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Electric Power Production Efficiency Improvements and Discussion of Carbon Dioxide Capture & Storage for Fossil-Fired Power Plants

South Texas Section (STS) of the American Institute of Chemical Engineers

Christopher Wedig
Senior Technology Specialist
The Shaw Group

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Topics

- Introduction
- Energy Efficiency Discussion – Power Plants
- CO_2 Capture and Storage Systems (CCS)
- Impact of Air Quality Control Systems (AQCS) on CCS – Energy Efficiency
- Summary

Power Plant Efficiency Discussion

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Topics Concerning Efficiency Improvements in Fossil-Fired Power Plants

- Heat rate and power plant efficiency improvements
- Definitions of efficiency
- Boiler steam pressure and temperature
- Improved integration of power plant auxiliary systems
- Different fuels
- Co-fired alternative fuels with coal
- Repowering
- CO_2 production, capture, and storage
- Other issues

Efficiency Definitions

(there are numerous definitions)

Net Electrical Efficiency is

net electrical energy divided by total heating value energy of input fuels

- Examples of why efficiency definitions and values vary:
  - Where and how net electrical energy is measured (generator vs. transmission tower)
  - Type of fuels (coal, natural gas, oil, hydrogen, etc.)
  - Higher or Lower heating value of fuels (HHV vs. LHV)
  - Auxiliary plant equipment in *or* out of service (feed water heaters, cooling, AQCS, CCS)
  - Weather conditions (summer or winter cooling loads)
  - Test methods and procedure (ASME, international standards)
  - Other reasons why efficiency definitions and values can vary

Boiler Steam Pressure and Temperature

(impacts plant efficiency, flue gas and CO_2 production, etc.)

- Ultra supercritical boilers
- Supercritical boilers
- Subcritical boilers
- Other

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Different Types of Fossil Fuels

(impact plant efficiency, flue gas and CO_2 production, etc.)

Fossil Fuel Type	Total Carbon Content (% carbon weight)	Higher Heating Value (HHV, Btu/pound fuel)	CO_2 Production Rate (lb CO_2 per million Btu, HHV)
Coal – A	83.7	11,890	258
Coal – B	74.0	12,540	216
Coal – SB	70.3	9,190	280
Coal – L	63.3	7,090	327
Bagasse	23.4	4,000	214
Fuel Oil – # 2	87.2	19,460	164
Fuel Oil – # 6	88.4	18,200	178
Natural Gas –1	75.2	23,170	119
Natural Gas –5	64.8	20,160	118
MSW	27.9	5,100	200
RDF	36.1	6,200	213

Mass & Energy Balance
CO_2 Issues

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

- Combustion Chemistry (related to carbon):

$$\textbf{Coal (carbon) + air } (O_2) \rightarrow CO_2$$

- Example (typical coal containing ~70% carbon):
  - ► 1.0 tonne Coal
  - ► 2.5 tonne CO_2
  - ► 6.6 million Kcal (HHV) total energy
  - ► ~85% of energy is from carbon

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Carbon Dioxide Capture

(Energy Efficiency Issues)

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Energy Efficiency and Carbon Dioxide Reduction for Various Types of Power Plants

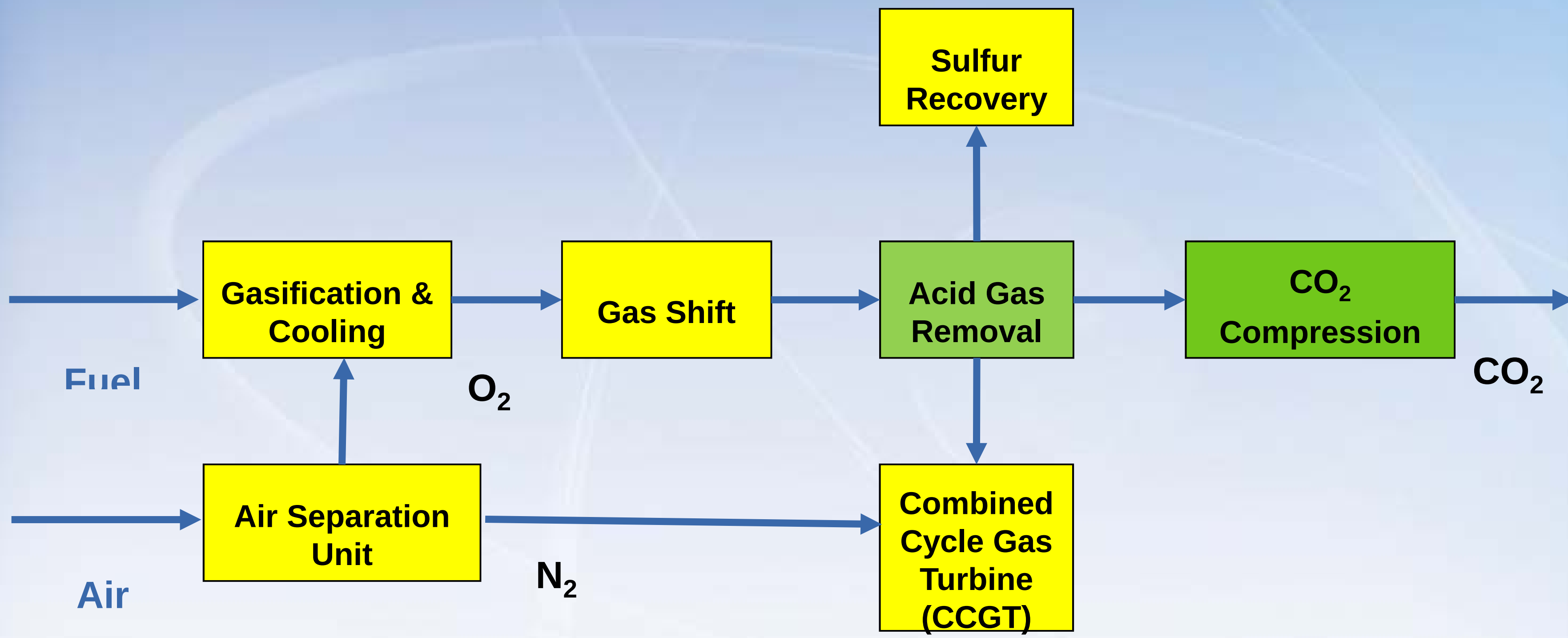
CO_2 Reduction

- Heat rate and power plant efficiency improvements
- Co-fired alternative fuels with coal
- Repowering
- Other methods

