# U.S. Department of Energy
# Office of Fossil Energy

# U.S. DOE Supported CCS R&D

**Darin Damiani**
**Carbon Storage Program Manager**


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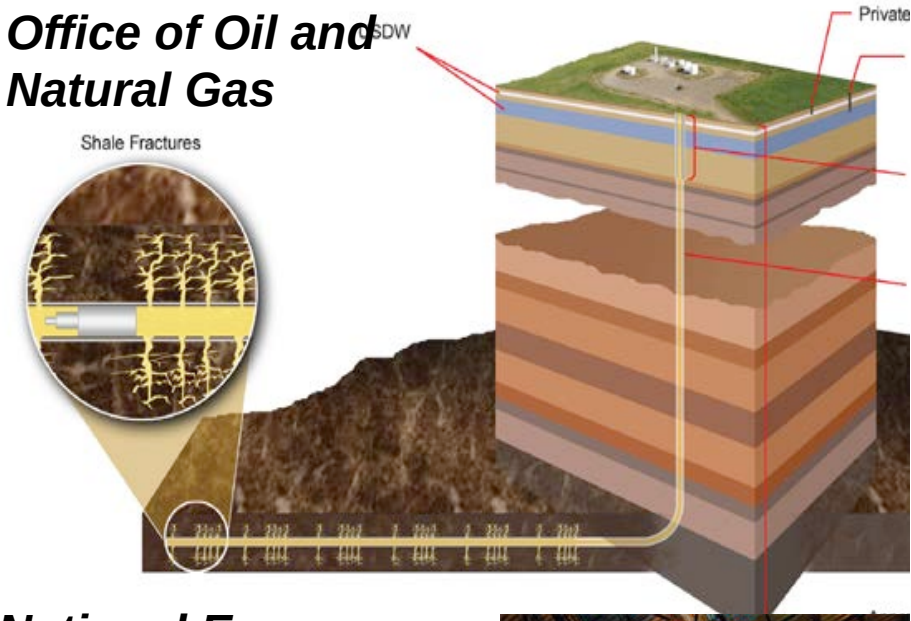
# DOE's Office of Fossil Energy (FE)


**Office of Oil and Natural Gas**

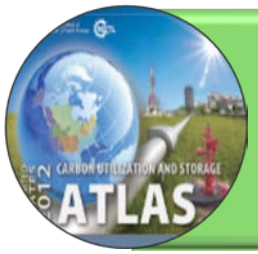




**National Energy Technology Laboratory**

# FE's Clean Coal and Carbon Management Division, CCS R&D

**Carbon Capture**
R&D and scale-up technologies for capturing $CO_2$ from new and existing industrial and power-producing plants



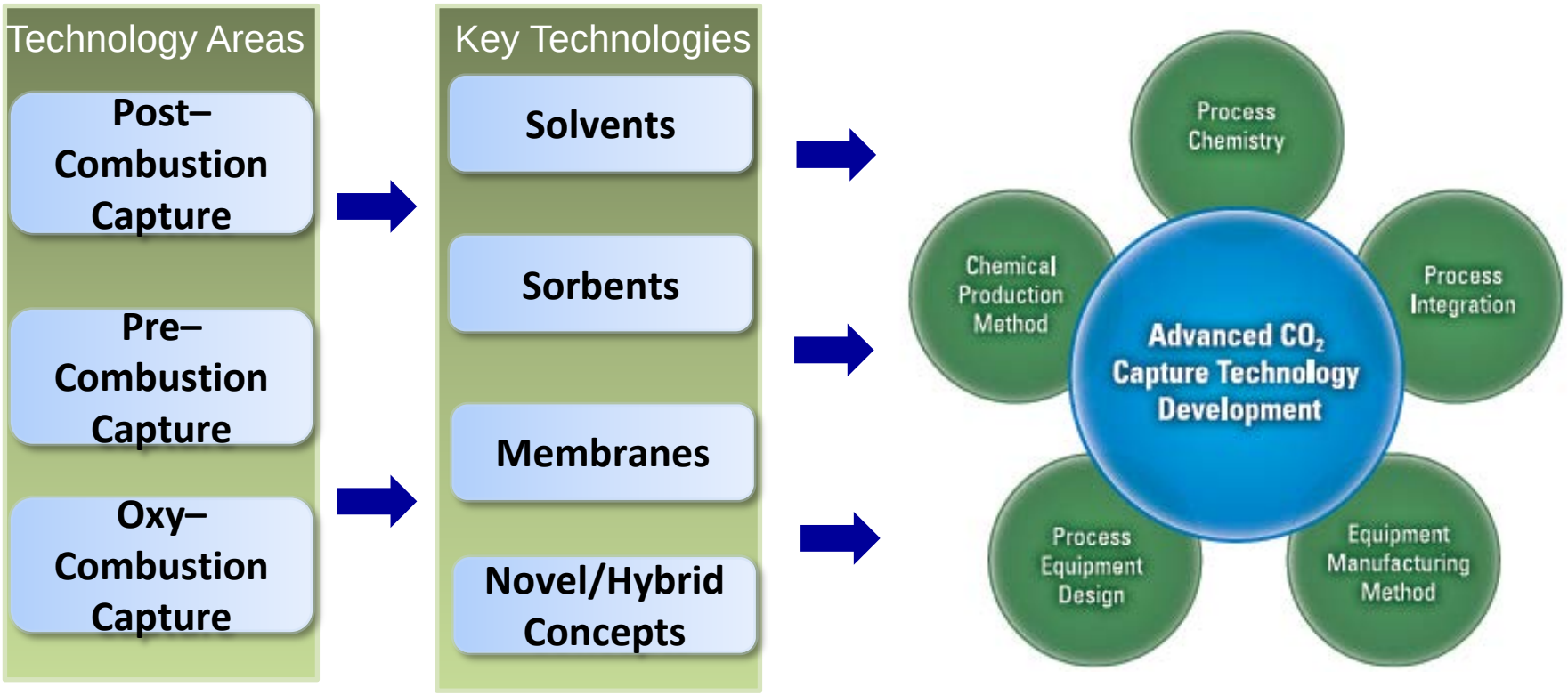

**Carbon Storage**
Safe, cost- effective, and permanent geologic storage of $CO_2$ , including beneficial uses

**Advanced Energy Systems (AES)**
Technologies that improve plant efficiencies, reduce $CO_2$ capture costs, increase plant availability, and maintain the highest environmental standards

**Cross Cutting Research**
Materials, sensors, water management, and advanced computer systems for future power plants and energy systems integrated with CCS

