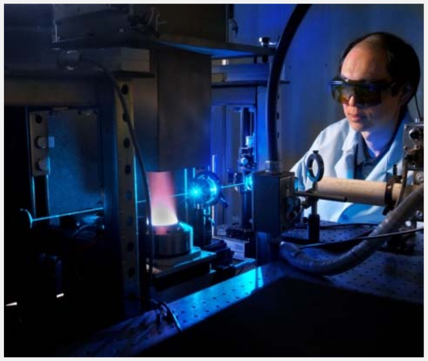
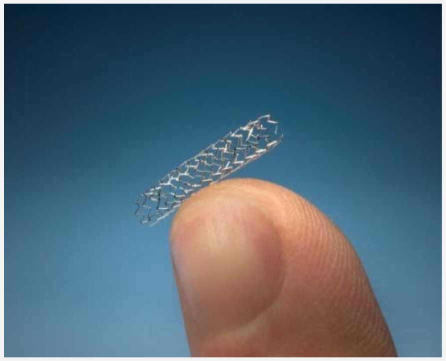
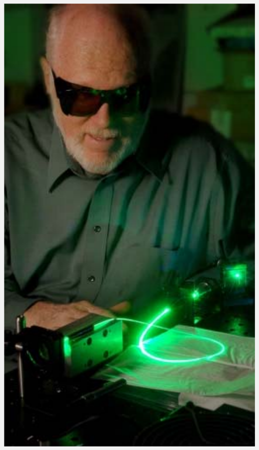
Driving Innovation ♦ Delivering Results

Clean Coal and Carbon Management

Presentation to National Coal Council

Sean I Plasynski, PhD

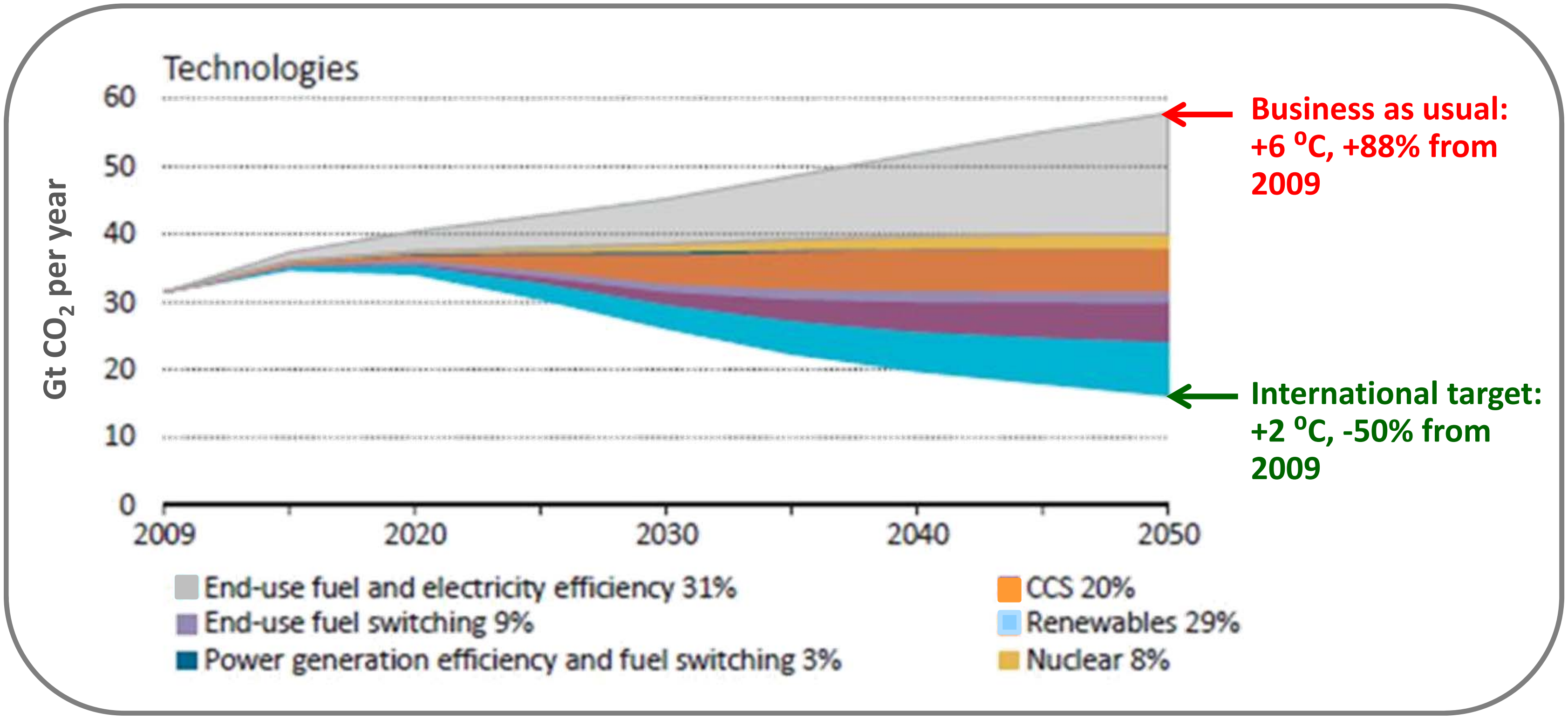
Director Strategic Center for Coal

November 5, 2015

Presentation Outline

- CCS Value Chain and Ingredients for Success
- Quick Overview of Strategic Center for Coal and the RD&D Areas providing the ‘Ingredients’ and ‘recipes’
- Examples of “Transformational” Technologies in R&D pipeline
- Storage: RCSP Success, Efforts in Developing a Storage Site, Key Questions for a large storage site (100 million tons +)
- CCS Demonstrations: Update on demos in Construction or Operation Phase

CCS is Essential for Stabilizing International Greenhouse Gas Emissions



- **CCS achieves 20% of cumulative reductions from 2015 to 2050 (storing over 123Gt)**
- **International Target Compared to business as usual, assumes 66% less fossil fuel use, ~80% less coal use**
- **Delaying or abandoning CCS would increase power sector compliance cost by 40+%**
- **Limits to efficiency gains, fuel switching reductions and CCS only option for some industrial sectors**