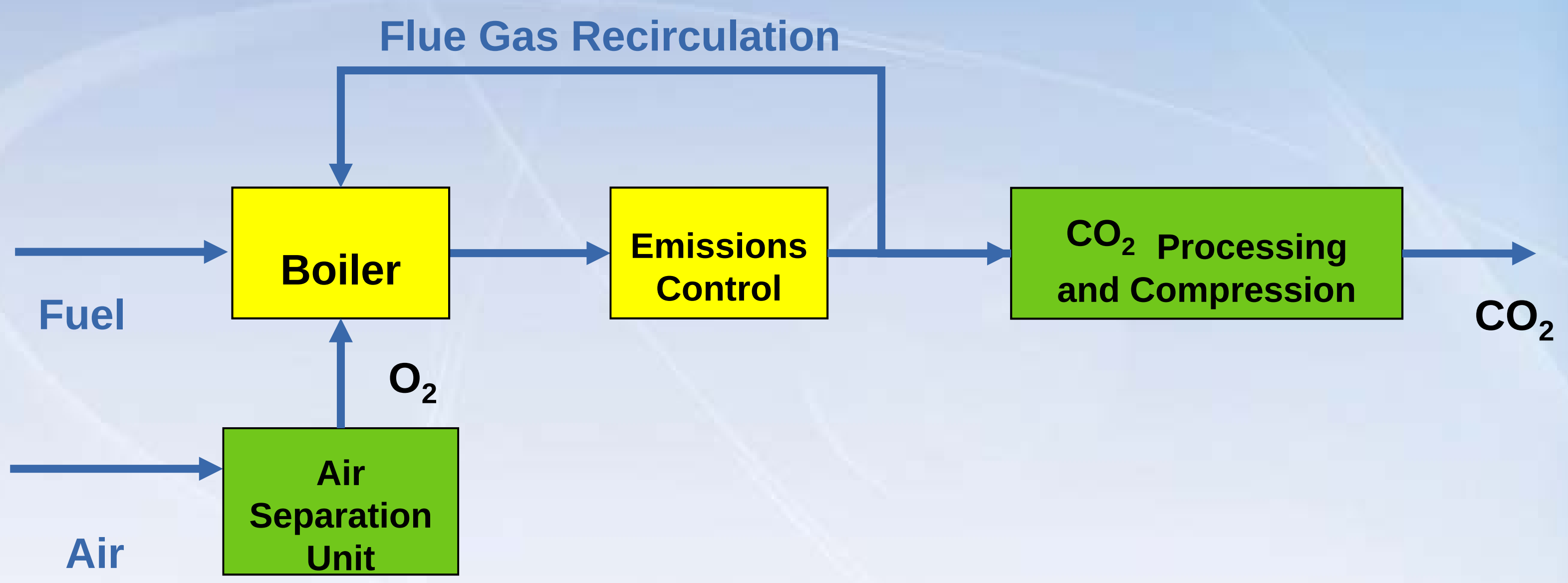
CO_2 Capture

- Pre-combustion CO_2 capture technologies for Integrated Gasification Combined Cycle (IGCC)
- Oxy-fuel combustion technology with CO_2 capture
- Post-combustion (flue gas) CO_2 capture processes

IGCC Process with Pre-Combustion Carbon Dioxide Capture



OxyFuel Process with Carbon Dioxide Capture



Post-Combustion Carbon Dioxide Capture

(Energy Considerations)

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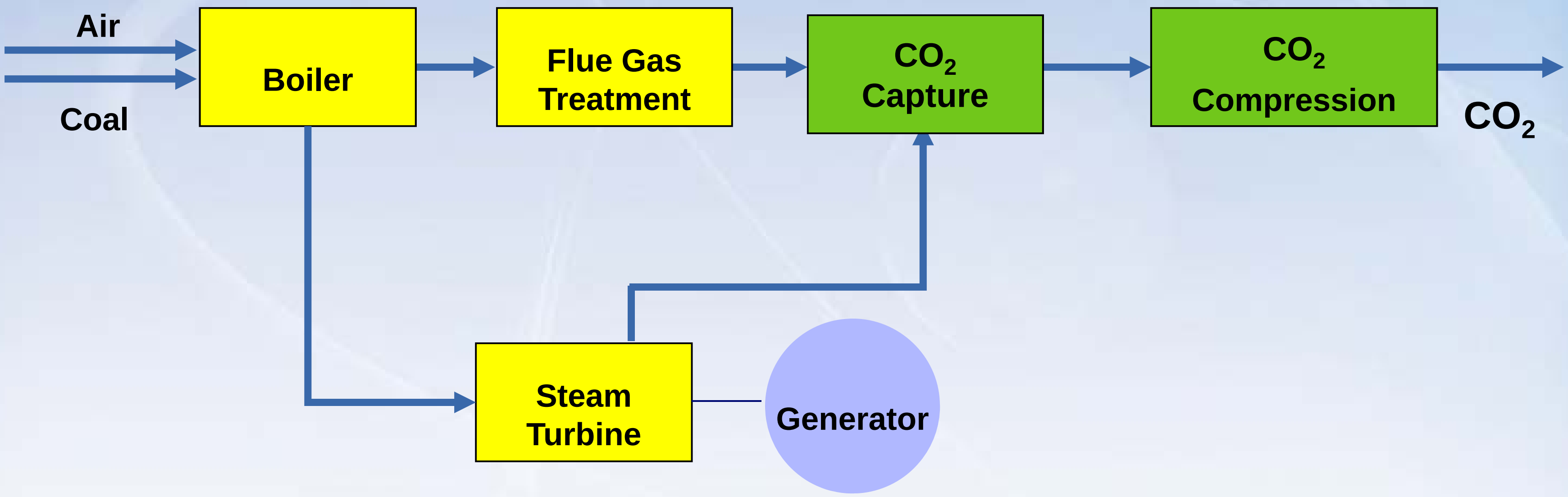
Pulverized Coal Post-Combustion Process CO_2 Capture



