Coal-Fired Power Plants, CCS, and a Use for the CO$_2$
National Energy Technology Laboratory

- Only DOE national lab dedicated to fossil energy
  - Fossil fuels provide 85% of U.S. energy supply

- One lab, one management structure, five locations
  - Full-service DOE Federal laboratory
  - 3 R&D locations

- >1,200 Federal and support-contractor employees

- Research spans fundamental science to technology demonstrations

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NETL
Energy Demand 2008

100 QBtu / Year
84% Fossil Energy

- Coal 22%
- Gas 24%
- Oil 37%
- Nuclear 8%
- Renewables 8%

5,838 mmt CO₂

Energy Demand 2035

114 QBtu / Year
78% Fossil Energy

- Coal 21%
- Gas 24%
- Oil 33%
- Nuclear 8%
- Renewables 14%

6,311 mmt CO₂

+ 14%

United States

Energy Demand 2008

487 QBtu / Year
81% Fossil Energy

- Coal 27%
- Gas 21%
- Oil 33%
- Nuclear 6%
- Renewables* 13%

29,259 mmt CO₂

Energy Demand 2035

716 QBtu / Year
79% Fossil Energy

- Coal 29%
- Gas 22%
- Oil 28%
- Nuclear 8%
- Renewables* 15%

42,589 mmt CO₂

+ 47%

World

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* Primarily traditional biomass, wood, and waste.
Operational Dates (above) / Retirement Dates (below)
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Progressing and Announced New Coal Units
Announced Coal-Fired Retirements (2012 – 2020)

Total retirement capacity at the plant level

24.7 GW of specific announced plant retirements
• Five new coal-plants totaling 2,343 MW were Commissioned in 2011

• Progressing/Commissioned projects by January 2012 have had a net increase of 3 plants; a net change in capacity of 1,388 MW (+10%) over Progressing projects

• 1,599 MW of new capacity has been Announced and 2,890 MW have been canceled
  – Of 2,890 MW canceled plants, 54% were Announced phase and 46% were Progressing

• Compared to previous years, fewer projects are being Announced to offset recent Commissioning
Pathways To CO$_2$ Emission Reduction

- **Energy efficiency** (14 GtCO$_2$e/yr)$^1$
  - Vehicles, Buildings, industrial equipment
- **Low-carbon energy supply** (12 GtCO$_2$e/yr)
  - Wind, Nuclear, Solar Energy
  - Biofuels for transportation
  - Fossil fuels with Carbon Capture and Storage
- **Terrestrial carbon** (12 GtCO$_2$e/yr)
  - Reforesting, halting deforestation
  - CO$_2$ storage in soils through changing agricultural practices
- **Behavioral change** (~4 GtCO$_2$e/yr)

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DOE/NETL CO₂ Capture RD&D

R&D Programs

Carbon Capture
- Post-Combustion (PC)
- Pre-Combustion

Carbon Storage

Advanced Energy Systems
- Advanced Combustion
- Gasification
- Hydrogen Turbines
- Fuel Cells
- Hydrogen and Syngas

Advanced Research

Demonstration Programs

NETL’s Carbon Capture R&D

- Clean Coal Power Initiative
- FutureGen 2.0
- Industrial Carbon Capture

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Deployment Barriers For CO₂ Capture On New And Existing Coal Plants Today

1. **Energy Penalty**
   - 20% to 30% less power output

2. **Cost**
   - Increase Cost of Electricity by 80%
   - Adds Capital Cost by $1,500 - $2,000/K

3. **Scale-up**
   - Current Post Combustion capture ~200 TPD
   - 550 MWe power plant produces 13,000 TPD

4. **Regulatory framework**
   - Transport — pipeline network
   - Storage

5. **Economies of Scale**
   - Land, power, water use, transportation, process components, …
High Efficiency Low Emission (HELE) Coal-Fired Power Plants

• Coal is an inexpensive and abundant energy source

• World coal usage is projected to more than double by 2050 in base-line scenarios

• U.S. coal usage is projected to increase by ~10%

• Non-OECD countries will be the main coal consumers

• CCS and efficiency improvements are critical for future use of coal in power generation
Technologies For Improving The Efficiency Of Existing Power Plants

• Renovation and Modernization Technologies for Existing Power Stations
  – ~40% of U.S. CO₂ from electricity generation [1]
  – Average age of >250 MW plants in U.S. is 34 years [1]

