology Advances Are Starting to Emerge



Example -- Ionic Liquids as Novel Absorbents

Are salts that are liquid at room temperature which have high absorption potential and never evaporate.



Accomplishments:

- Synthesized ILs have achieved the highest CO_2 solubility ever measured for an ionic liquid:
  - **over *40 times more soluble* than the "best" compound prior to the start of the project**
- Demonstrated[1] that *SO_2 is highly soluble in ILs*
  - **8 to 25 times more soluble than CO_2 at a different pressure range**
- NETL researchers prove that ILs can be used as the separating media in supported liquid membranes to separate CO_2 from H_2.

Participants: University of Notre Dame

The Challenge:

Permanence & Risk ?

The Direction:

- **Develop tools, protocols & best practices**
- **Verify 99% storage retention**

All Risks & Leakage Pathways Are Being Studied

- **Environmental Risks**
  - Increases atmospheric CO_2
  - Accumulation of CO_2 pockets on earth
  - Migration into other strata and contamination of fresh water
  - Leakage of CO_2 into a marine environment
  - Damage to nearby hydrocarbon resources
  - Displacement of underground fluids
  - Initiation of seismic activity

- **Health and Safety Risks**
  - Human and animal exposure can lead to asphyxiation
  - NIOSH defines CO_2 as a nontoxic, inert gas that displaces oxygen
  - Work hazard

- **Economic Risks**
  - Enhanced oil recovery is a commercially proven process
  - Additional research needed
  - Liability
  - Operational considerations

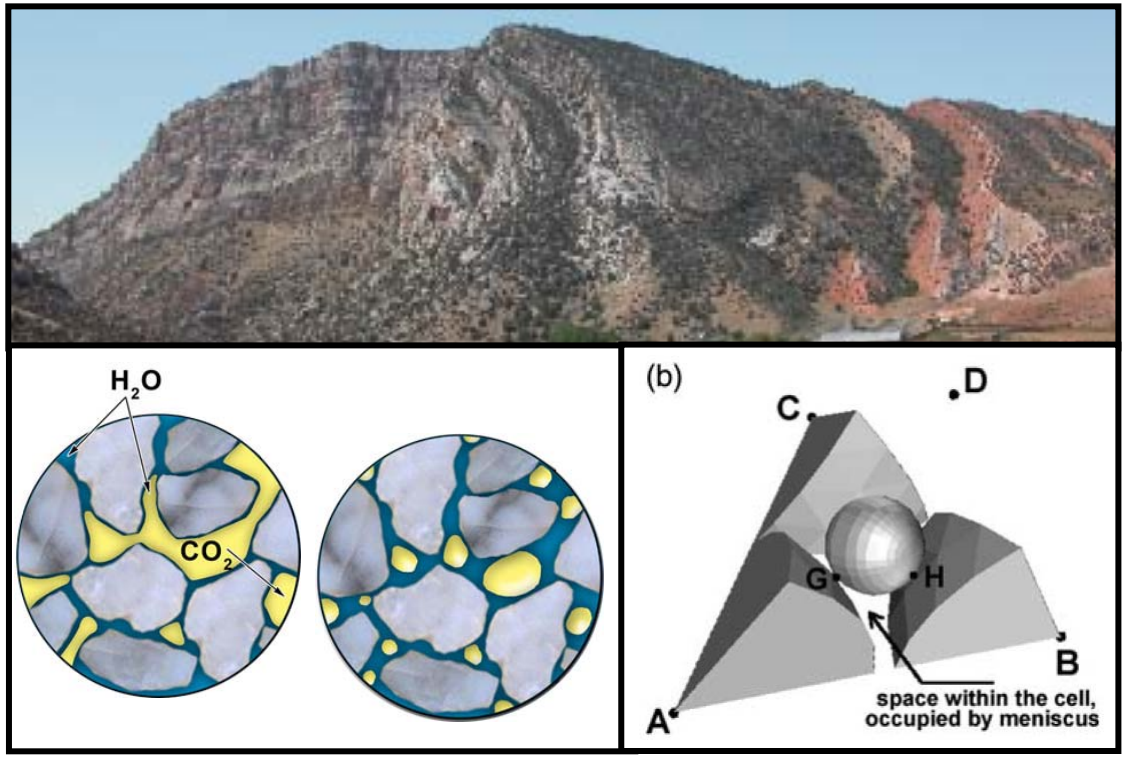
Once Injected, CO_2 is Difficult to Remove