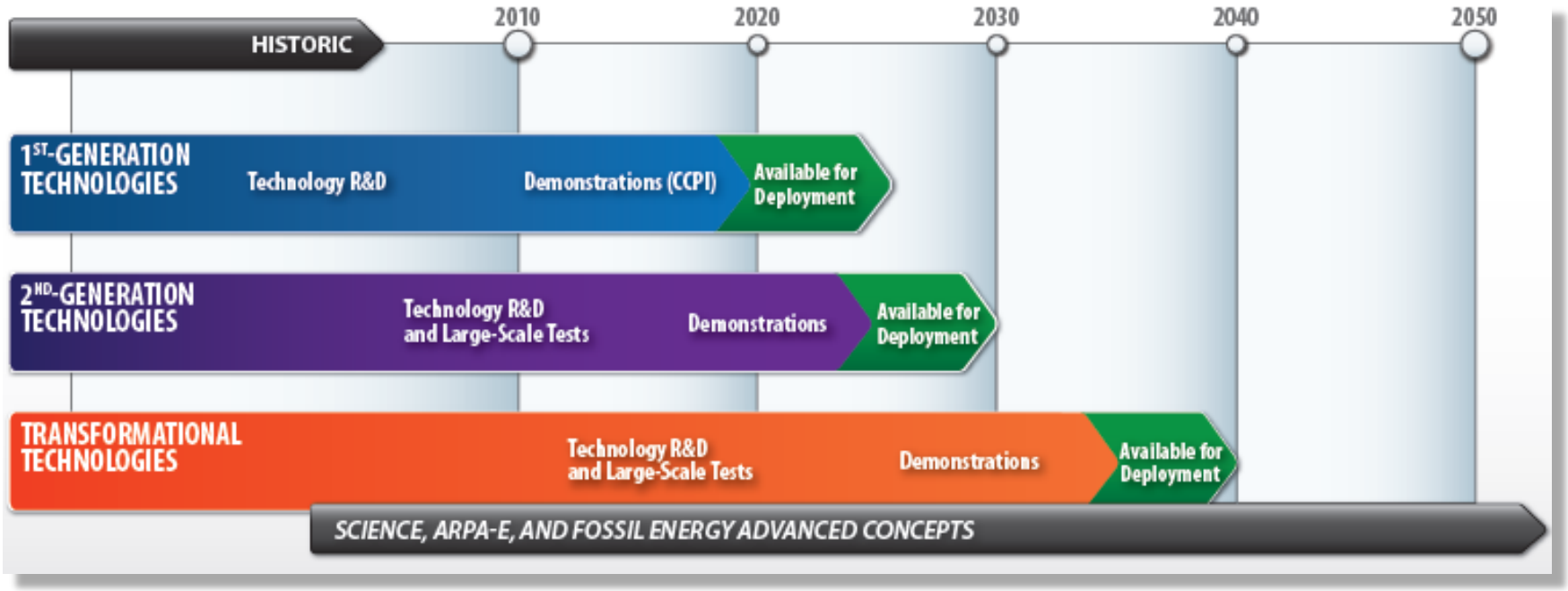
# $CO_2$ Capture

## Requires Multiple Technologies and Multiple Scientific and Engineering Disciplines

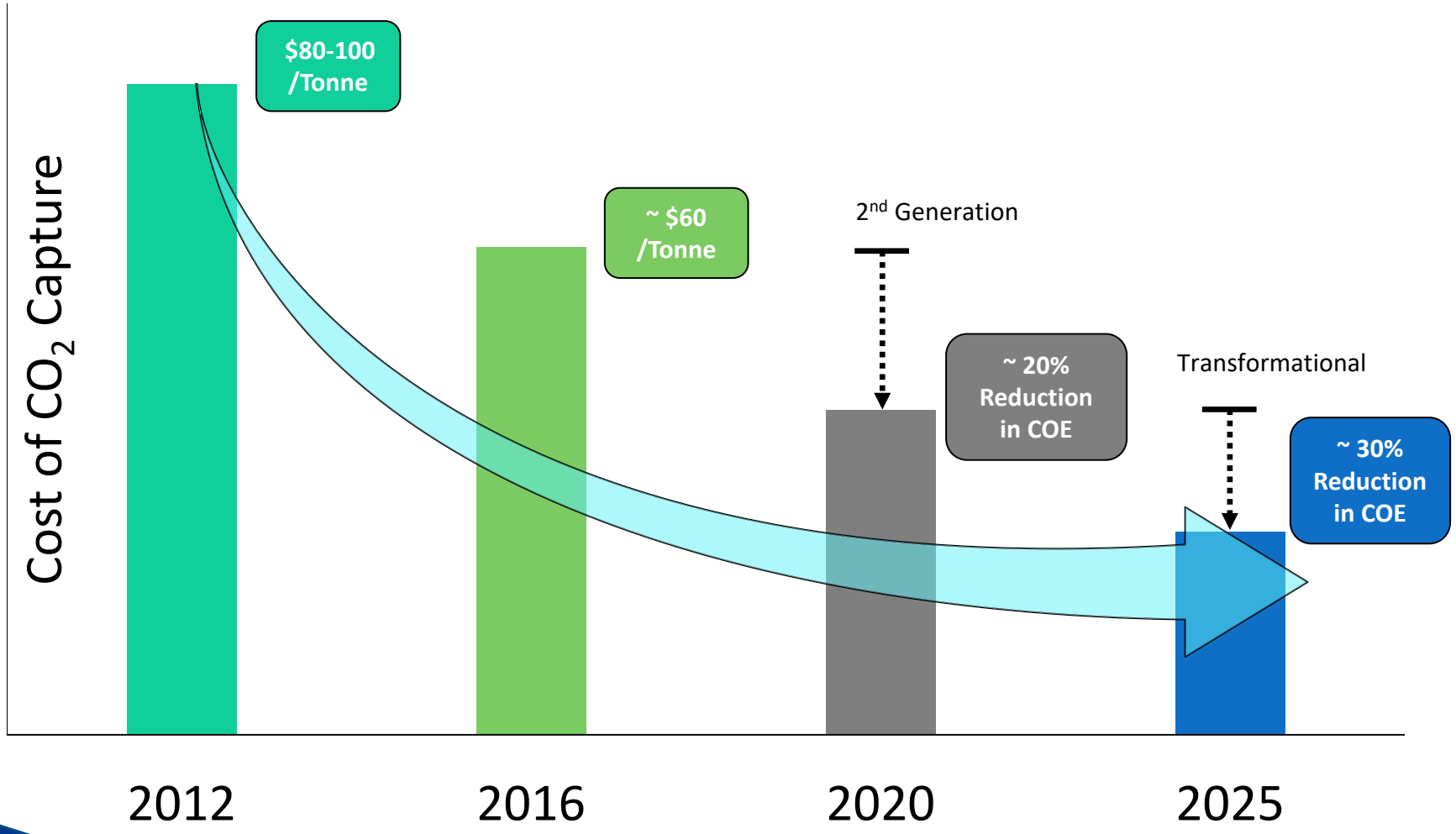



**This is the primary pathway to steep cost reductions**

# DOE's Carbon Capture Technology Development Schedule



# Capture Cost Goals



# 1st Generation CCUS Demonstrations

Southern Company Services, Inc.
Kemper Advanced IGCC

Operational feb/mar 2017

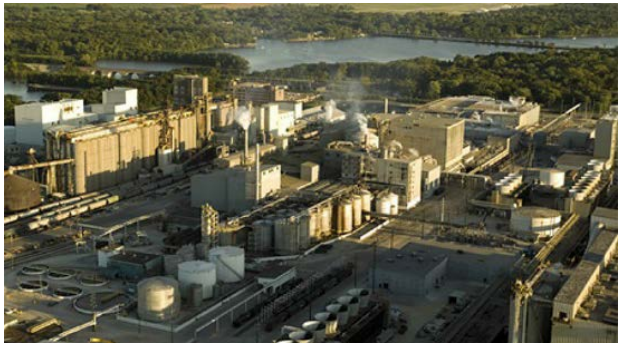
W.A. Parrish, TX NRG/PetraNova project


Broke Ground Sept. 2014 - On time & budget for 2016

Port Arthur Refinery, TX – Air Products 2013


3+ million tons $CO_2$ stored

ADM Agricultural Processing and Biofuels Plant, Decatur IL



Construction complete – Operational April 2017

# Petra Nova – NRG W.A. Parish

## *Advanced Post Combustion $CO_2$ Capture*

- Thompsons, TX (near Houston)
- 240 MWe slipstream at NRG Energy's W.A. Parish power plant (originally 60 MWe)
- Fuel: PRB sub-bituminous coal
- 90% $CO_2$ capture (KM CDR Process®)
  1,400,000 tonnes $CO_2$/year from unit 8 flue gas
- EOR: Hilcorp West Ranch oil field
- Total Project Cost: ~$1 billion
- Project Partners: NRG, JX Nippon, DOE

***Fantastic example of a successful collaboration between the US and Japan leading to a viable CCUS operation at commercial scale.***