Technology Options for Post-Combustion CO_2 Capture

(each process has its own energy efficiency issues)

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

Technical Feasibility of Pulverized Coal (PC) CO_2 Capture
(energy efficiency considerations)

- Most individual equipment components are demonstrated
- Most unit operations are demonstrated – (but often under conditions not typical for most coal-fired power plants)
- CO_2 capture systems need to be demonstrated (various scales)
- PC CO_2 capture – future pilot and demonstrations - (with lessons learned with regard to design, energy usage, operation, and maintenance)
  - Amine CO_2 capture process
  - Ammonia CO_2 capture process
  - Chilled ammonia CO_2 capture process
  - Solvent-based absorption (non-amine-solvents)
  - Algae/sunlight-based CO_2 capture process
  - Frosting or anti-sublimation process
  - Other

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Post-Combustion Carbon Dioxide Capture Integration and O&M Considerations

Energy Efficiency Issues of CCS on Fossil-Fired Power Plant

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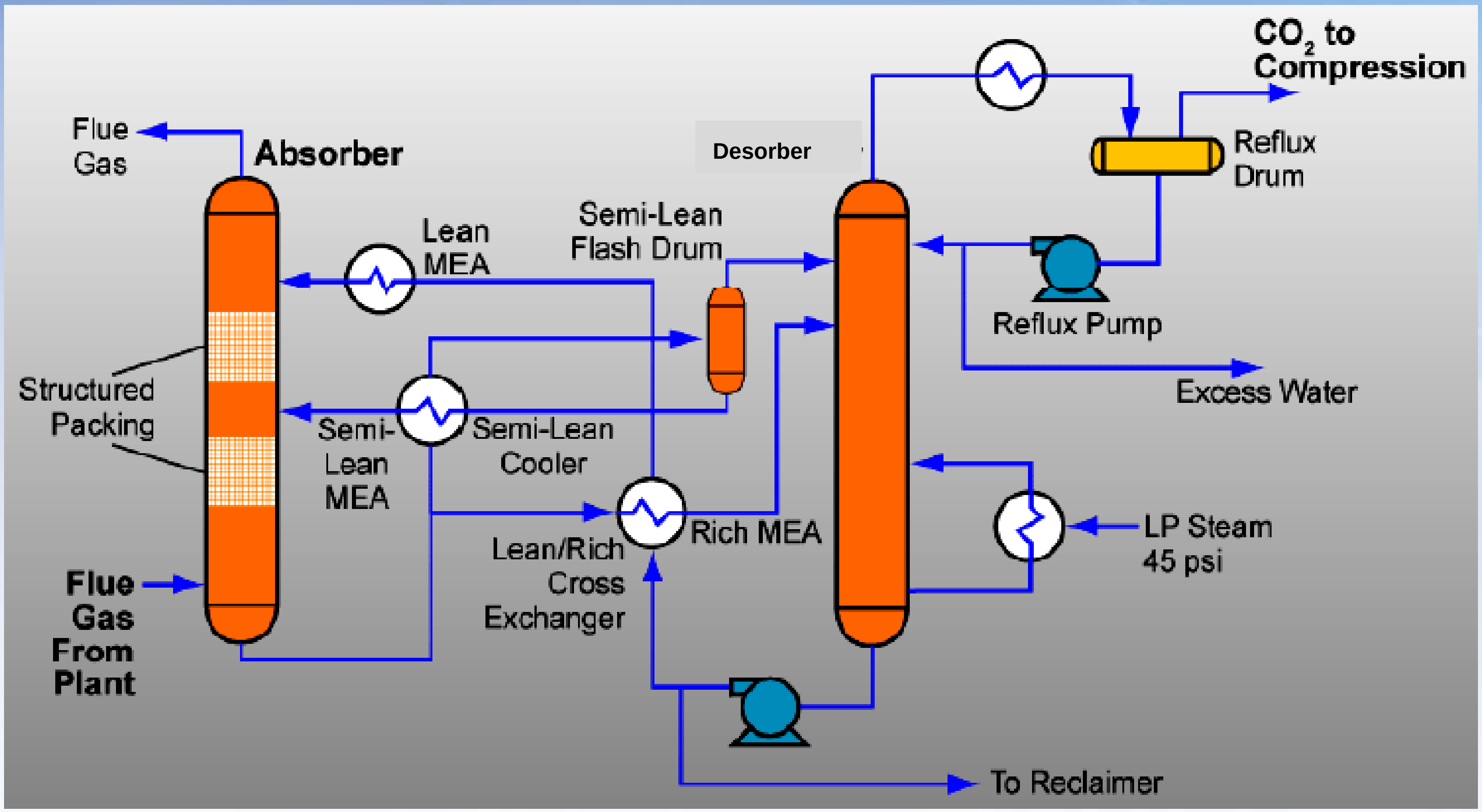
Sorbent Based – Flue Gas CO_2 Capture Process Schematic – Generic Example



Source: US DOE report

Typical CO_2 Capture and Storage Equipment

(Designed for Proper Energy Efficiency, O&M, Layout)

- Flue gas booster fan
- Deep FGD equipment (if required)
- CO_2 absorber column
- Heat exchangers (cooling water)
- CO_2 capture solvent delivery, storage, and handling equipment
- CO_2 desorber column
- Steam generator (reboiler) for CO_2 desorber column
- Spent CO_2 solvent storage, handling, and disposal equipment
- CO_2 coolers, dryers and compressors
- CO_2 pipeline and storage equipment

Impacts and Integration of CO_2 Capture and Storage System

(Design in Advance for Energy Efficiency Considerations)

- Real estate (land area) for deep FGD equipment (if required)
- Real estate for additional NO_X 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 CO_2 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
- Route for interconnections

Impacts and Integration of CO_2 Capture and Storage System

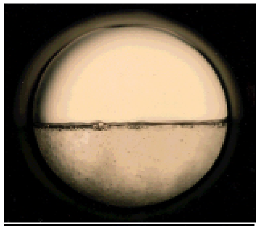
(Design in Advance for Energy Efficiency Considerations) (cont.)

