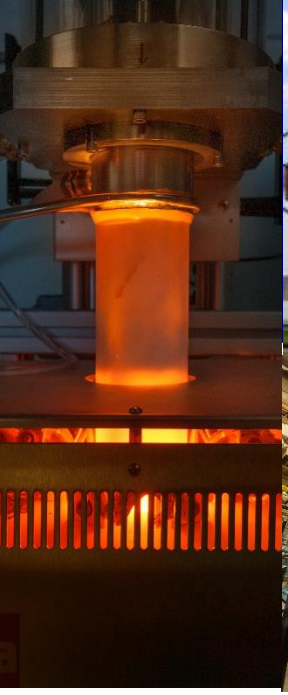
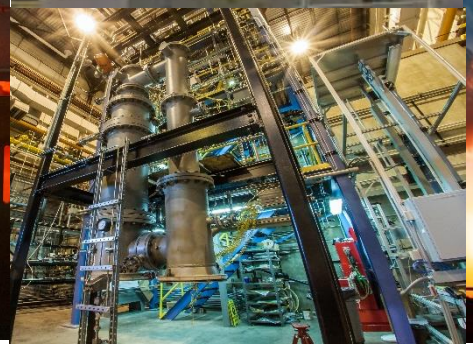





U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy

Looking at the Future of CCUS and Clean Coal Technologies

Angelos Kokkinos
Associate Deputy Assistant Secretary

Office of Clean Coal and Carbon Management

Western States Coal Strategies Forum | November 2019 | Moab, Utah

OFFICE OF CLEAN COAL AND CARBON MANAGEMENT

Mission:

Discover and develop advanced coal technologies that ensure America's access to resilient, affordable, reliable, and near-zero emitting coal energy resources.

R&D Priorities:

1. Advancing small-scale modular coal plants of the future, which are highly efficient and flexible, with near-zero emissions
2. Improving the performance, reliability, and efficiency of the existing coal-fired fleet
3. Reducing the cost of carbon capture
4. Creating new market opportunities for coal

HOLISTIC APPROACH TO ENERGY GENERATION FROM FOSSIL FUELS

COAL R&D OVERVIEW

Advanced Energy Systems	Crosscutting Research	CO_2 Capture and Utilization	CO_2 Storage
Efficiency improvements for new and existing units	***Crosscutting technology development program***	***Reducing the cost of CO_2 capture for new and existing units***	***Safely and permanently storing CO_2***
• Advanced energy materials • Advanced gasification • Solid oxide fuel cells • Advanced coal processing • Advanced turbines • Advanced combustion • Sensors and controls	• Power generation efficiency • Supercritical transformational electric power • Critical minerals • Coal utilization science • Transformational coal pilots • University research • SBIR/STTR* • Technology Commercialization Fund (TCF)*	• Post-combustion capture • Pre-combustion capture • New pathways to utilize captured CO_2	• Safe use and permanent storage of CO_2 from power generation and industry • Minimizing subsurface risks (coordinated with other subsurface offices, e.g., Office of Oil and Natural Gas) • CO_2 infrastructure analysis

Note: Programmatic not necessarily budgetary groupings
**SBIR/STTR and TCF are managed under the Crosscutting Program but funded by all R&D programs*

CLEAN COAL AND CARBON MANAGEMENT BUDGET OVERVIEW

(SUBJECT TO APPROPRIATION)

CCS and Power Systems ($ in thousands)	FY 2019 Enacted	FY 2020 House	FY 2020 Senate	Future Plants	Existing Plants	Cost of Capture	New Markets
Carbon Capture	100,671	125,000	113,000	✓	✓	✓	
Carbon Storage	98,096	102,000	103,000			✓	✓
Advanced Energy Systems	129,683	107,000	139,000	✓	✓	✓	✓
Crosscutting Research*	56,350	65,255	64,300	✓	✓		
Rare Earth Elements*	18,000	23,000	25,000				✓
STEP (Supercritical CO2)	22,430	24,000	14,000	✓	✓		
Transformational Coal Pilots	25,000	20,000	17,000	✓	✓	✓	
NETL Coal R&D*	36,000	38,000	42,000	✓	✓	✓	✓
TOTAL CCS & Power Systems	**486,230**	**504,255**	**517,300**				

Coal R&D Budget Priorities

- **Implementing** the **Coal FIRST** (Flexible, Integrated, Resilient, Small, Transformative) initiative: R&D on first-of-a-kind small-scale modular coal plants of the future, which are highly efficient and flexible, with near-zero emissions
- **Improving** the performance, reliability, and efficiency of the existing coal-fired fleet
- **Reducing** the cost and risk of carbon capture for commercial deployment
- **Creating** new market opportunities for coal

Coal FIRST: THE FUTURE OF POWER GENERATION

(Flexible, Innovative, Resilient, Small, Transformative)

Secure, Stable, Reliable Power
Near-Zero Emissions

Flexible **coal plant operations to meet the needs of the grid**

Transforms **how coal technologies are designed and manufactured**

Innovative **and cutting-edge components; improved efficiency and near-zero emissions**

Smaller **than conventional utility-scale coal plants**

Resilient **power generation**

COAL FIRST – A FLAGSHIP INITIATIVE

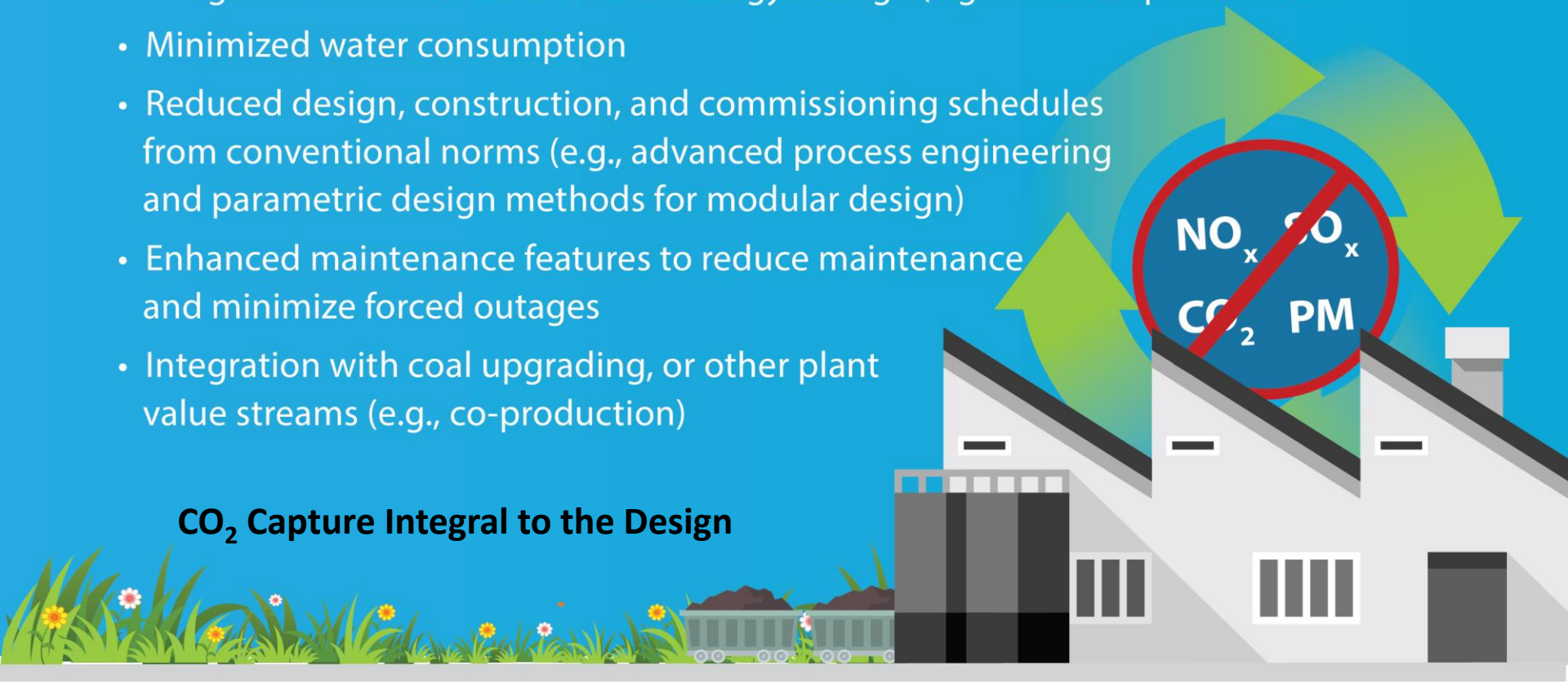
Per International Energy Agency (IEA), coal will be the largest source of electricity production in the world by 2040, and likely beyond

