Reinhold Environmental Ltd.

2009 NOx-Combustion Round Table & Expo Presentation

February 9 & 10, 2009, Cleveland, OH

The Shaw Group Inc.®

Impact of Carbon Dioxide Capture and Storage (CCS) on Existing Coal-Fired Power Plants

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February 9, 2009

Reinhold Environmental
2009 - NOx Round Table – PCUG Conference
Cleveland, Ohio

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Topics

- Overview
- Process Options and Feasibility
- Integration and Impacts
- Re-Use and Storage of CO_2
- Economics
- Summary

Carbon Dioxide Reduction and Capture Various Types of Power Plants

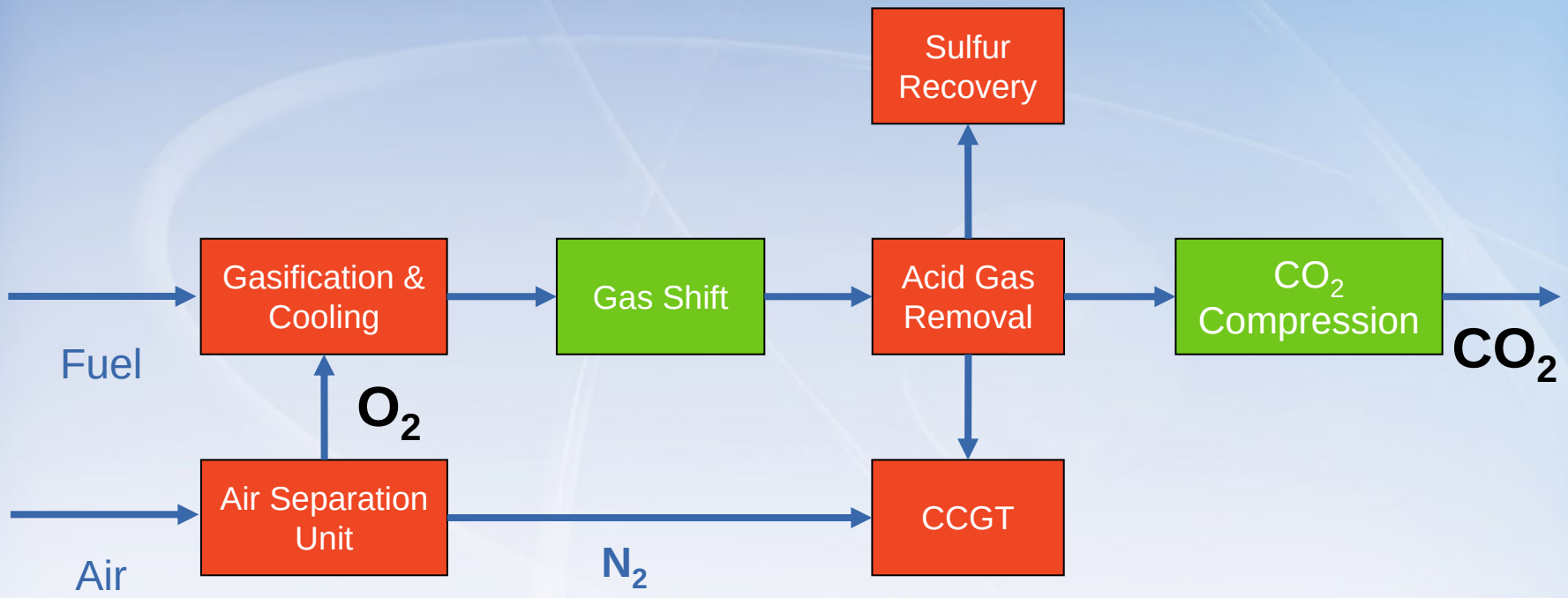
CO2 Reduction

- Heat Rate Improvements
- Co-Fired Alternative Fuels with Coal
- Re-Powering
- Other Methods