# Carbon Capture Small Pilot Projects

| Performer | Project Focus | Scale |
|---|---|---|
| **Post-Combustion Solvents 2nd Gen** | | |
| Linde, LLC | Slipstream Novel Amine-Based Post-Combustion Process | 1 MWe |
| Neumann Systems Group, Inc | Carbon Absorber Retrofit Equipment | 0.5 MWe |
| University of Kentucky | Slipstream Demonstration Using the Hitachi Advanced Solvent | 0.7 MWe |
| General Electric | Novel Aminosilicone Solvent | 0.5 MWe |
| ION Engineering | Amine Solvent in Ionic Liquid | 0.7 MWe |
| **Post-Combustion Sorbents 2nd Gen** | | |
| ADA-Environmental Solutions | Solid Sorbents as Retrofit Technology | 1 MWe |
| TDA Research, Inc. | Alkalized Alumina Solid Sorbent | 0.5 MWe |
| SRI International | Novel Solid Sorbent | 0.5 MWe |
| **Post-Combustion Membranes 2nd Gen** | | |
| Membrane Technology & Research | Polymeric Membranes | 0.6 MWe |
| Gas Technology Institute | Hollow-Fiber-Membrane Contactor with aMDEA Solvent | 0.5 MWe |
| **Post-Combustion Novel Concepts - Transformational** | | |
| FuelCell Energy, Inc. | Electrochemical Membrane | 3 MWe |
| Air Liquide | Cold Membrane | 0.3MWe |
| **Pre-Combustion - Transformational** | | |
| SRI International | CO2 Capture Using AC-ABC Process | 0.1 MWe |
| TDA, Inc. | High Capacity Regenerable Sorbent | 0.1 MWe |

# DOE Capture Priorities

- 2nd gen Large Scale Pilots by 2020 for Coal Plant
- Accelerate Transformational Technology Development
- Industrial applications for carbon capture

# $CO_2$ Utilization

- **Fossil Energy R&D Program supporting projects coupling $CO_2$ storage with Enhanced Oil Recovery (EOR)**
- **Small R&D program focused on $CO_2$ conversion**
  - Mineralization, Chemicals Production, Biological capture (algae)
- **FY15 Funding Opportunity Announcement (FOA)** – "Lab- and Bench-Scale technologies - $6.5M
- **Enacted FY16 budget includes $10M for $CO_2$ utilization additional to EOR**

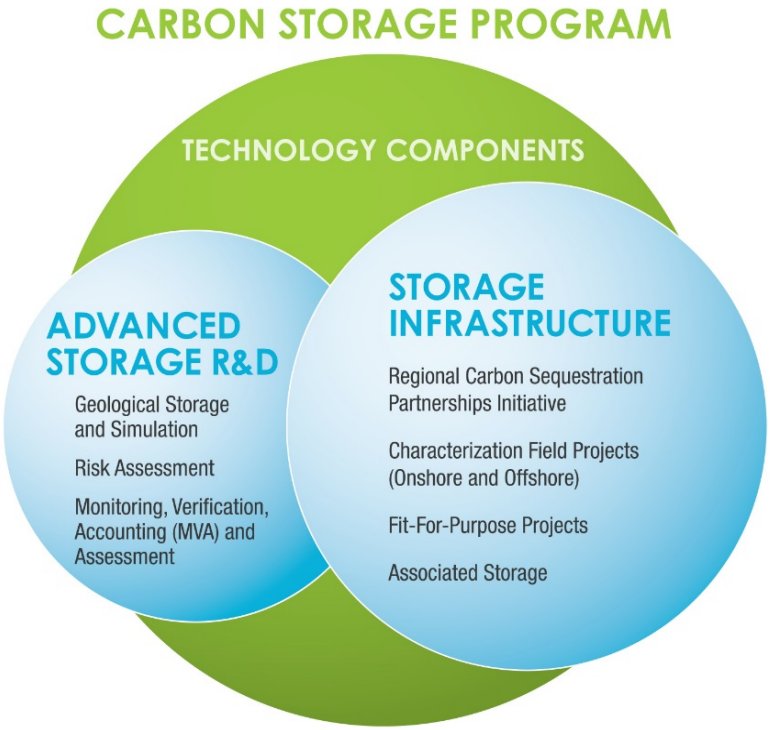
**Project Highlight: Skyonic**

- Operational as of October 2014
- Capturing 75,000 metric tons per year
- Converting $CO_2$ into useful, saleable products
- Received $28 million in ARRA funding

Skyonic Carbon Capture Unit

# Carbon Storage Program

- Initiated in 1997
- Carbon Storage Program's primary goal is to demonstrate the technical viability of geologic carbon storage as an effective solution for mitigating carbon emissions.
- The primary objective is to develop and advance the effectiveness of onshore and offshore storage technologies, reduce the challenges to their implementation, and prepare them for widespread commercial deployment in the 2025–2035 timeframe.



# Advanced Storage R&D

Development of technologies aimed to…

- improve wellbore integrity
- increase reservoir storage efficiency
- improve management of reservoir pressure and fluids
- ensure storage permanence
- quantitatively assess risks
- identify and mitigate potential release of $CO_2$ in all types of storage formations

# Advanced Storage R&D

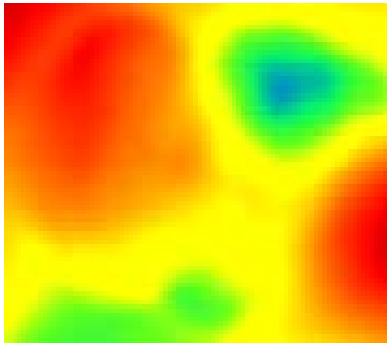
## Geologic Storage and Simulation

### Key R&D Pathways

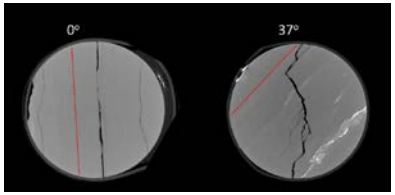
- Wellbore leakage assessment and detection
- Mitigation technologies for wells and natural pathways
- Fluid flow, reservoir pressure, and water management
- Geochemical  effects on formation, brine, and microbial communities
- Geomechanical impacts on reservoirs- seals and basin-scale coupled models, and microseismic monitoring

# Geological Storage and Simulation

## *Well Integrity & Mitigation, Predicting Plume & Pressure Impacts*

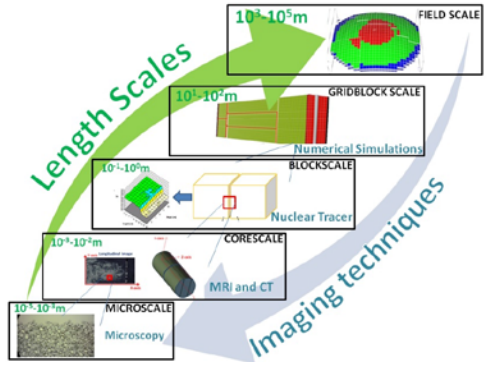


Lawrence Livermore National LaboratoryMicroseismic Toolset for Fault Detection and Seismicity Mitigation -

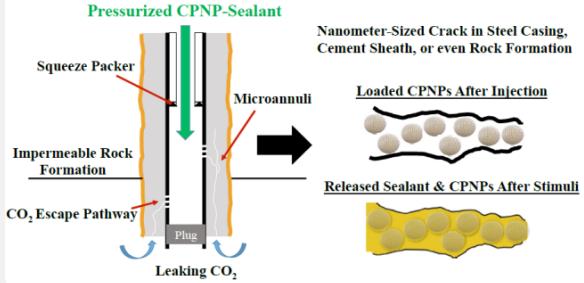



A Coupled Geomechanical, Acoustic, Transport, and Sorption Study of Caprock Integrity in $CO_2$ Sequestration - Colorado School of Mines

- Development and implementation of new modeling algorithms: Reduced Order Models, Statistical Learning Based Models, Invasion Percolation, Constrained Optimization and others
- Improved simulators to model coupled processes (flow, mechanical deformation/failure, geochemistry) in complex, fractured reservoirs and caprock
- Use of super-computing to improve understanding of errors in simulations resulting from upscaling geologic models
- New signal processing algorithms to extract information on faults from natural seismic signals
- New laboratory measurements of geomechanical properties and coupled processes in reservoir, caprock and faults
- Next-generation materials and methods for mitigating wellbore leakage: biomineralization , pH-triggered polymers, nanocomposites, mesoporous nanoparticles