- 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
- Safety, environmental and other issues

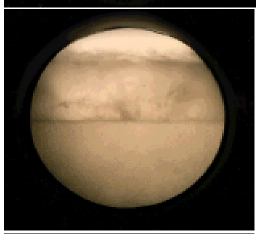
Example of Potential Heat Integration

PT Diagram & Supercritical Phase

RAMGEN POWER SYSTEMS™

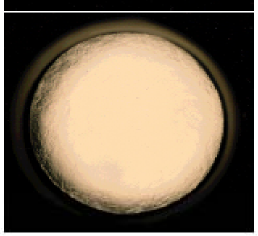


Separate Phases Visible- Meniscus Clearly Observed



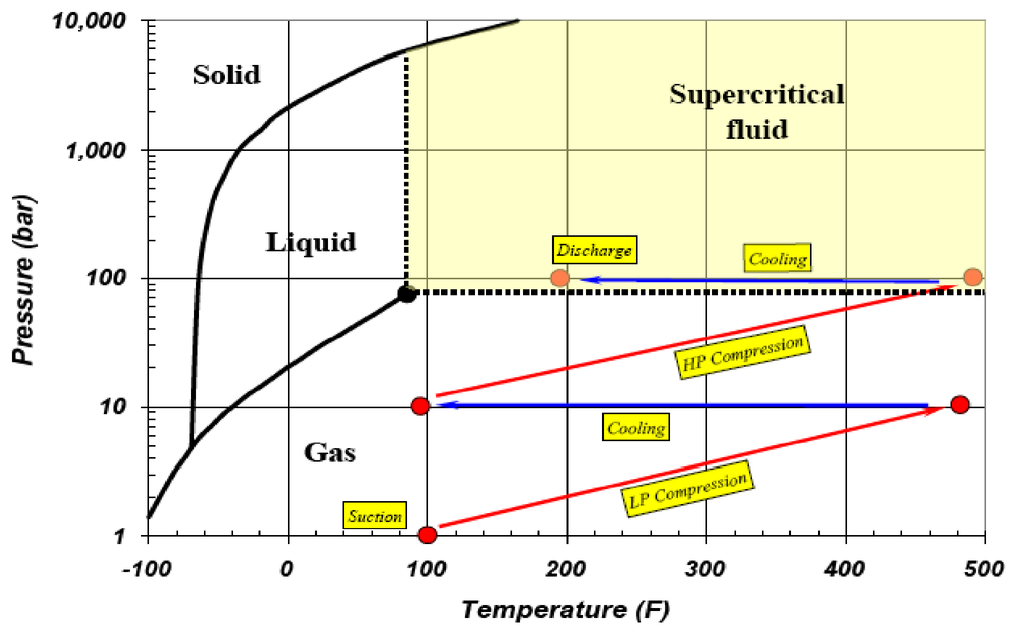
Increase in Temperature- Diminished Meniscus

Further Increase in Temperature- Gas & Liquid Densities more Similar



At Critical P & T- Distinct Gas & Liquid Phases no Longer Visible "Supercritical Fluid" with Properties of Both Liquids & Gases

- Compression process transitions from superheated to supercritical phases
- Avoids liquid (sub-cooled) phase



Disposition of the Captured CO_2

(energy efficiency considerations)

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

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Mass Balance
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):

► 12,000 tonne CO_2 per day

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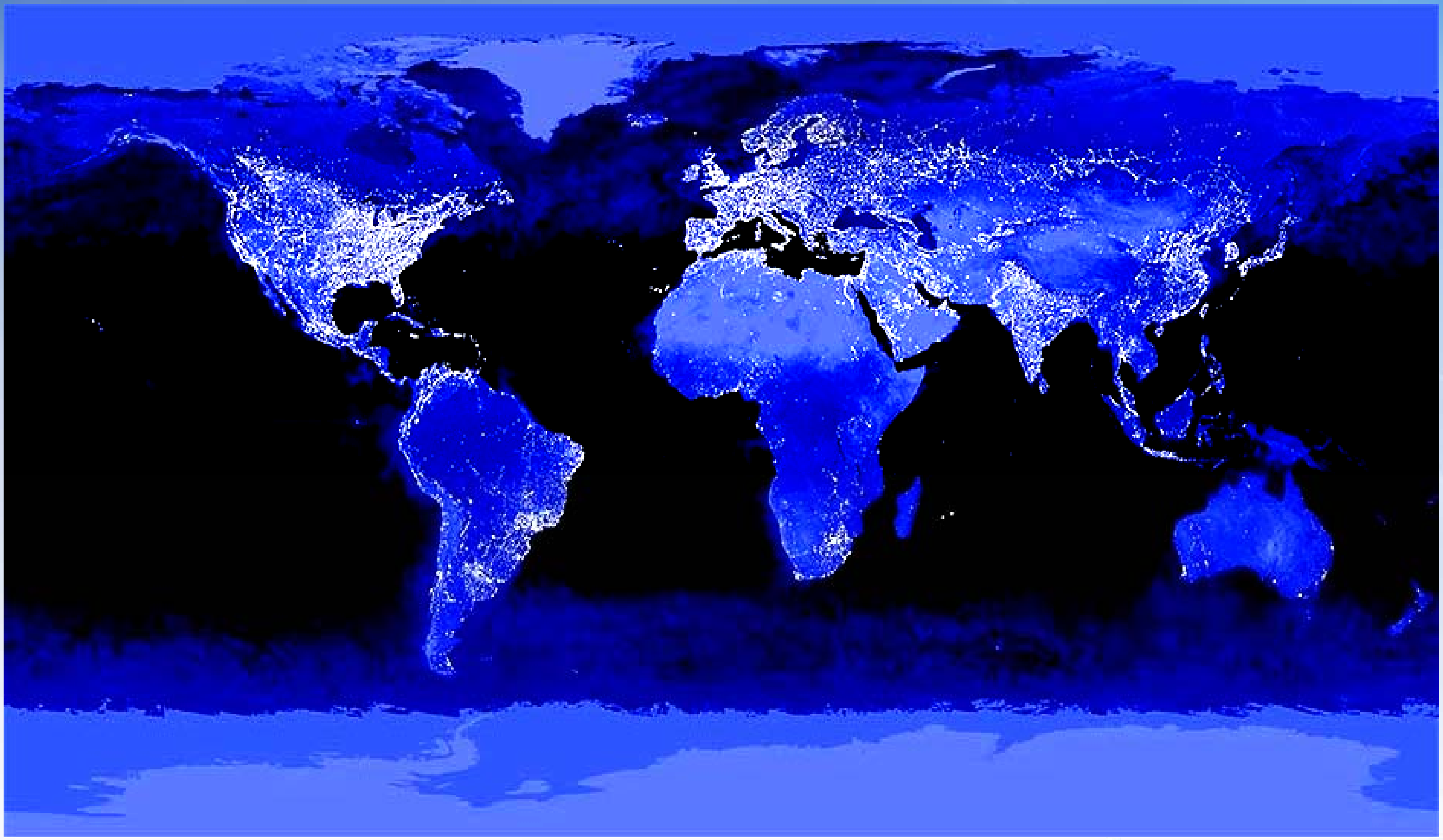
Earth at Night