• Waste Heat Recovery from Power Plants

• Higher-Efficiency New Power Plant Technologies
  – Supercritical and Ultra-Supercritical Technologies
  – Integrated Coal Gasification Combined Cycle (IGCC)
  – Advanced Ultra-Supercritical Technology

• Development and Deployment of Other Innovative High-Efficiency Cycles
  – More Efficient CO₂ Capture Technologies


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Advanced Combustion Systems

A – Supercritical PC, Current Amine
B – Ultrasupercritical PC, Current Amine
C – Supercritical PC, Amine + Adv. Comp.
D – Supercritical PC, Adv. CO₂ Sorbent
E – Supercritical PC, Adv. CO₂ Membrane
H – Advanced Oxycombustion

*USC = Ultra-supercritical PC (4,000 psig/1,350°F/1,400°F)

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Advanced Gasification Systems

A – Current State of the Art IGCC
B – Advanced Coal Pump
C – Advanced Gasifier Materials
D – Warm Gas Cleanup
E – Hydrogen Membrane
F – Advanced Hydrogen Turbine (2,550°F)
G – Ion Transport O2 Membrane
H – Advanced Hydrogen Turbine (2,650°F)
I – Advanced Controls

*USC = Ultra-supercritical PC (4,000 psig/1,350°F/1,400°F)
Fossil Energy CO₂ Capture Solutions

- Post-Combustion (existing, new PC)
- Post-Combustion (IGCC)
- Oxy-Combustion (new PC)
- CO₂ Compression (all)

- 1st Generation Physical Solvents (CCPI)
- 1st Generation Chemical Solvents (CCPI)
- Cryogenic Oxygen
- Amine Solvents
- Physical Solvents

- H₂ and CO₂ Membranes
- 2nd Generation Solvents
- Oxygen Membranes
- Chemical Loopping
- 2nd Generation Oxyboiler
- Biological Processes
- Solid Sorbents

2010 - 2015 - 2020 - 2025 - 2030

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CO$_2$ Capture Technologies

1) Solvents
2) Sorbents
3) Membranes
4) Oxy-combustion
5) Chemical looping
6) CO$_2$ Compression
**Pulverized Coal Power Plant System**

*Post-combustion CO₂ Scrubbing*

**Post-combustion advantages:**
- Back-end retrofit
- Slip-stream (0 to 90% capture)

**Amine scrubbing Advantages:**
- Proven Technology (Petroleum refining, NG purification)
- Chemical solvent → High loadings at low CO₂ partial pressure
- Relatively cheap chemical ($2-3/lb)

**Key Challenges:**
- Dilute flue gas (12-15 volume %)
- 2-3 MM acfm for a 500-600 MWe plant
- ~50% currently scrubbed for SOx/NOx
- Increased cooling requirements

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IGCC Power Plant System

*Pre-combustion CO₂ Scrubbing*

**IGCC CO₂ Capture Advantages:**
- High chemical potential (Temp, $P_{CO₂}$)
- Low Volume Syngas Stream

**Selexol™ CO₂ Capture Advantages:**
- 30+ years of commercial operation (55 worldwide plants)
- Physical Liquid Sorbent
- Highly selective for $H₂S$ and $CO₂$
- $CO₂$ is produced at “some” pressure

**Key Challenges:**
- Complex, integrated power process
- Additional process (WGS) to get high capture rates
- Current technology (Selexol) requires cooling and reheating

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Pulverized Coal Oxyfuel Combustion

Technology Opportunities

Cheap Oxygen
Oxygen Membranes

Coal + O₂ → CO₂ + H₂O

Advanced MOC*
Reduce CO₂ Recycle Handle High Sulfur Conc.