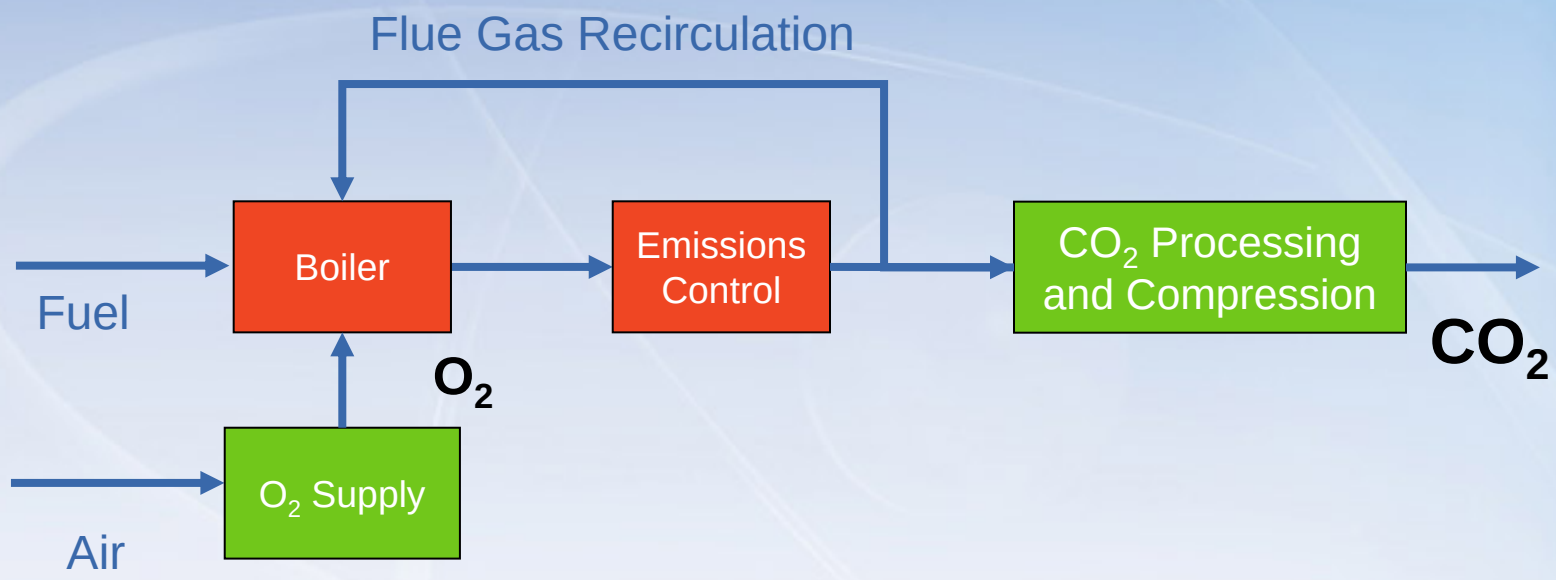
CO2 Capture

- Pre-Combustion CO2 Capture Technologies for IGCC
- Oxy-Fuel Combustion Technology with CO2 Capture
- Post-Combustion (flue gas) CO2 Capture Processes

IGCC Process with Pre-Combustion Carbon Dioxide Capture



OxyFuel Process with Carbon Dioxide Capture



Post-Combustion Carbon Dioxide Capture

Process Options and Feasibility
Existing Coal-Fired Power Plant

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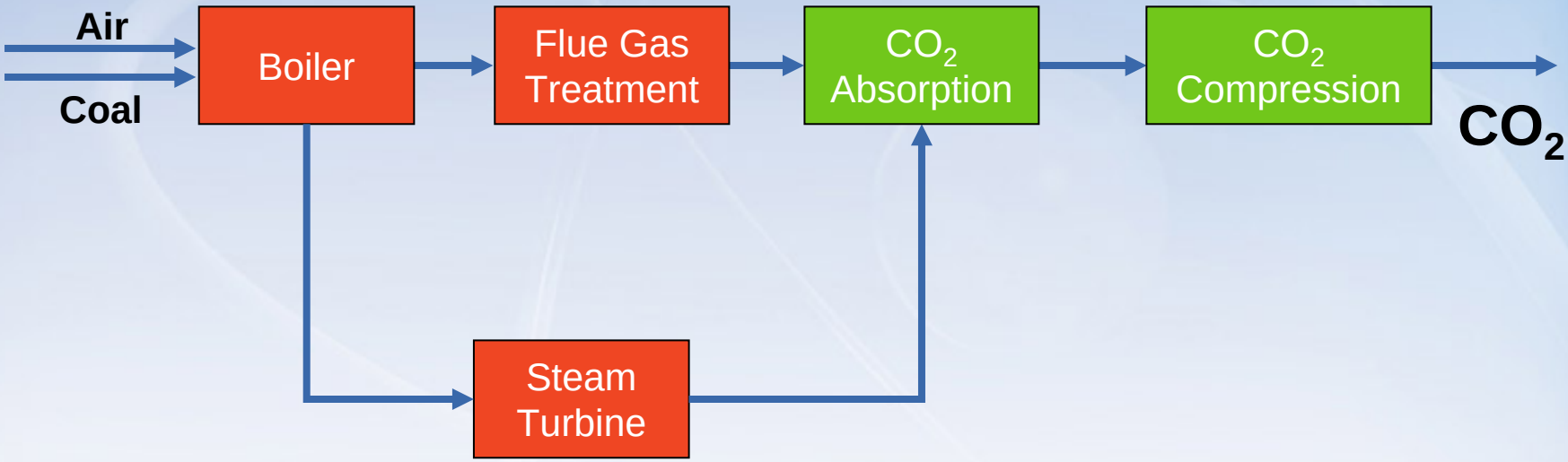
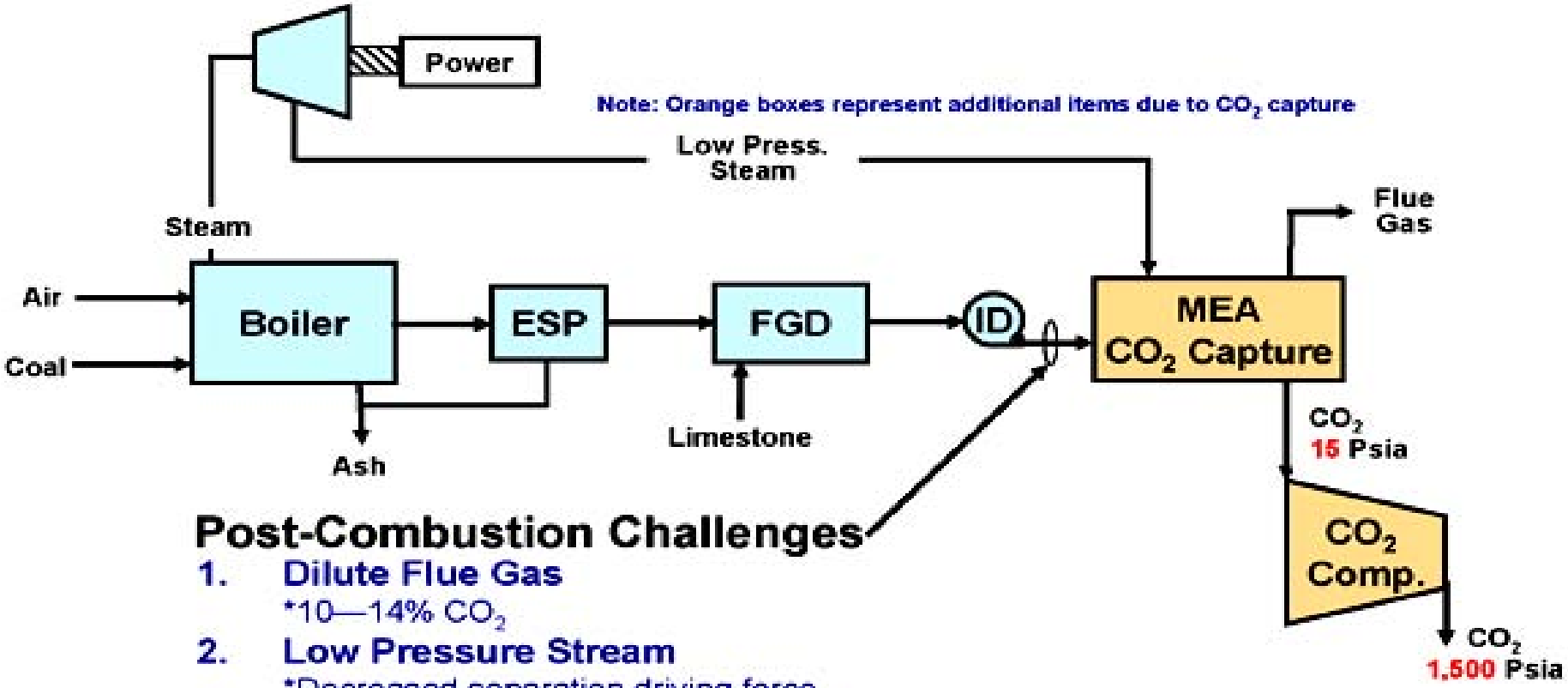
Pulverized Coal Post-Combustion Process CO_2 Capture