Internet Source: Sky Image Lab – Earth at Night Photo –

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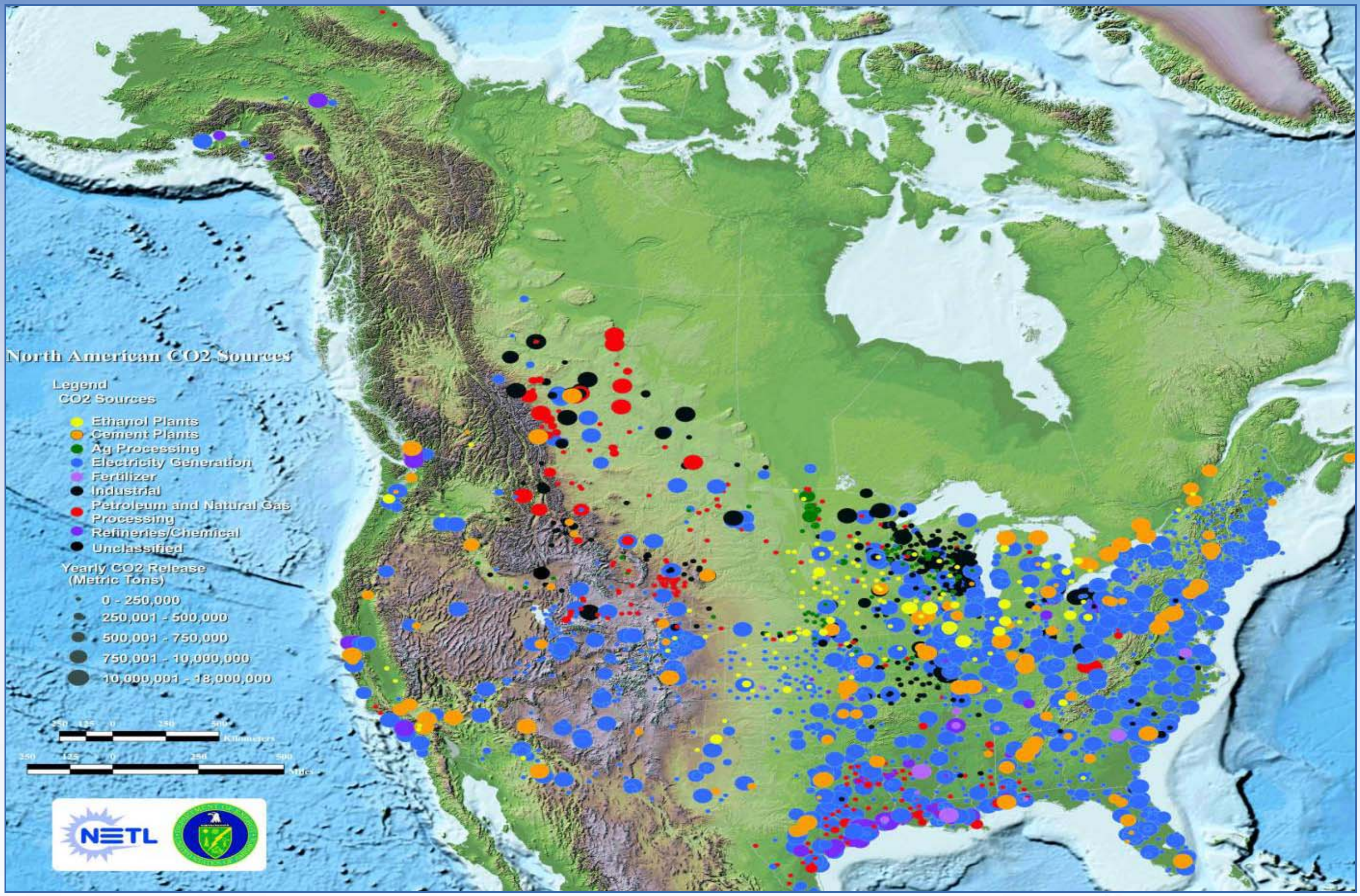
U.S. and Canada – CO_2 Sources and Size