Advanced Compression
Ramgen, SwRI

Oxyfuel Boilers
Compact Boiler Designs
Adv. Materials (USC)
Advanced Burners

Co-Sequestration
Multi-pollutant capture

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*Materials of Construction
**Advanced CO₂ Solvents**

**R&D Focus**
- High CO₂ working capacity, optimal ΔHrxn, low heat capacity, non-volatile
- Fast kinetics (enzymes)
- Thermally and chemically stable
- Non-corrosive, environmentally safe
- Low cost solvent and process MOC*
- Improved mass transfer systems
- Advanced Process Design/Integration

**Solvent Technologies**
- Novel high capacity oligomers
- Phase change solvents
- Ionic liquids
- Amino Acids
- Carbonates
- Enzymes
- Advanced Processes

**Partners:**
1. GE Research Corporation (Polymers)
2. 3H (Phase change)
3. Ion Engineering (IL/Amine mixtures)
4. University of Notre Dame (IL)
5. Georgia Tech. (IL)
6. Akermin (Enzymes)
7. Illinois St. Geological Survey (Carbonate)
8. University of Illinois (Carbonate)
9. URS Group (Piperazine)
10. Southwest Research Institute (Carbonate)*
11. LBNL (Bicarbonate, Membrane ILs)
12. Babcock and Wilcox (Amine-based)
13. Novozymes (Enzymes)
15. Battelle (CO2BOLs)
16. NETL ORD (Amino Acid)
17. Linde (amine, process)
18. Southern Company (HX Process)
19. University of Kentucky (amine, process)
20. Siemens Energy (Amino Acids)

*Pre-combustion Applications
Advanced CO$_2$ Sorbents

**R&D Focus**
- Optimal CO$_2$ working capacity, low heat capacity, fast kinetics (enzymes)
- Matching systems to sorbents
- Durability: thermally, chemically and physically
- Non-corrosive, environmentally safe
- Low cost sorbent and process MOC
- Hybrid (Shift + Capture) for IGCC

**Project Types**
- Metal organic frameworks
- Supported amines
- Metal organic framework (MOF)
- Carbon-based
- Alumina
- Water-gas shift (IGCC)
- Sorbent systems development

**Partners:**
1. ADA-ES (amine, process)
2. University of Akron (amine)
3. SRI International (carbon)
4. TDA (Carbon, alumina)*
5. URS Group (IGCC WGS sorbent)*
6. NETL ORD (Supported amines)
7. NETL/LBNL (Membrane/MOFs)
8. Innosepra (Zeolite, process)
9. W.R. Grace (Zeolite, process)
10. RTI International (Amines)
11. Univ. of North Dakota
12. Georgia Tech.

**2011:** Bench scale → 1 MWe slipstream design (ADA-ES)
**2016:** 10 – 25 MWe Pilot Scale
**2020:** 50 MWe – ready for demonstration

*Pre-combustion Applications*
Advanced Membranes

Membrane Advantages
- Simple operation; no chemical reactions, no moving parts
- Tolerance to acid gases & O₂
- Compact, modular → small footprint
- Builds on existing technology at similar scale (NG purification)

Membrane Approaches
- Spiral wound & hollow fiber
- Cryogenic membrane separation
- Membrane/solvent hybrid
- Fuel Cell Hybrid
- Integrated water-gas shift*
- H₂ Selective zeolite*
- High Temperature Polymer*
- Nanoporous*
- PSA/Membrane Hybrid*
- Palladium Alloy*

Partners:
1. Membrane Technology Research (MTR)
2. RTI International
3. Air Liquide
4. Gas Technology Institute
5. GE Research
6. Ohio State University
7. Rice University
8. Fuel Cell Energy
9. Univ. of Minnesota*
10. Pall Corporation*
11. Arizona State University*
12. Gas Tech. Institute*
13. Membrane Technology*
14. New Jersey Institute of Technology*
15. LANL/SRI*

*Pre-combustion Applications
**Pulverized Coal Oxy-combustion**

**Challenges**
- Cryogenic ASUs are capital and energy intensive
- Existing boiler air infiltration
- Corrosion and process control
- Excess O₂ and inerts (N₂, Ar) ↑ CO₂ purification cost

**Project Types**
- “2nd Gen” oxyboiler designs
  - Adv. Materials and burners
- Existing boiler retrofits
  - Air leakage, heat transfer, corrosion, process control
- Low cost O₂ (membrane)
- CO₂ purification
- Co-sequestration

**Partners:**
1. Praxair (O₂ Membrane, CO₂ Purification)
2. Air Products (CO₂ Purification)
3. Jupiter Oxygen (Burners)
4. Alstom (Pilot plant)
5. B&W (Cyclone pilot test)
6. Foster Wheeler (Corrosion)
7. Reaction Engineering Int. (Retrofit)
8. Southern Research Institute (Retrofit)
9. NETL ORD (Modeling, CO₂ Purification)