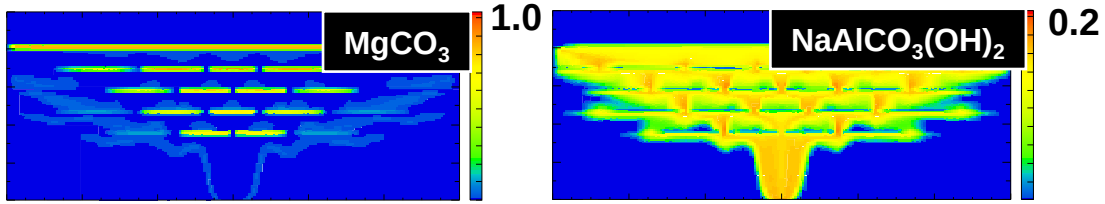
Physical trapping

Residual phase trapping

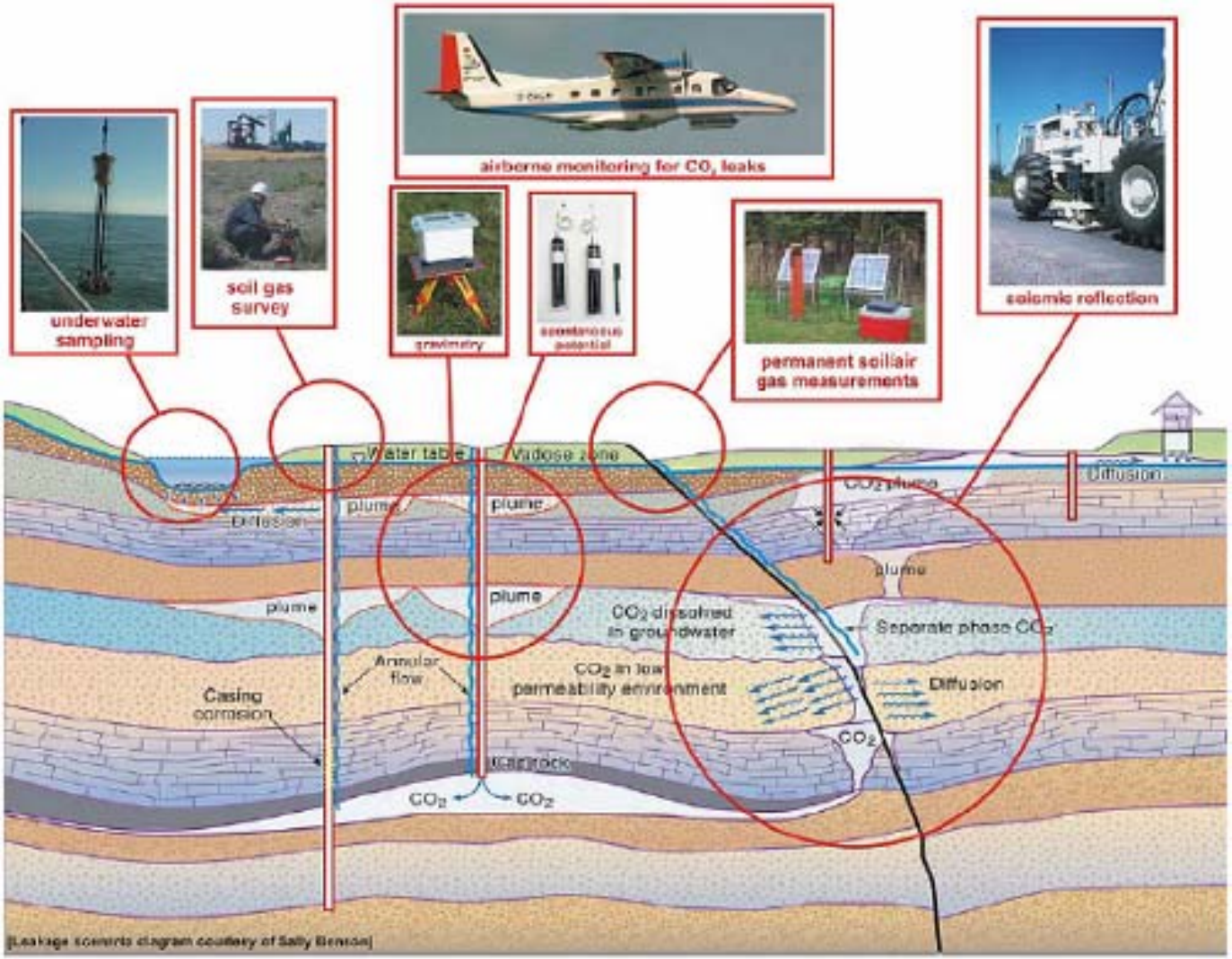
Solution/Mineral Trapping

Gas adsorption





Best Practice Technologies & Protocols Are Emerging



National Risk Assessment Program

National Goals/Needs

- Assurance of Permanence, Capacity, etc.
- Best Practice Manual
- Common Assessment Framework

Site Specific Goals/Needs

- prediction of site performance
- site-specific risk assessment
- strategic MMV
- field data
- GIS data

Risk assessment supports and is supported by other elements of the CCS program.

Regional Partnerships

→ risk assessment for field sites
→ strategic MMV
← field data
← GIS data

Base Programs

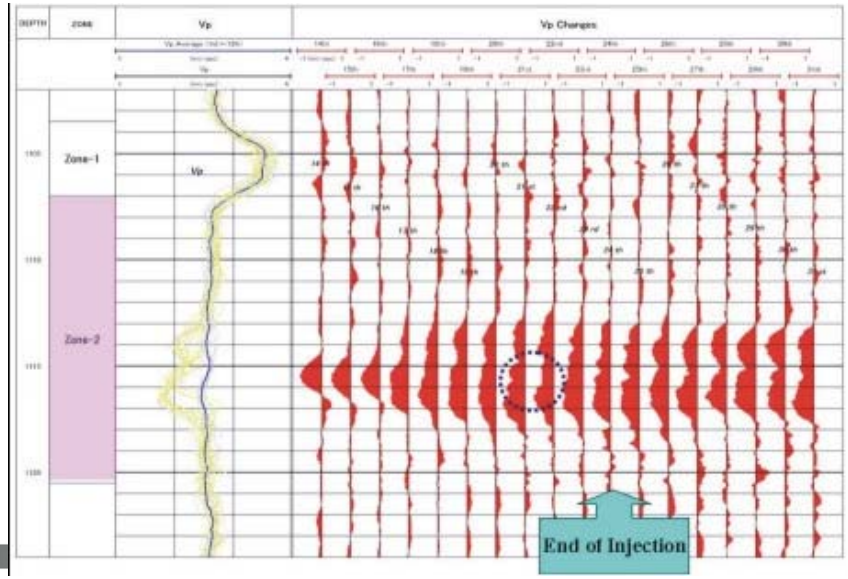
→ key remaining R&D needs
← computational tools
← experimental data
← MMV tools