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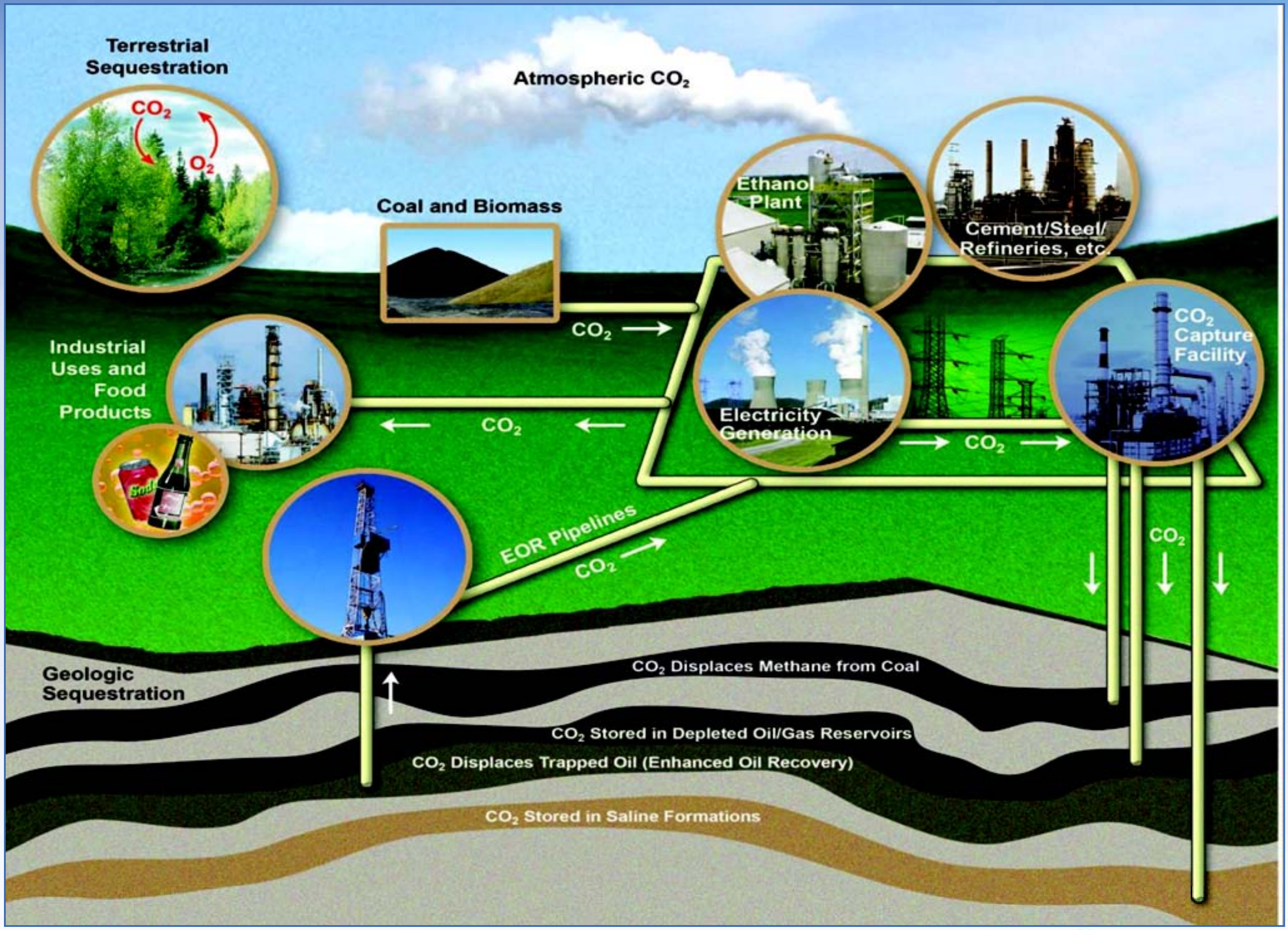
Re-Use of Carbon Dioxide
(energy efficiency considerations)

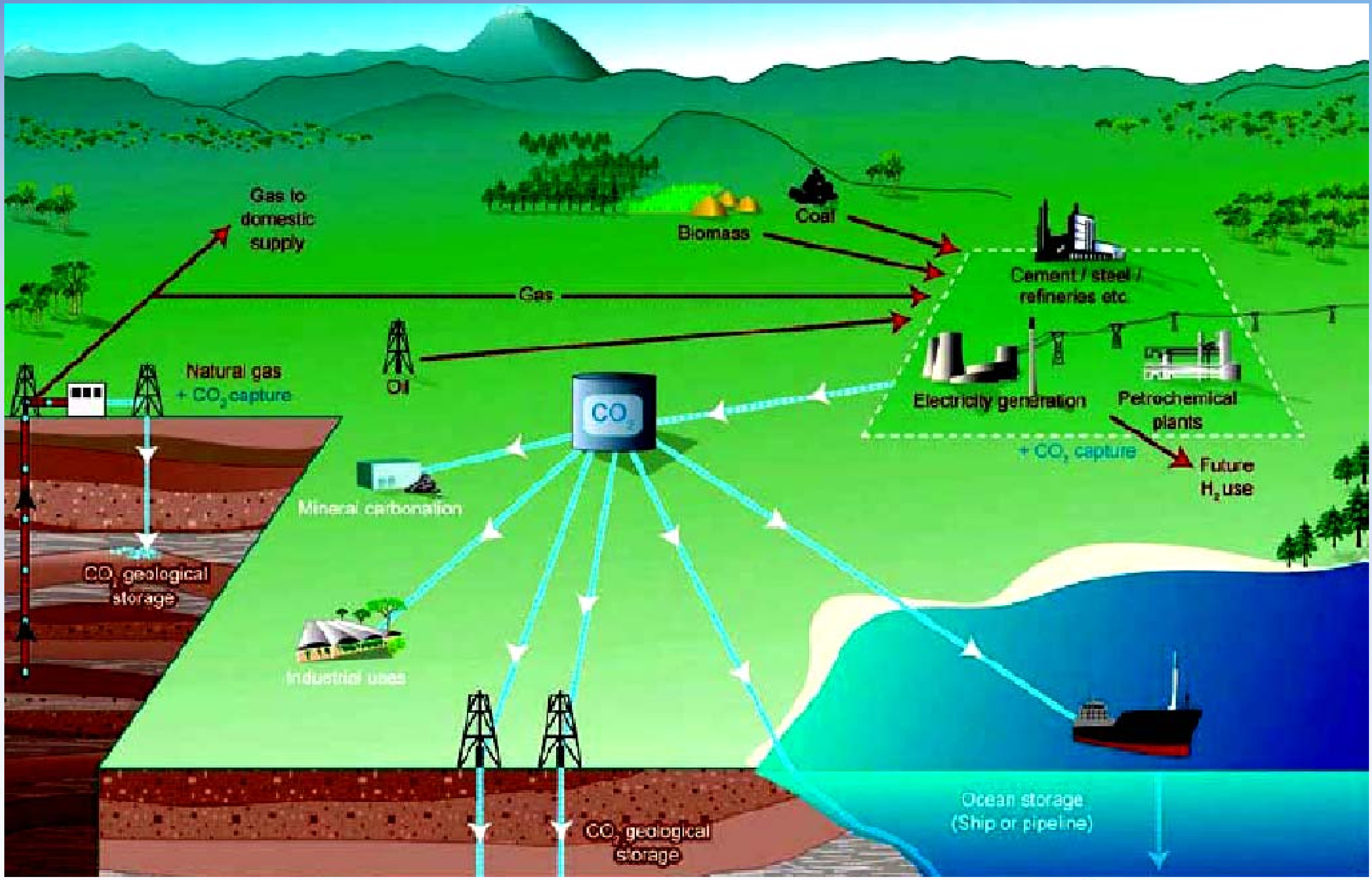
- Enhanced oil recovery (EOR) with CO_2 sequestration (storage)
- Enhanced gas recovery (EGR) with CO_2 storage
- Manufacture of chemicals (e.g., urea, methanol, etc.)
- Carbonated beverages
- Refrigeration medium and dry-ice refrigerant
- Algae-based bio-diesel fuels
- Algae-based bio-mass fuel
- Algae-based fish-food
- Ammonia-based fertilizers
- Other methods to re-use the CO_2 (e.g., propellants, health care, cast molds, transport fluid, etc.)