Technology Options for Post-Combustion CO_2 Capture

- Amine-based absorption (generic and advanced amines)
- Ammonia absorption process (not chilled)
- Chilled ammonia absorption
- Solvent-based absorption (non-amine-solvents)
- Algae-based process
- Enzyme-based process
- Membrane-type processes
- Physical adsorption of CO_2 in solvents
- Solid sorbents for CO_2 absorption and/or adsorption.
- Other technologies (being developed, R&D, piloted)

Post-combustion Capture

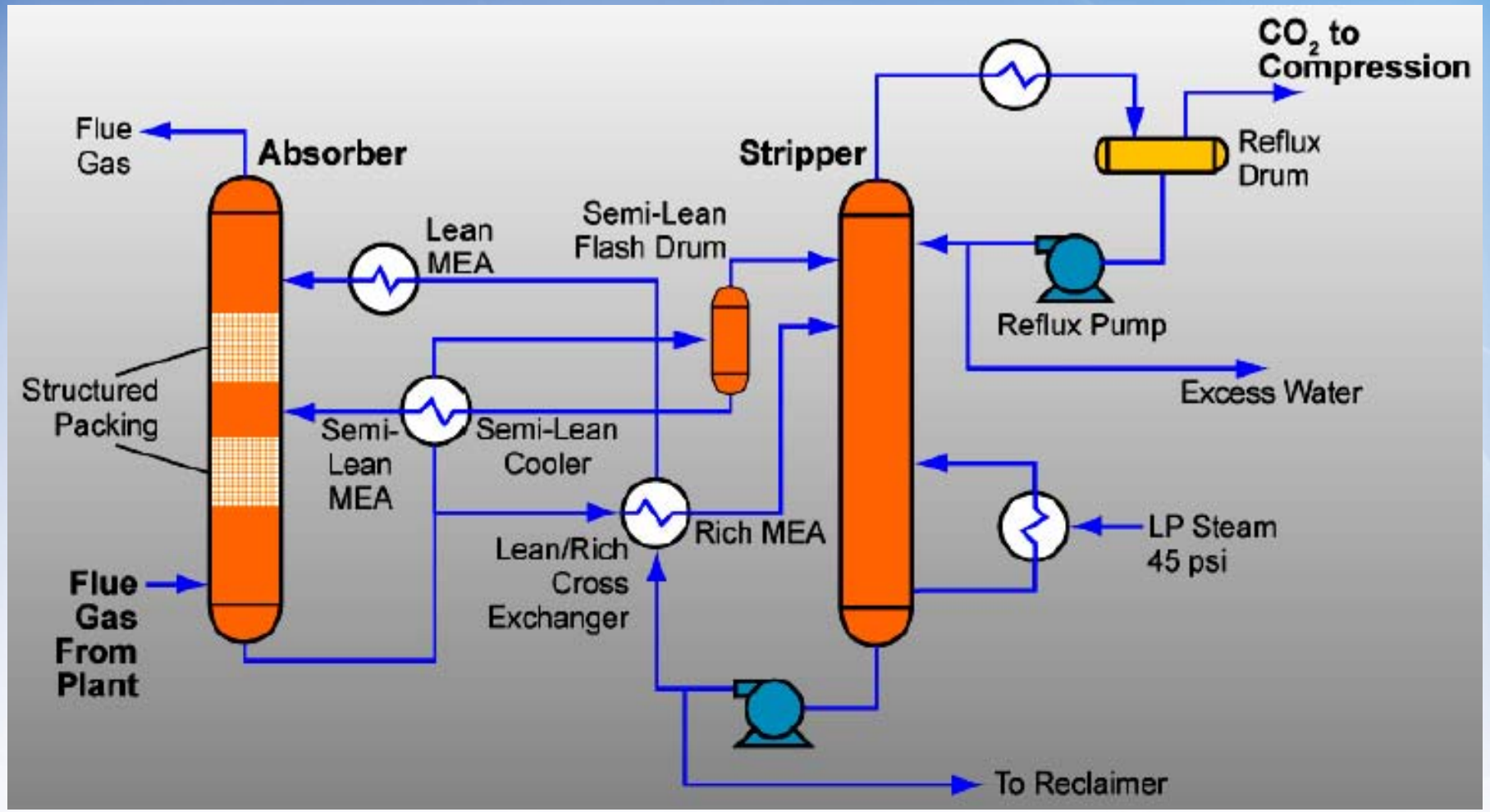


Post-Combustion Challenges

1. **Dilute Flue Gas**
   - *10—14% CO_2
2. **Low Pressure Stream**
   - *Decreased separation driving force
3. **Contaminants**
   - *SO_2, Particulates, etc.
4. **Large Parasitic Load (regeneration steam)**