Other Research Consortia

→ key remaining R&D needs
← computational tools
← experimental data
← MMV tools

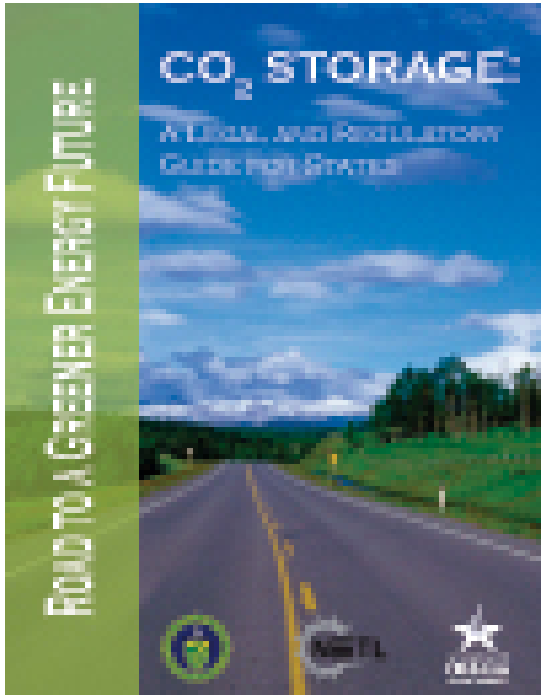
Japan CO_2 Injection Site … Following Earthquake

- **On 10/23/04, a 6.8 magnitude quake hit the Niigata Japan**
- **Epicenter was ~20 kms away from the Nagaoka CO_2 injection site**
- **Notably, there was no seismic activity observed during CO_2 injection before the earthquake.**
- **Absolutely no CO_2 leakage or well damage observed**



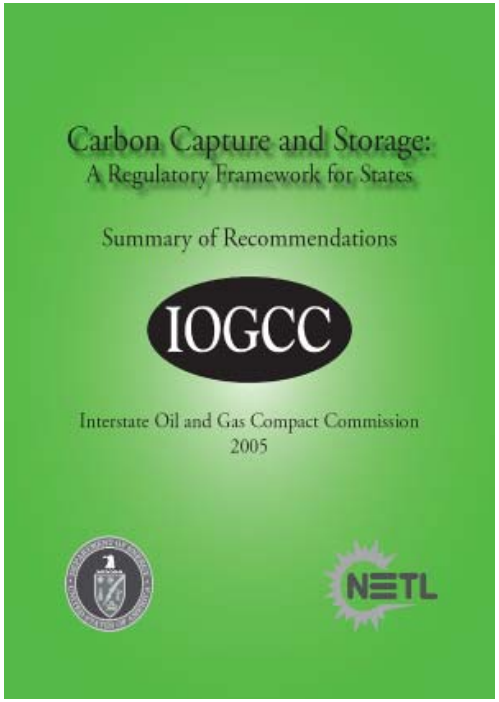
Regulatory

Regulatory Guidelines Emerging



CO2 Storage: A Legal and Regulatory Guide for States

- **EPA taking a lead role**
  - Guidance released Mar 2007
  - Draft rule summer 2008
- **EPA & DOE Working Group**
- **IOGCC Framework Released May 2005**
- **IOGCC Legal & Regulatory Framework Released in September 2007**



Carbon Capture and Storage
A Regulatory Framework for States

The Challenge:

Field Tests & Infrastructure ?

The Direction:

- **Put “first of kind” projects in place**
- **Develop protocols & best practices**
- **Regional Carbon Sequestration Partnerships**

Regional Carbon Sequestration Partnerships

Creating Infrastructure for Wide Scale Deployment

Characterization Phase

- **24 months (2003-2005)**

Validation Phase

- **4 years (2005 - 2009)**
- **Field validation tests**
  - 24 Geologic
  - 11 Terrestrial