A modeling-based workflow for evaluating geomechanical effects associated with $CO_2$ injection– University of Texas, Austin




Programmable sealant-loaded mesoporous nanoparticles for gas/liquid leakage mitigation - C-Crete Technologies, LLC

# Advanced Storage R&D

## Monitoring, Verification, Accounting & Assessment (MVAA)

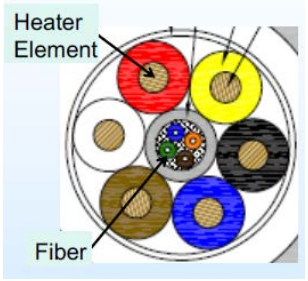
Key R&D Pathways

- Atmospheric Monitoring and remote sensing technologies
- Near-Surface Monitoring of soils and vadose zone
- Subsurface Monitoring in and near injection zone, and above seal(s).
- Intelligent Monitoring Systems for field management

# Advanced Storage MVA

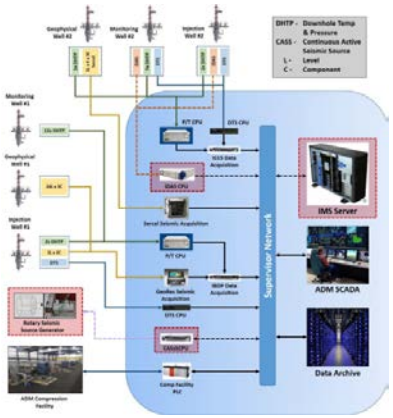
## *Monitoring the Plume & Pressure Front, Detecting Leakage*

Deep, Controlled Source Electro-Magnetic Sensing: A Cost Effective, Long-term Tool for Sequestration Monitoring – Multi-Phase Technologies

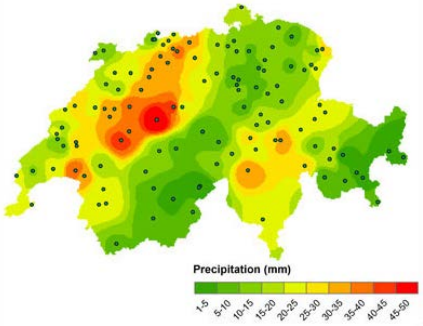



Distributed Fiber Optic Arrays: Integrated Temperature and Seismic Sensing for Detection of $CO_2$ Flow, Leakage and Subsurface Distribution - Electric Power Research Institute

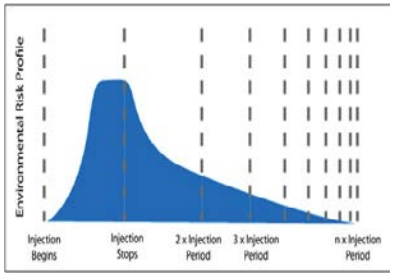
- Successful performance field testing of Distributed Acoustic Sensor (DAS) arrays in vertical seismic profiling (VSP) and crosswell seismic survey configurations
- A new seismic method (scalable, automated, semi-permanent seismic array) for tracking the $CO_2$ plume
- Initial field validation testing of a hydrologic pulse testing technology for leakage detection
- Initial field testing of a controlled source electromagnetic (CSEM) system incorporating a borehole source for monitoring changes in electrical properties of $CO_2$ reservoirs
- Measuring and interpreting the in situ strain tensor during $CO_2$ injection
- Intelligent systems software frameworks for monitoring, controlling, and optimizing $CO_2$ injection operation
- Time reversal methods for the detection and monitoring of $CO_2$/brine leakage pathways in wellbore systems




Intelligent monitoring system for real-time geologic storage, optimization, and reservoir management– Archer Daniels Midland




SASSA for Detecting $CO_2$ Plume Extent During Geological $CO_2$ Injection – Univ. of North Dakota




# Advanced Storage R&D

## Risk Assessment

## National Risk Assessment Partnership (NRAP)

NRAP is developing toolsets to reduce uncertainty and quantify potential impacts related to release of $CO_2$ and induced seismicity.

### Technical Team

National Energy Technology Laboratory

Berkeley Lab

Los Alamos National Laboratory EST.1943

Lawrence Livermore National Laboratory

Pacific Northwest National Laboratory

### Stakeholder Group

AEP American Electric Power

Blue Source

bp

EPA United States Environmental Protection Agency

ExxonMobil

ieaghg

IEc

MIT

NRDC

Schlumberger

Southern States Energy Board

Stanford University

Texas Railroad Commission

USGS

The University of Utah

Wade, LLC

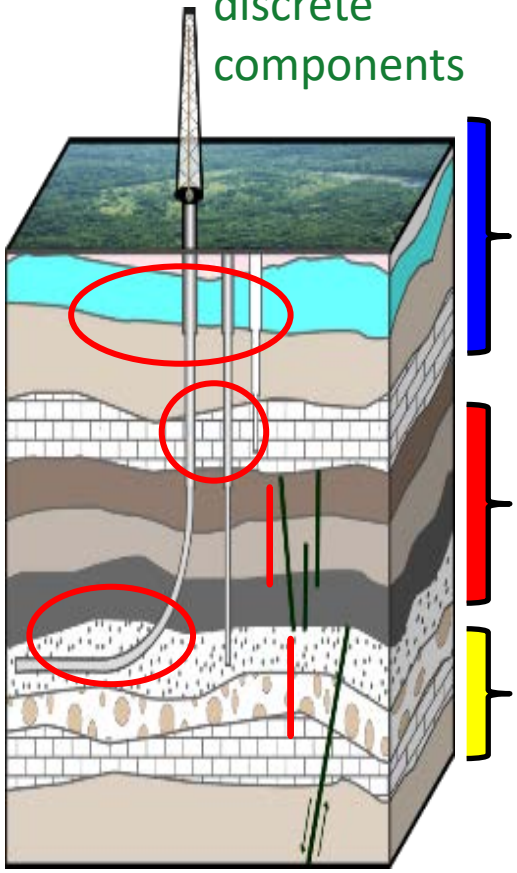
Whiting

Zurich

www.edx.netl.doe.gov/nrap

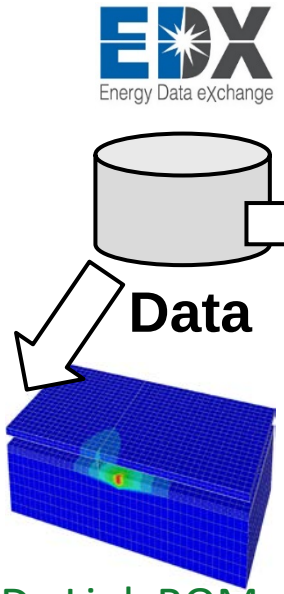
# NRAP Method

A. Divide system into discrete components

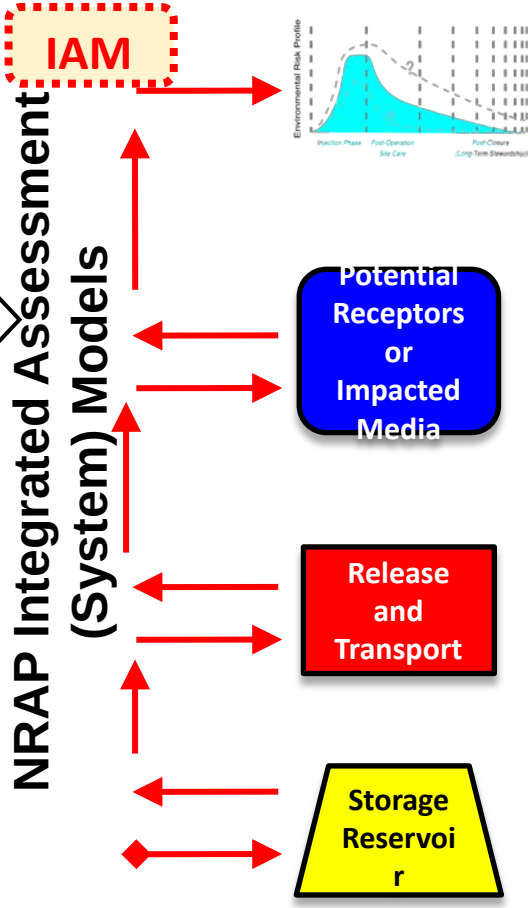


B. Develop detailed component models that are validated against lab/field data

C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions




D. Link ROMs via integrated assessment models (IAMs) to predict system performance




E. Exercise whole system model to explore risk performance

# ROMs available for public use

## Integrated Assessment Model – Carbon Storage (NRAP-IAM-CS)

- Simulates long-term full system behavior (reservoir to aquifer/atmosphere)
- Generates risk profiles (time-lapse probability of leakage and GW impact)
- Estimates storage permanence quantitatively amidst system uncertainty
- Identifies key drivers of risk amidst system uncertainty