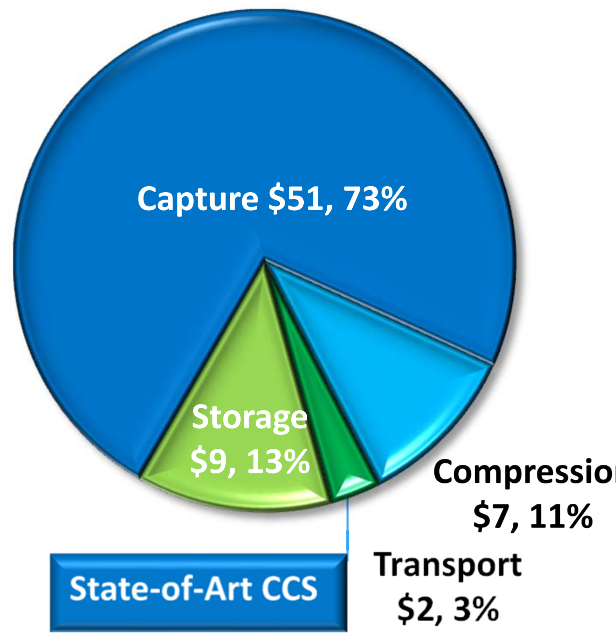
Carbon Capture and Storage Value Chain

Large Stationary Sources

Capture and Compression

Pipeline Transport

Deep Subsurface Storage

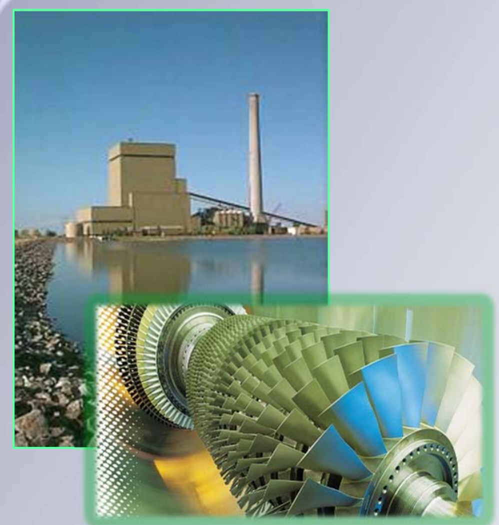


All costs in $ per metric ton CO_2 ($2011)

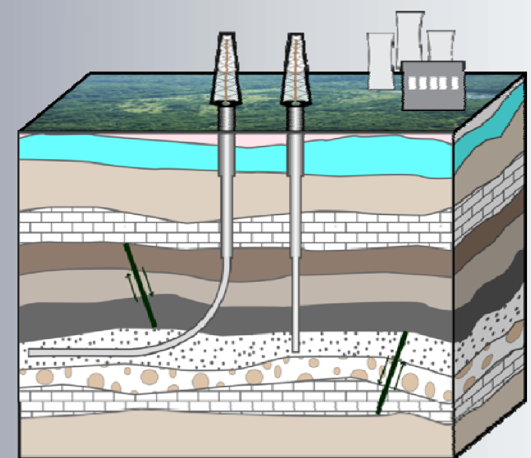
Carbon Capture and Storage

Ingredients for Success

Capture Technology
Low Cost



Efficient Power Systems



Sufficient and Secure
Storage Formations

Integrated Demonstration Projects

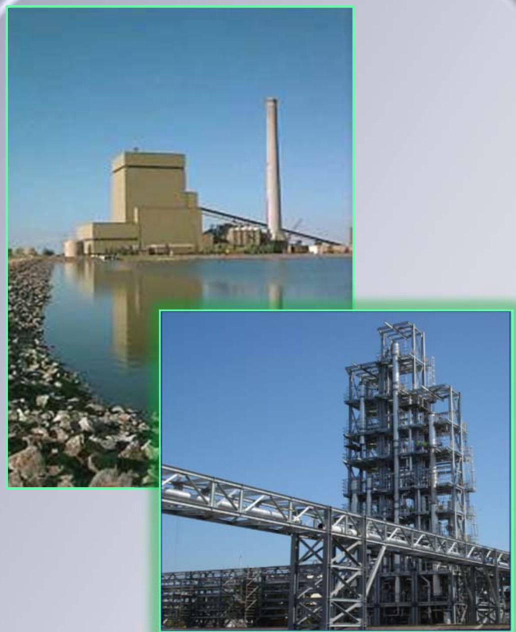
Strategic Center for Coal

Advancing Technologies in Power Generation Utilizing Coal

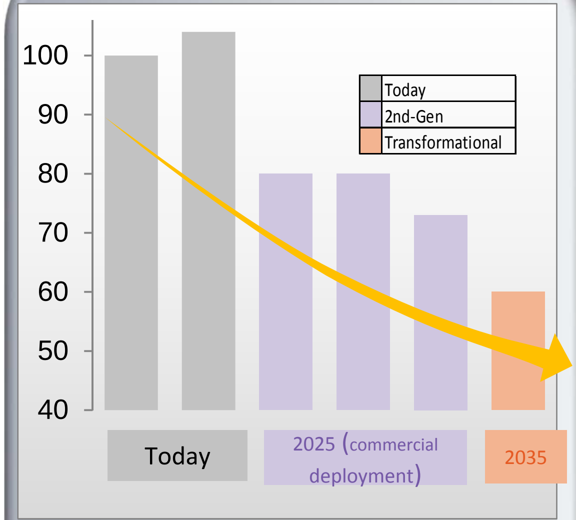
~420 projects $11.3B Total ($3.3B DOE) *

Relevance of R&D, Leverages, Promotes Commercialization

Office of Coal and Power R&D



Office of Major Demonstrations

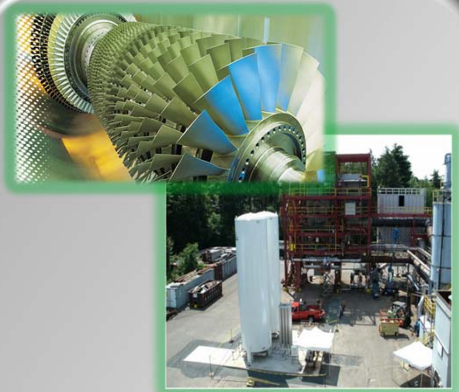


Office of Program Performance & Benefits

* *Data for active projects as of October 28, 2015*

Office of Coal and Power R&D

Advancing Technologies that Transform Power Generation



Advanced Energy Systems

STEP

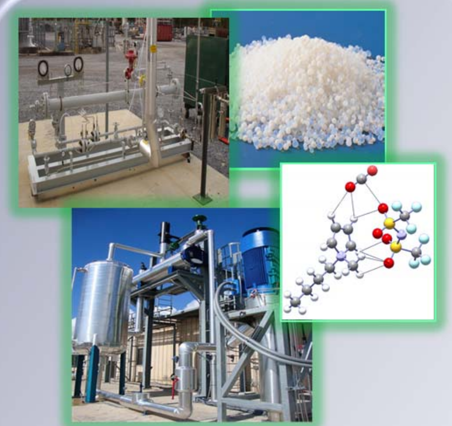
Gasification

Turbines

Combustion

Fuel Cells

Coal & Coal-Biomass to Liquids



CO_2 Capture Program

Pre-combustion

Post-Combustion

CO_2 Storage Program

Storage Infrastructure

Geologic Storage

Monitoring, Verification, Accounting & Assessment

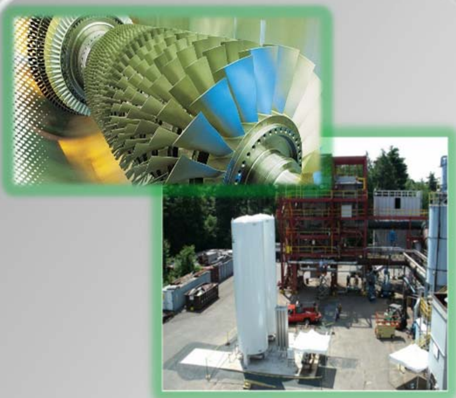
Applied Research → **Engineering Development** → **Pre-commercial Testing** → **Demonstration**