- Provides a **zero or near zero CO_2 emissions**
- Provides **low cost power generation**; economically competitive
- Uses advanced materials and processes; **maximizes efficiency**
- **Global solution for CO_2 emissions** -- carbon capture
- **Only** zero or near zero CO_2 emissions power plant **R&D effort in the world**
- Potential to **revive the US coal industry**; provide a source of **high value exports**
- Provides stability and reliability to the grid of the future, and offers both **"firm and flexible" operations**

TRAITS OF THE COAL FIRST TECHNOLOGIES

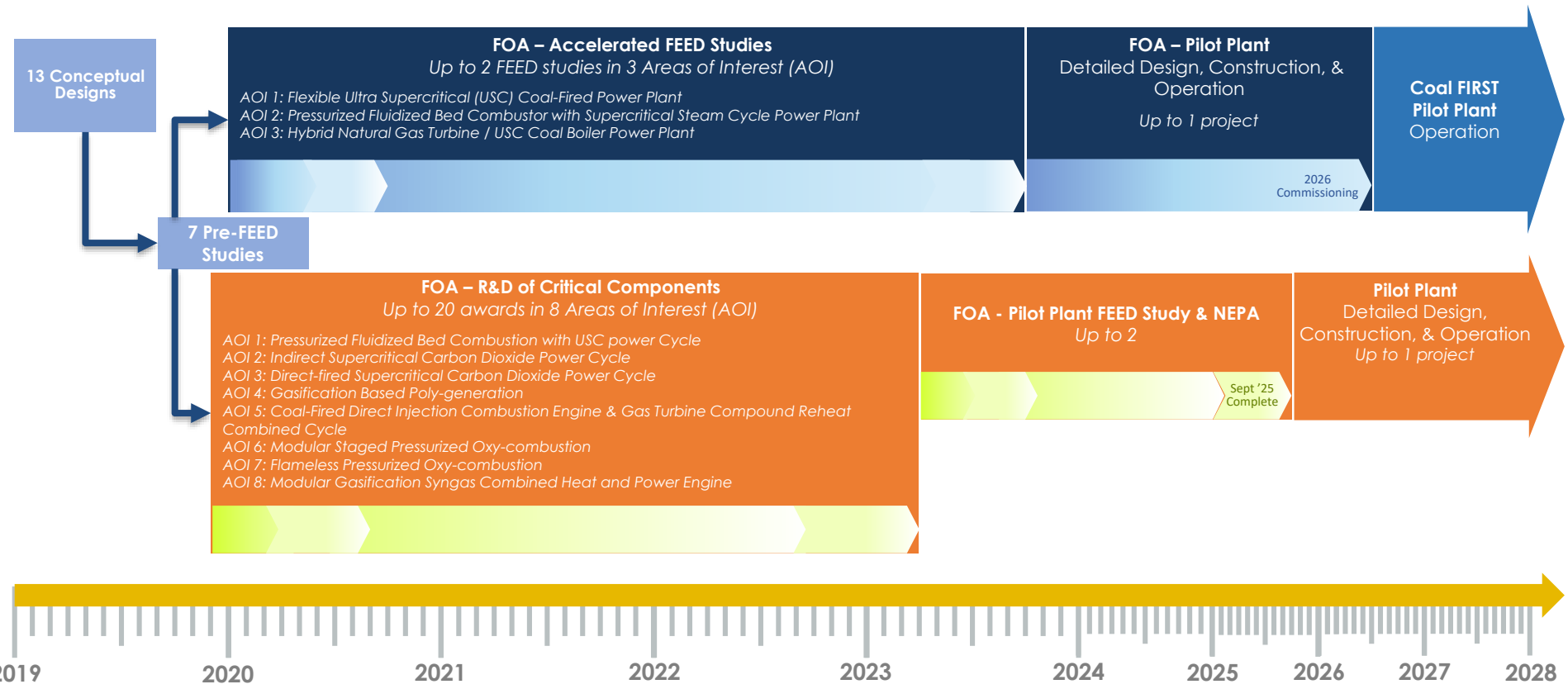
- High overall plant efficiency (40%+ HHV or higher at full load)
- Small (unit sizes of approximately 50 to 350 MW)
- Near-zero emissions
- Capable of high ramp rates and minimum loads
- Integration with thermal or other energy storage (e.g. chemical production
- Minimized water consumption
- Reduced design, construction, and commissioning schedules from conventional norms (e.g., advanced process engineering and parametric design methods for modular design)
- Enhanced maintenance features to reduce maintenance and minimize forced outages
- Integration with coal upgrading, or other plant value streams (e.g., co-production)

CO_2 Capture Integral to the Design



COAL FIRST TIMELINE

As of October 2019



Coal FIRST: THE FUTURE OF POWER GENERATION

Selectee	Project Description
Barr Engineering Co.	USC Coal Boiler with Gas Turbine
Electric Power Research Institute	Small-Scale Flexible AUSC Power Plant
Nexant Inc.	DICE w/Gas Turbine and Steam Bottoming Cycle
Barr Engineering Co.	Gasification w/Syngas Chemical Looping and H2 Storage
Allegheny Science & Technology	Gasification/Polygeneration w/Bottoming Cycle
HECA	IGCC w/Chemical Plant, H_2 Fuel Cells, and Battery Storage
WES Inc.	All Steam IGCC w/Polygeneration

Coal FIRST

All concepts include carbon capture

Selectee (cont.)	Project Description (cont.)
CONSOL Pennsylvania Coal Company	PFBC w/SC Steam and Benfield Process
Constantem Technologies	Pressurized Oxy CFB
Washington University	Stage Pressurized Oxy-Combustion USC or SC steam
Echogen Power Systems	Indirect SCO_2 and Electrothermal Energy Storage
WES Inc.	Direct Fired SCO2 All Steam Gasification w/Allam Cycle
8 Rivers Capital LLC	Direct Fired SCO_2 - Coal-fired w/Allam Cycle

GLOBAL LEADERSHIP

U.S. Leading on CCUS Research, Development, and Deployment

Key international partnerships

40+ year history of CO_2 utilization for EOR

Over 600 million tons of associated storage with EOR

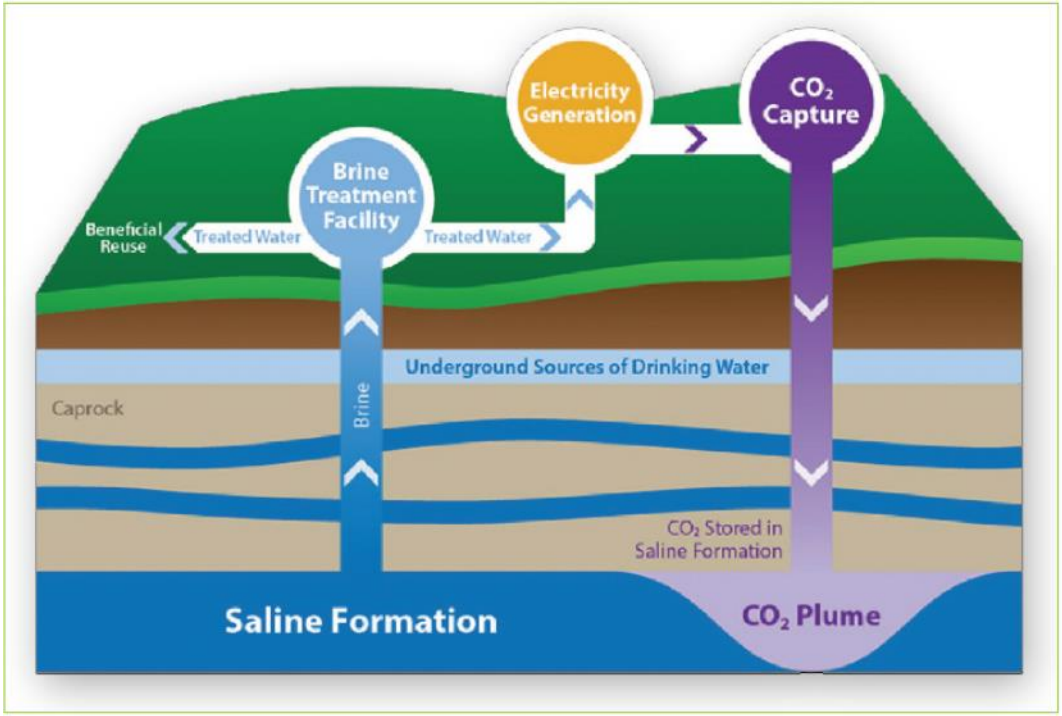
Over 4,000 miles of CO_2 pipelines in the United States

- **The strongest country in developing the human capital and enablers for CCUS deployment (scientists, engineers, trades)**
  - Broad R&D program engaging Private Industry, Universities, National Laboratories, small business, and the financial community.
- **More major CCUS demonstrations than any other country**
- **Through the DOE/FE, leading one of the most globally recognized and successful RD&D programs on CCUS…. And leveraging this technology, science, and knowledge with other agencies for sound policy development**

EXCITING TIME FOR CCUS

Carbon capture, utilization, and storage (CCUS) is increasingly becoming widely accepted as a viable option for fossil-based energy to lower their carbon dioxide (CO_2) emissions.

