NATIONAL ENERGY TECHNOLOGY LABORATORY

Emerging Fossil Energy Technologies

Fossil Energy Coal R&D Program

A History of Innovative Solutions

1970's | *1980's* | *1990's* | *2000's*

Clean Air Act → *Oil Embargo* → *Acid Rain* → *Utility Deregulation* → *Climate Change*

Office of Fossil Energy

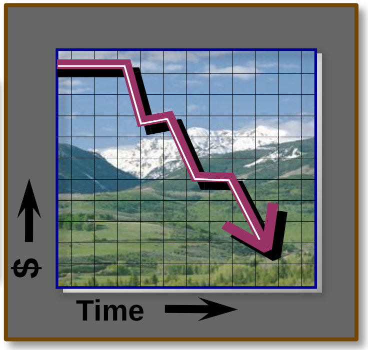
Notable Program Successes

Advanced Pollution Controls

- Installed on 75% of U.S. coal plants
- 1/2 to 1/10 cost of older systems

HAPS & Hg Data

- Quantified HAPS Levels
- Basis for Hg Regulations



FGD Scrubbers

Low-NO_x Burners

Advanced Coal Power Systems

- World's largest CFBC power plant
- Two "super-clean" coal-based IGCCs

JEA CFBC

Tampa IGCC

Wabash IGCC

Return On Investment from Coal R&D

FE RESEARCH — THE RETURN ON INVESTMENT

$111 Billion in Benefits (2000-2020) **$13 return for every $1 invested**	**1.2 million jobs created (2000-2020)** **Thousands of Trained Engineers and Scientists**	**25 Million Tons of Avoided NOx Emissions**	**2 Million Tons of Avoided SO_2 Emissions**	**850 Patents** **Fossil Energy Patents (1978-2010)**	**$1.3 Trillion** **Estimated Health Benefits From Reduced Pollution**

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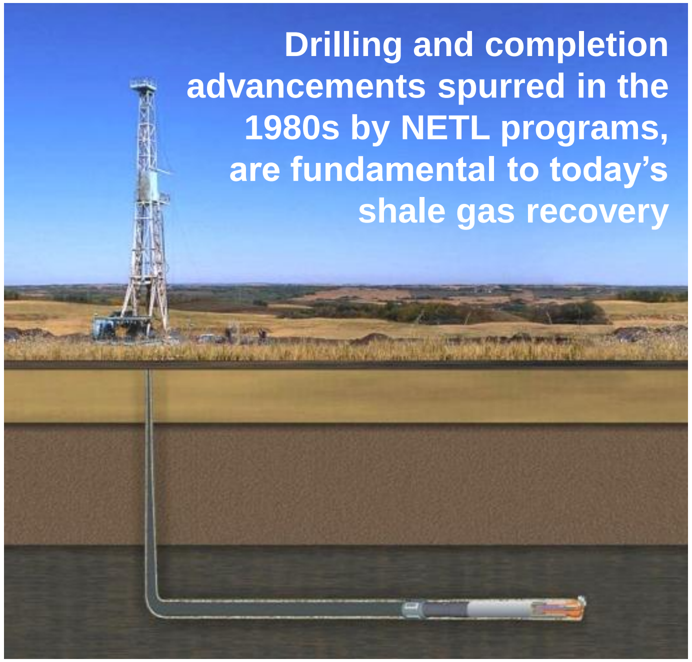
Sources : http://www.americancoalcouncil.org/associations/10586/files/Benefits_of_Investment_in_Clean_Coal_Technology_Bezdek_MSI.pdf, http://kammen.berkeley.edu//margoliskammenEpolicy.pdf, NAS report, Energy Research at DOE, Was it Worth It, pg 180-181, http://da2ec.info/doepatents/index.jsp, http://www.fe.doe.gov/aboutus/FE_ResearchProgram_Brochure_012309.pdf

Tapping Unconventional Natural Gas

- **Shale gas contributes 14% of today's domestic natural gas supply; could supply 45% by 2035**
  - Employed resource characterization and technology development to match technology to geology to chart a path for resource development
  - NETL programs developed technologies that increased per-well gas-recovery efficiencies, reduced unit development costs, and protect public health and environment.



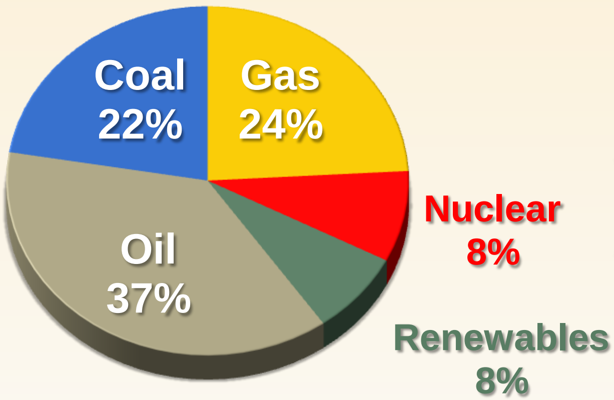
- **Coalbed methane recovery rose from <100 Bcf in 1989 to ~2 Tcf in 2009**
  - Today, coalbed methane accounts for ~8% of U.S. natural gas produced and increases safety by reducing methane concentrations ahead of mining operations

Early Involvement of Public Research Proves Beneficial

The Future of Natural Gas: An Interdisciplinary MIT Study (Interim Report), MIT Energy Initiative, 2010
Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000, National Research Council , 2001

Energy Demand 2008

100 QBtu / Year
84% Fossil Energy



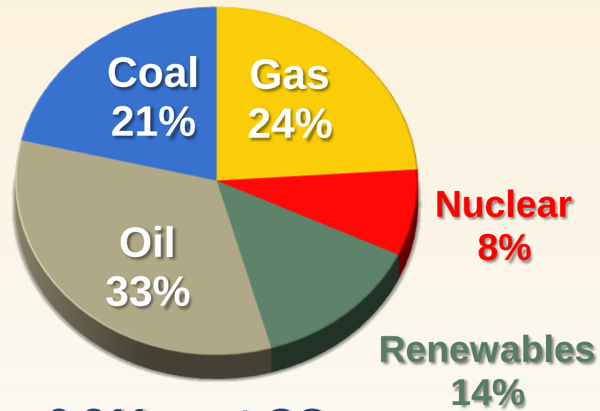
5,838 mmt CO_2

+ 14%

United States

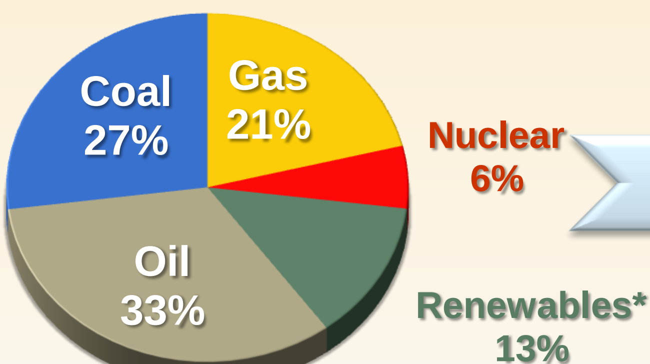
Energy Demand 2035

114 QBtu / Year
78% Fossil Energy



6,311 mmt CO_2

487 QBtu / Year
81% Fossil Energy

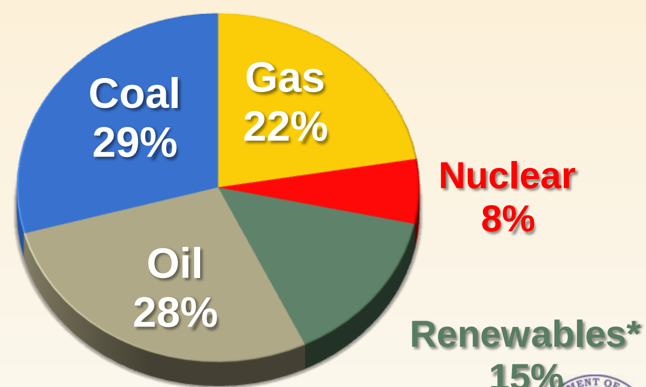


29,259 mmt CO_2

+ 47%

World

716 QBtu / Year
79% Fossil Energy



42,589 mmt CO_2

NETL

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Sources: U.S. data from EIA, Annual Energy Outlook 2011; World data from IEA, World Energy Outlook 2010, Current Policies Scenario

* Primarily traditional biomass, wood, and waste.