Source: US DOE report

Amine Based – Flue Gas CO2 Capture Process Schematic - Generic



Source: US DOE report

Technical Feasibility of PC CO_2 Capture

- Most individual equipment components are demonstrated
- Most unit operations are demonstrated
- CO_2 Capture Systems need to be demonstrated (various scales)
- PC CO_2 Capture – Future Pilot and Demonstrations
  - Algae-based CO_2 capture process
  - Amine CO_2 capture process
  - Ammonia CO_2 capture process
  - Chilled Ammonia CO_2 capture process
  - Solvent-based absorption (non-amine-solvents)
  - Other

Post-Combustion Carbon Dioxide Capture Integration

The Impact of CCS on Existing Pulverized Coal Plant

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Impacts and Integration of CO_2 Capture and Storage System

- Real estate for deep FGD equipment (if required)
- Real estate for additional NOx and PM reduction systems (if required)
- Real estate required for CO_2 capture system equipment
- Real estate for CO_2 cooling, drying, and compression equipment
- Real estate for CO_2 transport (pipeline)
- Real estate for interconnecting piping, roads, ductwork, BOP equipment, etc.
- Real estate for CO2 sequestration or re-use system (if onsite)
- Electrical power usage and impact on plant electrical system
- Steam requirement and impact on plant steam turbine system
- Cooling water usage

Impacts and Integration of CO_2 Capture and Storage System (cont.)

- Impact on flue gas cleaning system (e.g. deep FGD, if required)
- Impact on stack for the processed flue gas
- Water balance issues
- O&M personnel requirements
- Maintenance and spare part requirements
- Disposal or regeneration of the spent CO_2 sorbent/material
- Permit issues
- CO_2 by-product reuse or CO_2 storage
- Other impacts

Integration of CO_2 Capture into Pulverized Coal or Natural Gas Combined Cycle Plant

- New Plant – CO_2 capture-ready vs. enhanced-ready
- New Plant – CO_2 initially installed – demo or pilot
- Retrofit CCS (possible) – demo or pilot

Disposition of the Captured CO_2

Where will 12,000 tons CO_2/day of liquid CO_2 product be sent?

Mass Balance Concerning CO_2 Issues

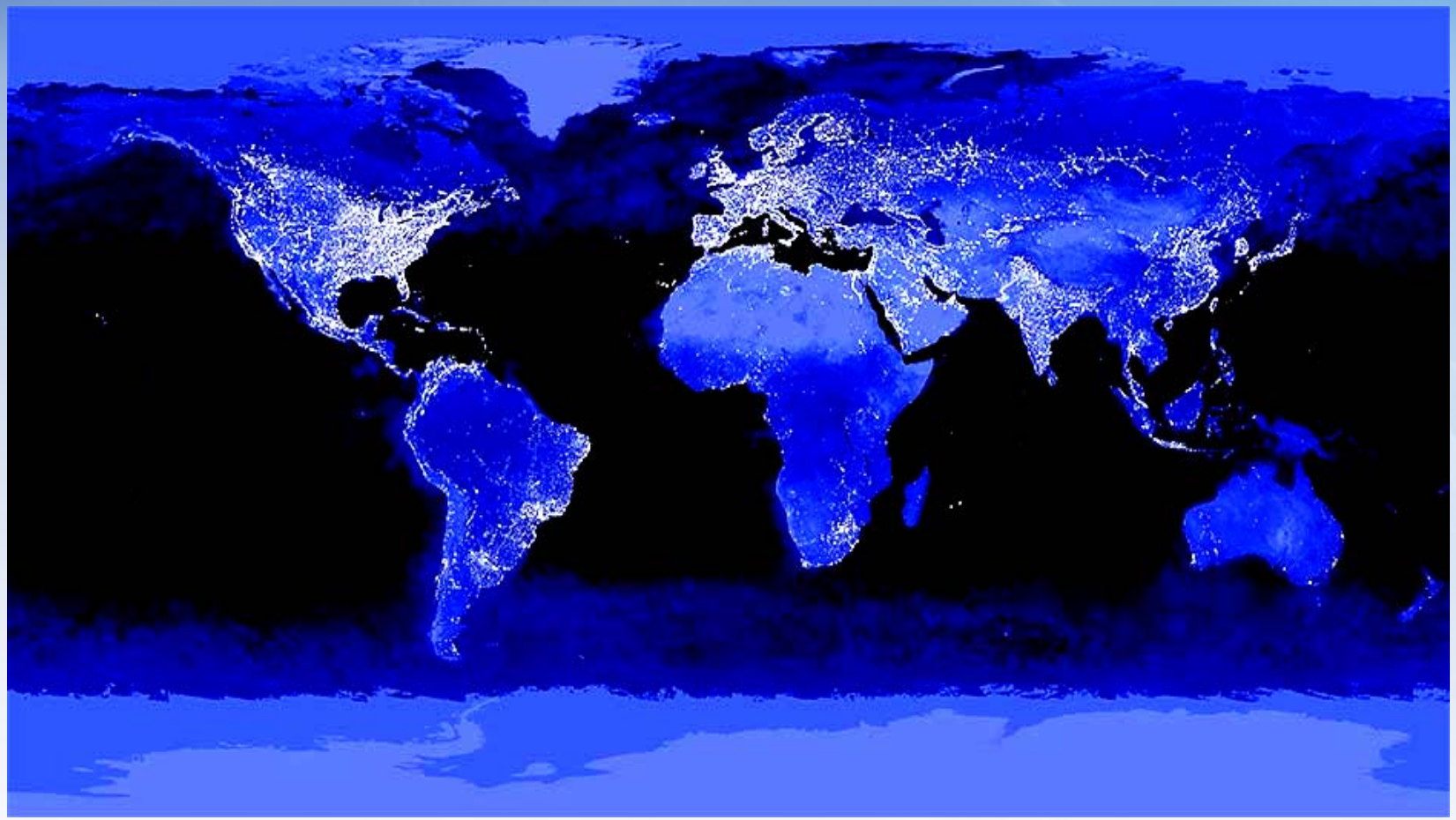
Coal is readily available to generate electricity reliably, efficiently and cost-effectively, while meeting environmental regulations.