**Development Timeline**
- Today: 10 MWe wall-fired test (B&W)
  5 MWe T-fired pilot (Alstom)
  5 MWe burner pilot (Jupiter)
- by 2015: 1st Gen (Cryogenic) demo.
- 2020: 2nd Gen demonstration*

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Chemical Looping Combustion

Oxy-combustion without an O₂ plant
- Potential lowest cost option for near-zero emission coal power plant
- New and existing PC power plant designs

Key Challenges
- Solids transport
- Heat Integration

Air Reactor (Oxidizer)
CaS + 2O₂ → CaSO₄ + Heat

Oxy-Firing without Oxygen Plant
- Solid Oxygen Carrier circulates between Oxidizer and Reducer
- Oxygen Carrier: Carries Oxygen, Heat and Fuel Energy
- Carrier picks up O₂ in the Oxidizer, leaves N₂ behind
- Carrier Burns the Fuel in the Reducer
- Heat produces Steam for Power

Fuel Reactor (Reducer)
CaSO₄ + 2C + Heat → 2CO₂ + CaS
CaSO₄ + 4H₂ + Heat → 4H₂O + CaS

2011 Alstom Pilot test (1 MWe)
✓ 1000 lb/hr coal flow
✓ 1st Integrated operation
✓ 1st Autothermal Operation

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Key Partners (2 projects): Alstom Power (Limestone Based), Ohio State (Metal Oxide)
Advanced CO₂ Compression

Challenges
• Scale-up (550 MWe plant = 15,000 TPD)
• Parasitic load
• Contaminants (O₂, SOx, NOx, …)
• Cost

R&D Objectives
• Increase compression efficiency
• Reduce footprint and capital cost
• Power plant integration/heat recovery

Approach 1:
High PR 2-Stage Inter-stage Heat Recovery

Approach 2:
Compression → Cool → Pump

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DOE National Carbon Capture Center

Post-combustion Carbon Capture

- 6 MWe Transport Gasifier
- 3 MWe Post-Combustion Slipstream

Pilot Solvent Test Unit
Wilsonville, AL

Pilot Solvent Test Unit:
* Amine baseline
* B&W Advanced CO₂ Capture Solvent

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Would Advanced CCS Technologies Dispatch?

- EIA uses the National Energy Modeling System (NEMS) to project energy-economic-environmental impacts of policy through 2035.
Enhanced Oil Recovery (EOR) As A Catalyst For CCS

• **Current Status**
  – 50 years of experience
  – 50MMT added to system every year
  – 1\textsuperscript{st} Gen capture technologies economic at today’s oil prices

• **Advantages**
  – Existing infrastructure and knowledge base

• **Challenges**
  – Is it storage? 1:0.8 BAU and 1:1.2 at best
  – Second generation recovery approaches need to be demonstrated
  – Distributing Value of CO\textsubscript{2} to incentivize capture
Methods of Oil Production

Primary Recovery
Produces 12 – 15% of oil in place*

Secondary Recovery
Another 15 – 20% of the original oil in place* may be produced by waterflooding

Enhanced Oil Recovery (EOR)
Another 4 – 11% of the original oil in place* may be produced using current and advanced technology

Current Processes
• Thermal
• Gas Miscible
• Chemical

Advanced Processes
• Improved mobility control
• Deep steam
• Microbial
• Gravity mining

*Approximately 460 billion bbl of oil estimated to be in place before any production

Approximately 65% (300 billion bbls of oil) still locked in earth place after secondary recovery
Currently, over 48 million metric tons (tonnes) per year of CO$_2$ are used for EOR. Of this total, about 25% is anthropogenic in origin.

Worldwide, potential for CO$_2$ EOR is 130 billion tonnes.

