Efficient Utilization of Coal
Oxy-Combustion Coal-Fueled Power with CO₂ Storage

Charles E. Taylor
Director, Chemistry and Surface Science Division
National Energy Technology Laboratory

- **Full-service DOE Federal laboratory**
  - Program Planning
  - Budget Formulation and Execution
  - Procurement
    - Contracting and Financial Assistance
  - Project Management
    - Including NEPA Compliance
  - Legal
  - Financial Management and Reporting
  - On-site Research
  - Program Performance and Benefit Analysis

- **Dedicated to energy RD&D, domestic energy resources**
  - Fossil Energy
  - Support DOE’s Offices of Electricity and Energy Efficiency

- **Fundamental science through technology demonstration**
- **Unique industry–academia–government collaborations**
1977 – All four sites join new U.S. Department of Energy


1918 – Petroleum research begins in Bartlesville, OK

1910 – Coal research begins in Pittsburgh, PA

1946 – Synthesis gas research begins in Morgantown, WV

1977 – Materials research begins in Albany, OR

1996 – PA & WV sites form new Federal Energy Technology Center (FETC)

1999 – FETC becomes National Energy Technology Laboratory (NETL)

2000 – National Petroleum Technology Office in OK joins NETL

2001 – NETL opens Arctic Energy Office in Fairbanks, AK

2005 – Albany Research Center joins NETL

2009 – OK office moves to Sugar Land, TX

2000 – NETL opens Arctic Energy Office in Fairbanks, AK

2001 – NETL becomes National Energy Technology Laboratory (NETL)

2005 – Albany Research Center joins NETL

2009 – OK office moves to Sugar Land, TX

NETL Celebrates Its Centennial

NETL – A Century of Energy Innovation

Enhanced Resource Recovery & Operational Safety

Systems & Policy Analysis

Climate & Energy

Collaborative R&D Management

Alternative Fuels

Materials Science & Advanced Metallurgy

Energy Efficiency & Renewable Energy

Electrical Delivery & Energy Reliability
Energy Demand 2008

100 QBtu / Year
84% Fossil Energy

Energy Demand 2035

114 QBtu / Year
78% Fossil Energy

Sources: U.S. data from EIA, Annual Energy Outlook 2011; World data from IEA, World Energy Outlook 2011
Energy Demand 2007

- Energy Demand: 22.8 QBtu / Year
- 84% Fossil Energy
- Oil: 44%
- Coal: 22%
- Gas: 17%
- Nuclear: 11%
- Renewables: 6%
- 1,262 mmt CO₂

Energy Demand 2035

- Energy Demand: 22.2 QBtu / Year
- 78% Fossil Energy
- Oil: 37%
- Coal: 17%
- Gas: 19%
- Nuclear: 19%
- Renewables: 8%
- 1,071 mmt CO₂

Japan's energy demand is projected to decrease by 0.1% from 2007 to 2035.

Data from IEA, World Energy Outlook 2010
Projected World Growth in CO₂ Emissions

*(EIA-IEO 2010 BAU Projection)*

World energy-related CO₂ emissions (gigatonnes)

- **OEDC**
- **Non-OEDC**

<table>
<thead>
<tr>
<th>Year</th>
<th>OEDC</th>
<th>Non-OEDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>2015</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>2020</td>
<td>13</td>
<td>21</td>
</tr>
<tr>
<td>2025</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>2030</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td>2035</td>
<td>14</td>
<td>28</td>
</tr>
</tbody>
</table>

World CO₂ emissions from coal combustion (gigatonnes)

- **Non-OEDC**
- **OEDC**

<table>
<thead>
<tr>
<th>Year</th>
<th>Non-OEDC</th>
<th>OEDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**EIA’s International Energy Outlook 2010** Reference case -- current laws and policies remain unchanged

FE Coal R&D Program
A History of Innovative Solutions

1970’s
- Clean Air Act
- Oil Embargo

1980’s
- Acid Rain
- Utility Deregulation

1990’s
- Climate Change

2000’s
- A global issue

- President targets 80% reduction in CO2 by 2050
- Congress considers cap-and-trade