- Combustion Chemistry (related to carbon):

  Coal (carbon) + air (O_2) → CO_2

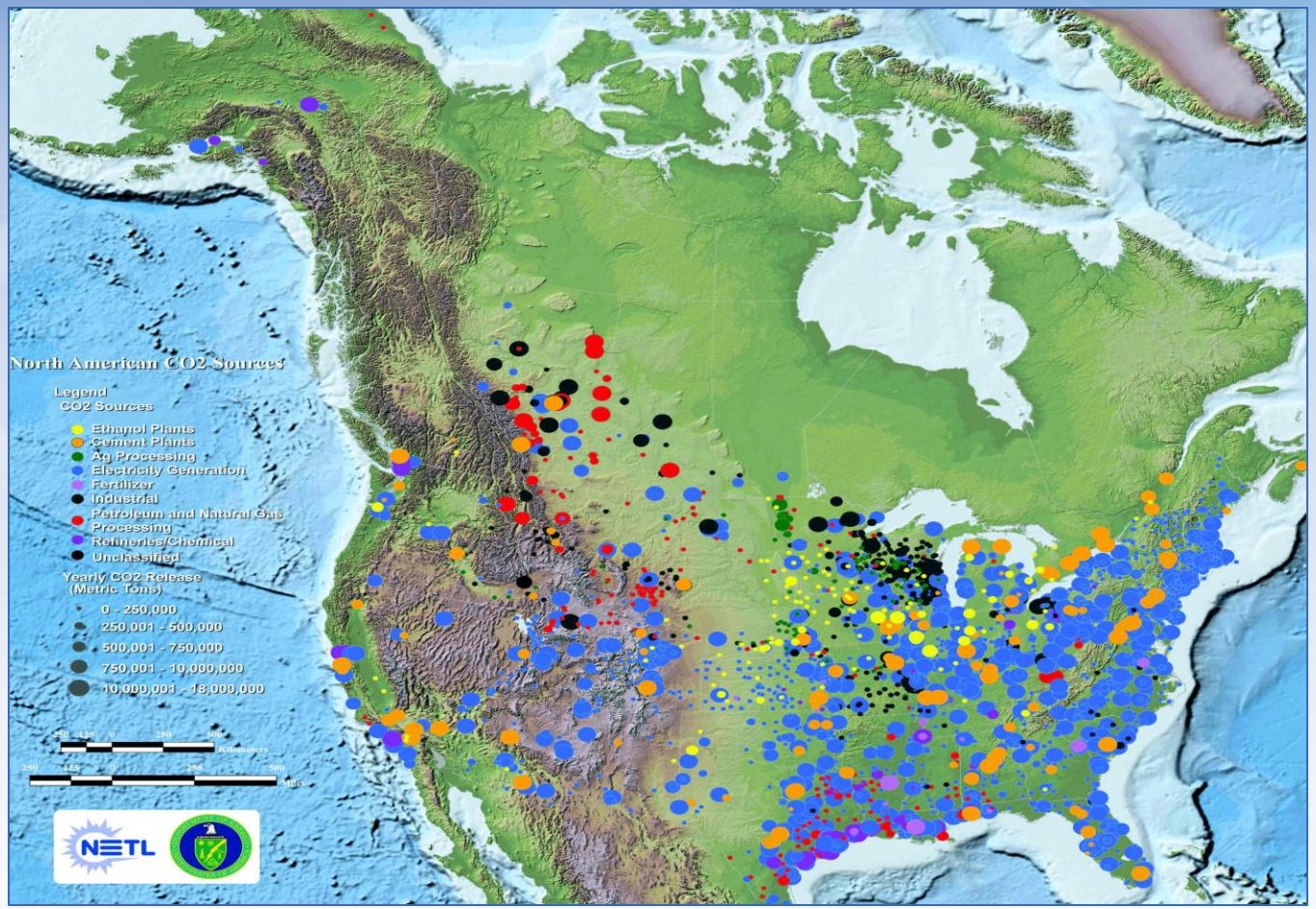
- Example (typical coal containing ~ 70% carbon):
  - ► 1.0 tone Coal
  - ► 2.5 tone CO_2

Earth at Night



Internet Source: Sky Image Lab – Earth at Night Photo – http://www.skyimagelab.com/earatnitlar.html