Enabling Technologies (Crosscutting) Program

Materials, Computational Tools, Intelligent Sensors and Controls

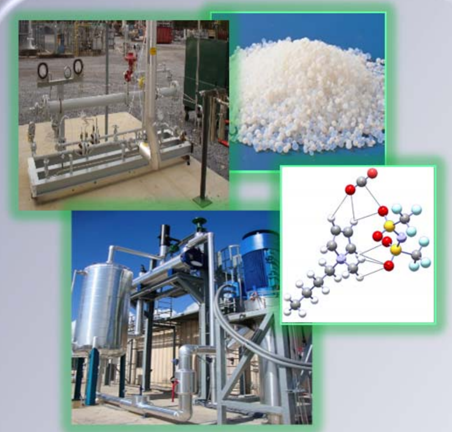
Office of Coal and Power R&D

FY15 ~ $400* Million, Active Projects ~ 410



Advanced Energy Systems STEP

$113 Million**
136 Projects



CO_2 Capture Program

$88 Million
58 Projects

CO_2 Storage Program

$100 Million
100 Projects

Applied Research → **Engineering Development** → **Pre-commercial Testing** → **Demonstration**

Enabling Technologies (Crosscutting) Program
$49 Million, 115 Projects

*Includes $15 M for Rare Earth Research and $35Million to NETL Office of Research and Development
** Includes AES and STEP (Supercritical CO_2 Power Cycles)

Coal Power and CO_2 Capture Technologies

Aspects Also Applicable to Natural Gas

Gasification

2nd-Generation

- Oxygen Production
- High-Pressure Dry Feed
- Warm Syngas Cleanup
- Combustion Turbine Components
- Pre-Combustion CO_2 Capture
- DG SOFC
- Bio-Gasification

Transformational

- 65% LHV Combustion Turbines
- Pressure Gain Combustion
- Transformational H2 Production
- Integrated Gasification Fuel Cells (IGFC)
- Oxygen Production
- Radically Engineered Modular Systems (REMS)

2nd-Generation — *Transformational*

Combustion

2nd-Generation

- AUSC Steam Cycles
- Atmospheric Oxy-Combustion
- Post-Combustion CO_2 Capture

Transformational

- Chemical Looping
- Transformational CO_2 Separation
- Pressurized Oxy-combustion
- Supercritical CO_2 Cycles
- Direct Power Extraction

Cross-cutting:

- Sensors & Controls
- Water Management
- Simulation-Based Engineering
- High Performance Materials

Some Examples of Promising Transformational Technologies

1. **"Advanced" Ultra Supercritical Power Plant (2nd-Gen)**
2. **Supercritical CO2 Power Cycles**
3. **Pressure Gain Combustion**
4. **Chemical Looping**
5. **Radically Engineered Modular Systems (REMS)**
6. **IGFC Power Systems**
7. **Transformational CO_2 Capture**
8. **Brine Extraction Storage Test (BEST)**
9. **Identification of Residual Oil Zones (ROZs) in the Williston and Powder River Basins**

Advanced Ultra Supercritical Steam Cycles

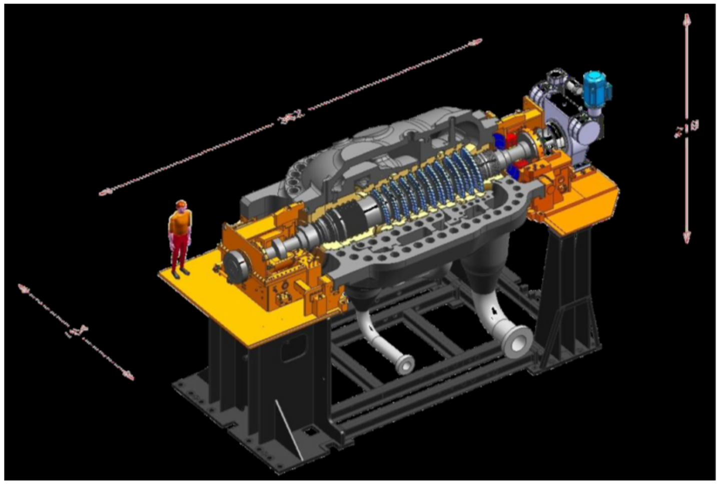
Operating up to 5,000 psi and 1,400 °F (760 °C)

Benefits

- Plant efficiency can be improved to 44% HHV (Illinois #6 coal) at AUSC conditions (5000 psig/1350F/1400F).
- Corresponds to CO_2 emissions reductions up to 27%, relative to that of the existing fleet with an average efficiency of 32% HHV.
- Higher efficiency requires less coal and creates less flue gas yielding lower balance of plant cost

R&D Activities – ComTest

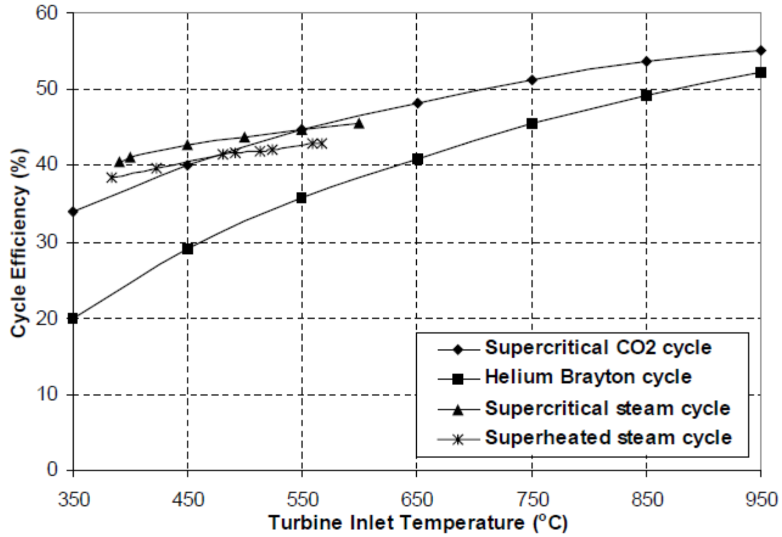
- Test AUSC components to reduce the economic risk of the first AUSC demonstration plant
- Exercise complete project execution process (design, procurement through supply chain, manufacturing, delivery, site construction and commissioning)
- Status – project awarded in FY15 to Energy Industries of Ohio ($75M Total – DOE $56.2M, CS-$18.8M)
  - Boiler Consortium: EPRI, Alstom, B&W, ORNL, Foster-Wheeler and Riley-Power
  - Turbine Consortium: EPRI, ORNL and GE