Deployment Phase

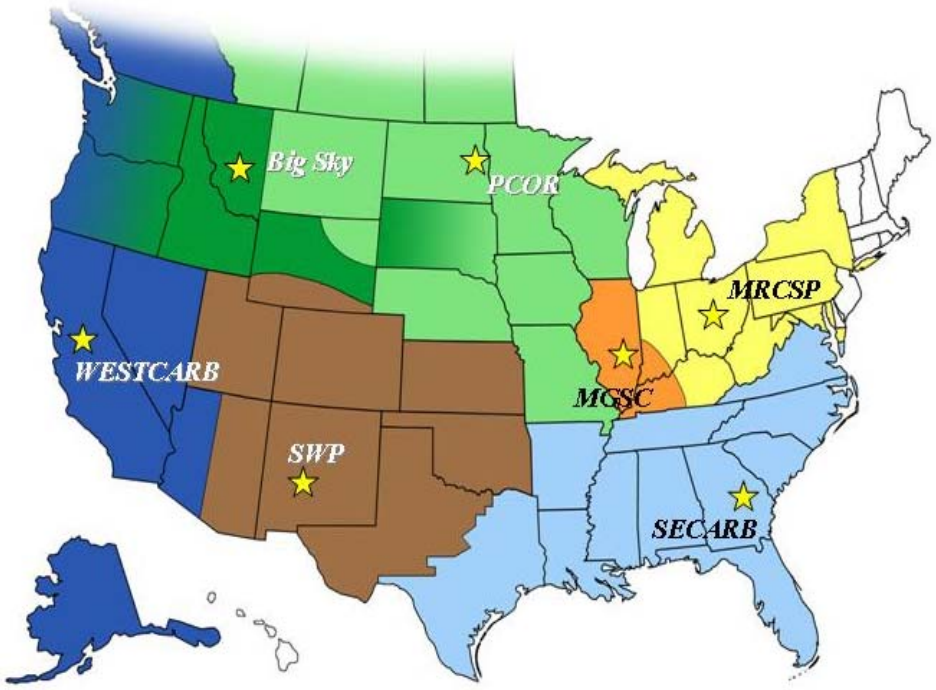
- **10 years (2007-2016)**
- **Up to 7 large volume injection tests**

Addressing:

- **Permitting**
- **Regulatory framework**
- **Public Acceptance**
- **Liability**
- **Best Practices**

Representing:

- **>350 Organizations**
- **42 States**
- **4 Canadian Provinces**
- **3 Indian Nations**
- **34% cost share**



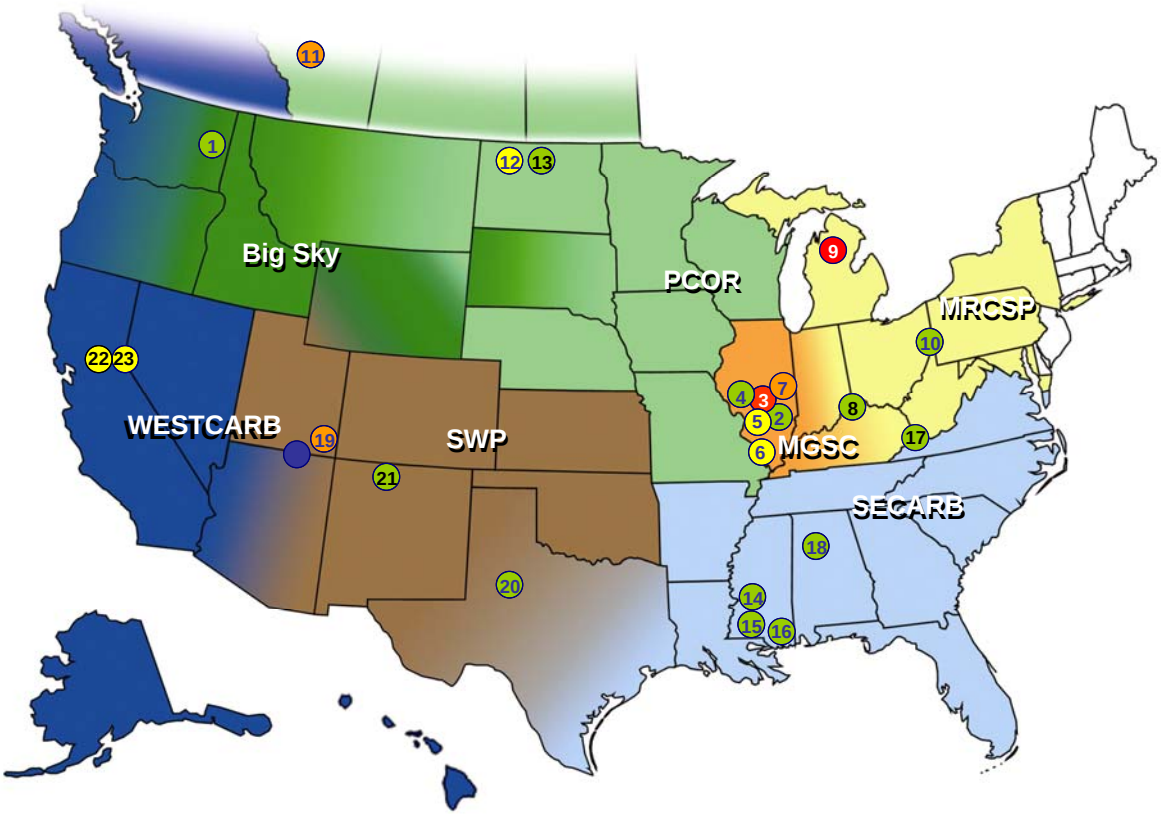
Growing Membership

160 organization in Phase I

> 350 organizations in Phases II and III

Organizations Involved	Number		Organizations Involved	Number
Chemical Companies	5		Land Management/Development Company	2
CO2 Trading Organizations	3		Law Firm	2
Coal Companies	8		Local Agencies	4
Electric Utilities	1		Media/Outreach	6
Electric Utilities	52		National Laboratories	10
Engineering and Research Firms	44		Oil & Gas Companies	36
Environmental NGOs	11		Other State Agencies	51
Foreign Government Agencies	10		Pipeline Company	1
Forest Products Companies	4		State Geologic Surveys	18
Governmental Advisory Groups	2		U.S. Federal Agencies	6
Indian Nations	4		University and Academic Institutions	47
Industry Trade Groups	22		**Total**	**349**