## Reservoir Evaluation and Visualization (REV) Tool

- Generates pressure and CO2 plumes sizes over time
- Suitable for Area of Review (AoR) determination
- Visualizes reservoir behavior probabilistically

## Wellbore Leakage Analysis Tool (WLAT)

- Evaluates existing wells for leakage potential
- Explores leakage response as a function of well disposition
- Evaluates the implications of permeable overburden zones

## Natural Seal ROM (NSealR)

- Estimates flux through a fractured or perforated seal
- Accounts for storage outside of primary target zone

## Aquifer Impact Model (AIM)

- Rapid estimation of aquifer volume impacted by a leak
- Distinguishes between impact of CO2 and brine leaks
- Used to determine impact of threshold criteria.

## Design for Risk Evaluation and Monitoring (DREAM)

- Estimates time to detection for a monitoring system
- Evaluates and select optimal monitoring designs

## Short Term Seismic Forecasting (STSF)

- Forecasts seismic event frequency over the short term
- Potential to complement stoplight approach for induced seismicity planning and permitting

**NRAP Beta Tool Training Materials available at,**
https://edx.netl.doe.gov/nrap


IJGGC Virtual Special Issue (August, 2016)

# NRAP will improve our ability…

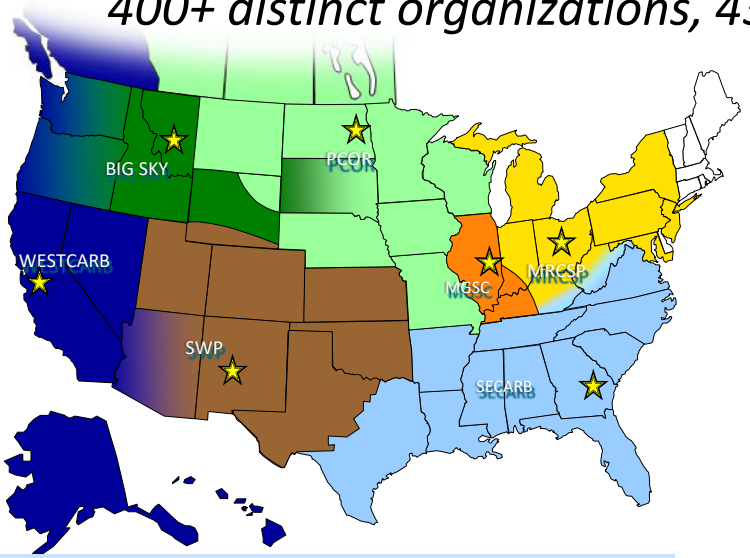
- To evaluate risk at specific carbon storage sites.
- To estimate costs of long-term liability and increase investor confidence
- To safely store CO2 by using improved science to aid in design and application of monitoring and mitigation strategies.
- To monitor for seismic activities and the potential for leakage fluid

# Regional Carbon Sequestration Partnerships

## *Developing a Foundation 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
- Validate sequestration technology and infrastructure

### Characterization Phase (2003-2005)

| | |
|---|---|
| Search of potential storage locations and $CO_2$ sources | Found potential for 100s of years of storage |

### Validation Phase (2005-2011)

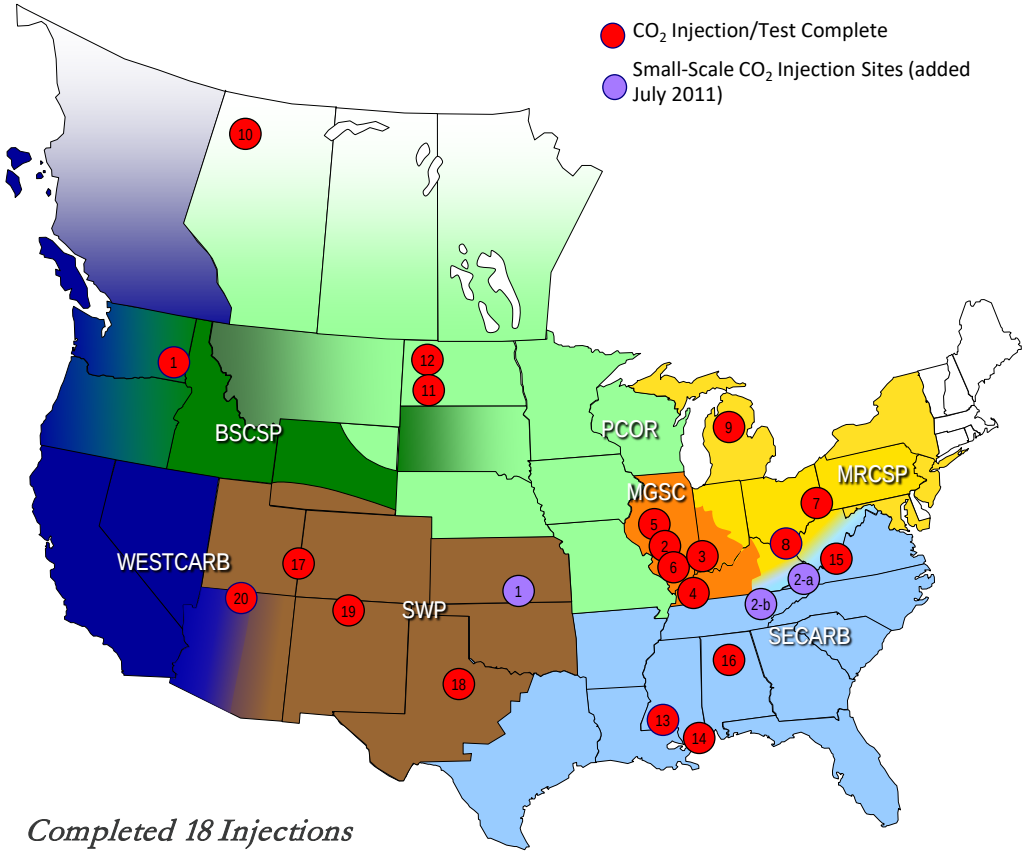
20 injection tests in saline formations, depleted oil, unmineable coal seams, and basalt

### Development Phase (2008-2018+)

| | |
|---|---|
| 8 large scale injections (over 1 million tons each) | Commercial scale understanding and validation |