- Capture FEED Studies
- CarbonSAFE Initiative
- Regional Initiative to Accelerate CCUS
- 45Q Tax credit
- CCUS Demonstration Projects



Here's what we can do moving forward…

U.S. POLICY INCENTIVES FOR CCUS - 45Q TAX CREDITS

"Technology push" through R&D is matched with "market pull" through financial incentives

- Tax benefits in "45Q" for qualified CCUS projects have been available since 2008
- The February 2018 "Bipartisan Budget Act of 2018" extended and significantly expanded the tax benefits:

  - **Increased the credit amount**:
    $20/ton → up to $50/ton for geologic storage, $10/ton → up to $35/ton for EOR (by 2026)
  - **Qualified facilities** must begin construction by January 1, 2024, include carbon capture in original design, and capture 25,0000/500,000 tons of CO_2
  - **Expanded the qualified carbon oxides** to include carbon monoxide (CO) and CO_2 captured from an industrial source or the ambient air
  - **Expanded qualified uses** to include CO_2 utilization (beyond EOR)
  - **Lowered the qualifying threshold** for the amount of CO_2 captured
  - **Increased the flexibility for assignment of credits**
  - **Removed the program cap**

Treasury working to finalize guidance for project developers

HIGH-LEVEL R&D PROGRAM GOALS AND CHALLENGES

Reduce the cost of capture by 50%

- Capital cost
- Energy penalty
- Integration or process intensification

2012:$80/tonne
2016: $60
2020: $40
2030: $30

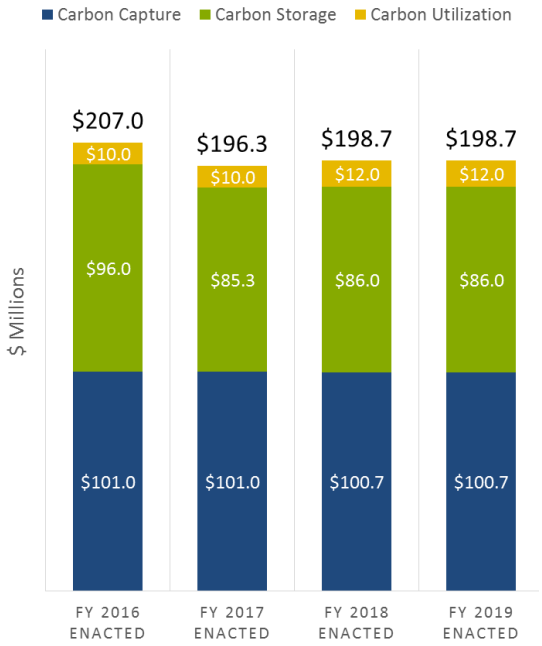
Source: NETL, Cost and Performance Baseline for Fossil Energy Plants, Revision 3, July 2015

Develop viable carbon utilization alternatives ($1T opportunity)

- Reduce Capital cost
- Reduce energy requirements
- Lifecycle assessment better than existing products

Reduce the risk of geologic storage – improve monitoring and simulation

- Higher resolution and quantification (e.g., accurate characterization of faults and fractures)
- Geomechanics (pressure and state of stress)
- Costs/uncertainty/enabling real-time decision making



CCUS FEED STUDIES SELECTIONS

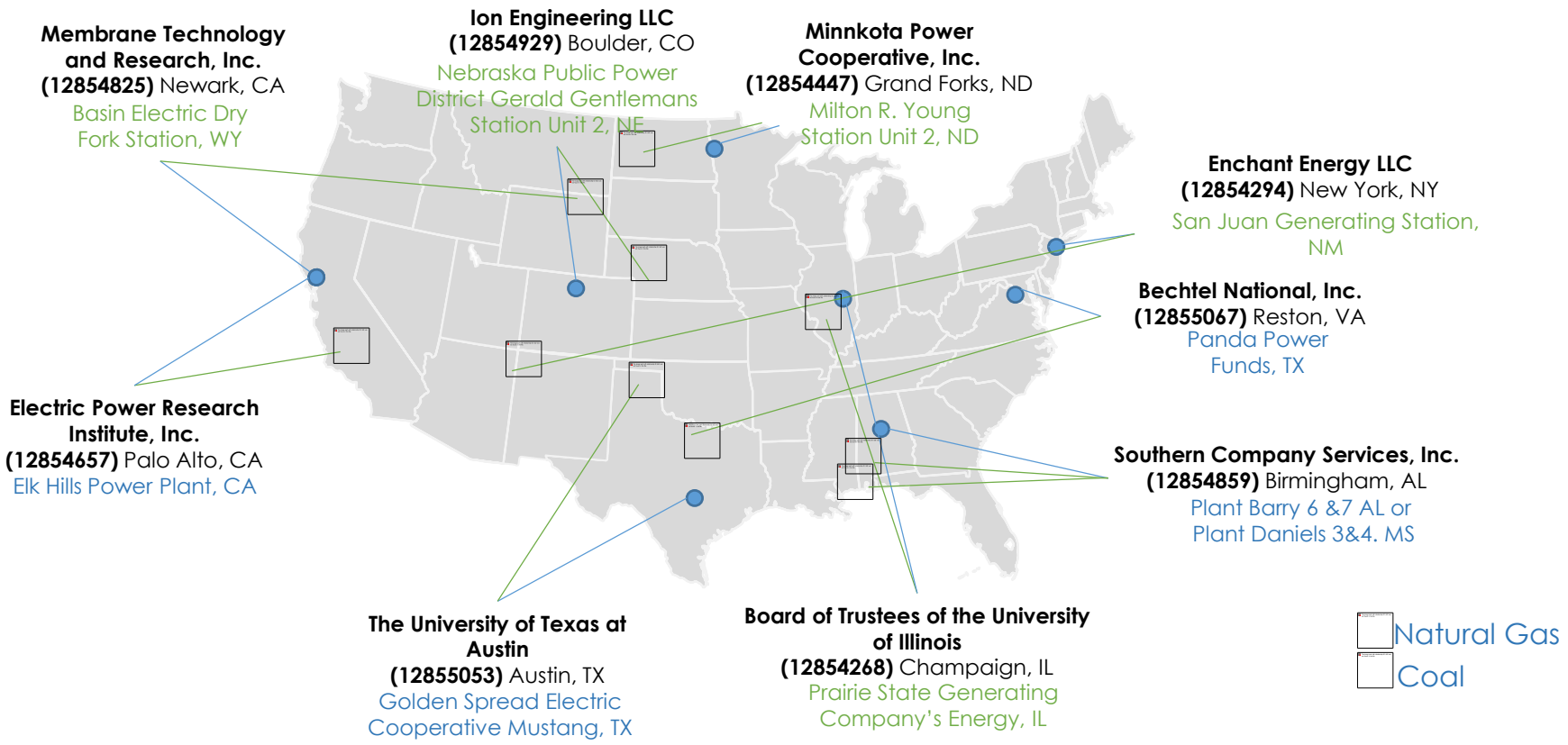
Front-End Engineering Design (FEED) Studies for Carbon Capture Systems on Coal and Natural Gas Power Plants (DE-FOA-0002058, 000001)