Supercritical CO_2 Power Cycles

Benefits

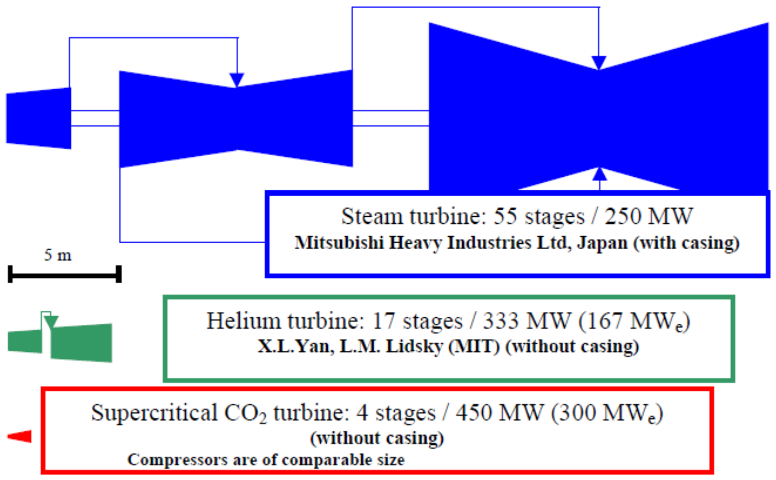
- Potential higher efficiency relative to traditional fossil energy cycles
- Reduced turbomachinery equipment sizes due to higher working fluid density results in reduced capital costs
- sCO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O



R&D Activities

- Turbo Machinery and Recuperators / Heat Exchangers for Indirect and Direct Cycles
- Oxy-fuel Combustors for Direct Cycles
- Materials, Fundamentals and Systems

DOE SCO2 Crosscut Initiative with FE, EE and NE

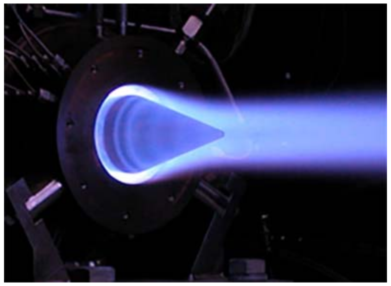


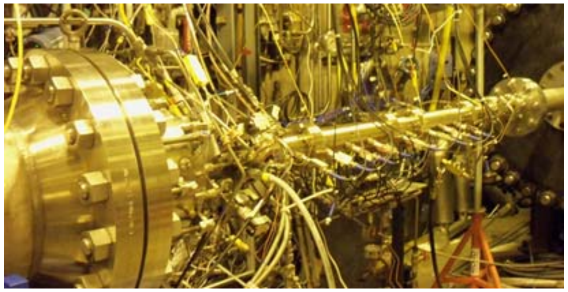
Source of Figures: V. Dostal, M.J. Driscoll, and P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Report MIT-ANP-TR-100, March 2004.

Pressure Gain Combustion

Benefits

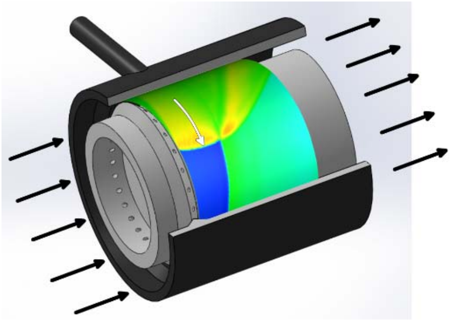
- 4-5 percentage point increase in simple cycle efficiency and 2-3 percentage point increase in combined-cycle (CC) efficiency
- Works well with high reactivity fuels like coal derived H_2
- Alternate pathway to reaching efficiency goals vs. raising turbine inlet temperature

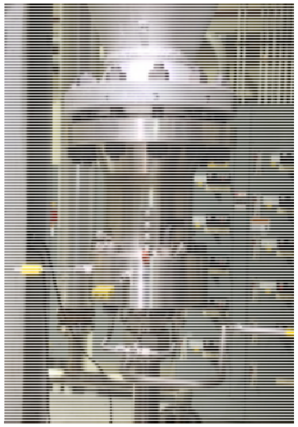




R&D Activities

- Systems model for rotating detonation engine (RDE) combustor
- Realistic assessment of efficiency improvement on CC power generation using pulse detonation engines
- Basic research and fundamental studies
- Experimental and numerical studies of loss mechanisms within the RDE





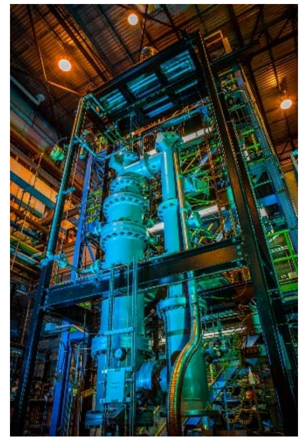
Chemical Looping

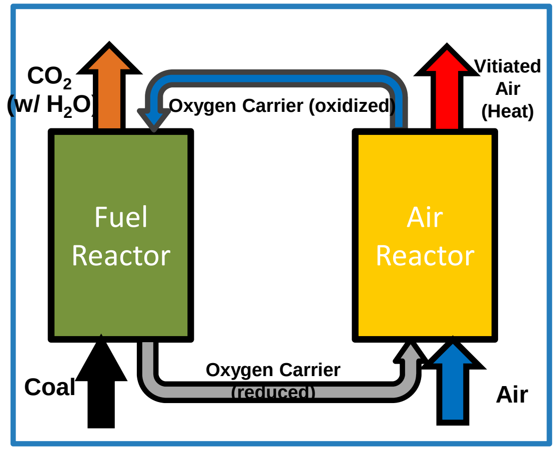
Benefits

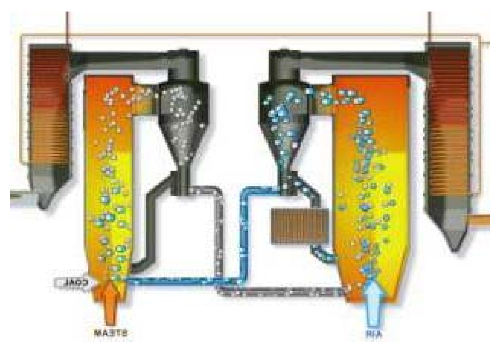
- Transformational cost reduction potential
- No need for O_2 production
- High CO_2 concentration exhaust
- Uses conventional materials and fabrication techniques
- Leverages large-scale CFB experience, especially with limestone carriers

R&D Activities

- Limestone-based chemical looping combustion
- Iron-based chemical looping combustion
- Chemical looping combustion with oxygen uncoupling
- Pressurized chemical looping
- H_2 production from syngas
- Chemical looping coal gasification
- Chemical looping oxygen carrier development







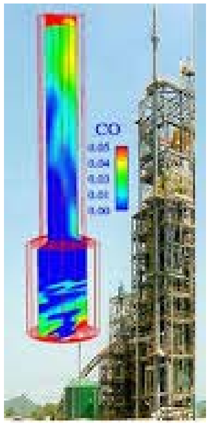
Radically Engineered Modular Systems (REMS)