# RCSP Validation Phase Field Projects

## *Small-Scale Field Projects*

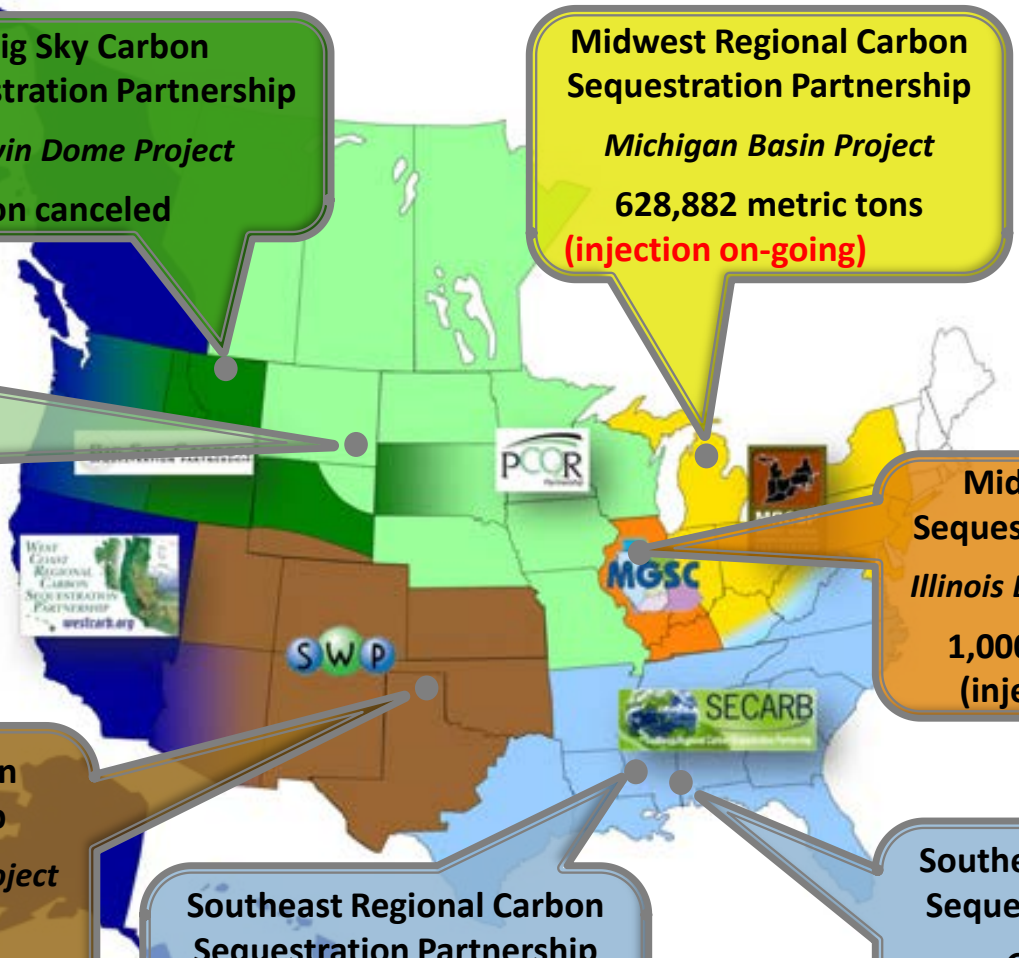



*Completed 18 Injections*
*Over 1.35 Metric Tons Injected*

| RCSP | Type | Province |
|---|---|---|
| **BIG SKY** | SALINE 1 | Columbia Basin |
| **MGSC** Midwest Geological Sequestration Consortium | OIL-BEARING 2 3 4<br>SALINE 5<br>COAL SEAM 6 | Illinois Basin |
| **MRCSP** Midwest Regional Carbon Sequestration Partnership | SALINE 7 8 9 | Cincinnati Arch, Michigan Basin, Appalachian Basin |
| **PCOR** The Plains $CO_2$ Reduction Partnership | OIL-BEARING 10 11<br>COAL SEAM 12 | Keg River, Duperow, Williston Basin |
| **SECARB** Southeast Regional Carbon Sequestration Partnership | OIL-BEARING 13<br>SALINE 14<br>COAL SEAM 15 16 | Gulf Coast, Mississippi Salt Basin, Central Appalachian, Black Warrior Basin |
| **SWP** Southwest Regional Partnership on Carbon Sequestration | OIL-BEARING 17 18<br>COAL SEAM 19 | Paradox Basin, Aneth Field, Permian Basin, San Juan Basin |
| **WESTCARB** West Coast Regional Carbon Sequestration Partnership | SALINE 20 | Colorado Plateau |
| **Other Small Scale Injections** | | |
| University of Kansas | OIL-BEARING & SALINE 1 | Sedgwick Basin |
| Virginia Tech | COAL SEAM 2-a<br>ORGANIC SHALE 2-b | Appalachian Basin; Sourwood or Oakwood CBM fields |

# RCSP Development Phase Large-Scale Field Projects

***>10 million metric tons stored.***




**Big Sky Carbon Sequestration Partnership**

***Kevin Dome Project***

**Injection canceled**

**Midwest Regional Carbon Sequestration Partnership**

***Michigan Basin Project***

**628,882 metric tons**

**(injection on-going)**

**Plains $CO_2$ Reduction Partnership**

***Bell Creek Field Project***

**2,982,000 metric tons (injection complete)**

**Midwest Geological Sequestration Consortium**

***Illinois Basin Decatur Project***

**1,000,000 metric tons (injection complete)**

**Southwest Regional Carbon Sequestration Partnership**

***Farnsworth Unit – Ochiltree Project***

**505,494 metric tons**

**(Injection on-going)**

**Southeast Regional Carbon Sequestration Partnership**

***Cranfield Project***

**4,743,898 metric tons (injection complete)**

**Southeast Regional Carbon Sequestration Partnership**

***Citronelle Project***

**114,104 metric tons (injection complete)**

*Injection volumes as of December 2016*

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# RCSP Key Accomplishments

- Demonstrated large-scale injectivity and available capacity in regionally important storage formations.
- Provided examples of simulation models and MVA technologies that can reasonably predict $CO_2$ movement and confirm confining system integrity.
- Contributing toward developing and evaluating innovative storage technologies for a cost-effective commercial toolbox.
- Developed and implemented risk management strategies.
- Demonstrated the benefits of early engagement with local communities and stakeholders.

# RCSP Lessons Learned

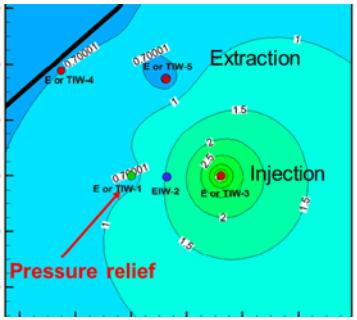
- Injection-induced seismicity is very hard to predict
  - World-class microseimic dataset in Illinois
- Reservoir heterogeneity greatly affects $CO_2$ movement
  - Internal reservoir baffles are hard to model
- 3D imaging of injected $CO_2$ has resolution challenges
  - Need improvements in plume detection
  - Integration of monitoring technologies required
- Early communications with public & regulators is a must
- Many depositional environments yet to test
  - Each geology presents unique challenges and opportunities

# Lessons learned documented in a series of best practice manuals

| Best Practices Manual | Version 1 (Phase II) | Version 2 (Phase III) | Final Guidelines (Post Injection) |
|---|---|---|---|
| Monitoring, Verification and Accounting (MVA) for Geologic Storage Projects | 2009/2012 | 2017 | 2020 |
| Public Outreach and Education for Geologic Storage Projects | 2009 | 2017 | 2020 |
| Site Screening, Selection, and Characterization for Geologic Storage Projects | 2013 | 2017 | 2020 |
| Risk Analysis and Simulation for Geologic Storage of $CO_2$ | 2010 | 2017 | 2020 |
| Operations for Geologic Storage Projects | - | 2017 | 2020 |

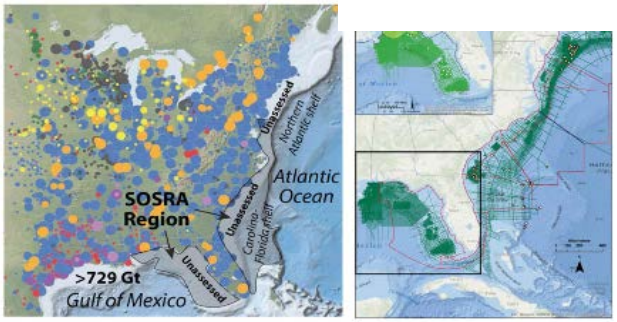
**http://www.netl.doe.gov/research/coal/carbon-storage/publications**

# Fit for Purpose Projects



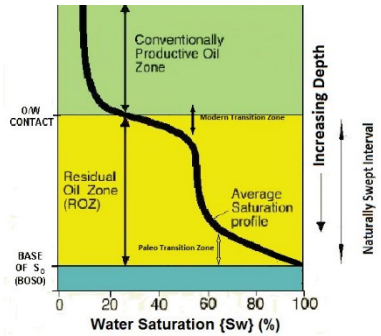

**Brine Extraction Storage Test (BEST)**

- Developing approaches to manage reservoir pressure to improve reservoir storage efficiency while ensuring containment effectiveness and reducing the risk of induced seismicity.