Validation Phase – Geologic Field Tests Injection Schedule

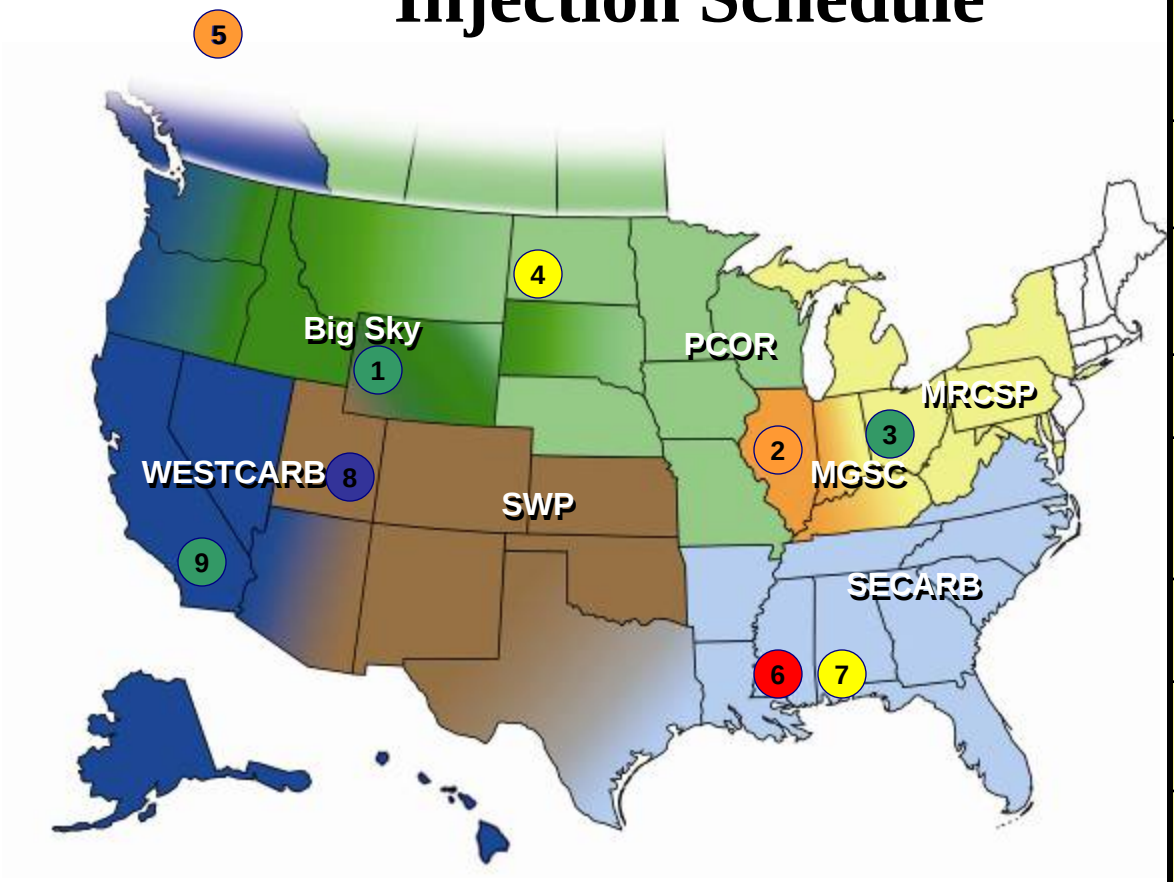


Injection Schedule

- Injection Complete
- Injection Ongoing
- 2008 Injection Scheduled
- 2009 Injection Scheduled

	Partnership	Geologic Province	Formation Type
1	BigSkyCarbon	Columbia Basin	Saline
2	MGSC	Illinois Basin	Saline
3		IllinoisBasin	Oil Bearing Heavy
4		Illinois Basin	Oil Bearing Well Conversion
5		Illinois Basin	Oil Bearing Pattern Flood I
6		Illinois Basin	Oil Bearing Pattern Flood II
7		Illinois Basin	Coal Seam
8	MRCSP	Cincinnati Arch	Saline
9		Michigan Basin	Saline
10		Appalachian Basin	Saline
11	PCOR	Keg River Formation	Oil Bearing
12		Duperow Formation	Oil Bearing
13		Williston Basin	Coal Seam
14	SECARB	Gulf Coast (stacked test)	Oil-Bearing
15		Gulf Coast	Saline
16		Mississippi Salt Basin	Saline
17		Central Appalachian	Coal Seam
18		Black Warrior Basin	Coal Seam
19	SWP	Paradox Basin, Aneth Field	Oil Bearing
20		Permian Basin	Oil Bearing
21		San Juan Basin	Coal Seam
22	WESTCARB	Thornton Gas Field (stacked test)	Saline
23		Thornton Gas Field	Gas Bearing
24		Colorado Plateau	Saline

Large Scale Field Tests Injection Schedule



Injection Schedule

- 2008 Injection Scheduled
- 2009 Injection Scheduled
- 2010 Injection Scheduled
- 2011 Injection Scheduled

	Partnership	Geologic Province	Formation Type
1	BigSkyCarbon	Triassic Nugget Sandstone/ Moxa Arch	Saline
2	MGSC	Mt. Simon Sandstone	Saline
3	MRCSP	Mt. Simon Sandstone	Saline
4	The Plains CO2 Reduction Partnership PCOR	Williston Basin	Saline/Oil Bearing
5		Devonian Age Carbonate Rock	Oil Bearing
6	Southeast Regional Carbon Sequestration Partnership	Lower Tuscaloosa Formation Massive Sand Unit	Saline
7			
8	SWP	Regional Jurassic and Older Formations	Saline
9	westcarb.org	San Joaquin Basin	Saline

MMV Tools being Applied

■ Near Surface/Surface ● Sub-surface

Technology Impact and Resolution

Low Cost High Res.