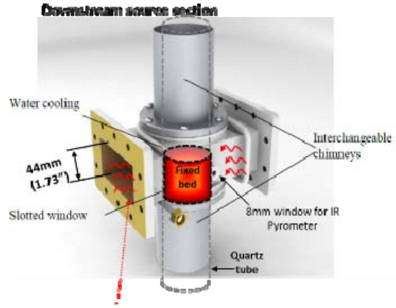
Benefits

- New approaches for coal to power/chemicals technologies
- Reduced time/risk in scale-up
- Reduce build/capital costs (modular plants)
- Fuel-flexible designs, distributed power/products generation
- Enhanced reactor/process performance
  - *Reaction manipulation at the particle level*

R&D Activities

- CFD-led reactor & process design
  - Development of physics-based sub-models
  - CFD optimization and toolsets
- Reactor characterization and CFD model validation
  - 3D printing for rapid testing
  - Development of characterization tools
- Advanced Manufacturing and Reactor Materials Development
  - Materials for unusual reactor geometries & conditions
  - Rapid, cheap fabrication techniques
- Reaction Intensification
  - Microwave/Plasma driven reactors
  - Catalyst Design

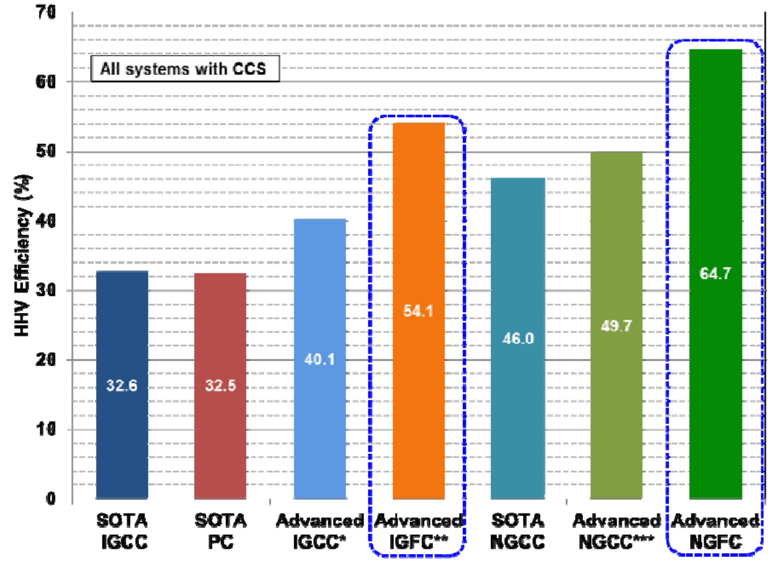




IGFC Power Systems

Benefits

- Intrinsic carbon capture, greater than 97%
- Reduced emissions: near zero SO_x, NO_x, criteria pollutants, and particulates
- Water consumption approximately 1/3 of coal-based power systems
- Potential to achieve greater than 50% efficiency (HHV)
- COE projected to be 40% below presently available IGCC systems with carbon capture



R&D Activities

- Improved cell and system performance
- Improved system durability and reliability
- Reduced system performance degradation
- 60 kWe-class thermally self-sustaining stack tests
- 100 kWe-class stack tests
- 400 kWe integrated prototype field test
- Novel cell and stack concepts

** *"Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems Created by Energy Sector Planning and Analysis for SEAP & OPPB"*, DOE/NETL- 341/112613, November 2014

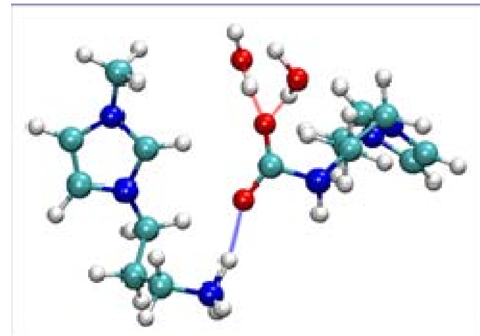
Transformational CO_2 Capture

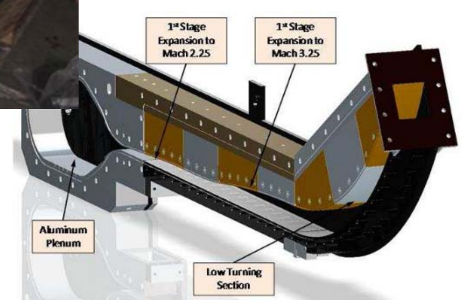
Benefits

- Advanced, efficient technologies that produce ultraclean near-zero emissions, including CO_2
- Reduced energy penalty and capital costs
- Improved equipment designs
- Efficient system integration

R&D Activities

- Sub-ambient pressure swing adsorption
- Electrochemical regeneration
- Amine–incorporated porous polymer networks
- Hybrid encapsulated ionic liquids
- Phase-change solvents
- Cryogenic separation
- Hybrid processes
- Enhanced water-gas shift reactor





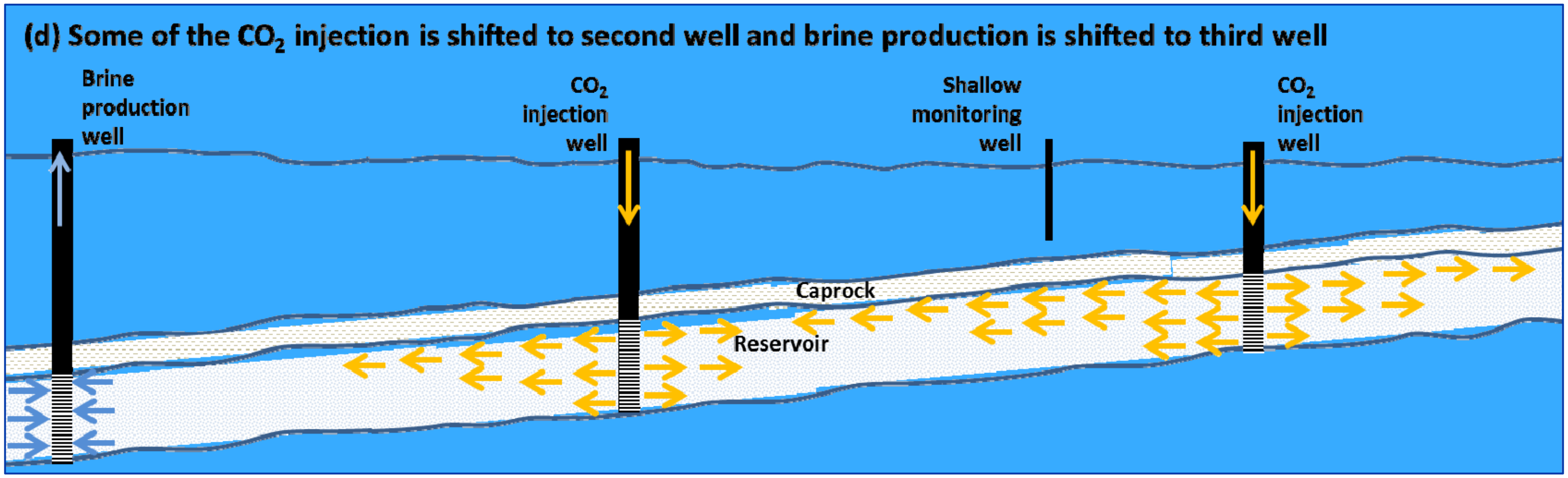
Brine Extraction Storage Test (BEST)