- National response to address air quality concerns
- Profound impact on existing (and future) coal burning power plants

- New power system technology (CFBC)
- Emission control technologies for existing plants target NOX, SO2, and Particulates
  - Installed on 75% of U.S. coal plants; 1/2 to 1/10 cost of older systems

- Coal processing technology advances - but markets fail to develop
  - Successful demonstrations (coal liquids, SNG, chemicals)
  - First gasification-based pioneer plants – Dakota Gasification

- Integrated CCS energy systems (highly efficient, zero emission, affordable)
  - CCS (pre & post-combustion capture, site characterization, MVA, Best Practices)
  - Fuel processing & separation (gasifiers, O2/H2 membranes, feed-pump, gas cleaning)
  - Power generation (H2 turbines, SECA-SOFC, oxy-combustion, chemical looping)

- Technology advancements were achieved that can provide energy security benefits and are available to be deployed if market conditions materialize … the ability to use the nation’s large coal reserves in an efficient manner was improved substantially …


- …fossil’s programs made a significant contribution to the well-being of the United States, lead to realized economic benefits, energy options for the future, and significant knowledge …


…the Regional Partnerships is an excellent program that will achieve significant results for CCS in the United States, Canada and internationally … the Partnerships Programme will significantly advance and accelerate the CCS field. The individual projects will together build a comprehensive and expansive research programme, the size and scope of which is unique throughout the world …

Adequate Geologic CO₂ Storage Projected for U.S.

National Atlas Highlights (Atlas II)

U.S. Emissions ~6 GT CO₂ per year all sources
(U.S. Coal-Fueled Emissions ~2.1 GT CO₂ per year)

North American CO₂ Storage Potential (GT)

<table>
<thead>
<tr>
<th>Sink Type</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline Formations</td>
<td>1,653</td>
<td>20,213</td>
</tr>
<tr>
<td>Unmineable Coal Seams</td>
<td>60</td>
<td>117</td>
</tr>
<tr>
<td>Oil and Gas Fields</td>
<td>143</td>
<td>143</td>
</tr>
</tbody>
</table>

Conservative Resource Assessment

Hundreds of Years of Storage Potential

Adequate Geologic CO$_2$ Storage Projected for Japan

2008 Emissions = 1,208 x10$^6$ metric tonnes$^1$

Storage Capacity = 146,096x10$^6$ metric tonnes$^2$


Distribution Map of CO$_2$ Storage Capacity$^2$
Mission & Approach
Critically Linked to DOE Climate & Security Goals

**Develop Technologies and Best Practices That Facilitates Wide Scale Deployment of Coal Based Energy Systems Integrated With CCS**

- Develop plant designs & components optimized for CCS
- Reduce capture costs
- Validate storage capacity
- Validate storage permanence
- Create private/public partnerships
- Promote infrastructure development
- Put “first of kind” field projects in place
- Develop tools, protocols & best practices

DOE Regional Carbon Sequestration Partnerships

NATIONAL ENERGY TECHNOLOGY LABORATORY
Fossil Energy CO₂ Capture Solutions

- Post-combustion (existing, new PC)
- Pre-combustion (IGCC)
- Oxycombustion (new PC)
- CO₂ compression (all)

Cost Reduction Benefit

- Amine solvents
- Physical solvents
- Cryogenic oxygen
- 1st Generation physical solvents (CCPI)
- 1st Generation chemical solvents (CCPI)
- Adv. CO₂ compression (Ramgen)

CO₂ Capture Targets:
- 90% CO₂ Capture
- <10% increase in COE (IGCC)
- <35% increase in COE (PC)

2010 2015 2020

Ready for Demonstration
CCS Commercial Experience

- Carbon capture technology is commercially available
  - Post-combustion capture at 20-80 MWe coal power plants
  - Pre-combustion (coal gasification) capture at full scale