Pathways to CO_2 Emission Reduction

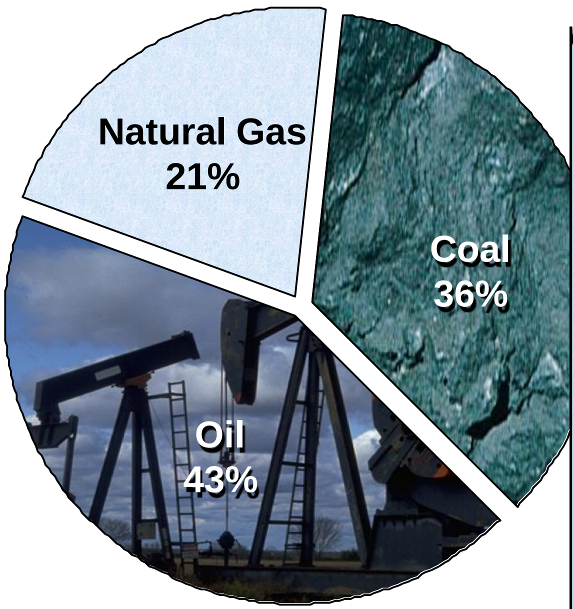
- **Energy efficiency (14 $GtCO_2e/yr$)[1]**
  - Vehicles, Buildings, industrial equipment
- **Low-carbon energy supply (12 $GtCO_2e/yr$)**
  - Wind, Nuclear, Solar Energy
  - Biofuels for transportation
  - Fossil fuels with Carbon Capture and Storage
- **Terrestrial carbon (12 $GtCO_2e/yr$)**
  - Reforesting, halting deforestation
  - CO2 sequestration in soils through changing agricultural practices
- **Behavioral change (~4 $GtCO_2e/yr$)**

1. CO_2 Reduction opportunities by 2030 from Pathways to a Low-Carbon Economy, McKinsey & Company, 2009.

It’s Not Just About Coal !!!

United States CO_2 Emissions

Emissions By Fuel Type



Natural Gas Power Plants

Natural Gas Processing

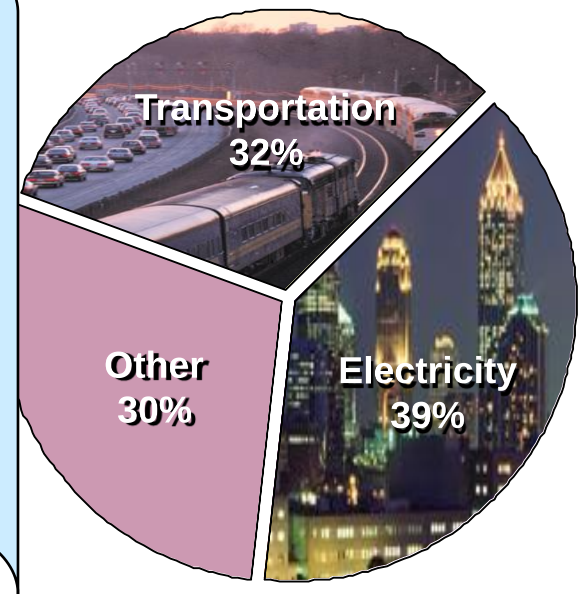
Ethanol Plants

Cement Production

Refineries

Etc.…

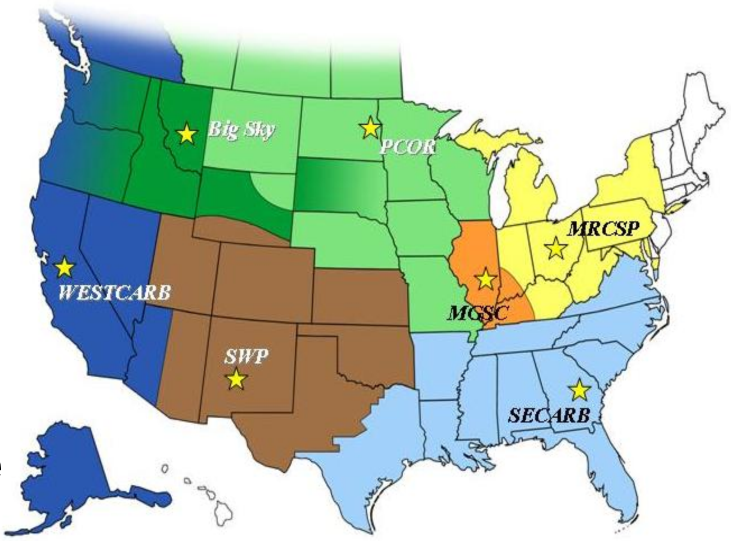
Emissions By Sector



Mission & Challenges

Develop Technologies and Best Practices That Facilitates Wide Scale Deployment of Coal Based Energy Systems Integrated With Carbon Capture and Storage

- **Develop and optimize plant designs & components**
- **Reduce capture costs**
- **Validate storage capacity**
- **Validate storage permanence**
- **Create private/public partnerships**
- **Promote infrastructure development**
- **Put "first of kind" field projects in place**
- **Develop tools, protocols & best practices**



DOE Regional Carbon Sequestration Partnerships

The Challenge:

Sufficient Storage ?

Is Storage Where We Need It ?

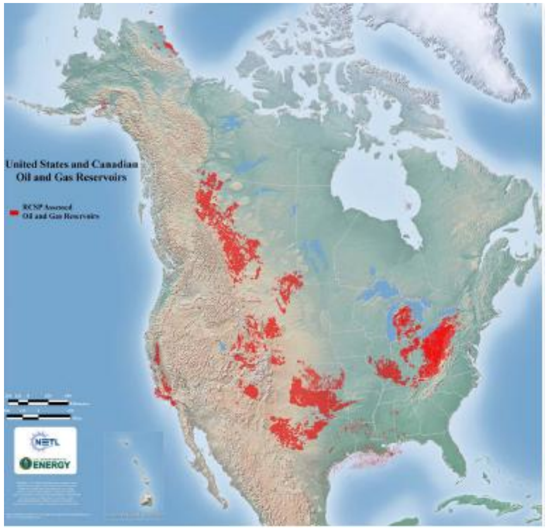
The Direction:

- Validate Storage Capacity to +/- 30% Accuracy
- Develop GIS Systems for Source/Sink Matching

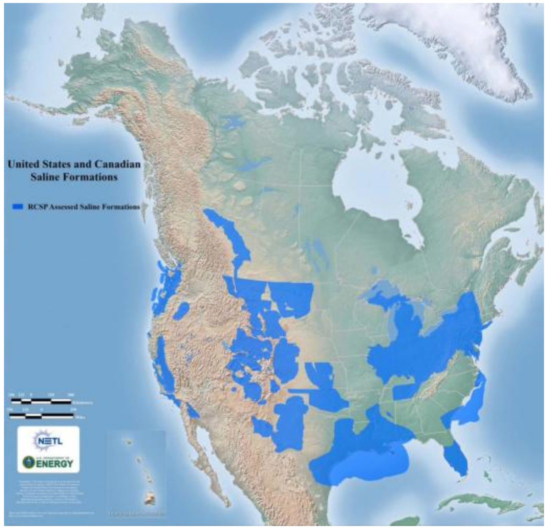
Sufficient Storage Capacity Emerging

National Atlas Highlights - 2010

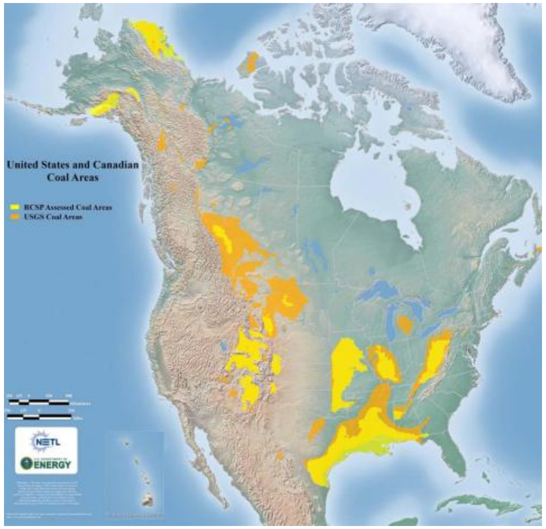
U.S. Emissions: ~3.5 GT CO_2/yr from large stationary sources