Benefits

- Potential reduction in the risk of induced seismicity
- Improve reservoir storage efficiency while ensuring containment effectiveness
- Pressure Mgmt and Plume Control

R&D Activities

- Simulations have shown that
  - Induced seismicity is related to increased saline formation pressure due to CO_2 injection
  - Localized pressure reduction can be used to steer the plume/pressure front
- BEST Phase 2 will be conducted to confirm simulation results
- Brine treatment technologies will also be tested



Source of Figure: Thomas A. Buscheck, "Active CO_2 Reservoir Management." DOE/NETL Carbon Storage R&D Project Review Meeting, August, 2015

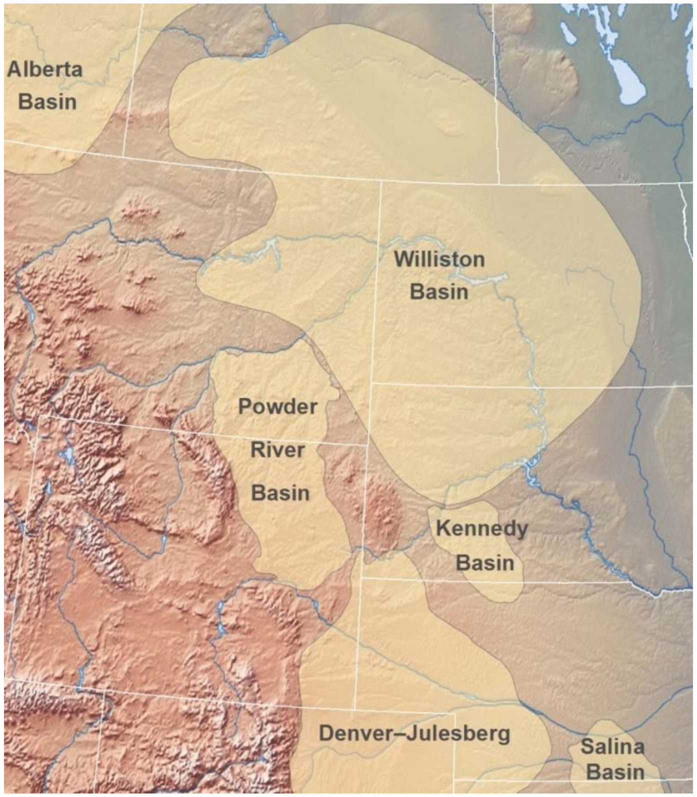
Enhanced Oil Recovery in Residual Oil Zones

Benefits

- Improve reservoir storage efficiency while ensuring containment effectiveness
- Estimate residual oil in place and CO2 storage potential

R&D Activities – Energy and Environmental Research Center

- Identify and characterize the presence and extent of potential residual oil zones (ROZ) in the Williston Basin (WB) and Powder River Basin (PRB)
  - Potential ROZ identified near Elkhorn Ranch Field
  - 3-D model of Elkhorn Ranch Field completed and simulated
- Determine feasibility of CO_2 enhanced oil recovery (EOR) in identified ROZs.