Projects will support FEED studies for commercial-scale carbon capture systems

- $55.4 million in Federal funding awarded
- Nine projects selected

Awardee	Project
Bechtel National	FEED Study for Retrofitting a 2x2x1 Natural Gas-Fired Gas Turbine Combined Cycle Power Plant for Carbon Capture Storage/Utilization – MEA Solvent
The Board of Trustees of the University of Illinois	Full-Scale FEED Study for Retrofitting the Prairie State Generating Station with an 816 MWe Capture Plant Using Mitsubishi Heavy Industries of America Post-Combustion CO2 Capture Technology – MHI Solvent
Electric Power Research Institute	Front End Engineering Design Study for Retrofit Post-Combustion Carbon Capture on a Natural Gas Combined Cycle Power Plant – Fluor's amine-based Econamine FG Plus
Enchant Energy	Large-Scale Commercial Carbon Capture Retrofit of the San Juan Generating Station – Commercial Solvent
Ion Engineering	Commercial Carbon Capture Design & Costing: Part Two – Ion Engineering Non- aqueous Solvent
Membrane Technology and Research Inc.	Commercial-Scale Front-End Engineering Study for MTR's Membrane CO2 Capture Process – MTR, Inc Polymeric Membrane
Minnkota Power Cooperative Inc.	Front-End Engineering & Design: Project Tundra Carbon Capture System – Fluor's amine-based Econamine FG Plus
Southern Company Services	Front End Engineering Design of Linde-BASF Advanced Post-Combustion CO2 Capture Technology at a Southern Company Natural Gas-Fired Power Plant – Linde BASF amine Solvent
The University of Texas at Austin	Piperazine Solvent/Advanced Stripper Front-End Engineering Design (PZAS FEED)

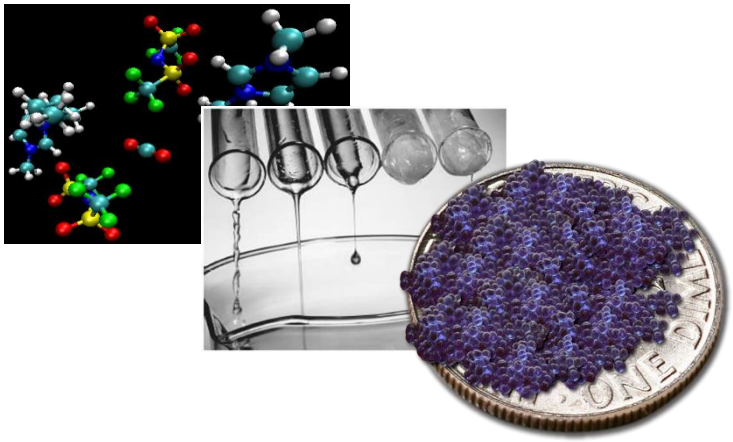
CARBON CAPTURE FRONT-END ENGINEERING DESIGN (FEED) STUDIES



Applicant Locations and Host Sites

FUTURE CARBON CAPTURE ACTIVITIES

- $30/tonne - Transformational Carbon Capture Technologies for both pre and post combustion capture
- Expanding beyond coal: natural gas, industrial, direct air capture (leverage historical investments)
- Process development and design – R&D and Carbon Capture Simulation Initiative for Industry
- Technology Validation – National Carbon Capture Center and other test centers



CCSI

Carbon Capture Simulation for Industry Impact

FUTURE CARBON STORAGE ACTIVITIES

CarbonSAFE Phase III – directed by Congress in FY2019 Appropriations

Machine learning applications

Transformational sensor development

- Improved accuracy, reliability and performance
- Characterize faults and fractures

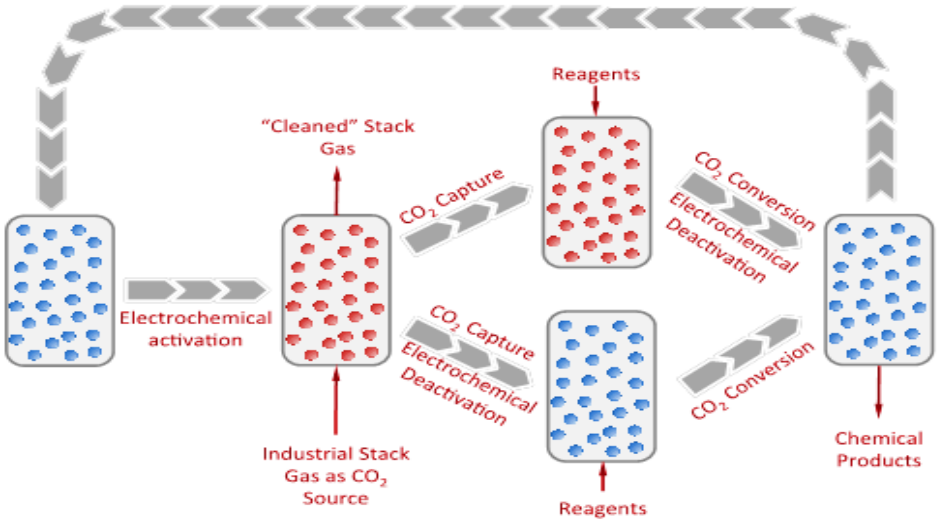
Modeling and simulation tools

CARBON UTILIZATION

OFFSET CO_2 CAPTURE COSTS + FIX CO_2 IN STABLE PRODUCTS

Biological Capture & Conversion

Fuels & Chemicals



Mineralization & Cements

24 Active Projects – Recently selected 11 lab and 4 field-scale projects

Catalysis and Biological Pathways - Fuels and Chemicals

- Projects creating CO or direct to fuels using low-carbon energy and/or hydrogen

Concrete: Solidia Technologies - Utilizes CO_2 to make cement and concrete

- Reduce carbon footprint up to 70%
- $1.9M DOE investment leveraged by industry
- Oil and Gas Climate Initiative's Climate Investment Funded and other parties

Questions?

U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy

Angelos.Kokkinos@hq.doe.gov

COAL & BYPRODUCTS END USE APPLICATIONS

Iron and Steelmaking

- Metallurgical Coke
- Slag Foaming Agent
- Charge Carbon
- DRI Reductant

Non-Ferrous Metallurgy

- Ferroalloys
- Silicon Metal
- Aluminum
- Titanium
- Germanium

Environmental Applications

- Municipal Water/Wastewater Filtration Media
- Activated Carbons

Construction Products

- Cement Additives (Pozzalons)
- Lightweight Aggregates

Chemicals

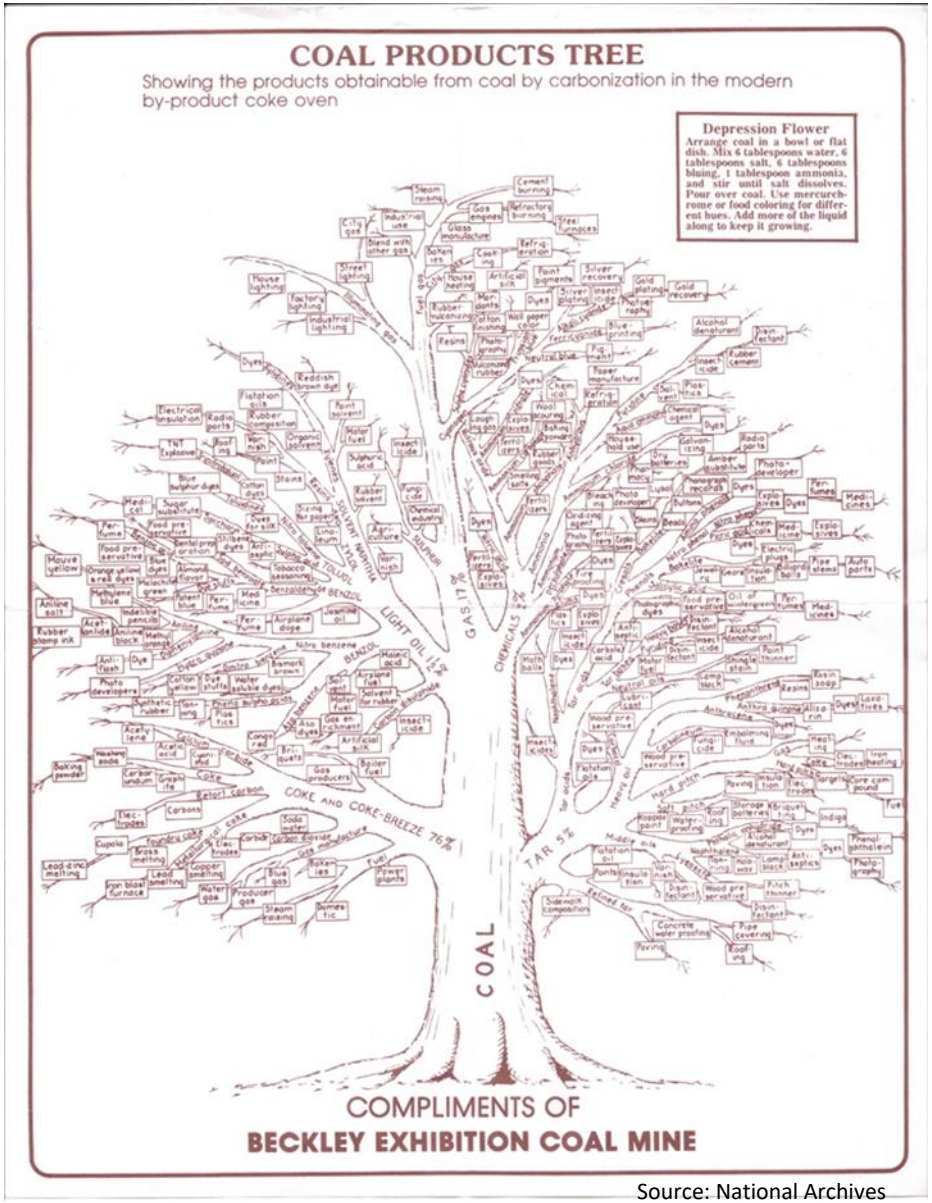
- Wood Preservatives
- Fertilizer
- Aromatics