Oil and Gas Fields



Saline Formations



Unmineable Coal Seams

Conservative Resource Assessment

North American CO_2 Storage Potential (GT)

Sink Type	Low	High
Saline Formations	1650	20,000
Unmineable Coal Seams	60	117
Oil and Gas Fields	143	143

Hundreds to Thousands of Years Storage Potential

Office of Fossil Energy

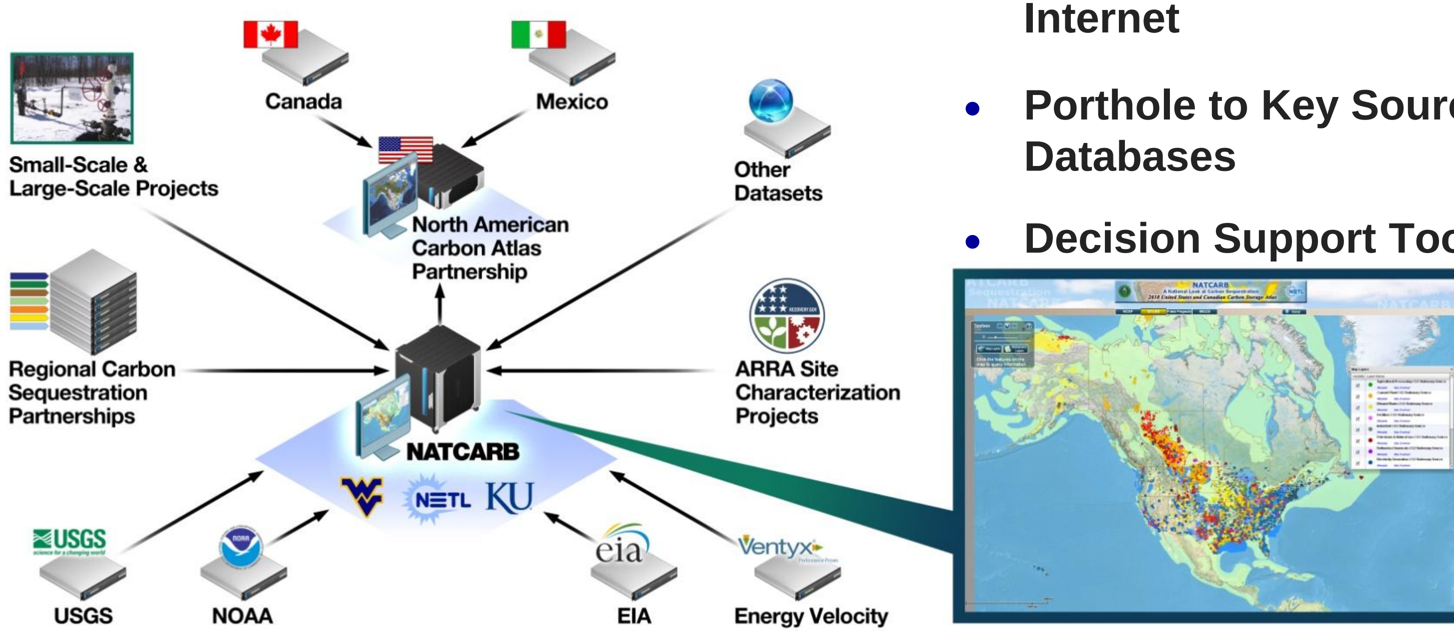
Download at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasII/atlasII.pdf

GIS Database – Sources & Sinks

United States & Canada

National Carbon Sequestration Database and Geographical Information System (NATCARB)

- Available "Free-Of-Charge" on Internet
- Porthole to Key Source & Sink Databases
- Decision Support Tools



www.natcarb.org

– Web-site gets 600+ unique visitors every month from around the world

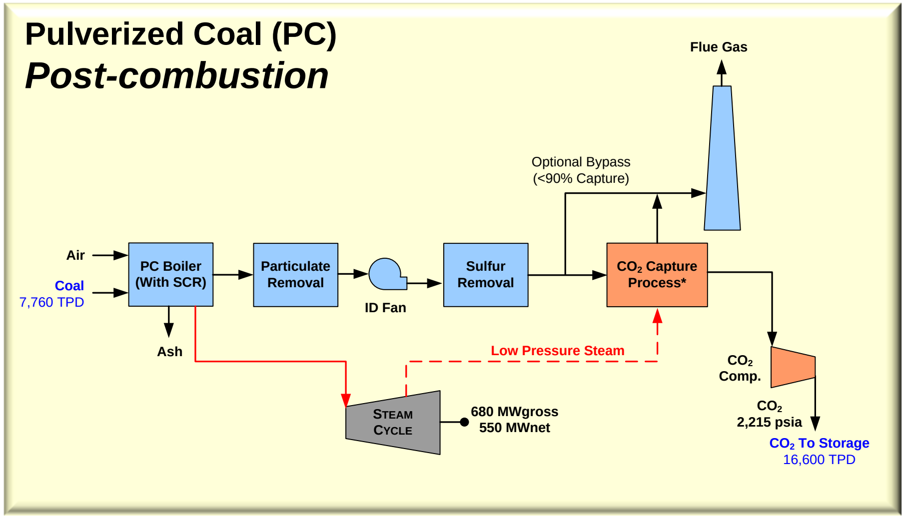
The Challenge:

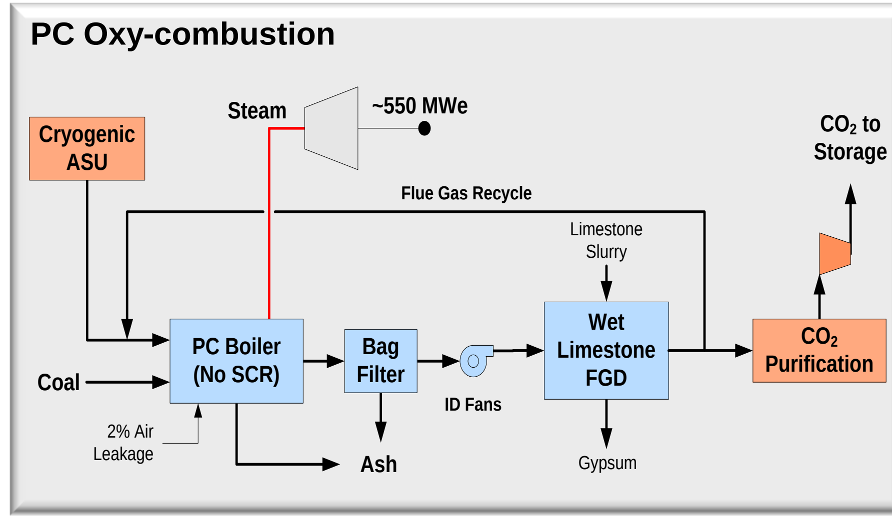
Cost of Carbon Capture ?