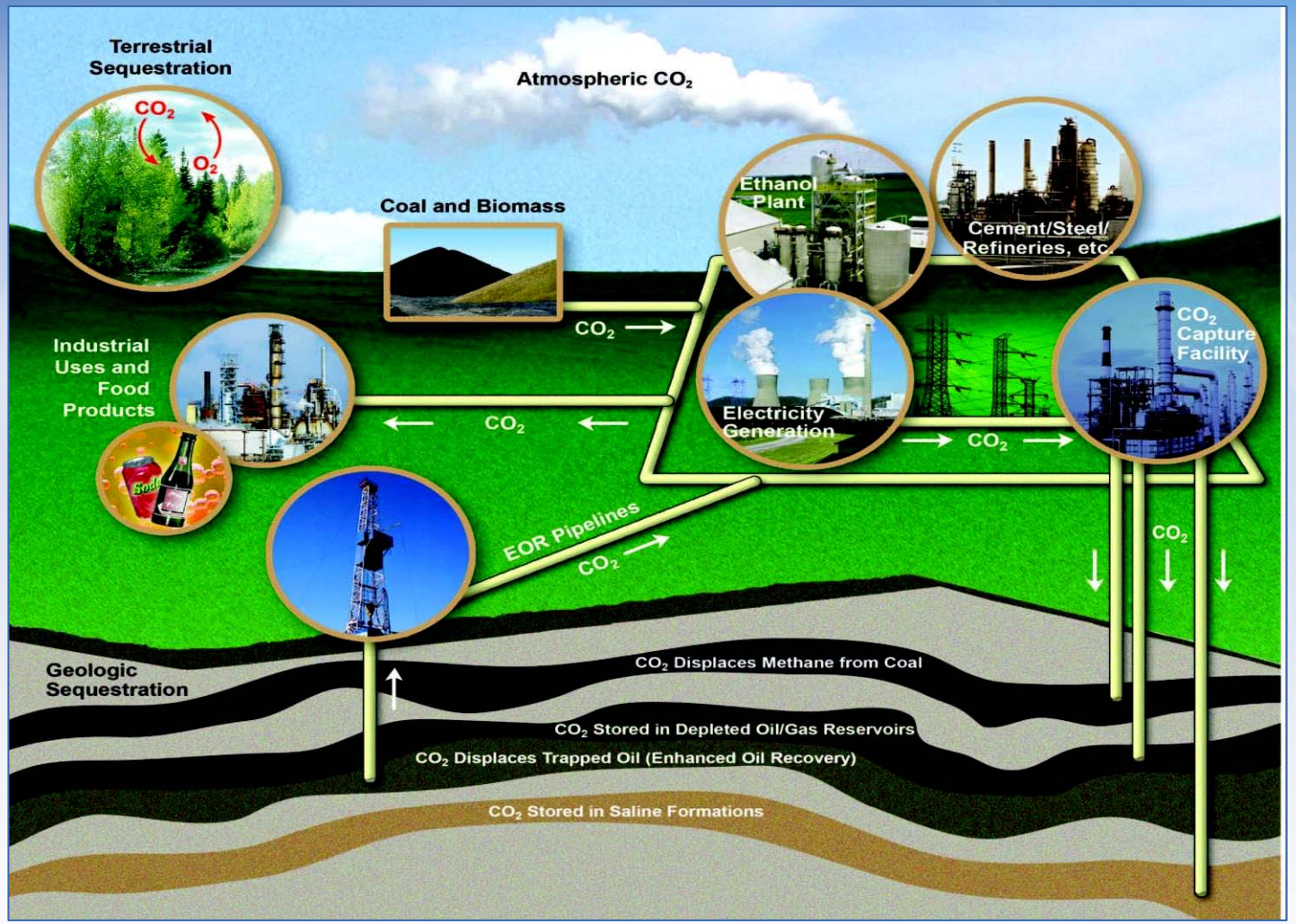
USA and Canada – CO_2 Sources and Size



Re-Use of Carbon Dioxide

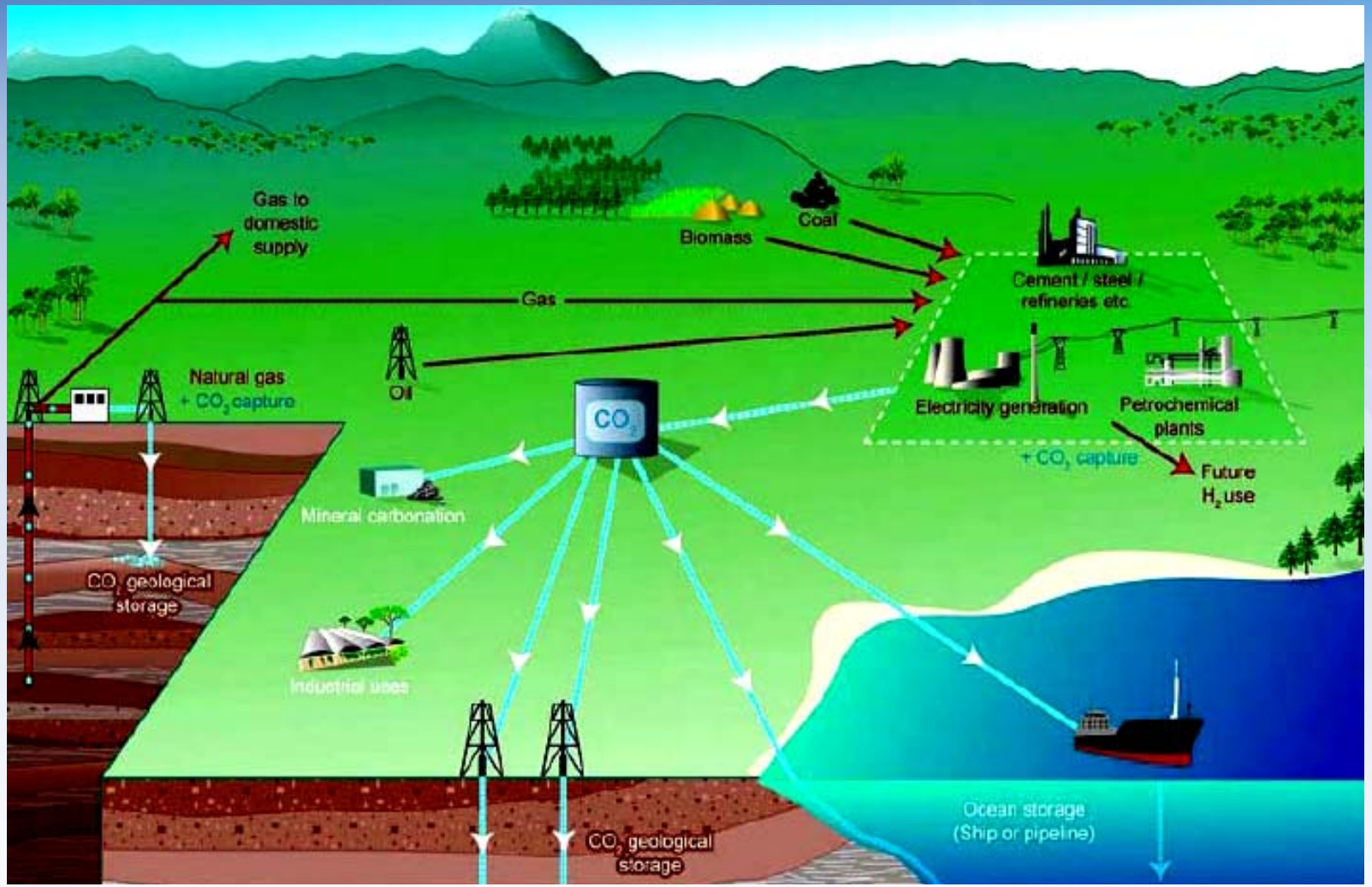
- Enhanced oil recovery (EOR) with CO2 sequestration (storage)
- Enhanced gas recovery (EGR) with CO2 storage
- Manufacture of chemicals (e.g. urea, methanol, etc.)
- Carbonated beverages
- Refrigeration medium and dry-ice refrigerant
- Algae based bio-diesel fuels
- Algae based bio-mass fuel
- Algae based fish-food
- Ammonia based fertilizers
- Other methods to re-use the CO2 (e.g. propellants, health care, cast molds, transport fluid, etc.)

Carbon Capture and Storage (CCS)



US DOE

Carbon Dioxide Storage Options



IPCC Special Report, Carbon Dioxide Capture and Storage, Technical Summary

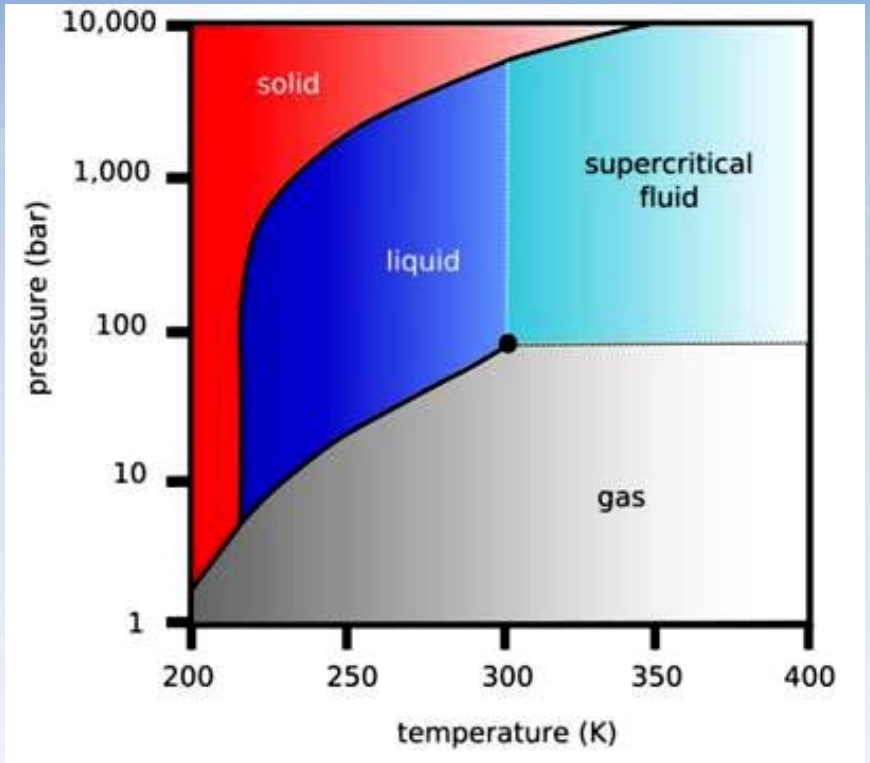
Carbon Dioxide Properties

- Molecular weight CO_2 = 44.01 lb/lb-mole (grams/gram-mole)
- Triple Point = -56.6°C at 5.11 atm
- Critical Temperature = 31.0°C