Consumer Products

- Medicines
- Shampoo

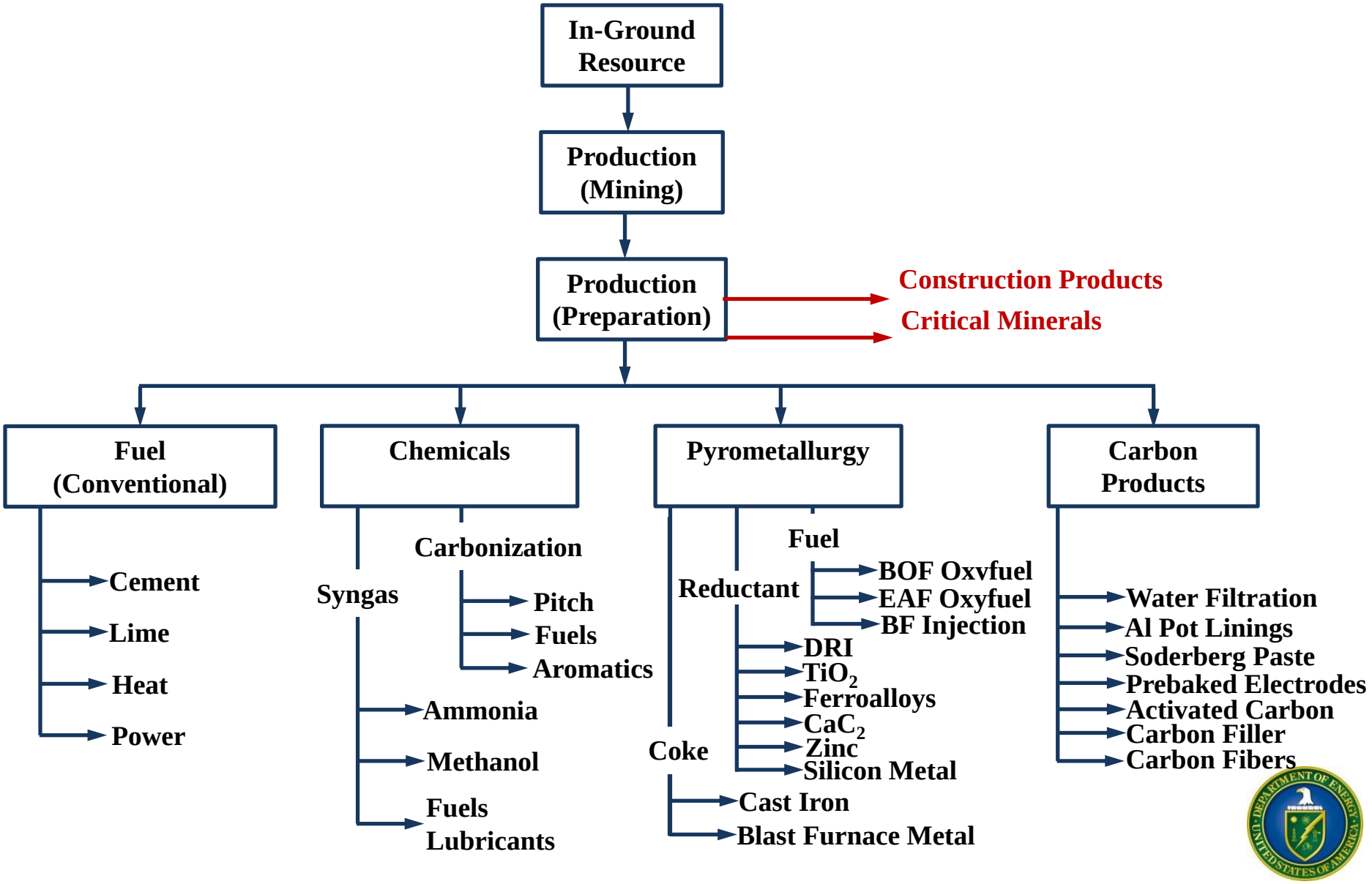
Carbon Products

- Graphite
- Fibers
- Rubber Fillers
- Electrodes



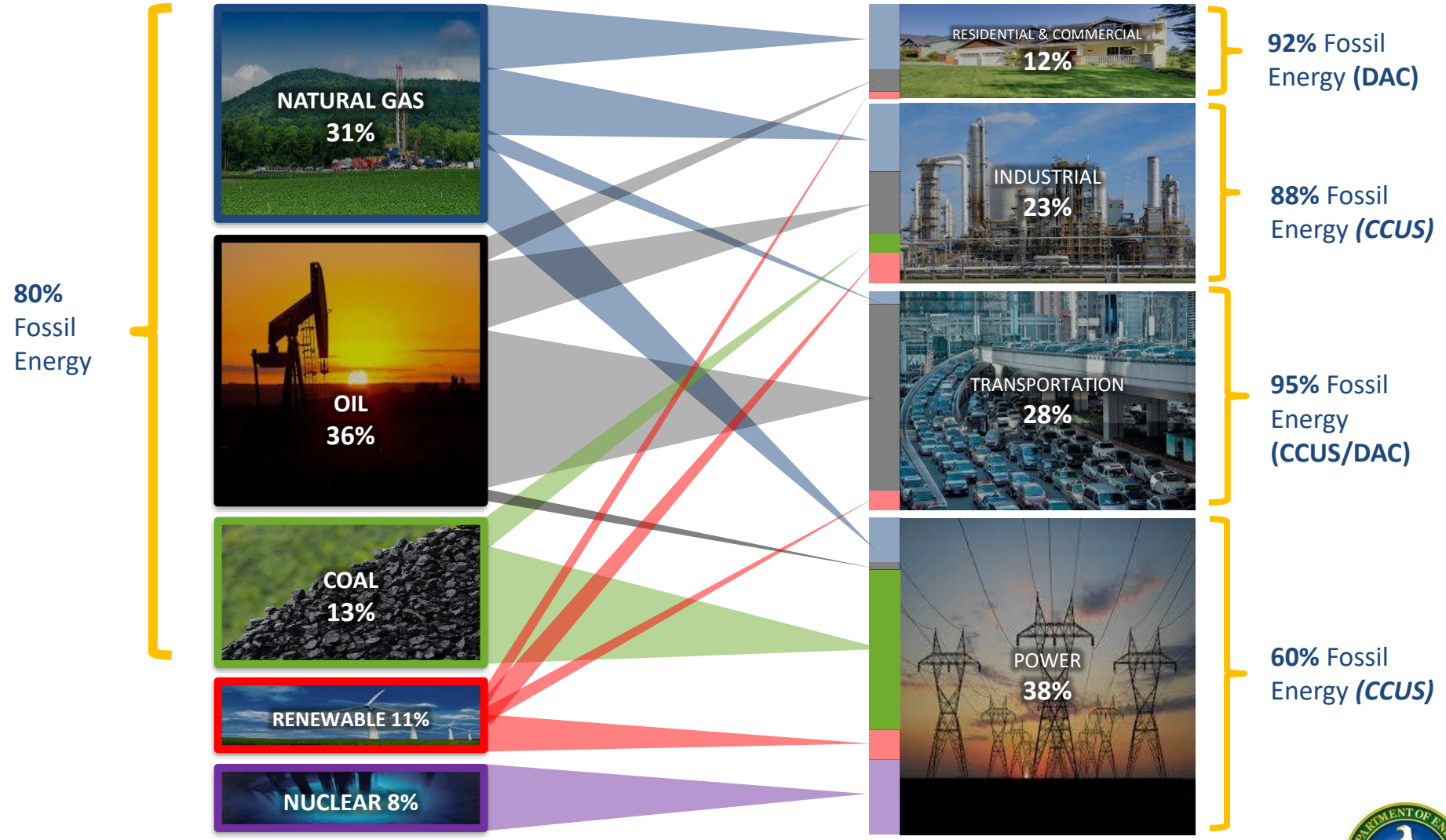
Source: National Archives

COAL USE IN THE MANUFACTURE OF USEFUL PRODUCTS



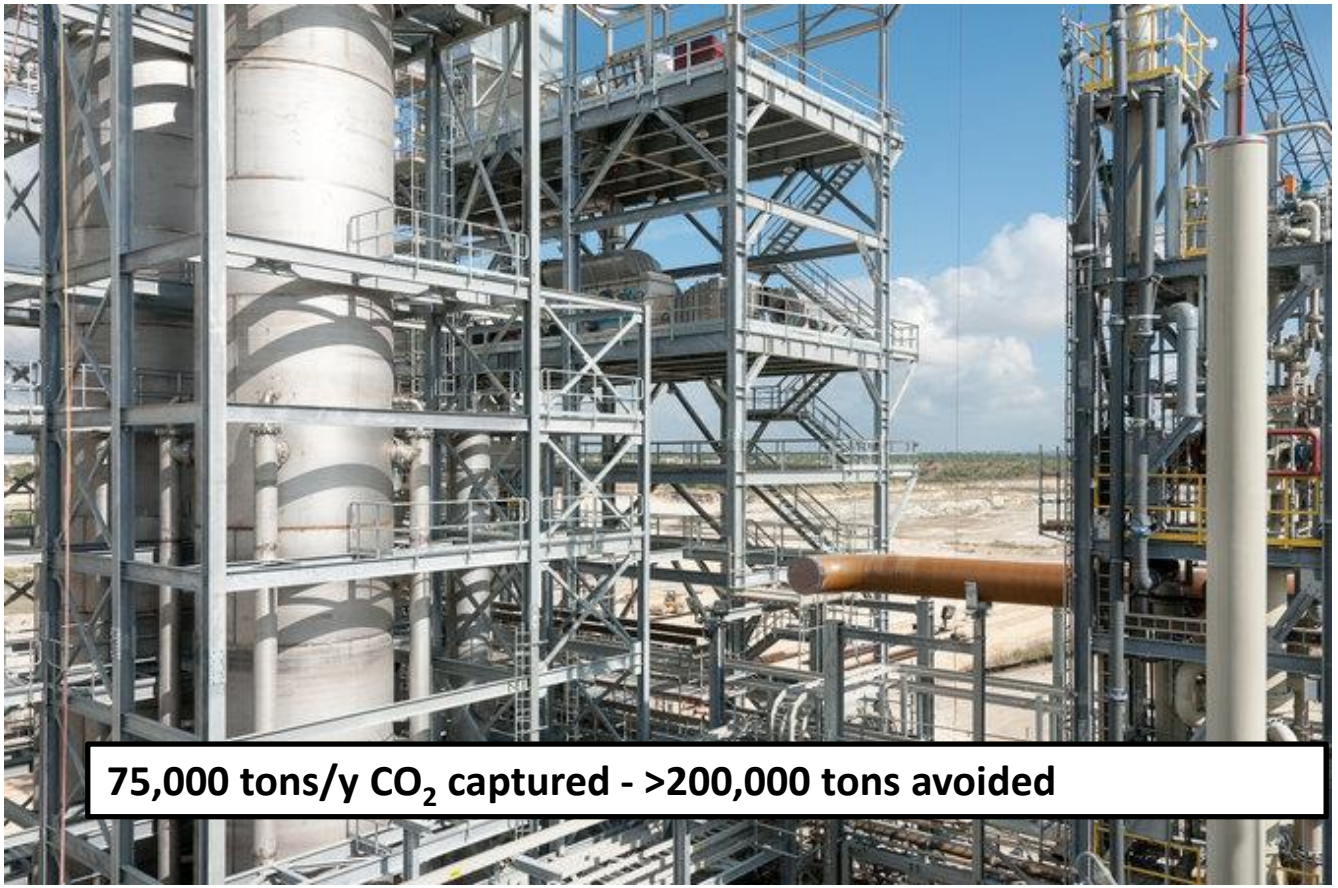
FOSSIL ENERGY IS CRITICAL IN ALL SECTORS

CCUS IS A PLATFORM TECHNOLOGY FOR MANY INDUSTRIAL SECTORS



EIA, *Annual Energy Outlook 2019*, Reference Case, *https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf*

SKYONIC "SKYMINE" PROJECT, SAN ANTONIO, TX



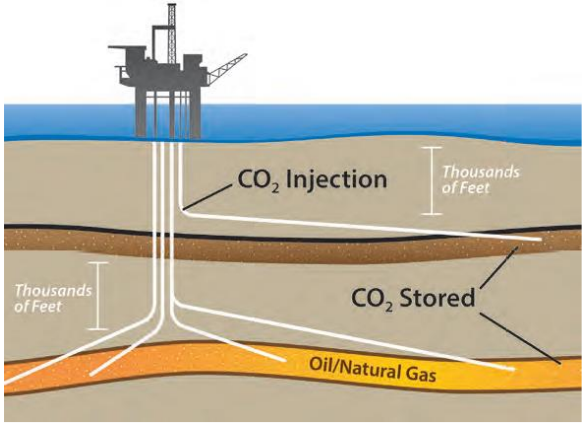
Carbon Storage Infrastructure/Field Tests

Addressing Large-Scale Challenges

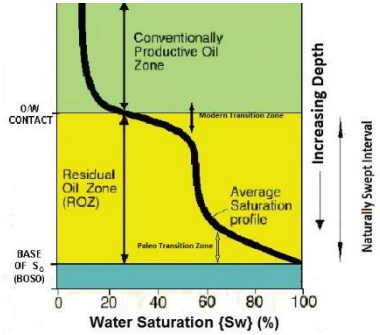
Regional Carbon Sequestration Partnerships (RCSPs)

CarbonSAFE

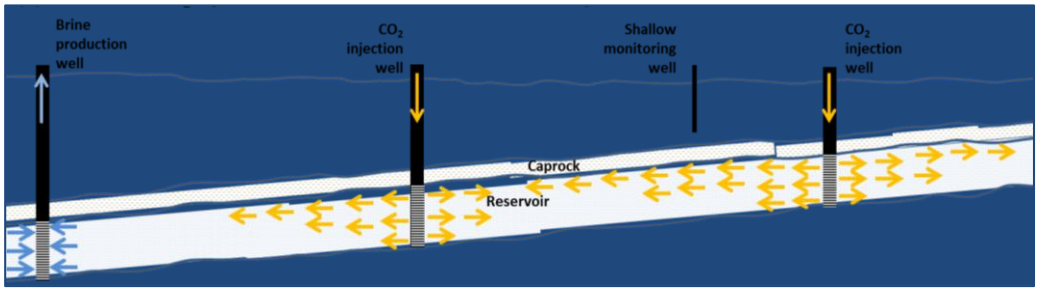
Offshore Storage



Unconventional EOR



Brine Extraction Storage Tests (BEST)



CARBONSAFE PHASED APPROACH

The intent of CarbonSAFE is to address the R&D knowledge gaps and technologies needed for a 50+ million metric tons CO_2 storage:

Phase I: Integrated CCS Pre-Feasibility (18 months)

Formation of a CCS team, Development of a feasibility plan and High-level technical evaluation of the sub-basin and potential CO_2 sources

Phase II: Storage Complex Feasibility (2 years)

Data collection, Geologic analysis, Identification of contractual and regulatory requirements and plans to satisfy them, Subsurface modelling to support geologic characterization, risk assessment, and monitoring, and Public outreach

Subject to Funding Phase III: Site Characterization (2-3 years)

Tentative - Address pore/surface rights, Rights of way, Permitting processes and requirements, Liability relief and Finance agreements