- ● VSP
- ■ Remote Sensing
- ● Passive seismic monitoring
- ● Aqueous geochemistry
- ● Wireline logging
- ● Pressure monitoring

High Cost High Res.

- ● ■ High-res 2D reflection
- ■ Soil and vadose zone gas monitoring
- ● ■ Modeling/Simulation
- ● 3D Seismic survey

Low Cost Low Res.

- ■ Time-lapse gravity survey
- ■ Vegetative stress
- ■ Groundwater monitoring
- ● Magnetotelluric sounding
- ● Gravity Survey

High Cost Low Res.

- ■ Eddy covariance
- ■ Flux accumulation
- ■ Hyperspectral Remote Sensing
- ● Cross-well survey

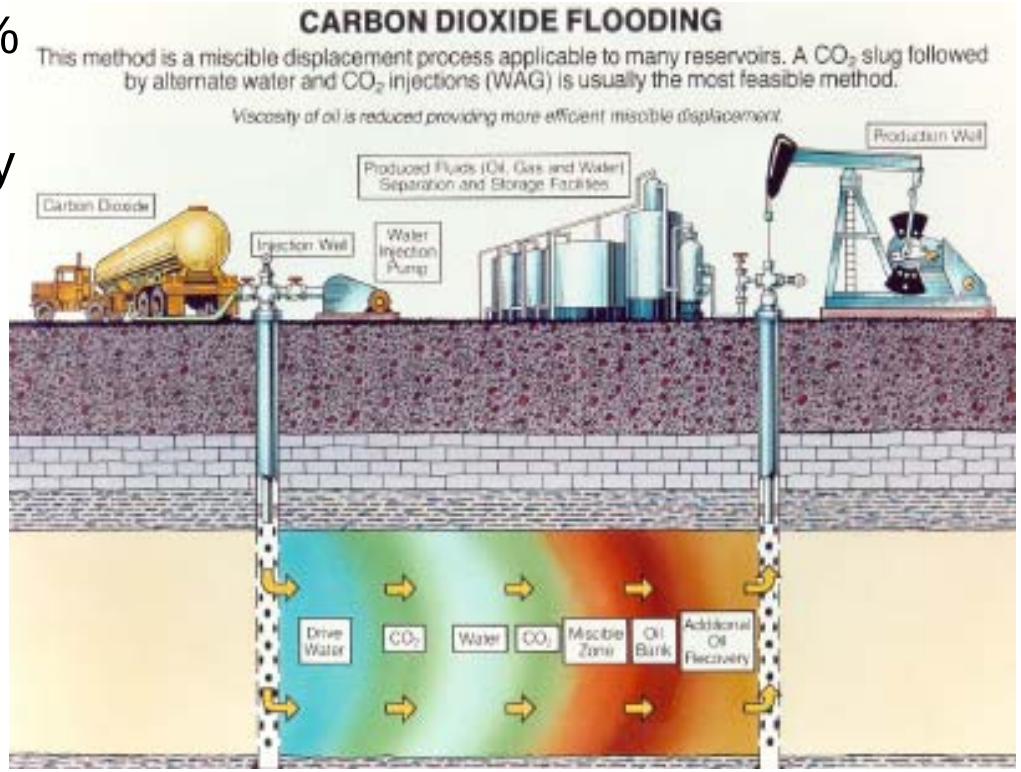
Overall Cost

Value Added Options

EOR
ECBM
Carbon Recycling

Enhanced Oil Recovery – Beneficial Use of CO_2

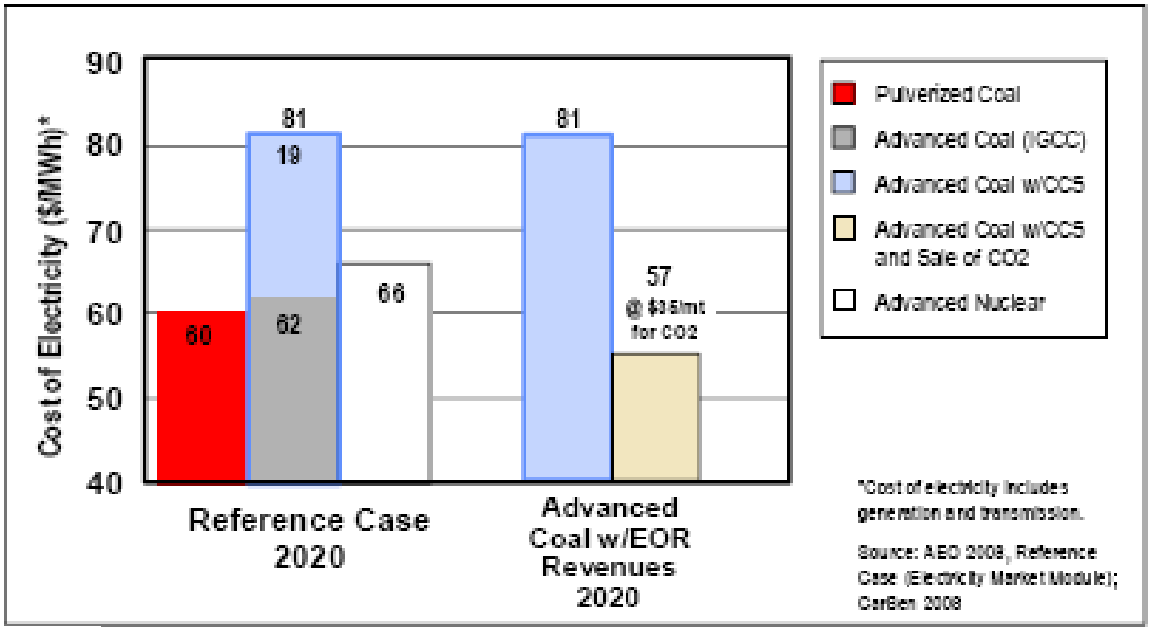
- **EOR increasing its role in domestic oil production**
  - EOR 650,000 bbls/day - 13% of domestic production
  - CO_2-EOR - 237,000 bbls/day and growing
  - 90 billion barrels of light oil can yet be recovered in the U.S. using EOR
- **Reduces cost of CCS**
- **Lowers carbon footprint of transportation sector**
  - Oil produced with "next generation" CO_2-EOR may be <u>well-better than carbon neutral</u>
- **Increases energy security**