- Critical Pressure = 72.80 atm (1070.16 psia)
- Critical Point = 87.8°F and 1,071 psia
- Sublimation Temperature of CO_2 = -109.3°F (equals -78.5°C), (@ 1atm)
- Melting Point CO_2 = -56.6°C (@ 5.2 atm)
- Density as CO_2 gas = 0.001977 grams/cubic centimetre (@ 1 atm pressure, 0°C)
- Density as CO_2 liquid = 1.101 grams/cubic centimetre (@ -37°C)
- Density as CO_2 liquid = 0.914 grams/cubic centimetre (@ 0°C and 34.3 atm)
- Density as CO_2 solid = 1.56 grams/cubic centimetre (@ -79°C)
- Density as CO_2 solid = 1.512 grams/cubic centimetre (@-56.6°C)
- Latent Heat of Vaporization = 149.6 Btu/lb CO_2 (equals 83.12 gram-cal per gram CO_2) at the triple point and 101.03 Btu/lb at 0°C
- Solubility in cold water = 0.348 grams CO_2/100 cubic centimetres water (@ 0°C)
- Solubility in warm water = 0.097 grams CO_2/100 cubic centimetres water (@ 40°C)
- Heat of combustion of carbon to CO_2 = 14,093 Btu per lb of carbon.