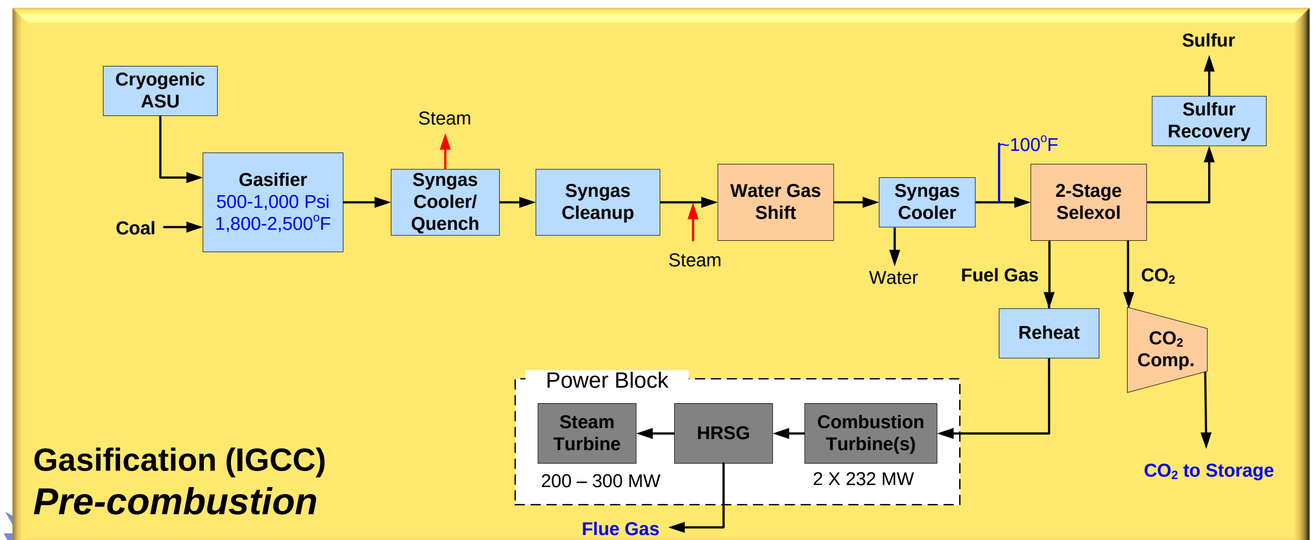
The Direction:

- < 10% increase in COE (pre-combustion capture)
- < 35% increase in COE (post- and oxy-combustion)
- Validate ability to capture at least 90% CO_2

CO_2 Capture Applications







Technologies also applicable to:

- Industrial sources (cement, refinery, chemical…)
- NGCC power plants

CO_2 Capture Deployment Barriers

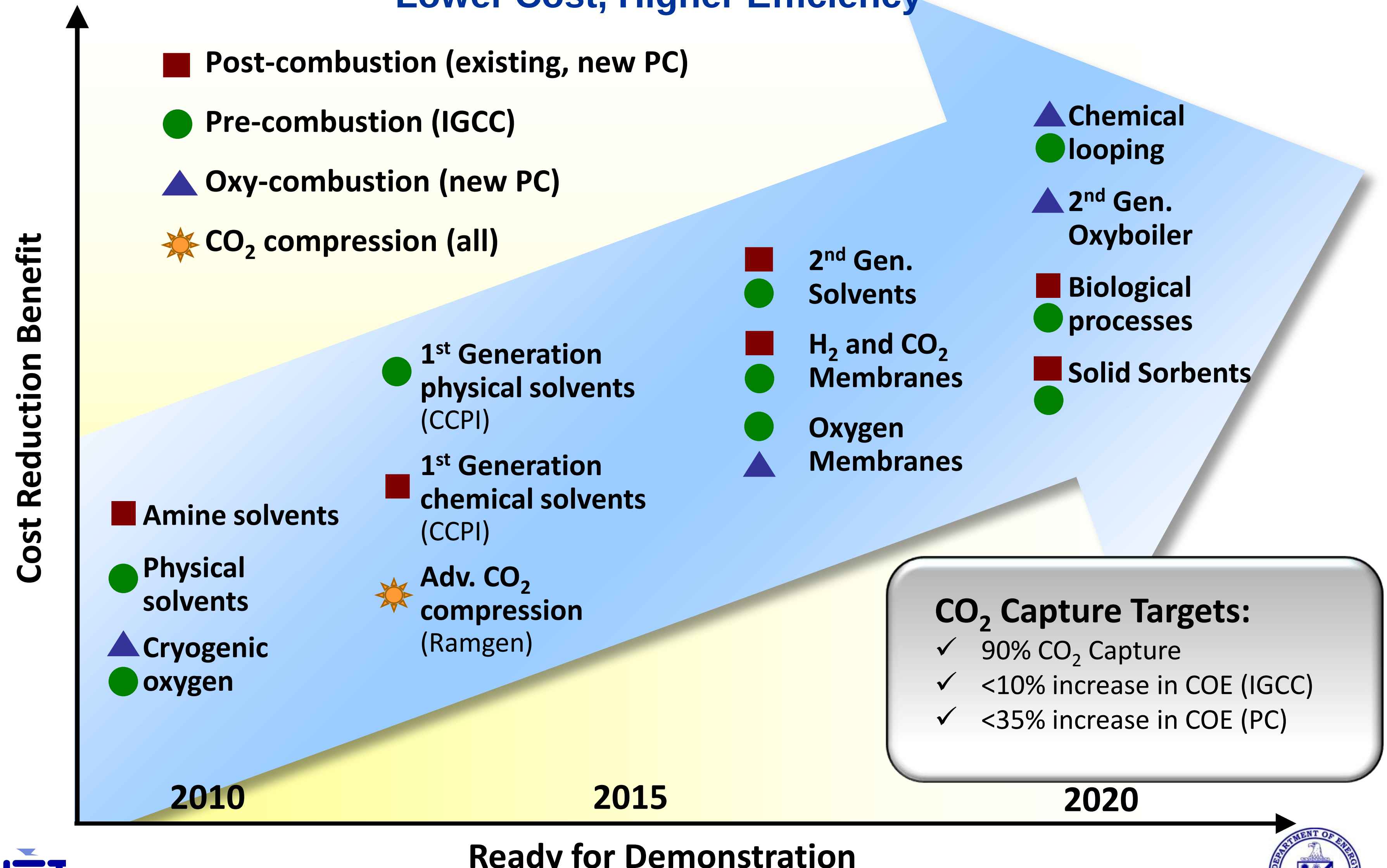
1. **Energy Demand**
   - 20% to 30% ↓ in power output

2. **Cost**
   - Incremental Capital $1,500 to $2,000/kWh
   - Increase Cost of Electricity up to 100%

3. **Scale-up**
   - Current capture experience <1,000 TPD
   - 550 MWe plant produces 13,000 TPD

New Technologies Are Emerging

Lower Cost, Higher Efficiency



Advanced CO_2 Solvents

Solvent R&D Focus

- High CO_2 working capacity
- Optimal ΔHrxn
- Low heat capacity
- Fast kinetics
- Thermally and chemically stable
- Non-corrosive, environmentally safe

Project Types

- Ionic liquids
- Novel high capacity oligomers
- Potassium carbonate/enzymes
- Phase Change Solvents

2011: Laboratory to 1 Mwe Pilot Scale

2015: 10 – 25 Mwe Pilot Scale

2020: 50+ Mwe Demonstration Scale

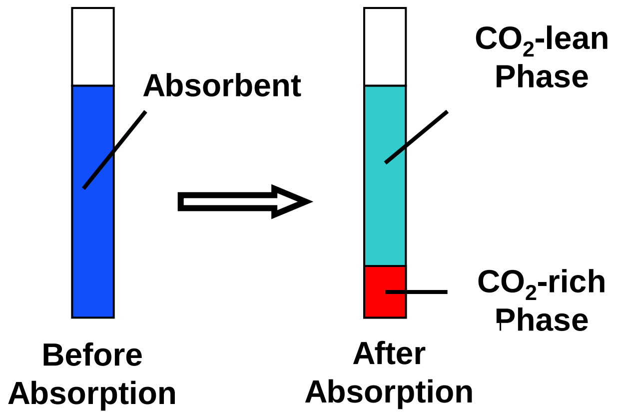
Recent progress:

New Solvent Synthesis by GE:

✓ **50% increase capacity vs. MEA**

✓ **< 48% increase in COE**

Phase change chemical systems shown to reduce regeneration energy relative to MEA by 50%



Advanced CO_2 Sorbents

Advantages

- Low regeneration energy (no water, low heat capacity, low heat of reaction)
- High equilibrium capacity

Challenges

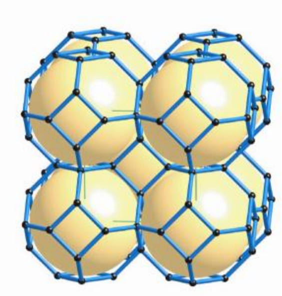
- System design
  - Pressure drop, heat integration, solids transport
- Durability (attrition, chemical stability)

Project Types

- Supported amines (silica, clay)
- Metal zeolites
- Carbon-based
- Alumina
- Sorbent systems development

Sorbent R&D Focus

- **High CO_2 loading capacity**
- **Minimize regeneration energy**
- **Fast reaction kinetics**
- **Durable**
  - Thermally & chemically stable
- **Gas/solid systems**
  - Low pressure drop, heat management