Electric Power and CO_2 - Enhanced EOR

Working more efficiently with carbon

- **Electric power from coal – competitive in a carbon-constrained world**
- **CO_2 – enhanced EOR can lead to "green oil"**
- **Finding synergy in satisfying Power and Transportation Sector energy needs**



	"State of the Art"	"Next Generation"
	(millions)	(millions)
CO_2 Storage (tonnes)	19	109
Storage Capacity Utilization	13%	76%
Oil Recovery (barrels)	64	180
% Carbon Neutral ("Green Oil")	80%	160%

Storing CO2 with Enhanced Oil Recovery – NETL and Vello A. Kuuskraa
DOE/NETL-402/1312/02-07-08 February, 2008

Algae-based Carbon Capture

What is it?

- **Process to capture fossil fuel derived CO_2 with controlled biomass growth**
- **Carbon Recycling (capture and reuse) – Not Sequestration**
  - Does <u>not permanently remove</u> CO_2 from the air
  - Can re-use power plant CO_2 (burn it twice)
- **Makes useful by-products (bio-fuels)**
  - Potential to produce specific fuels and chemicals
  - Increased energy security – displaces petroleum with domestic resource
- **Can reduce carbon footprint of fossil power plants**

NETL Researchers using Soxhlet extraction method to recover oil from microalgae

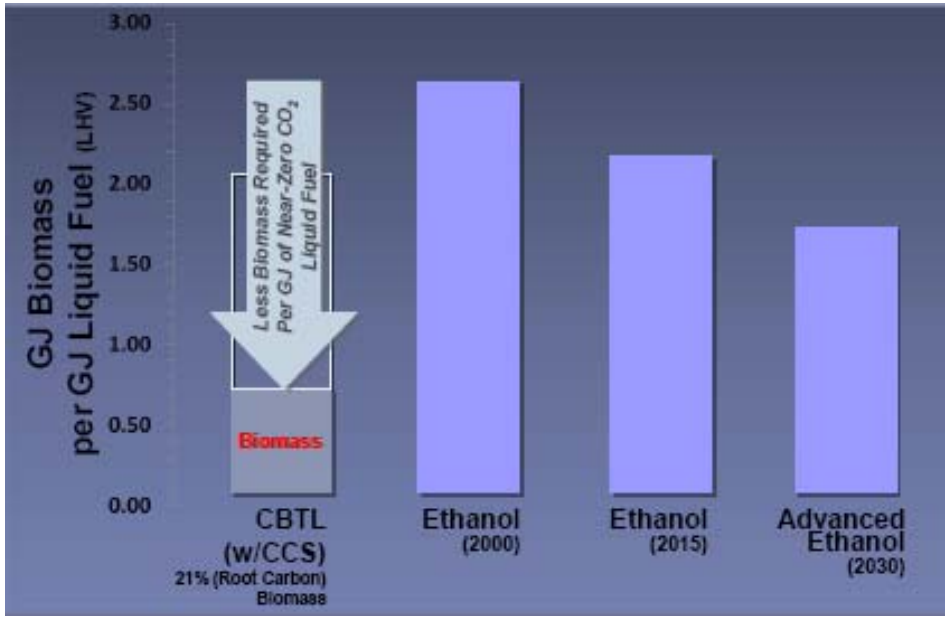
Algae-based Carbon Capture

What are its potential benefits?

- **Algae may offer similar benefits to Coal/Biomass-to-Liquids (CBTL) strategies**
- **Lowers carbon footprint of transportation sector**
  - Micro-algae is a renewable fuel source
  - Algae-derived oil may be co-processed with petroleum in traditional refining operations (good blend-stock)
- **Increases domestic energy security**
  - Algae-oil can reduce oil imports by displacing petroleum-derived fuels
- **Opportunity to sequester CO_2**
  - Oxy-fired or gasification systems with CCS of algae residual biomass (~50% of CO_2 recycled for algae growth reports to algae body)
  - Reduced energy intensity of power/fuels co-production facility