**Offshore Storage Resource Assessment**

- Prospective Storage Resource for East Coast and/or Gulf of Mexico
- Depleted Oil and Natural Gas Reservoirs and Saline Formations.



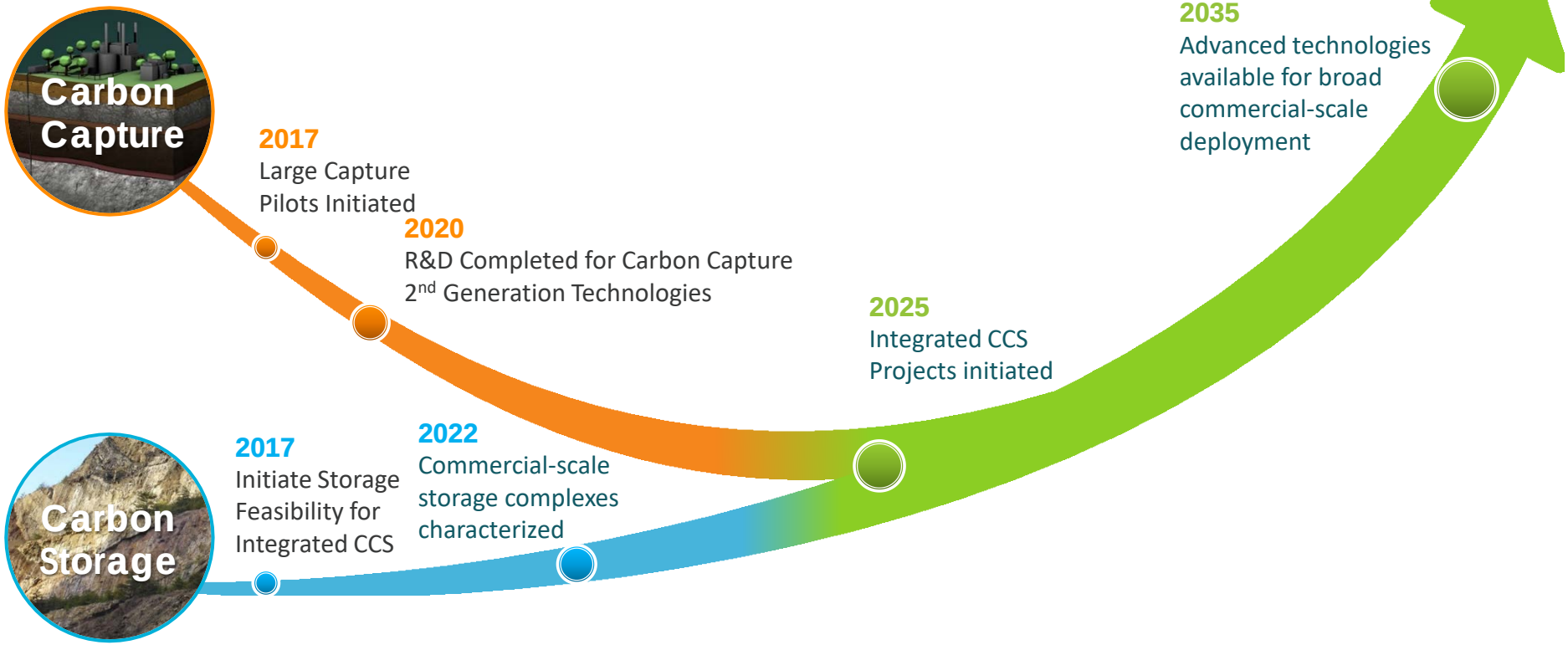

**Unconventional EOR and Associated Storage**

- Residual Oil Zones (ROZ)
- EOR from tight oil formations (organic-rich shale)

# Carbon Storage Assurance Facility Enterprise (CarbonSAFE)

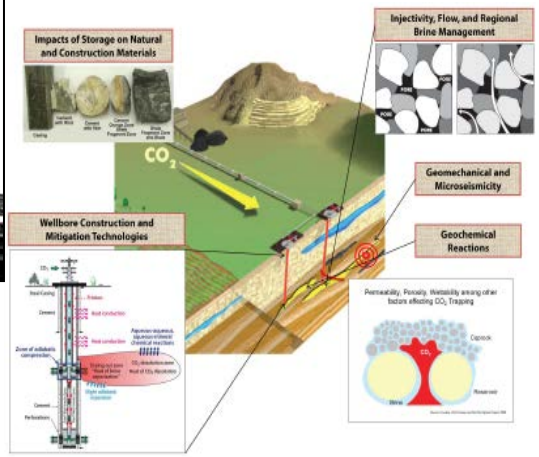
- CarbonSAFE's aim is to develop integrated $CO_2$ storage complexes with storage capacity greater than 50 million metric tons that are characterized, constructed, and permitted for operation.
- Will be implemented as a phased approach, concluding around 2025.
  - Phase I – Pre-Feasibility
  - Phase II – Storage Complex Feasibility
  - Phase III – Site Characterization
  - Phase IV – Permitting and Construction
- In November we selected 16 carbon storage projects selected; initial funding of $29 million.
- Down selection approach but competitive through each phase.
- We expected to award 1-3 Phase III projects depending on funding availability.

# Integrated R&D Approach for Future Commercial-Scale Deployment



# CCUS Technology Development and Market Mechanisms

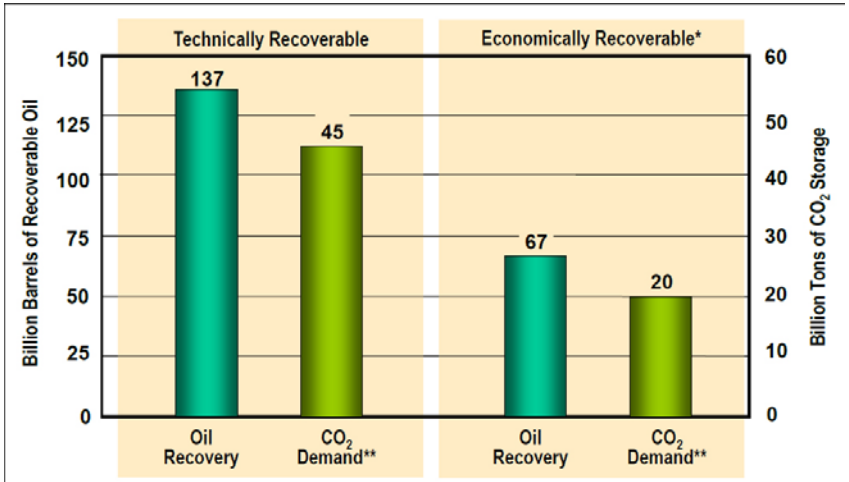
## *Technology Push*




- R&D
- Demos (integration and learning)

## *Market Pull*

**Domestic Oil Supplies and $CO_2$ Demand (Storage) Volumes from "Next Generation" $CO_2$-EOR Technology****




*At an oil price of $85/B, a $CO_2$ market price of $40/mt and a 20% ROR, before tax.
**Includes 2,300 million metric tons of $CO_2$ provided from natural sources and 2.6 billion barrels already produced or being developed with miscible $CO_2$-EOR.
Source: Advanced Resources Int'l (2011).