- CO$_2$ injection into geologic formations is widely practiced today
  - EOR: 48 million TPY in 2007
  - 3,900 mile pipeline network
  - 50 Acid gas injection projects
  - Megatonne/yr injection projects
    - Weyburn-Midale
    - Sleipner
    - In Salah
    - Others

Photo sources: E.S. Rubin, Carnegie Mellon, Statoil
Eight Major CCS Demonstration Projects

- **Southern Company**
  - Transport Gasifier/Selexol CO₂ Capture
  - Total: ~$2.9B; DOE: $270M
  - EOR Storage – 3.0 MTPY
  - 582 MWe (net)

- **FutureGen 2.0**
  - B&W Oxy-Combustion
  - DOE: $1.048B
  - Saline Storage – 1.0 MTPY
  - 200 MWe (gross)

- **Summit TX Clean Energy**
  - Siemens Gasifier/Selexol CO₂ capture
  - Total: ~$1.7B; DOE: $450M
  - EOR Storage – 3.0 MTPY
  - 270 MWe (net)

- **Leucadia Energy**
  - Methanol, Rectisol
  - Total: $436M; DOE: $261M
  - EOR, 4.5 MTPY

- **NRG**
  - Fluor Econamine FG Plus SM
  - Total: $334M; DOE: $167M
  - EOR Storage – 0.4MTPY
  - 60 MWe Slipstream

- **Archer Daniels Midland**
  - Industrial Power & Ethanol
  - DOW Alstom Amine
  - Total: $208M; DOE: $141M
  - Saline, 1 MTPY

- **Air Products**
  - SMR H₂ Production, VPSA
  - Total $431M; DOE: $284M
  - EOR, 1 MTPY

- **Heat Energy Corporation (HECA)**
  - GE Gasifier/Rectisol CO₂ Capture
  - Total: ~$2.8B; DOE: $408M
  - EOR Storage – 2.0 MTPY
  - 250 MWe (net)

- **FutureGen 2.0**
  - B&W Oxy-Combustion
  - DOE: $1.048B
  - Saline Storage – 1.0 MTPY
  - 200 MWe (gross)

- **FutureGen 2.0**
  - B&W Oxy-Combustion
  - DOE: $1.048B
  - Saline Storage – 1.0 MTPY
  - 200 MWe (gross)

- **Summit TX Clean Energy**
  - Siemens Gasifier/Selexol CO₂ capture
  - Total: ~$1.7B; DOE: $450M
  - EOR Storage – 3.0 MTPY
  - 270 MWe (net)

- **Leucadia Energy**
  - Methanol, Rectisol
  - Total: $436M; DOE: $261M
  - EOR, 4.5 MTPY

- **Southern Company**
  - Transport Gasifier/Selexol CO₂ Capture
  - Total: ~$2.9B; DOE: $270M
  - EOR Storage – 3.0 MTPY
  - 582 MWe (net)
What is FutureGen 2.0?

- U.S. Department of Energy has awarded:
  - $590 million to Ameren, Babcock & Wilcox and American Air Liquide to demonstrate Oxy-Combustion technology at utility-scale
  - $459 million to FutureGen Alliance to transport and geologically store the CO₂

- The FutureGen 2.0 project will incorporate:
  - CO₂ Capture: Repower an existing Ameren 200 MWe power plant unit in Meredosia, Illinois with Oxy-Combustion and CO₂ compression & purification
  - Transport: Build a CO₂ pipeline to a CO₂ storage facility in Illinois (exact location TBD)
  - Storage: Develop a deep saline storage facility to sequester CO₂ from the power plant (and potentially other facilities in the region) in the Mt. Simon sandstone formation
Meredosia Power Station Site

Meredosia Plant

- Location - Meredosia, IL
- Operated by Ameren Energy Resources
- 4 existing units, 3-coal fired (Units 1 & 2 mothballed), Unit 4-oil-fired
- Illinois Coal, PRB or PRB Blends
- Truck & barge unloading facilities for coal
- Repower existing steam-turbine with purpose-built Oxy-Comb PC boiler
- Existing boiler, built in 1975, to be retired
- Infrastructure exists to accommodate repowering with coal
- Unit 4 turbine & generator have low operating hours
What is Oxy-Combustion?