Source: “Impact of CO2 Capture on Fossil-Fired Power Plants” – Power-Gen Asia, 2008

Carbon Dioxide Phases

Pure CO_2 can exist as a gas, liquid, or solid depending on its pressure and temperature.



Phase Diagram for CO_2

- **Carbon dioxide exists in four phases: gas, liquid, solid, and supercritical.**
- **Supercritical is important as CO_2 acts both as a gas and a liquid.**
- **In the supercritical phase, CO_2 acts like a gas, but has the density of liquid.**
- **The supercritical phase occurs at 31°C (88°F) and at 73 atm (1,070 psi).**

Carbon Dioxide Properties
(ground level and deep earth)

CO_2 Properties at Two Different Nominal Representative Conditions				
Property P (bar), T(°C)	**Depth in Earth (approximate)**	**Units**	**Brine**	**CO_2**
Density @ 201 bar and 60°C	**2 km**	**Kg/m^3**	**1191**	**725**
Density @ 1 bar and 10°C	**0 km (ground level)**	**Kg/m^3**	**1205**	**1.9**
Viscosity @ 201 bar and 60°C	**2 km**	**10^{-6} Pas**	**940**	**60**
Viscosity @ 1 bar and 10°C	**0 km (ground level)**	**10^{-6} Pas**	**1800**	**14**

"Carbon Capture and Sequestration, Integrating Technology Monitoring and Regulation," edited by Elizabeth J. Wilson and David Gerard, published by Blackwell Publishing, 2007.

Examples: CCS Demonstration Projects

(not post-combustion pulverized coal applications)

Weyburn

- Project launched in 1999
- Enhanced oil recovery
- Expected - 22 m/t of CO_2
- Dakota Gasification Company
- 320 Km pipeline

Sleipner

STATOIL

- Field on stream since 1996
- Contains 4 to 9.5% CO_2
- Need to reduce to 2.5%
- Elf - amine technology
- CO_2 - saline aquifer injection

In Salah

bp

- Field on stream since 2004
- Largest dry gas field in Algeria
- Jointly operated with Statoil
- 1,200 Km south of Algiers
- 1 m/t CO_2 injected/year

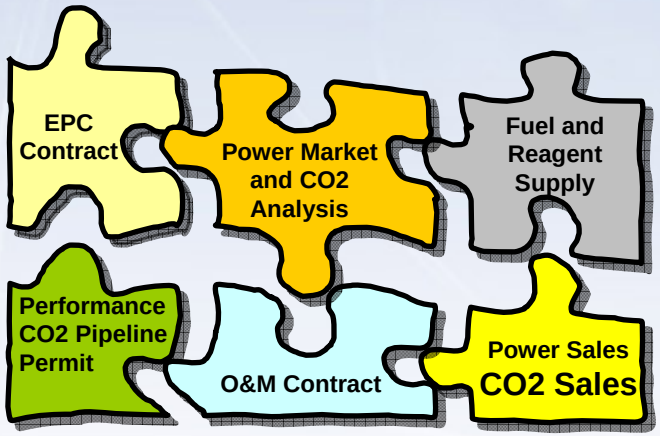
Planned CCS Programs
(some on pulverized coal units)

United States	Norway
Canada	Italy
United Kingdom	China
Germany	Australia
Japan	Netherlands
Sweden	Other

Economics and Managing Risk

Project Economics and Managing Risks

- Technology scale-up
- Installed capital cost (material and labor)
- Annual Operation & Maintenance costs
- Carbon dioxide value ($/ton, sale price, carbon credits, disposal cost, etc.) and disposition



Process Parameters Influencing Installed Capital Cost of Post-Combustion CO_2 Capture Systems

- Percent (%) of total flue gas that is treated
- Percent (%) removal of CO_2 removed from flue gas
- Total mass of CO_2 (tons/day) removed from flue gas
- Type of CO_2 capture process chosen
- Degree of Flue Gas Pre-Treatment (if required)
- Disposition of CO_2 product

Process Parameters Influencing Annual Operation and Maintenance Costs of Post-Combustion CO_2 Capture Systems

- Total mass of CO_2 removed (tons/day) from flue gas
- Type of CO_2 capture process chosen
- Steam unit cost and usage rate
- Electricity unit cost and usage rate
- Cooling water unit cost and usage rate
- Reagent(s) unit cost and make-up rate
- Waste by-product(s) disposal cost
- Corrosion issues
- Solar flux, air humidity & temperature (e.g., algae process)
- O&M costs of flue gas pre-treatment (if required)
- Disposition of CO_2 product
- Other issues

Summary
Post-Combustion CO_2 Capture Options

- CO_2 capture technologies are available for pilot or demonstration
- CO_2 capture technology demonstration systems are being installed
- CO_2 capture process **greatly impacts** PC plant or NGCC power plant
- Long term operating experience is needed (steady state & upset)
- ***Significant*** cost issues (capital and annual O&M)
- CO_2 can be used in Enhanced Oil or Gas Recovery projects
- CO_2 storage projects (geological, saline, or depleted oil/gas reservoirs)
- New and/or improved PC CO_2 capture technologies being developed

Contact Information

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Thank You

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