Viscosity of oil is reduced providing more efficient miscible displacement.
### Examples of DOE-Sponsored CO₂ Sequestration Projects in the U.S. Involving EOR

<table>
<thead>
<tr>
<th>EOR Field</th>
<th>CO₂ Source</th>
<th>Geological Stratum</th>
<th>Injection Start Date</th>
<th>Cumulative CO₂ Injection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zama Field, Alberta, Canada</td>
<td>Natural Gas Processing Plant</td>
<td>Pinnacle Reef, Middle Devonian Keg River</td>
<td>December 2006</td>
<td>230,000 tons</td>
<td>The Zama oil field validation test being conducted in Alberta, Canada, is evaluating the potential for geologic sequestration of CO₂ in an acid gas stream that also includes high concentrations of hydrogen sulfide (H₂S) for the concurrent purposes of CO₂ sequestration, H₂S disposal, and EOR. The acid gas is generated as a by-product during the processing of raw natural gas being extracted from the field.</td>
</tr>
<tr>
<td>Williston Basin</td>
<td>Pulverized Coal Power Plant</td>
<td>Devonian Duperow or Mississippian Madison Group</td>
<td>2011</td>
<td>500,000 tons/year</td>
<td>The Williston Basin demonstration test will evaluate the potential for geological sequestration of CO₂ in a deep carbonate reservoir for the dual purpose of CO₂ sequestration and EOR. Characterization studies indicate that the oil fields of the Williston Basin may have over 1 billion tons of CO₂ storage capacity. Additionally, the volume of incremental oil that could be produced from Williston Basin oil fields has been estimated to be approximately 1 billion barrels.</td>
</tr>
<tr>
<td>Louden Field, Illinois</td>
<td>Refinery or Ethanol Plant</td>
<td>Mississippian Weiler Sandstone</td>
<td>March 2007</td>
<td>43 tons</td>
<td>The Louden field test, an enhanced oil recovery “huff-n-puff” project, is designed to inject (huff) CO₂ into a producing well for 3-5 days, allow the gas to soak for approximately one week, then place the well back on production and measure the amount of petroleum fluids produced (puff).</td>
</tr>
<tr>
<td>Louden Field, Illinois</td>
<td>Refinery or Ethanol Plant</td>
<td>Mississippian Weiler Sandstone</td>
<td>February 2008</td>
<td>2,500 tons</td>
<td>The well conversion EOR field test does not require the drilling of any new wells because available well(s) will be converted to handle CO₂ injection and the pattern and spacing of existing wells is adequate to test EOR processes in the reservoir. Well conversion represents a potential near-term, low-cost opportunity to implement EOR.</td>
</tr>
<tr>
<td>Snyder, Permian Basin, Texas</td>
<td>McElmo Dome</td>
<td>Strawn- and Canyon-age carbonate reefs</td>
<td>Second Quarter 2008</td>
<td>700,000 tons</td>
<td>This test will include a post-audit modeling analysis of injected CO₂ for EOR over the last 30 years at the SACROC Unit in the Permian Basin of Texas, in addition to intense monitoring analyses of ongoing CO₂ injection at SACROC.</td>
</tr>
<tr>
<td>Aneth Oil Field, Bluff, Utah</td>
<td>McElmo Dome</td>
<td>Paradox Formation, Pennsylvanian Desert Creek</td>
<td>Second Quarter 2007</td>
<td>300,000 tons</td>
<td>The primary research objective of this EOR-sequestration test is to evaluate and maximize the efficacy of CO₂ subsurface monitoring technologies, and to improve the ability to track the fate of injected CO₂ and to calculate ultimate storage capacity.</td>
</tr>
<tr>
<td>Weyburn, Saskatchewan</td>
<td>Dakota Gasification Plant</td>
<td>The Midale Beds of the Mississippian Charles Formation,</td>
<td>September 2000</td>
<td>33 million tons</td>
<td>The Weyburn program is organized around five technical themes: geological integrity, wellbore integrity, storage monitoring methods, risk assessment and storage mechanisms, and data validation and management. The technical objectives are to determine the long-term storage risks and monitoring requirements to mitigate such risks.</td>
</tr>
</tbody>
</table>
Summary of CO₂ EOR

CO₂ EOR is a promising technology to safely store CO₂ underground so that it cannot contribute to climate change. While this technology has been implemented by the oil industry since 1972, further research is needed to ensure that the stored CO₂ remains isolated from the atmosphere and the biosphere on the order of thousands of years and that the storage process remains as safe and economically viable as possible.

DOE’s Carbon Sequestration Program is currently addressing the following challenges:

• Improving understanding of oil reservoir characteristics relative to CO₂ fate and transport
• Reducing the costs of capturing, processing, and transporting anthropogenic CO₂, particularly from power generation facilities
• Further developing technologies to monitor and verify CO₂ storage, and
• Developing CO₂ emissions trading protocols.