2011: Laboratory to 1 Mwe Pilot Scale

2015: 10 – 25 Mwe Pilot Scale

2020: 50+ Mwe Demonstration Scale

Advanced CO_2 Membranes

Membrane Advantages

- Simple operation; no chemical reactions, no moving parts
- Tolerance to contaminants
- Compact, modular→ small footprint

Challenges

- Low flue gas CO_2 partial pressure
- Particulate matter
- Cost reduction and device scale-up
- Power plant integration

2011: Laboratory to 1 Mwe

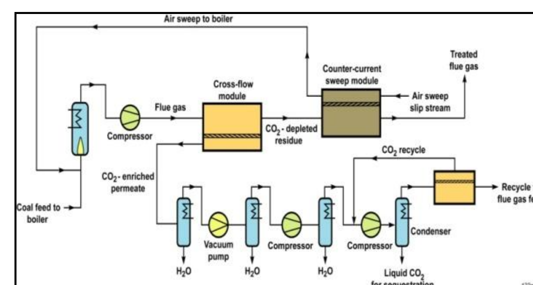
2015: Large pilot scale 10 - 25 Mwe

2020: 50+ Mwe Demonstration Scale

Advanced Membrane R&D Focus

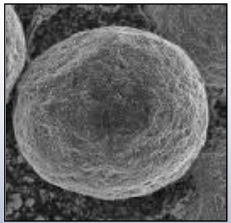
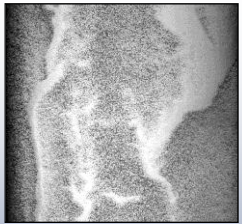
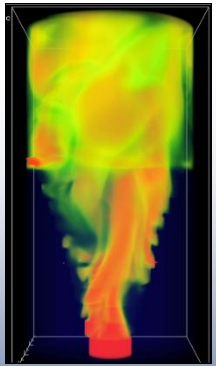
- High CO_2/N_2 selectivity & permeability
- Durability
  - Chemically (SO_2), thermally
  - Physically
- Membrane systems
  - Process design critical
- Low cost
  - Capital and energy penalty

1 TPD CO_2 , 6 month test



CCSI will develop M&S tools to accelerate the commercialization of CCS

CCSI
Carbon Capture Simulation Initiative


Identify promising concepts → **Reduce the time for design & troubleshooting** → **Quantify the technical risk, to enable reaching larger scales, earlier** → **Stabilize the cost during commercial deployment**

National Labs

Berkeley Lab
Pacific Northwest National Laboratory
NETL
Los Alamos National Laboratory EST. 1943
Lawrence Livermore National Laboratory

Academia

Carnegie Mellon
Virginia Tech
Penn State 1855
Princeton University
West Virginia University
University of Pittsburgh

Industry

ADA Environmental Solutions
Ameren
B&W the babcock & wilcox company
Babcock Power Inc.
Air Products
Alstom
Fluor
Ramgen Power Systems USA
AEP American Electric Power
Duke Energy
GE
PG&E
Southern California Edison
An Edison International Company
San Onofre Nuclear Generating Station
Southern Company
Chevron
Eastman
EPRI Electric Power Research Institute
WorleyParsons
resources & energy
URS

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Office of Fossil Energy

United States Department of Energy

The Challenge:

Permanence & Risk ?

The Direction:

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

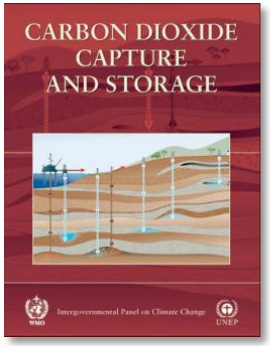
Many Good Analogs For Geological Storage

- Natural CO_2 reservoirs
- Oil and gas reservoirs
- Natural gas storage
- 70 CO_2 EOR projects in U.S.
- 50 acid gas injection sites in North America
- Numerical simulation of geological systems
- Current Large-Scale CO_2 storage projects

"At least 99%+ retention is likely for well selected and managed storage sites"

Bullets Based on Rubin, CMU; Quote from IPCC Special Report on Carbon Capture & Storage

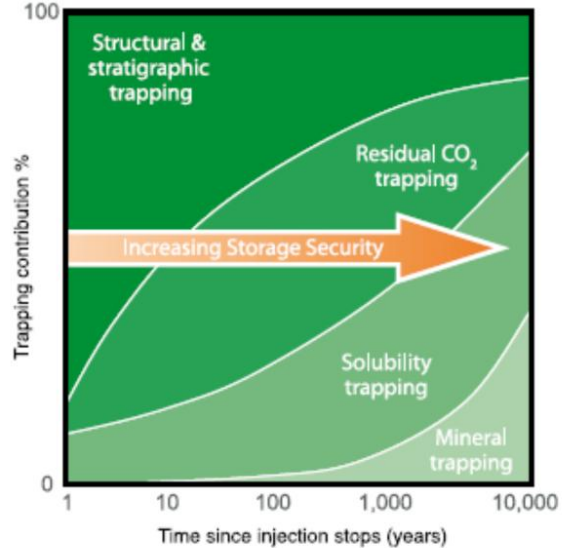
Security/permanence is expected to be high for CO_2 storage in geologic reservoirs.



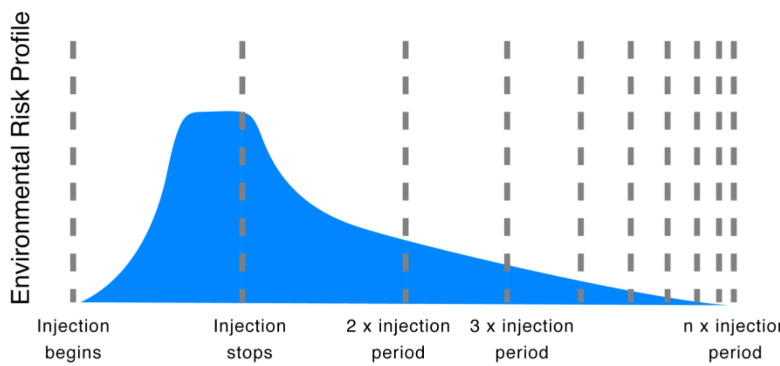
IPCC (2005)

"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.**"

Schematic evolution of trapping mechanisms over time (IPCC, 2005)



Schematic profile of environmental risk (Benson, 2007)

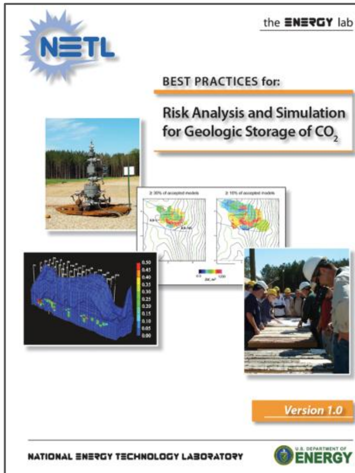


Multiple trapping mechanisms reduce CO_2 mobility over time

- structural/stratigraphic
- residual
- solubility
- mineralization; sorption

Risk profiles are expected to decline over time

Site characterization, site operations, and monitoring strategies will work to promote storage security (e.g., DOE Best-Practices documents)