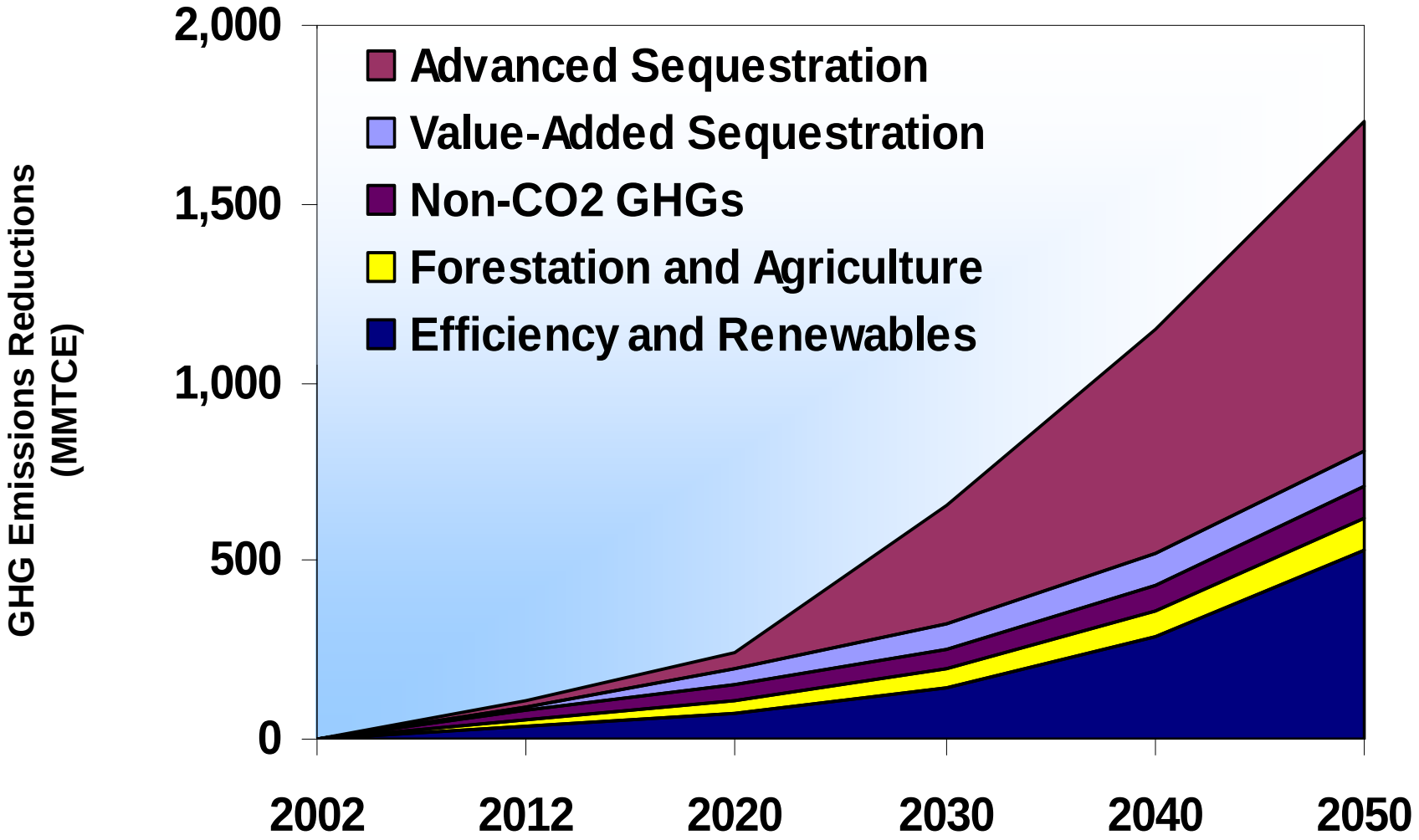
CBTL systems require significantly less energy input to achieve same energy output

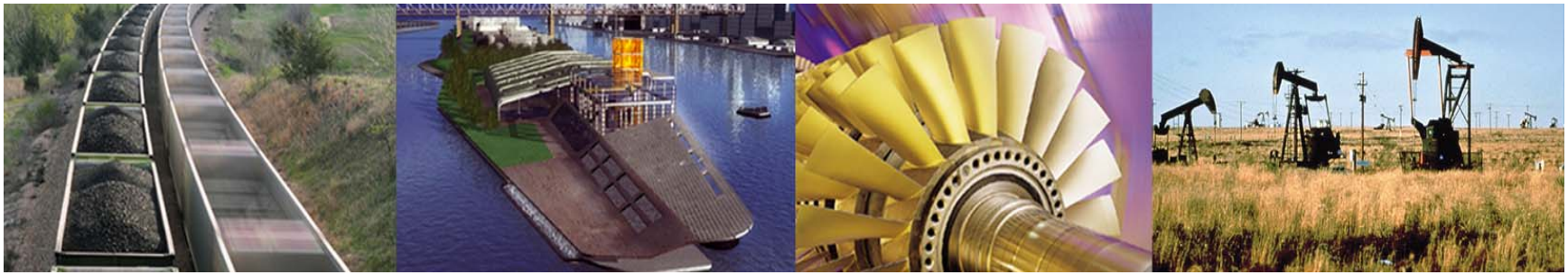
Producing near carbon neutral fuels



Attaining Energy Security in Liquid Fuels Through Diverse U.S. Energy Alternatives – DOE/NETL-2007/1278 August, 2007

Value Added Approaches Critical to Transition to Extreme Reductions



EIA Annual Energy Outlook 2002; EPA special studies; DOE/FE/NETL Sequestration Benefits Model

Questions ?