Storage Infrastructure

RCSP Development Phase CO_2 Injection Volumes

Injection Volumes ~8.9 Million Metric Tons

Big Sky Carbon Sequestration Partnership

Kevin Dome Project

Injection 2016

Plains CO_2 Reduction Partnership

Bell Creek Field Project

2,301,000 metric tons

Southwest Regional Carbon Sequestration Partnership

Farnsworth Unit Project

318,179 metric tons

Southeast Regional Carbon Sequestration Partnership

Cranfield Project

4,743,898 metric tons

Southeast Regional Carbon Sequestration Partnership

Citronelle Project

114,104 metric tons

Midwest Regional Carbon Sequestration Partnership

Michigan Basin Project

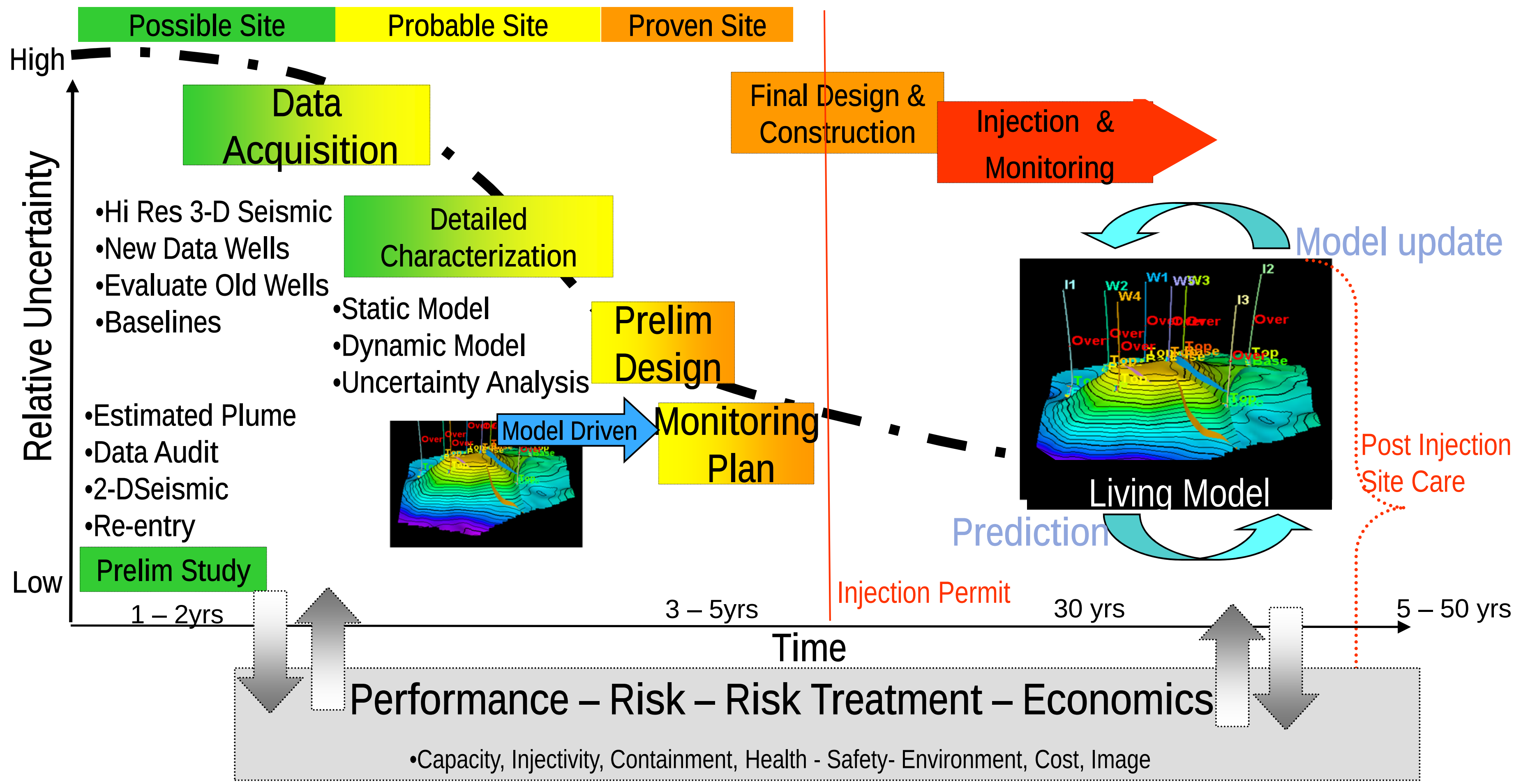
418,084 metric tons

Midwest Geological Sequestration Consortium

Illinois Basin Decatur Project

999,215 metric tons

Developing a Storage Project



(Modified from Schlumberger)

Thoughts on Regional Storage Sites (100 million tons +)

Subset of Key Decisions/Questions

1. **Who owns the commercial-scale storage sites?**
   – Private sector ? Federal government (like SPR or TVA)? States? Public-private partnerships?
2. **Government involvement in site? Mechanism?**
   – "Substantial involvement"? Grant/Cooperative Agreement or Contract? Other (tax incentives)? Cost-share requirements?
3. **Best Location of storage sites?**
   – Onshore sites only or both onshore and offshore sites? Foreign country or straddle int'l boundary – implications and perceptions?
4. **Hybrid (EOR and storage) projects?**
   - Stacked storage best so that revenues from EOR? Saline storage as backup or surge capacity for EOR? One permit for a Hybrid saline/EOR project – how would it look and work? Minimum price for oil to work ($50/bbl suggested by some)?
5. **Public Engagement and timing?**
   - Communities step forward to host sites? States propose? Commercial interests determine land location? Timing of Public Engagement, education and training activities?
6. **Number of initial sites to increase success** Possible Site | Probable Site | Proven Site
   - Multiple sites – perform characterizations – then down-select to most promising for further development. Minimize number of 'dry' holes.
7. **Sources of CO2 (not important to geologic formation if at a certain composition)**
   - Preference for storage if limitations? Business plan model created to address?

Office of Major Demonstration

Advancing Technologies that Transform Power Generation

Clean Coal Power Initiative (CCPI)

Industrial Carbon Capture and Storage (ICCS)

FutureGen

- ***Advanced technologies need tested at full scale in an integrated facility before they can be considered ready for commercial deployment.***
- ***Demos help industry to understand and overcome component integration and startup performance issues.***
- ***By reducing the risk profile associated with new and first-of-a-kind technologies, opportunities for private financing and investment for subsequent plants is greatly improved.***

Major CCS Demonstration Projects

Project Locations & Cost Share

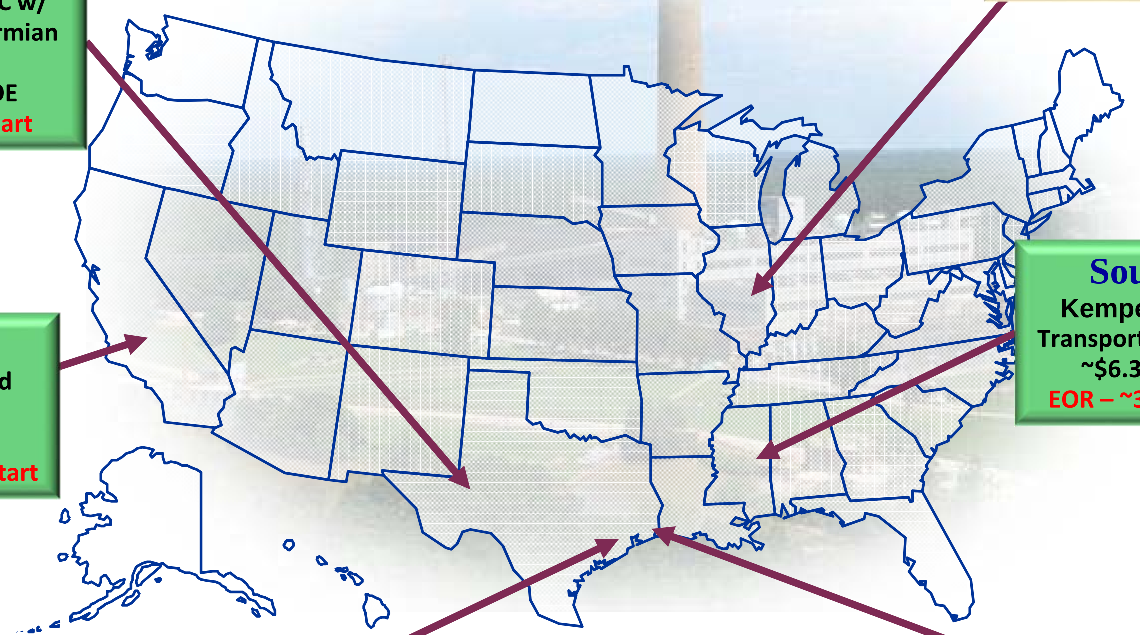
CCPI

ICCS Area 1

Summit TX Clean Energy
Commercial Demo of Adv. IGCC w/ Full Carbon Capture; EOR in Permian Basin
~$3.5B – Total; $450M – DOE
EOR – ~1.84 MMTPY; 2019 start

HECA
Commercial Demo of Advanced IGCC w/ Full Carbon Capture
~$5B – Total; $286M – DOE
EOR – ~2.6 MM TPY; mid 2020 start

Archer Daniels Midland
CO_2 Capture from Ethanol Plant
CO_2 Stored in Saline Reservoir
$208M – Total; $141M – DOE
SALINE– ~0.9 MM TPY; early 2016 start



Southern Company
Kemper County IGCC Project
Transport Gasifier w/ Carbon Capture
~$6.3 B – Total; $270M – DOE
EOR – ~3.0 MM TPY; mid 2016 start

Petra Nova
W.A. Parish Generating Station
Post Combustion CO_2 Capture
$1B – Total; $167M – DOE
EOR – ~1.4 MM TPY; early 2017 start

Air Products & Chemicals, Inc.
CO_2 Capture from Steam Methane Reformers
EOR in Eastern TX Oilfields
$431M – Total; $284M – DOE
EOR – ~0.93 MM TPY; started December 2012; 1.9 MMT stored as of April 2015