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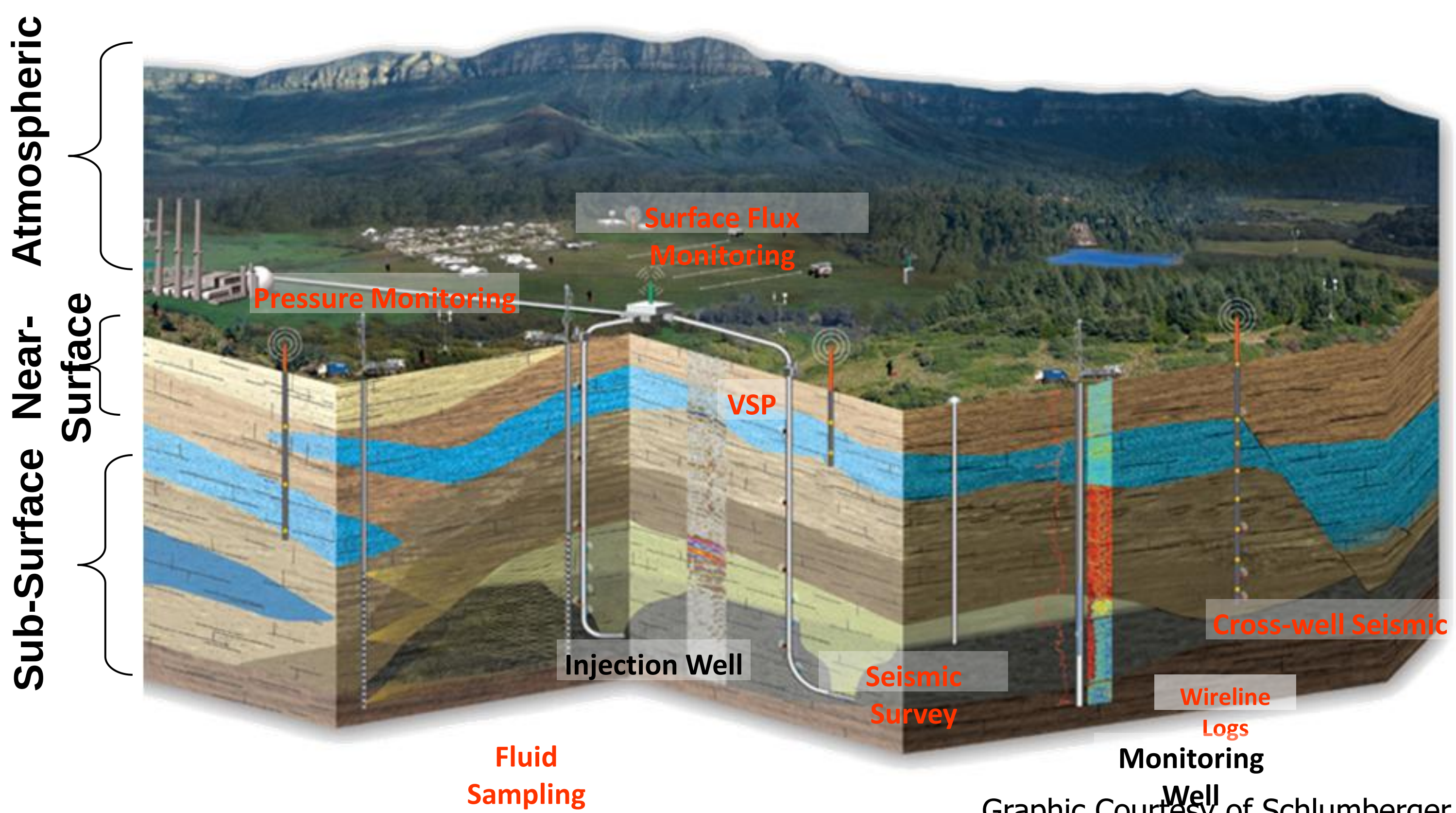
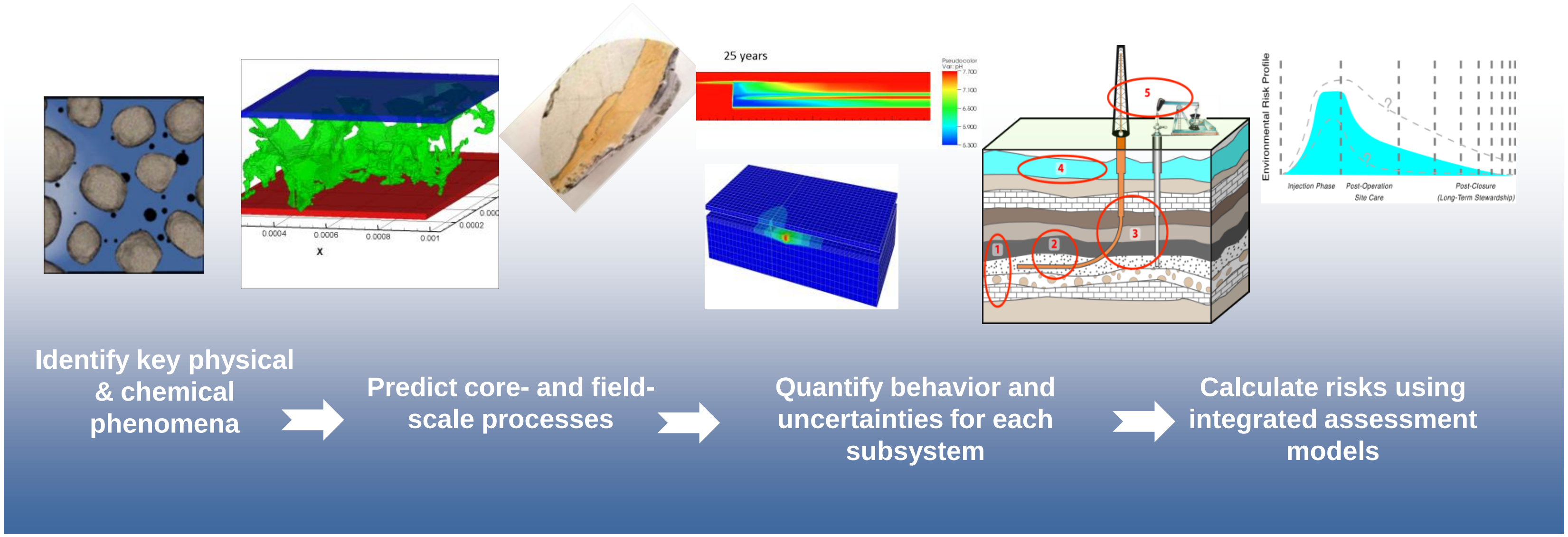
Monitoring Technologies & Practices Emerging



Graphic Courtesy of Schlumberger

National Risk Assessment Partnership



- **Overall NRAP goal: To develop and demonstrate a methodology for generating long-term quantitative risk profiles for carbon storage to support widespread commercial deployment.**
  - Develop framework and computational tools needed to generate quantitative risk profiles (long-term liability)
  - Use laboratory and field data to fill gaps in the science base as needed to confirm model validity, to reduce uncertainty, and to direct model development
  - Develop risk-based monitoring and mitigation strategy that lowers uncertainty and risk

The Challenge:

Field Tests & Infrastructure ?

The Direction:

- Put "first of kind" projects in place
- Develop protocols & Best Practices
- Public outreach & Training

“Commercial” Sequestration Projects

Sleipner Project- Norway

- CO_2 removed from natural gas produced on production platform in North Sea
- Injection into saline reservoir under sea
- Started 1996

Weyburn – Saskatchewan

- EOR project with 50 wells
- Uses CO_2 from coal gasification plant
- Started 2000

In Salah Gas Plant - Algeria

- Injection into saline formation downdip of gas reservoir
- 3 wells
- Started 2004

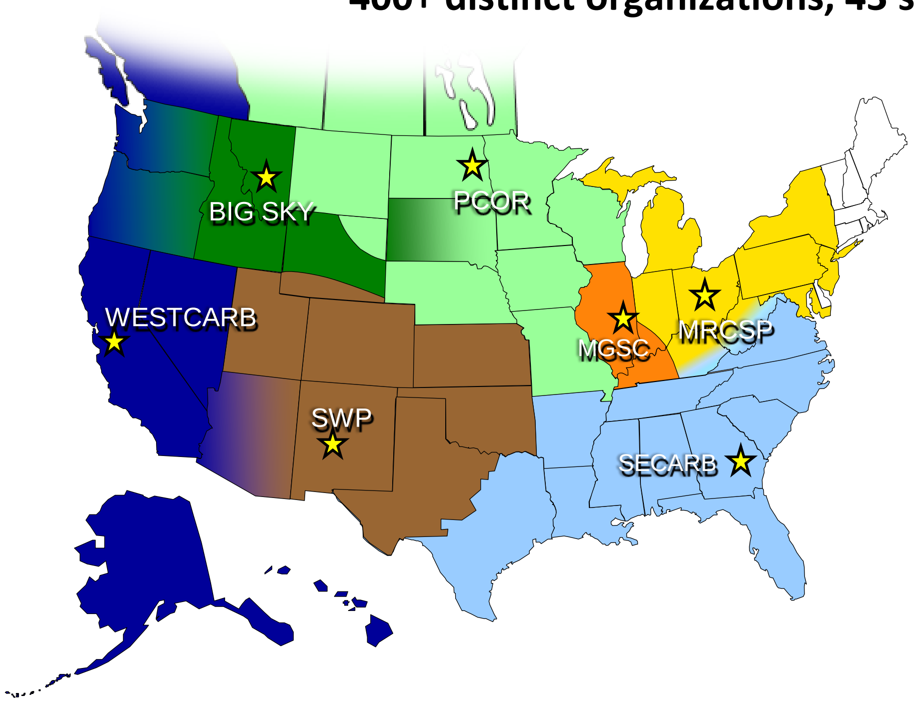
Photos from Staoil Website

Regional Carbon Sequestration Partnerships

Developing the Infrastructure for Wide-Scale Deployment

Seven Regional Partnerships

400+ distinct organizations, 43 states, 4 Canadian Provinces



- Engage regional, state, and local governments
- Determine regional sequestration benefits
- Baseline region for sources and sinks
- Establish monitoring and verification protocols
- Address regulatory, environmental, and outreach issues
- Validate sequestration technology and infrastructure