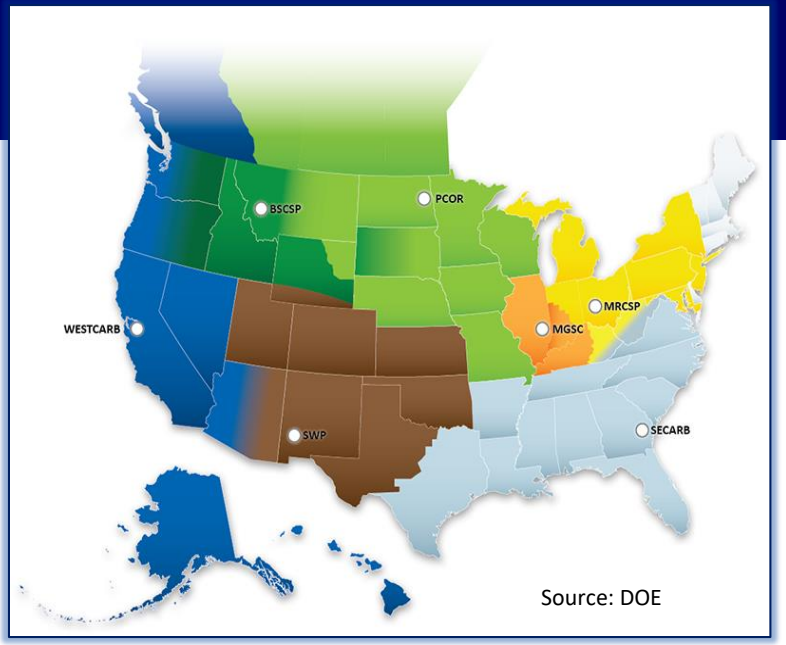
Funding Opportunity DE-FOA-0001999 Now Open

Subject to Funding Phase IV: Permitting and Construction of storage complex

Tentative - Submission of Class VI permits, Drill and Complete injection and monitoring wells, Acquisition of baseline monitoring data and Risk management and mitigation plan

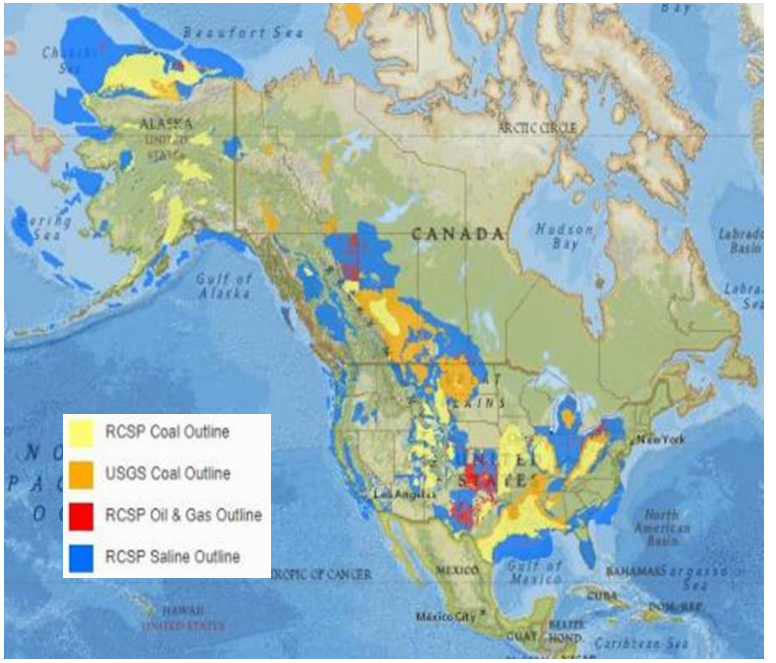
POWER OF REGIONAL PARTNERSHIPS

Injecting more than 10 million metric tons of CO_2 was a great achievement. But there is much more…



The RCSP Initiative has:

- Established the first U.S. carbon storage national network
- Provided the foundation for validating CCUS commercial deployment and monitoring
- Demonstrated the effectiveness of multiple secure storage technologies and use of storage resources
- Participated in the development of technologies regulatory and legal frameworks
- Documented 15 years of experience in a series of topical Best Practice Manuals (BPMs)



EXAMPLES OF MAJOR LEARNINGS

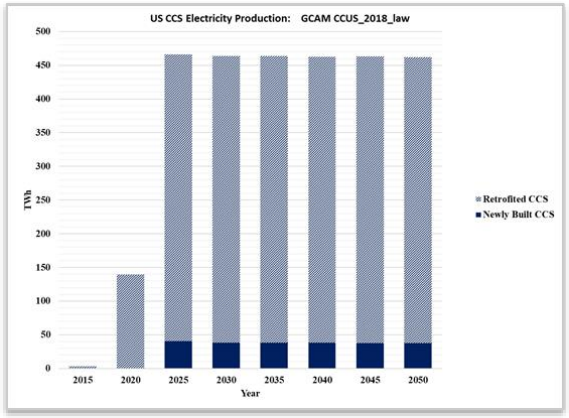
Geochemical risks are small and manageable	• Caprocks tend to get better over time • Wellbore geochemistry risks smaller than first thought
Far–field hydrology risks are small	• E.g., brine volume displacement
Many effective options for characterization and monitoring	• Seeking lower cost/higher certainty options • Sorting types and terrains

U.S. POLICY INCENTIVES FOR CCUS - 45Q TAX CREDITS

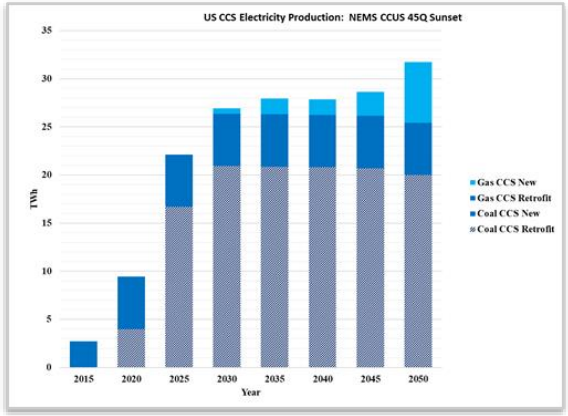
The 45Q tax credit provides an additional positive economic incentive for potential CCUS projects.

Regardless of modeling platform, analysts are finding that 45Q enables deployment of CCS in the power and industrial sectors.

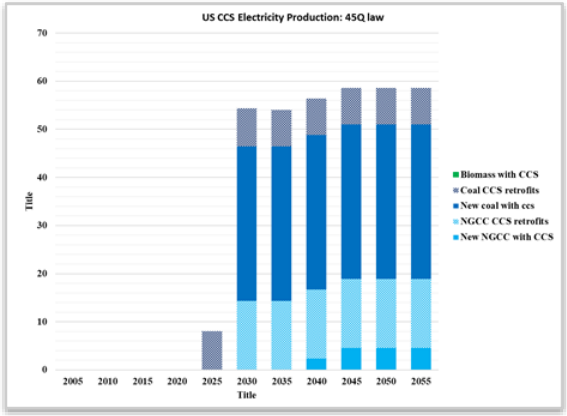
Comparison of electricity generation by CCS technologies – current 45Q



GCAM



NEMS

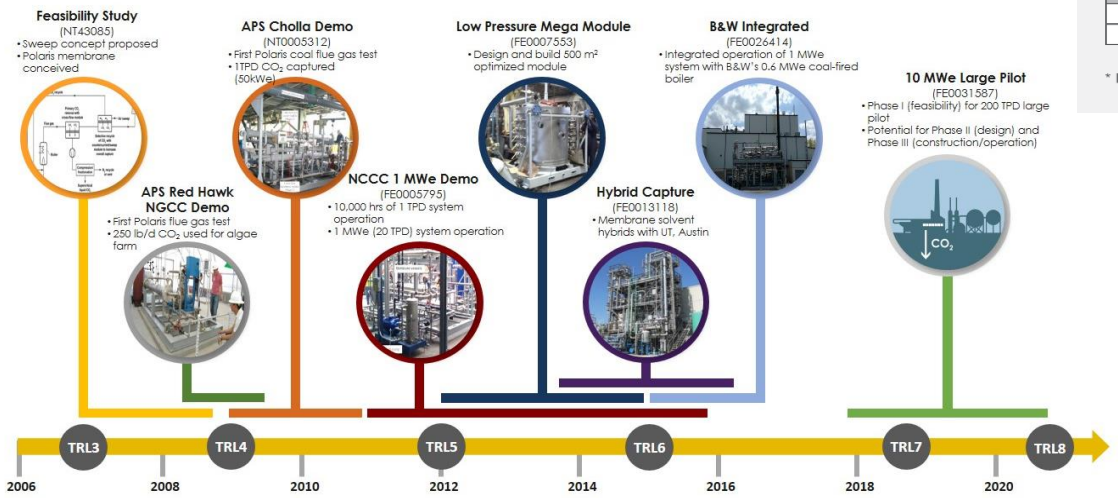


MARKAL

Carbon Capture: Post-Combustion, Pre-Combustion, and Direct Air Capture

Focus on Cost Reduction, Energy Penalty, and Integration

Requires improvements in multiple areas



Summary of Carbon Capture R&D Program Advancement of 2nd Generation Technologies

Cost Reduction	Energy Penalty Reduction	Program Activity
$100+/tonne	30+%	180+ Projects
$41/tonne	14-15%	15 Technologies Tested at Pilot Scale