- Existing Market Mechanisms: Enhanced Oil Recovery (EOR)
- Financing (Tax Credits and Loan Guarantees)
- Regulatory Framework (Evolving)

# Regulatory framework in place

- EPA Underground Injection Control (UIC) Program: Responsible for protection of underground sources of drinking water (USDWs)
  - Class II – EOR
  - Class VI – CO2 for Geologic Storage

- EPA Clean Power Plan – Clean Air Act Sections 111(b) and 111(d) Proposed Rules

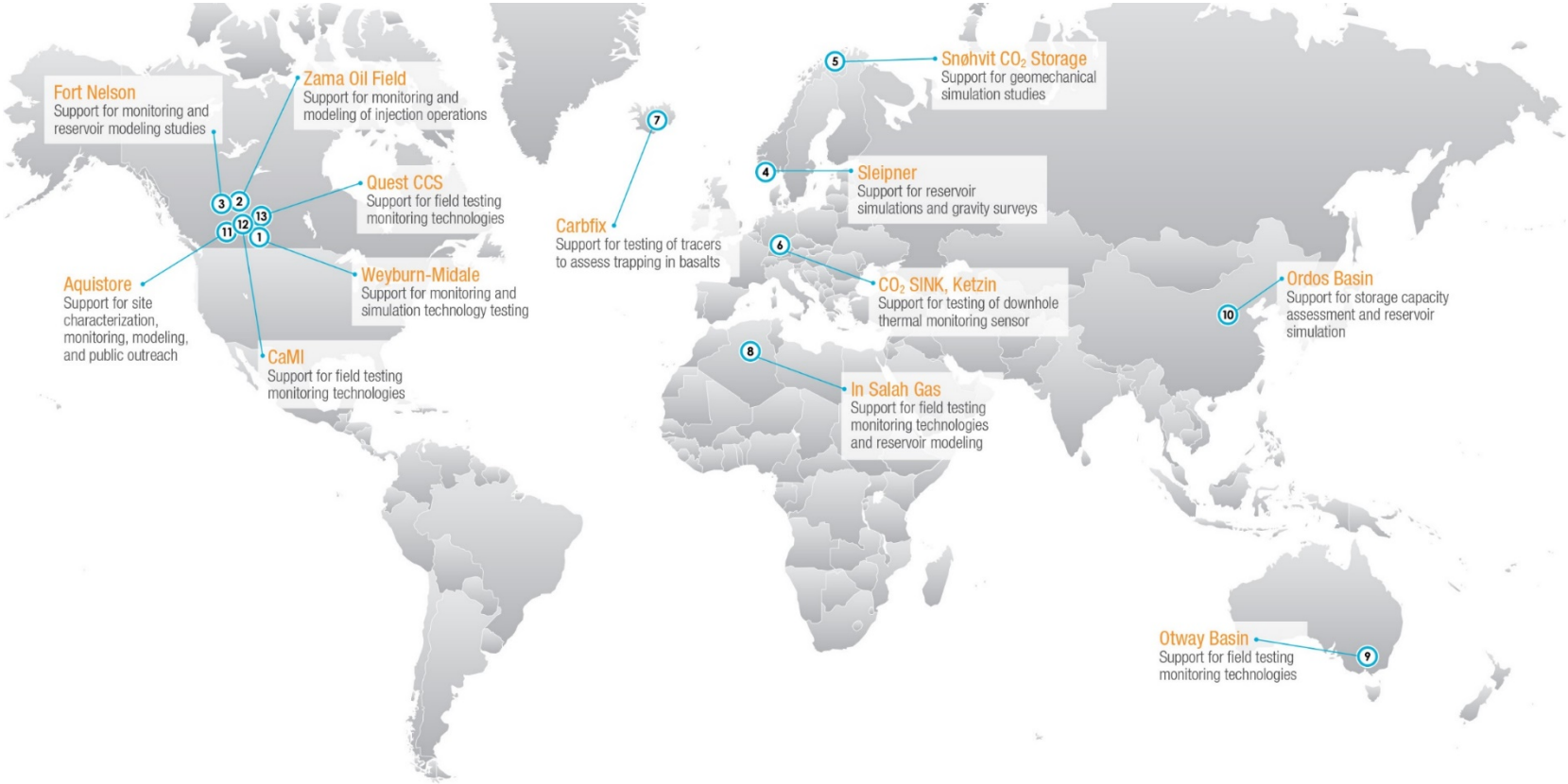
- EPA GHG Reporting Rule: Requires reporting of GHG emissions from sources (FINAL)
  - Subpart RR – CO2 Geologic Storage
  - Subpart UU – EOR
  - Geologic Storage R&D projects granted an exemption from subpart RR but subject to subpart UU reporting

# Lessons learned have help identify issues that still requiring further research

- Need to improve the fidelity of technologies to better characterize reservoir heterogeneity.
  - Leads to improved capability to predict and monitor CO2 plume and brine pressure front movement, stabilization, and impacts.
- Need to validate risk-assessment tools an methods
  - Leads to the capability to develop strategies and protocol for managing and mitigation risks at a particular site.
- Need MVA technologies that can better quantify $CO_2$ saturation in the far field, away from wellbores.
  - Leads to improved conformance verification.
- Need to better understand the relationship between induced microseismicity and the migration of pressure and fluid, as well as the risk of inducing larger (felt) seismic events.
  - Leads to the capability to forecast risk levels as a system to avoid induced seismicity.
- Need intelligent monitoring systems for real-time operating solutions.
  - Leads to the capability to optimize $CO_2$ storage capacity.

# Global Collaborations

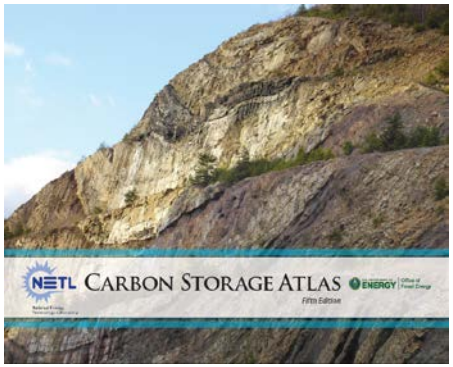
*Leveraging International Geologic Storage R&D Projects*



# Mission Innovation

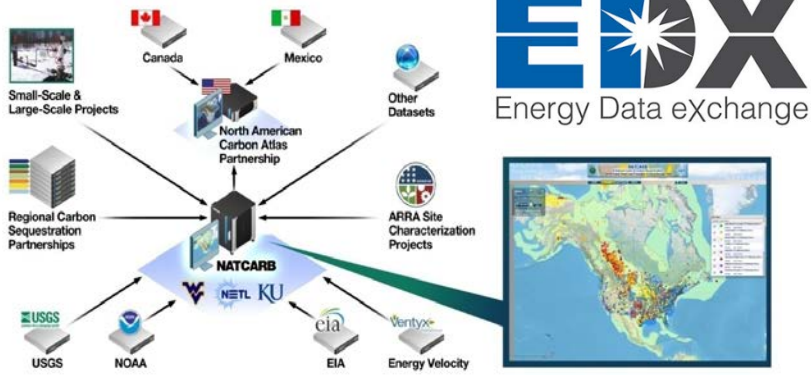
- U.S remains committed to MI
- A Technical Mission Innovation CCUS workshop is planned for mid-2017
- Co-lead by the United States and Saudi Arabia
- Will convene top experts to discuss breakthrough opportunities and find international RD&D synergies in carbon capture, storage, and $CO_2$ utilization

# Knowledge Sharing Products




*Worldwide CCS Project Database*


- Annual Carbon Storage Meeting
- RCSP Working Groups
- Domestic Collaborations
- International Collaborations
- Technical Workshops


EDX
Energy Data eXchange

# Thank you !

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