Carbon Capture and Storage (CCS) Options



US DOE

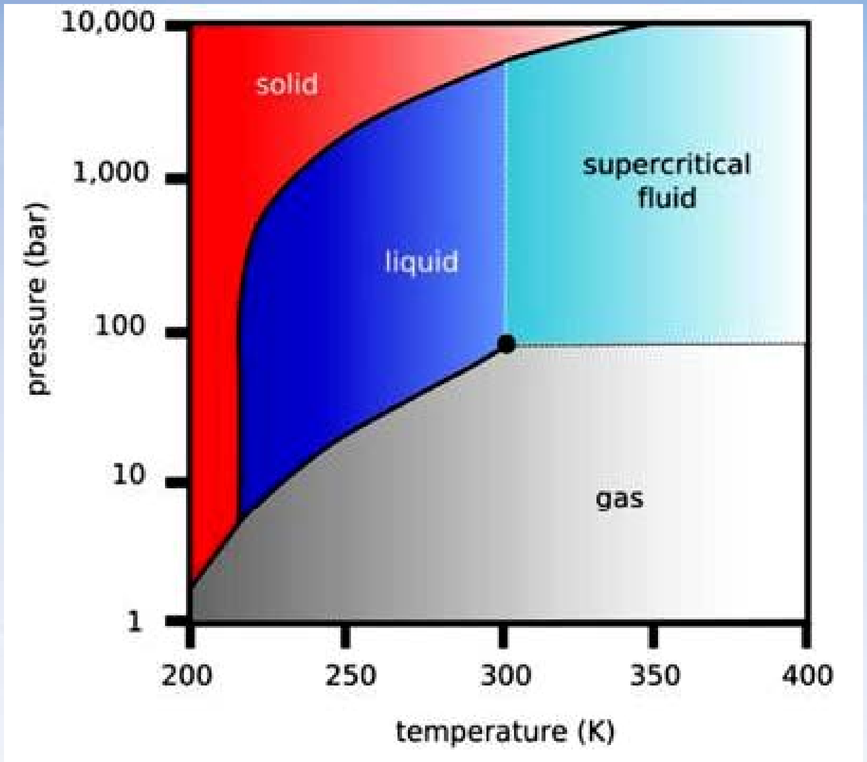
Carbon Dioxide Storage Options
(each option has its own energy efficiency issues)



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

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).**

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Carbon Dioxide Properties
(ground level and deep earth)
(useful for design and predicting energy related parameters)

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} Pa s	940	60
Viscosity @ 1 bar and 10°C	0 km (ground level)	10^{-6} Pa s	1800	14

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

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Examples: CCS Demonstration Projects
(O&M experience, although not on pulverized coal applications)

Weyburn

- Project launched in 1999
- Enhanced oil recovery
- Expected - 22 Million tonne CO_2
- Dakota Gasification Company
- 320 km pipeline

Sleipner

- 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

- Field on stream since 2004
- Largest dry gas field in Algeria
- Jointly operated with Statoil
- 1,200 km south of Algiers
- 1 Million tonne CO_2 / year

Ongoing or Planned CCS Programs

(each program will develop valuable CCS experiences with regard to energy efficiency results)

United States	Japan
Canada	Germany
United Kingdom	China
Italy	Australia
Norway	Netherlands
United Arab Emirates	Finland
France	Denmark
Sweden	Belgium
Spain	Other

Impact of Air Quality Systems on Fossil Power Plant and Carbon Capture Systems Energy Efficiency Issues

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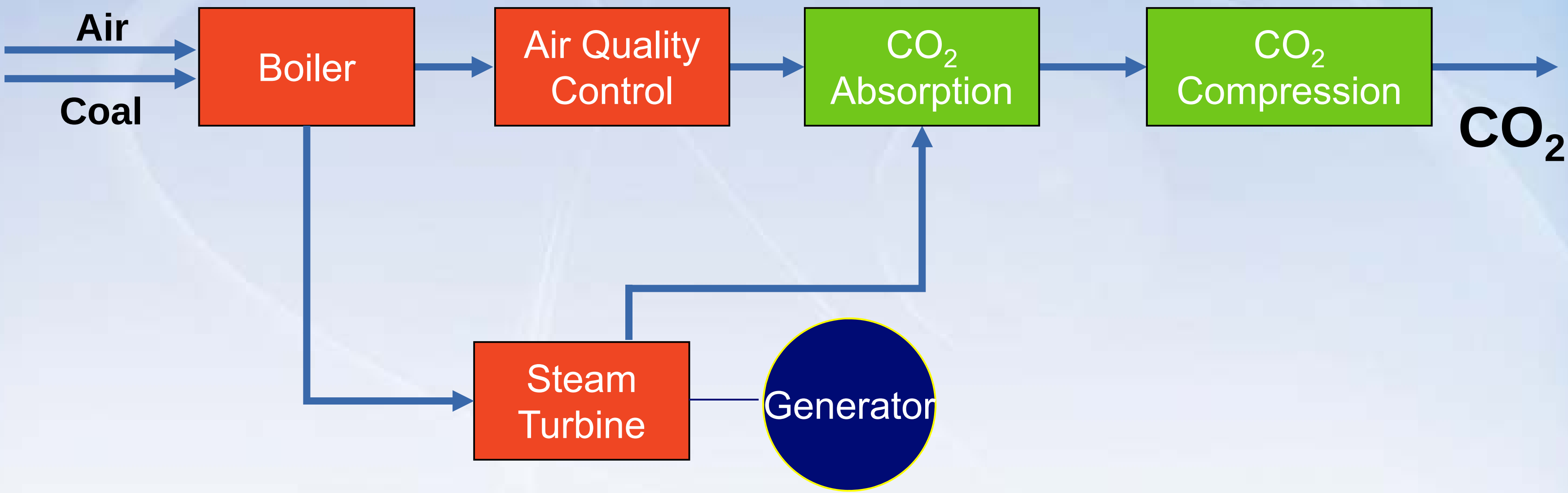
Coal – Fired Power Plant
Post-Combustion CO_2 Capture