Air Products & Chemical, Inc.
Steam Methane Reforming with CO_2 Capture

- Port Arthur, TX (Hydrogen plant at Valero Refinery)
- 90%+ CO_2 capture (Vacuum Swing Adsorption) from 2 steam-methane reformers (SMRs) yielding ~925,000 tonnes CO_2/year
- ~30 MWe cogeneration unit to supply makeup steam to SMRs and operate VSA & compression equipment
- CO_2 to Denbury "Green" pipeline for EOR in West Hastings, TX oilfield
- Total Project: $431 MM; DOE Share: $284 MM (66%)

Key Dates

- Phase 2 Awarded: June 15, 2010
- FEED completed: November 2010
- Permit By Rule (PBR) and Standard Air Permits issued: May 2011
- NEPA FONSI: July 2011
- Construction started: Aug. 2011
- Operation started: Dec. 2012

Status

- PA-1 initiated operation: March 3, 2013
- PA-2 initiated operation: Dec. 16, 2012
- Full capacity achieved: April 2013
- Has operated at >100% of design when necessary
- 2,367,012 tonnes CO_2 delivered as of 10/15/15

Southern Company Services, Inc. CCPI-2

Advanced IGCC with CO_2 Capture

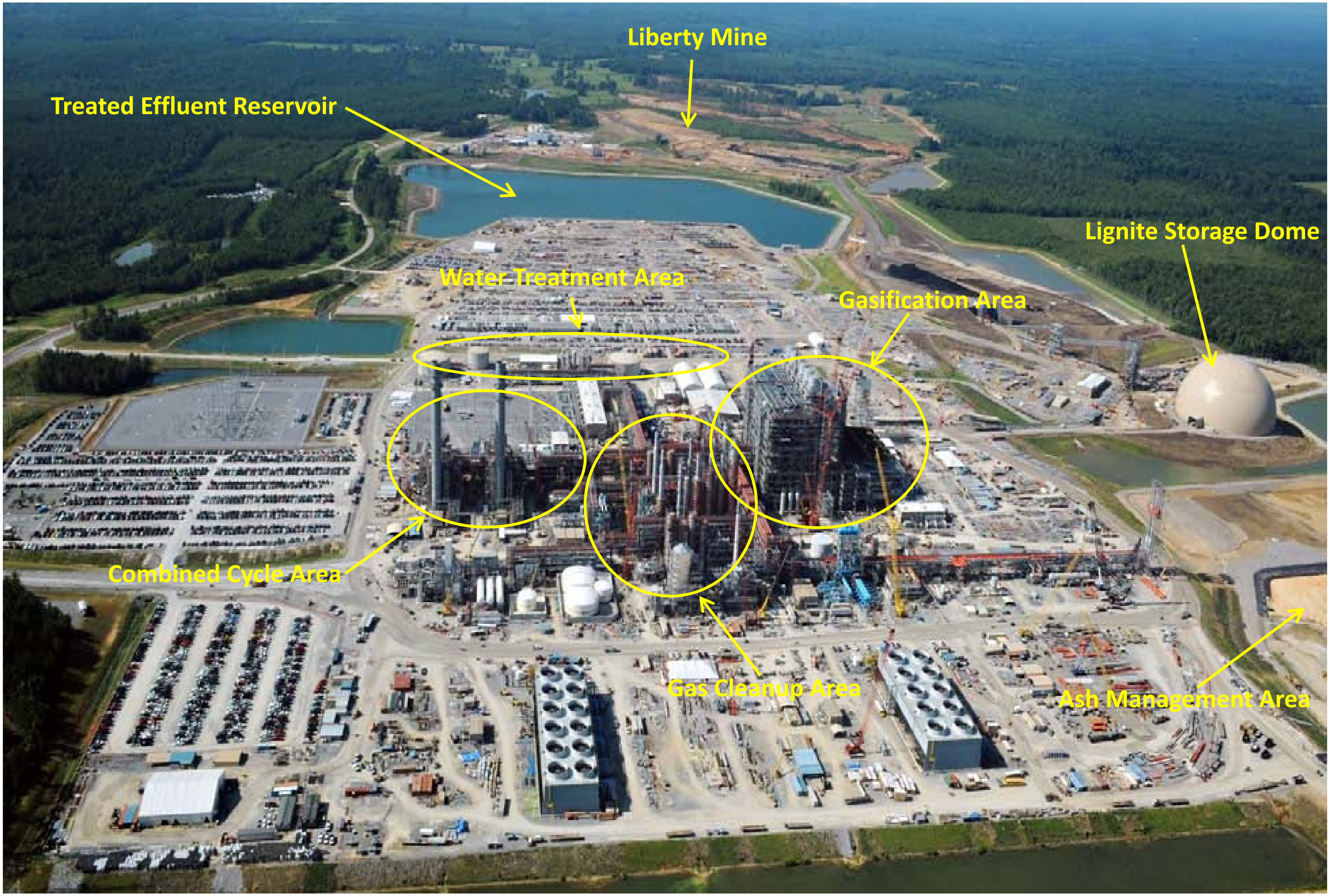
- Kemper County, MS
- 582 MWe (net) with duct firing; 2 TRIG™ gasifiers, 2 Siemens combustion turbines, 1 Toshiba steam turbine
- Fuel: Mississippi lignite
- 67+% CO_2 capture (Selexol® process); 3,000,000 tons CO_2/year
- EOR: Denbury Onshore LLC, Treetop Midstream Services LLC
- Total DOE CCPI Project: $2.01 B; DOE Share: $270 MM (13%)
- Total estimated project cost: ~$ 6.3B

Key Dates

- Project Awarded: January 30, 2006
- Project moved to MS: December 5, 2008
- NEPA Record of Decision: August 19, 2010
- Initiate excavation work: September 27, 2010
- Operations: Mid-2016

Status

- Plant construction >98% complete; Peak construction labor 6,121
- CO_2 off-take agreements signed
- Lignite mine in commercial operation: June 2013
- Subsystems commissioning in progress
- Combined cycle commercial operation on natural gas: August 2014
- Gasifier "First Fire": March 2015


Liberty Mine
Treated Effluent Reservoir
Lignite Storage Dome
Water Treatment Area
Gasification Area
Combined Cycle Area
Gas Cleanup Area
Ash Management Area

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
- EOR: Hilcorp West Ranch oil field (82-mi. pipeline)
- Total Project Cost: ~$1 billion
  DOE Share: $167 million

Key Dates

- Project Awarded: May 2010
- Air Permit: December 2012
- NEPA Record of Decision: May 2013
- Financial Close: July 2014
- Construction: March 2014 (LNTP);
  July 2014 (NTP)
- Operation: January 2017

Status

- Start cooling tower foundation: October 2014
- Start absorber foundation: December 2014
- Complete all pilings January 2015
- Start absorber/quencher foundation Feb. 2015
- Overall EPC effort: 95% complete
- Construction: 34% complete

Solutions for Today.....Options for Tomorrow




For More Information, Contact NETL

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