Oxy-Combustion burns coal with a mixture of oxygen and CO$_2$ instead of air to produce a concentrated CO$_2$ stream for safe, permanent, storage.

Oxy-Combustion has been tested at 0.5 MWe & 10 MWe. A large integrated commercial size test (150-200 MWe) will:

- Establish cost basis for retrofitting/repowering existing coal-fired units – as a pathway to lower new plant costs (e.g., 500-800 MWe scale)
- Prove operability and reliability of the integrated process - Boiler Island, Air Separation Unit, Compression & Purification Unit, & CO$_2$ storage
- Provide performance & emissions data for future commercial guarantees
- Establish operating & maintenance experience for future commercial plants
IGCC Pre-combustion CO₂ Capture Technologies

Advantages:
1. High Pₐ\text{CO₂}
2. Low Volume Syngas Stream

Challenges:
1. IGCC—system complexity
2. Additional water-gas-shift process

High Temperature H₂/CO₂ Membranes
High-efficiency solvents
Solid Sorbents
Novel Concepts
IGCC Pre-Combustion Polymer-Based High Temperature Membrane

Accomplishments:

• Developed polybenzimidazole (PBI) – based membrane exhibits the highest operating temperature (400 °C) of a polymer-based membrane.

• **Over 400 days** of testing in simulated synthesis gas environments at temperatures exceeding 250 °C conducted while demonstrating:
  – permeabilities and selectivities of commercial interest
  – operation temperatures well matched to process temperatures
  – chemical stability to primary synthesis gas components
  – mechanical stability in the presence of process cycling and simulated upset conditions
IGCC Carbon Capture: Phase Change Polymer

- Vessel on left is a fixed bed of solids (some polymer based)

- High pressure CO₂ is introduced (IGCC applications)

- Solids transform into homogeneous liquid phase, and extracted from bottom of vessel

- Pressure is decreased (only a small amount) in regeneration vessel, CO₂ is generated and the solids reform

- Heat is added to reliquify polymer and pump back to absorption column
NRAP is developing a defensible, science-based methodology for quantifying long-term liability.

Integrated Assessment Model
- Storage site described by subsystems
- Subsystem behavior can be treated in detail
- Uncertainty/heterogeneity handled by stochastic descriptions of subsystems

Potential Receptors or Impacted Media

Release and Transport

Storage Reservoir

National Risk Assessment Partnership (NRAP) Team

NETL
- fracture flow models
- geomechanics models
- geospatial databases
- high PT validation

LBNL
- reactive-flow models
- system models
- field geophysics
- groundwater models

PNNL
- reactive-flow models
- data integration platform
- groundwater models
- high PT validation

LLNL
- reactive-flow models
- geomechanics models
- groundwater systems
- high PT validation

LANL
- reactive-flow models
- geomechanics models
- systems models
- geomaterials properties
National Carbon Capture Center (NCCC) at Power Systems Development Facility (PSDF) Wilsonville, AL

**NCCC Mission:** Develop technologies that will lead to the commercialization of cost-effective, advanced coal fueled power plants with CO₂ capture

- 6 Mwe Transport Gasifier
- 3 Mwe Post-Combustion Slipstream
- Southern Company
  - Peabody Energy
  - American Electric Power
  - Luminant
  - Arch Coal
  - RioTinto
  - Electric Power Research Institute
Global Collaborations
Technology Transfer and Lessons Learned

Examples of Current Collaborations:

- **Sleipner (Norway, Europe)**
  - 1 Mt CO₂/y  <Commercial 1996>
  - StatoilHydro

- **In Salah (Algeria, Africa)**
  - 1 Mt CO₂/y  <Commercial 2004>
  - BP, Sonatrach, StatoilHydro

- **Weyburn-Midale (Saskatchewan, Canada)**
  - 1.8 Mt CO₂/y  <Commercial 2000>
  - Encana, Apache