Characterization Phase (2003-2005)

Search of potential storage locations and CO_2 sources	Found potential for 100’s of years of storage

Validation Phase (2005-2011+)

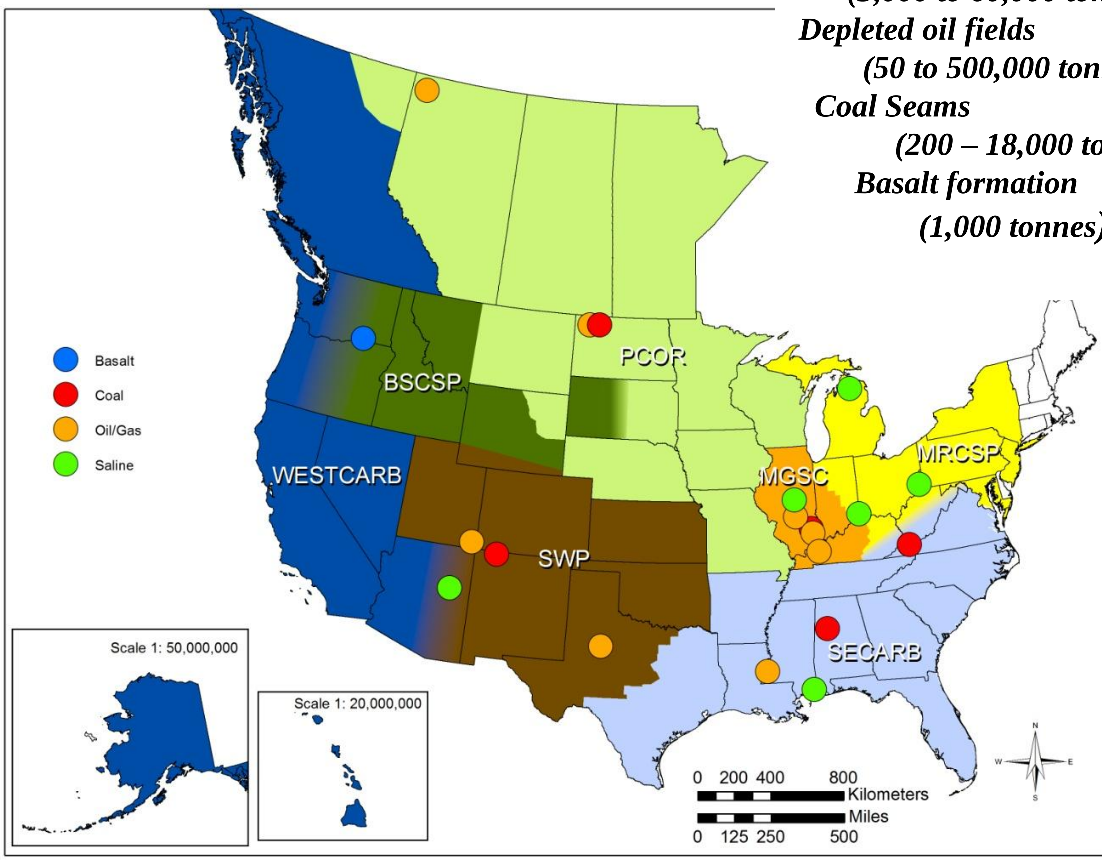
19 injection tests in saline formations, depleted oil, unmineable coal seams, and basalt

Development Phase (2008-2018+)

Large scale injections	Commercial scale understanding	Regulatory, liability, ownership issues

Small-Scale Geologic Field Tests

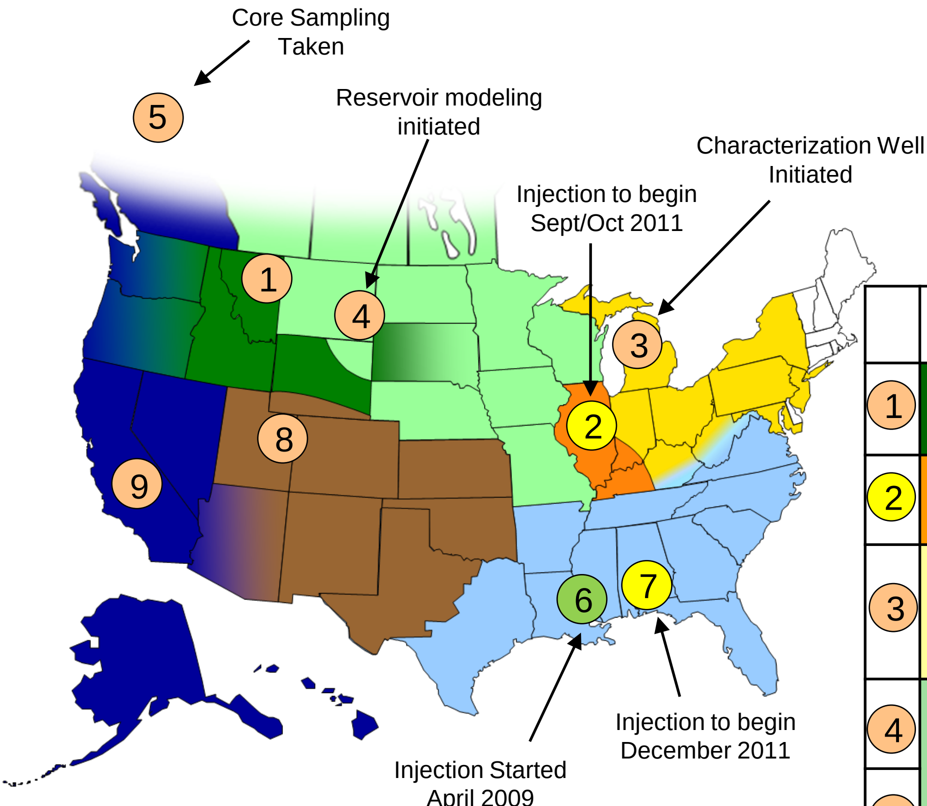
Saline formations
(3,000 to 60,000 tonnes)
Depleted oil fields
(50 to 500,000 tonnes)
Coal Seams
(200 – 18,000 tonnes)
Basalt formation
(1,000 tonnes)



Completed 18 Injections--Over 1.35 tonnes injected

RCSP	Geologic Province
Big Sky	Columbia Basin
MGSC	Illinois Basin
MRCSP	Cincinnati Arch, Michigan Basin, Appalachian Basin
PCOR	Keg River, Duperow, Williston Basin
SECARB	Gulf Coast, Mississippi Salt Basin, Central Appalachian, Black Warrior Basin
SWP	Paradox Basin, Aneth Field, Permian Basin, San Juan Basin
WESTCARB	Colorado Plateau

Large-Volume Geologic Field Tests



- ✓ **One injection commenced April 2009**
- ✓ **Remaining injections scheduled 2011-2015**