Pilot-scale Testing

TECHNOLOGY HIGHLIGHTS	Innovation Pathways: Materials	Processes	Equipment	PRINCIPAL DEVELOPER
POST-COMBUSTION				
Imbedded Amine Sorbent*	■	■		ADA-ES
Low-water Amine Solvent	■	■		Fluor/MHI
Hybrid Solvent/Membrane	■	■	■	Gas Technology Institute
Amino-silicone Solvent*	■			General Electric Company
Amine/Imidazole Solvent Mixture* *(Large Pilot)*	■			ION Engineering
Advanced Amine Solvent Process*	■	■		Linde/BASF
Advanced Membrane Process*	■	■		MTR
Nozzle-based Solvent Contactor*			■	Neumann Systems Group
Mixed Salt Solvent Process*	■	■		SRI International
Carbon-based Sorbent*	■			SRI International
Alkalized Alumina Sorbent*	■	■		TDA Research
Optimized Amine Solvent Process	■	■	■	University of Kentucky
Piperazine Solvent/Flash Stripper	■		■	URS/University of Texas
PRE-COMBUSTION				
Ammonium Carbonate/Bicarbonate Solvent*	■			SRI International
Integrated Sorbent Process	■			TDA Research

* Project Completed

Case Study of Technology Development Progression Through the Carbon Capture R&D Program – Membrane Technology Research, Inc.

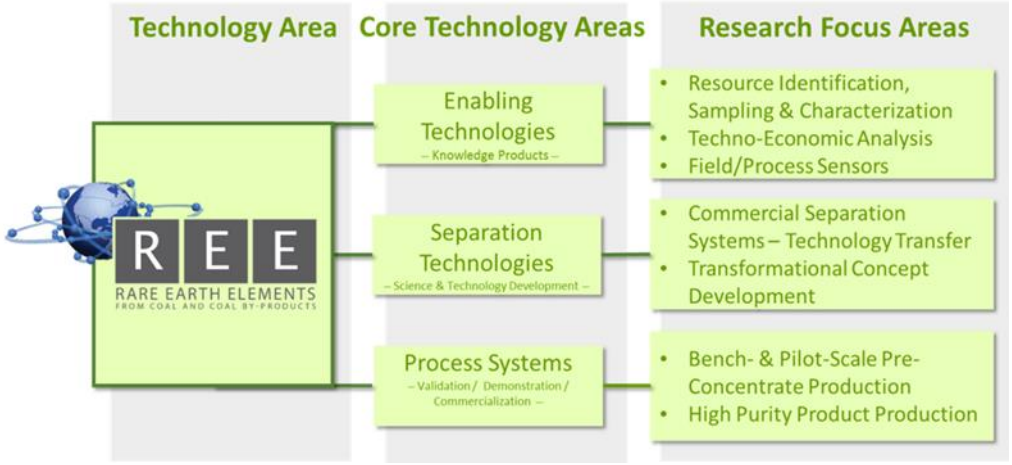
DOE CRITICAL MINERALS EFFORTS

OFFICE OF FOSSIL ENERGY AND OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

Office of Fossil Energy

Development of an economically competitive and sustainable domestic supply of rare earth elements (REEs) and critical materials (CMs) to assist in maintaining our Nation's economic growth and National Security

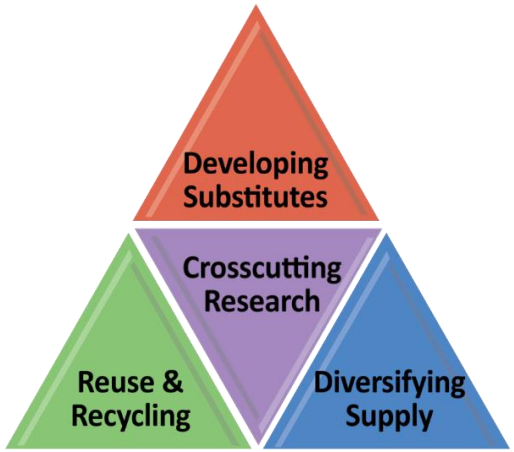


CMI Accelerating Energy Innovations

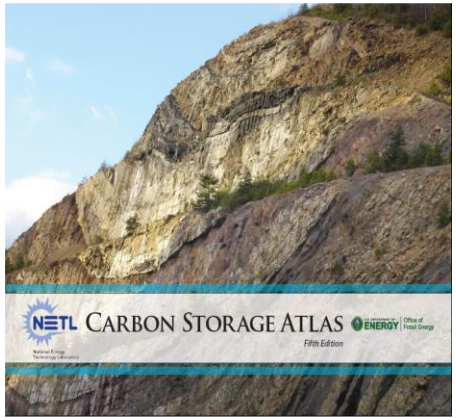
Critical Materials Institute

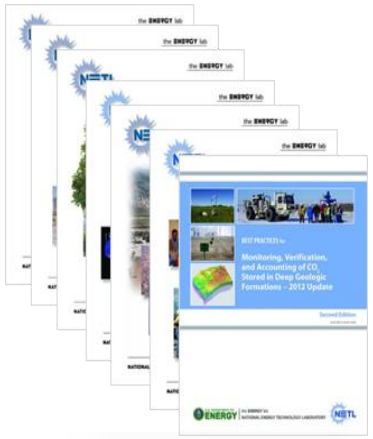
Office of Energy Efficiency and Renewable Energy

Eliminate materials criticality as an impediment to the commercialization of clean energy technologies for today and tomorrow

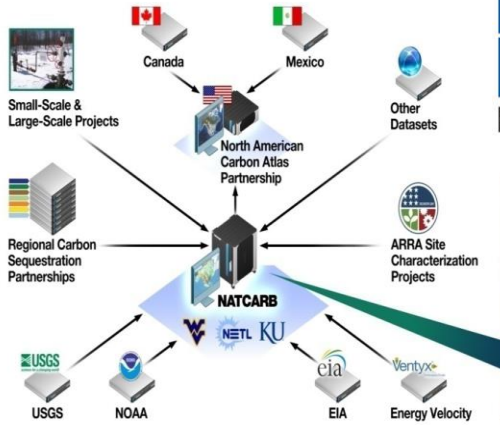


KNOWLEDGE SHARING PRODUCTS





Worldwide CCS Project Database



MAJOR CCUS DEMONSTRATION PROJECTS

Air Products Facility (Port Arthur, TX) – operations began in 2013

- Built and operated by Air Products and Chemicals Inc. at Valero Oil Refinery
- State-of-the-art system to capture CO_2 from two large **steam methane reformers**
- **5.0 million metric tons of CO_2** captured and transported via pipeline to oil fields in eastern Texas for **enhanced oil recovery (EOR)** since March 2013

Petra Nova CCS (Thompsons, TX) – operations began in 2017

- Joint venture by NRG Energy, Inc. (USA) and JX Nippon Oil and Gas Exploration (Japan)
- Demonstrating Mitsubishi Heavy Industries' solvent technology to **capture 90% of CO_2 from 240-MW flue gas stream** (designed to capture/store 1.4 million metric tons of CO_2 per year)
- **Nearly 2.5 million metric tons of CO_2** used for **EOR** in West Ranch Oil Field in Jackson County, Texas since January 2017

ADM Ethanol Facility (Decatur, IL) – operations began in 2017

- Built and operated by Archer Daniels Midland (ADM) at its existing biofuel plant
- CO_2 from **ethanol biofuels production** captured and stored in **deep saline reservoir**
- **First-ever CCS project** to use new U.S. Environmental Protection Agency (EPA) Underground Injection **Class VI well permit,** specifically for CO_2 storage
- **1.0 million metric tons of CO_2** captured, **0.8 million metric tons** of which **stored**, since April 2017