- **Fort Nelson (British Columbia, Canada)**
  - >1 Mt CO₂/y , 1.8 MT acid gas/yr  <Demo Scale>
  - Spectra Energy
## DOE’s Global CCS Project Involvement

<table>
<thead>
<tr>
<th>Location</th>
<th>Operations</th>
<th>U.S. Invol.</th>
<th>Reservoir</th>
<th>Operator /Lead</th>
<th>Int’l Recognition</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America, Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saskatchewan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weyburn-Midale</td>
<td>1.8 Mt CO₂/yr commercial 2000</td>
<td>2000-2011</td>
<td>oil field carbonate EOR</td>
<td>Encana, Apache</td>
<td>IEA GHG R&amp;D Programme, CSLF</td>
</tr>
<tr>
<td>North America, Canada, Canada</td>
<td>250,000 tons CO₂, 90,000 tons H₂S demo</td>
<td>2005-2009</td>
<td>oil field carbonate EOR</td>
<td>Apache (Reg. Part.)</td>
<td>CSLF</td>
</tr>
<tr>
<td>Zama oil field</td>
<td>&gt; 1 Mt CO₂/yr, 1.8 Mt acid gas/yr large-scale demo</td>
<td>2009-2015</td>
<td>saline formation</td>
<td>Spectra Energy (Reg. Part.)</td>
<td>CSLF</td>
</tr>
<tr>
<td>North America, Canada, Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>British Columbia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fort Nelson</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleipner</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe, North Sea, Norway</td>
<td>700,000 tonnes CO₂ commercial 2008</td>
<td>2009-TBD</td>
<td>marine sandstone</td>
<td>StatoilHydro</td>
<td></td>
</tr>
<tr>
<td>Snovhit CO₂ Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe, Germany</td>
<td>60,000 tonnes CO₂ demo 2008</td>
<td>2007-2010</td>
<td>saline sandstone</td>
<td>GeoForschungsZentrum, Potsdam(GFZ)</td>
<td>CSLF, European Commission, IEA GHG R&amp;D Prog</td>
</tr>
<tr>
<td>CO2SINK, Ketzin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia, Victoria</td>
<td>100,000 tonnes CO₂ demo 2008</td>
<td>2005-2010</td>
<td>gas field sandstone</td>
<td>CO2CRC</td>
<td>CSLF</td>
</tr>
<tr>
<td>Otway Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa, Algeria</td>
<td>1 Mt CO₂/yr commercial 2004</td>
<td>2005-2010</td>
<td>gas field sandstone</td>
<td>BP, Sonatrach, StatoilHydro</td>
<td>CSLF, European Commission</td>
</tr>
<tr>
<td>In Salah gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia, China,</td>
<td>assessment phase CCS</td>
<td>2008-TBD</td>
<td></td>
<td>Ordos Basin</td>
<td>Shenhua Coal</td>
</tr>
<tr>
<td>Ordos Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Oxy-Combustion Summary

• An advanced coal combustion technology
  – Capable of retrofitting or repowering an existing plant
  – As a base-load technology for new green field applications

• Opportunity for near-zero emissions from coal
  – Potential for nearly 100% CO₂ capture with minor economic penalty
  – Cleaner and with less CO₂ emissions than conventional NG combined-cycle
  – 40% lower water consumption than conventional amine CO₂ capture system

• Mature commercial technology cost projected to be lower than conventional post-combustion CO₂ capture

• Many Opportunities for Improvement:
  – Cryogenic ASU developments can reduce O₂ generation power consumption by 20-35%
  – Opportunity to incorporate Ion Transport Membranes, further increasing O₂ supply efficiency
  – Smaller Oxy-Combustion specific boiler designs can increase heat transfer & reduce capital cost
  – Co-sequestration of CO₂ with NOx and SO₂ possible
CCS Final Observations

• CCS technology is available today, however:
  – It is very expensive, energy intensive, and not fully proven

• Sequestration needs to be more widely demonstrated, especially in deep saline reservoirs with large-volume CO₂ injection

• DOE RD&D program is targeting the key issues

• Regulatory certainty is a prerequisite for commercial action.