Air Quality Control Systems (AQCS) for Carbon Capture Ready (CCR) Fossil fired Power Plants

- AQCS primary purpose is to clean the flue gas to meet environmental stack emission limits
- Most CO_2 capture systems require (or can be optimized with) a relatively clean gas stream (e.g., PM, SO_2, HCl, NO_X, Hg, etc.)

Air Quality Control Systems (AQCS) for Carbon Capture Ready Fossil Fired Power Plants

(energy efficiency considerations)

- Nitrogen Oxides (NO_X)
- Particulate Matter (PM)
- Sulfur Dioxide (SO_2)
- Sulfur Trioxide (SO_3/H_2SO_4)
- Mercury (Hg)
- HAPs (future MACT, including HCl)

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Air Quality Control Systems for CO_2 Capture & Storage (CCS) Systems

(energy efficiency issues)

- The potential benefits of AQCS on CCS include:
  - optimized energy efficiency,
  - reduced operation & maintenance (O&M) costs of CCS,
  - decreased equipment size and real estate of CCS system,
  - decreased installed capital cost of CCS,
  - improvement in reliability of CCS operation.

- **Question**: Does the CCS system require additional gas cleaning beyond what the CO_2 Capture Ready (CCR) power plant AQCS has already provided (e.g., upgraded FGD, CCS deep FGD, reduced PM, flue gas cooling, etc.)?

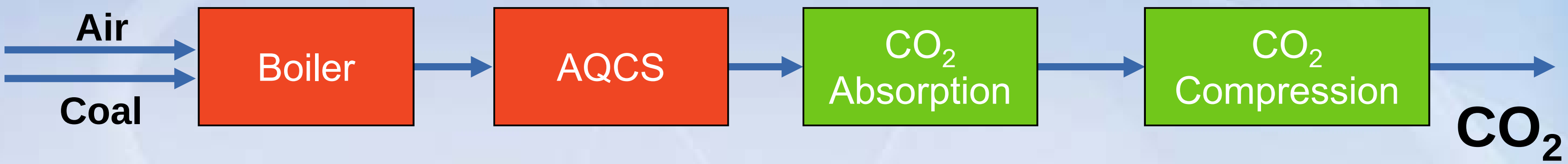
Stack Flue Gas Composition after AQCS and Post-Combustion CO_2 Capture

(energy efficiency issues)

- AQCS significantly reduces stack emissions (e.g. NO_X, PM, SO_2, SO_3, H_2SO_4, HCl, and Hg).
- CO_2 capture system further reduces stack emissions, depending on % of total flue gas treated by CO_2 capture system (e.g., CCS bypass).
- CO_2 capture system may further lower the flue gas temperature (e.g., stack flue gas dispersion issues).
- Stack flue gas from CO_2 capture system is N_2, O_2, H_2O, CO_2, and trace components.
- CCS may have its own stack (depends on site specifics)

Carbon Dioxide Product Composition from a CO_2 Capture System

(AQCS and energy efficiency considerations)



Type of AQCS can influence the composition of the CO_2 product and byproducts produced from CO_2 capture system.

Liquid compressed CO_2 product from a CO_2 capture system consists of mostly CO_2, some N_2, and trace O_2, H_2O, and other components.

Energy Efficiency, Economics and Managing Risk

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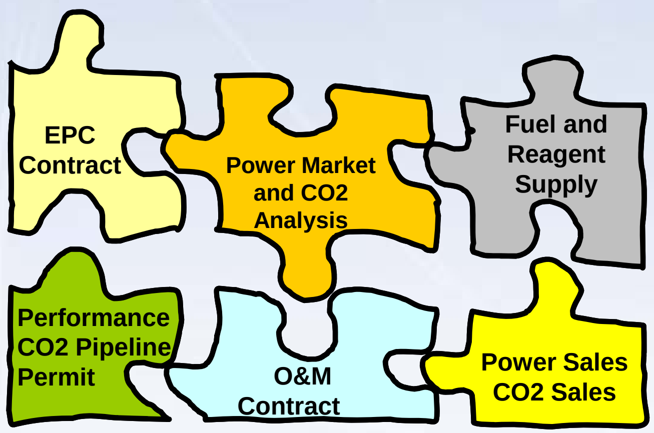
Project Economics and Managing Risks

(energy efficiency considerations are important, but not the only issue)

- Technology scale-up
- Installed capital cost (material and labor)
- Annual energy and operation & maintenance costs
- Carbon dioxide value or liability ($/tonne, sale price, carbon credits, disposal cost, etc.) and disposition



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Process Parameters Influencing Energy Consumption of 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 (tonnes/day) removed from flue gas
- Type of CO_2 capture process chosen
- Degree of flue gas pre-treatment (if required)
- Storage of CO_2 product

Process Parameters Influencing Annual O&M and Energy Costs of CO_2 Capture Systems

- Total mass of CO_2 removed (tonnes/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)
- Storage of CO_2 product
- Other issues

Key Issues
Energy Efficiency in CCS

- CO_2 capture system design **must** address energy issues.
- 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, load-following, & upset conditions)
- ***Significant*** cost issues (capital and annual O&M, including energy)
- 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 power plant designs and CO_2 capture technologies being developed

Summary

- Efficient electric power production technologies are available.
- CCS demonstration programs are being conducted, including addressing energy efficiency issues.
- New and/or improved power plants and CCS technologies are being developed.

Contact Information

Christopher Wedig
Senior Technology Specialist
The Shaw Group

christopher.wedig@shawgrp.com

Thank You

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