- Injection Ongoing
- 2011 Injection Scheduled
- Injection Scheduled 2012-2015

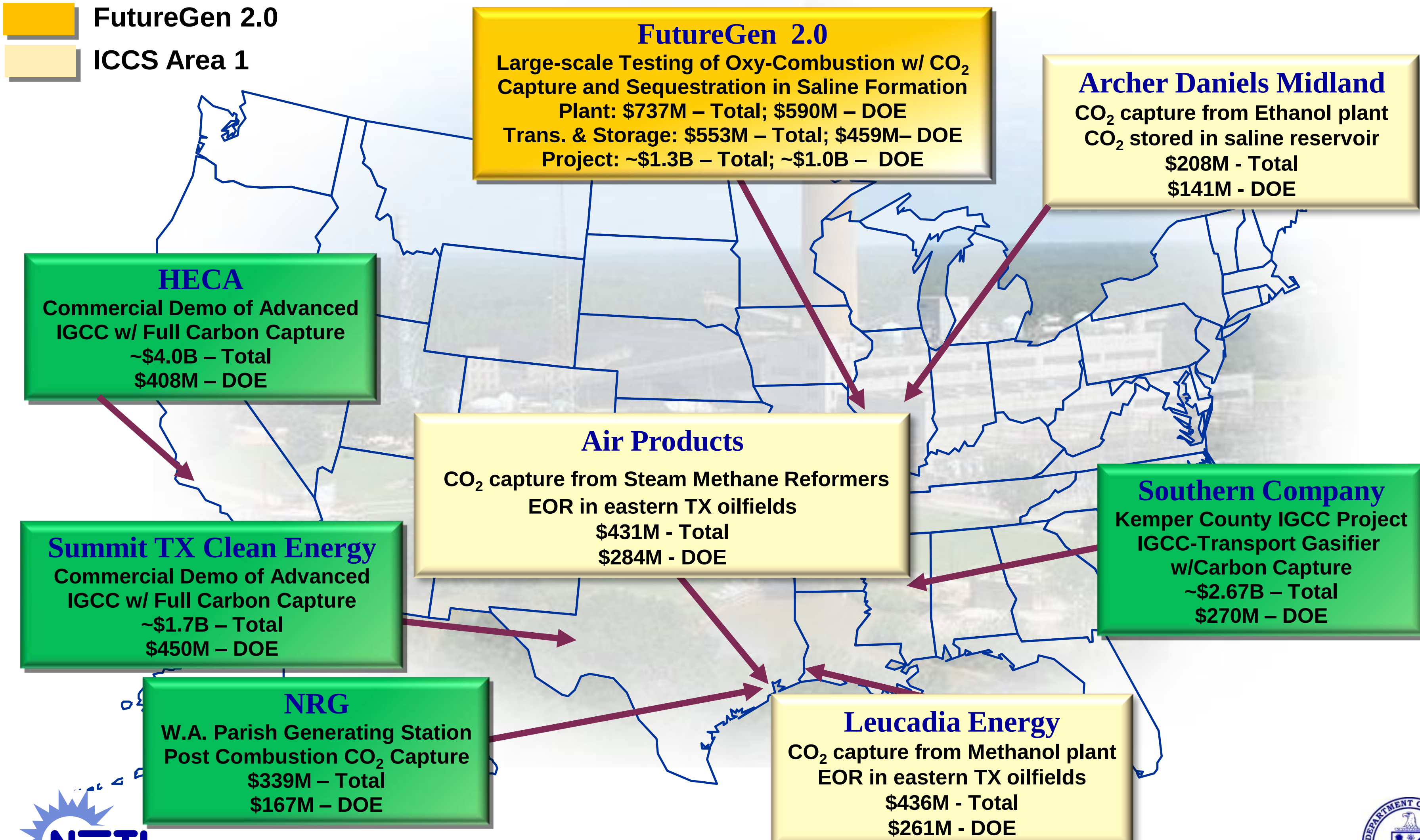
Note: Some locations presented on map may differ from final injection location

	Partnership	Geologic Province	Target Injection Volume (tonnes)
1	Big Sky	Sweetgrass Arch-Duperow Formation	1,000,000
2	MGSC	Illinois Basin-Mt. Simon Sandstone	1,000,000
3	MRCSP	Michigan Basin-St Peter SS or Niagaran Reef	1,000,000
4	PCOR	Powder River Basin-Muddy Formation	1,500,000
5		Alberta Basin-Sulphur Point Formation	1,000,000
6	SECARB	Interior Salt Basin-Tuscaloosa Formation	>2,000,000
7		Interior Salt Basin-Paluxy Formation	300,000
8	SWP	Wasatch Plateau-Navajo Sandstone	1,000,000
9	WESTCARB	Regional Characterization	TBD

Office

Major CCS Demonstration Projects
Locations & Cost Share

- CCPI
- FutureGen 2.0
- ICCS Area 1



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CCS Best Practice Manuals

Critical Requirement For Significant Wide Scale Deployment

Best Practices Manual	Version 1 (Phase II)	Version 2 (Phase III)	Final Guidelines (Post Injection)
Monitoring, Verification and Accounting	2009 2012	2016	2020
Public Outreach and Education	2009	2016	2020
Site Characterization	2010	2016	2020
Geologic Storage Formation Classification	2010	2016	2020
**Simulation and Risk Assessment	2010	2016	2020
**Well Construction, Operations and Completion	2011	2016	2020
Terrestrial	2010	**2016 – Post MVA Phase III**	

***Regulatory Issues will be addressed within various Manuals*

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http://www.netl.doe.gov/technologies/carbon_seq/refshelf/refshelf.html

DOE's Global Collaborations

Project Location	Operations	Reservoir Storage Type	Operator/Partner	DOE Contribution
North America, Canada Saskatchewan **Weyburn-Midale**	**2.8 MMt CO_2/yr commercial 2000**	**oil field carbonate EOR**	**Cenovus, Apache, Petroleum Technology Research Centre**	DOE is supporting U.S. scientists test multiple monitoring and simulation technologies.
North America, Canada, Alberta **Zama oil field**	**25,000 metric tons CO_2/yr CO_2/acid gas demo**	**oil field carbonate EOR**	**Apache (RCSP)**	Supporting the PCOR Partnership to conduct monitoring and reservoir modeling of CO_2 injection into pinnacle reef.
North America, Canada, British Columbia **Fort Nelson**	**> 1 MMt CO_2/yr, 1.8 MMt acid gas/yr large-scale demo**	**saline carbonate formation**	**Spectra Energy (RCSP)**	Supporting PCOR Partnership to conduct monitoring and reservoir modeling studies.
Europe, North Sea, Norway **Sleipner**	**1 MMt CO_2/yr commercial 1996**	**saline marine sandstone**	**StatoilHydro**	Supporting the Scripps Institute of Oceanography which is conducting time-lapse gravity surveys.
Europe, North Sea, Norway **Snøhvit CO_2 Storage**	**700,000 metric tons CO_2/yr commercial 2008**	**saline marine sandstone**	**StatoilHydro**	Supporting LBNL to simulate geo-mechanical conditions of the reservoir and caprock.
Europe, Germany **CO_2SINK, Ketzin**	**60,000 metric tons CO_2 demo 2008**	**saline sandstone**	**GeoForschungsZentrum, Potsdam(GFZ)**	Supported LBNL to deploy downhole monitoring technology based on thermal perturbation sensors.
Iceland **CarbFix**	**CO_2 stream from Hellisheidi geothermal power plant**	**saline basalt**	**Reykjavik Energy**	Supporting Columbia University Lamont-Doherty Earth Observatory to test tracer methods to assess trapping mechanisms in basalt formations.
Africa, Algeria **In Salah gas**	**1 MMt CO_2/yr commercial 2004**	**gas field sandstone**	**BP, Sonatrach, StatoilHydro**	Supporting LLNL and LBNL to test field and remote sensing monitoring technologies and modeling geomechanical and geochemical reservoir processes.
Australia, Victoria **Otway Basin**	**65,000 metric tons CO_2 Stage I 2008**	**gas field and saline sandstone**	**CO2CRC**	Supporting scientists at LBNL to test multiple monitoring technologies at depleted gas field and saline formation.
Asia, China **Ordos Basin**	**100,000 metric tons CO_2/yr model phase**	**Ordos Basin**	**Shenhua Coal**	Supporting West Virginia University and LLNL to assess capacity for storage, and simulating hydrogeologic and geochemical reservoir conditions.

For Additional Information

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