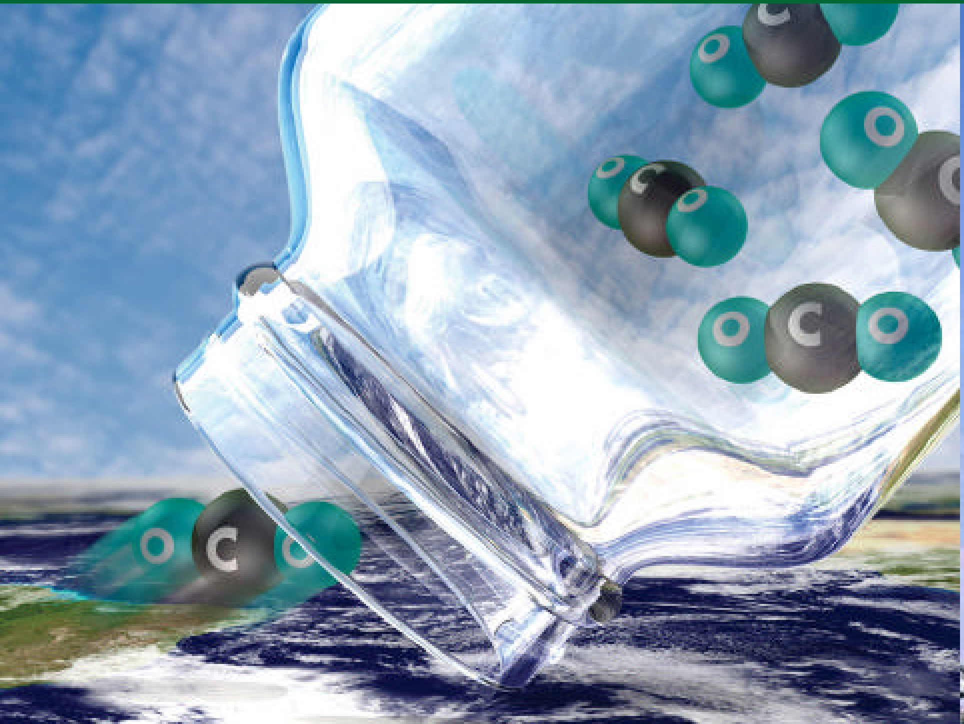
Achieving Reductions in U.S. Greenhouse Gas Emissions

There Are 2 Methods to Capture or Reduce CO_2 Emissions from Coal Use

1. **CO_2 Emissions Reductions:**
   - Can be achieved today by increasing the efficiency of a plant so less coal is used to produce the same amount of electrical output
   - Higher Efficiency = Lower Emissions
2. **CO_2 Emissions Capture and Storage:**
   - Can be achieved in the future by developing advanced coal systems with the equipment necessary to capture CO_2 before it is emitted from the plant

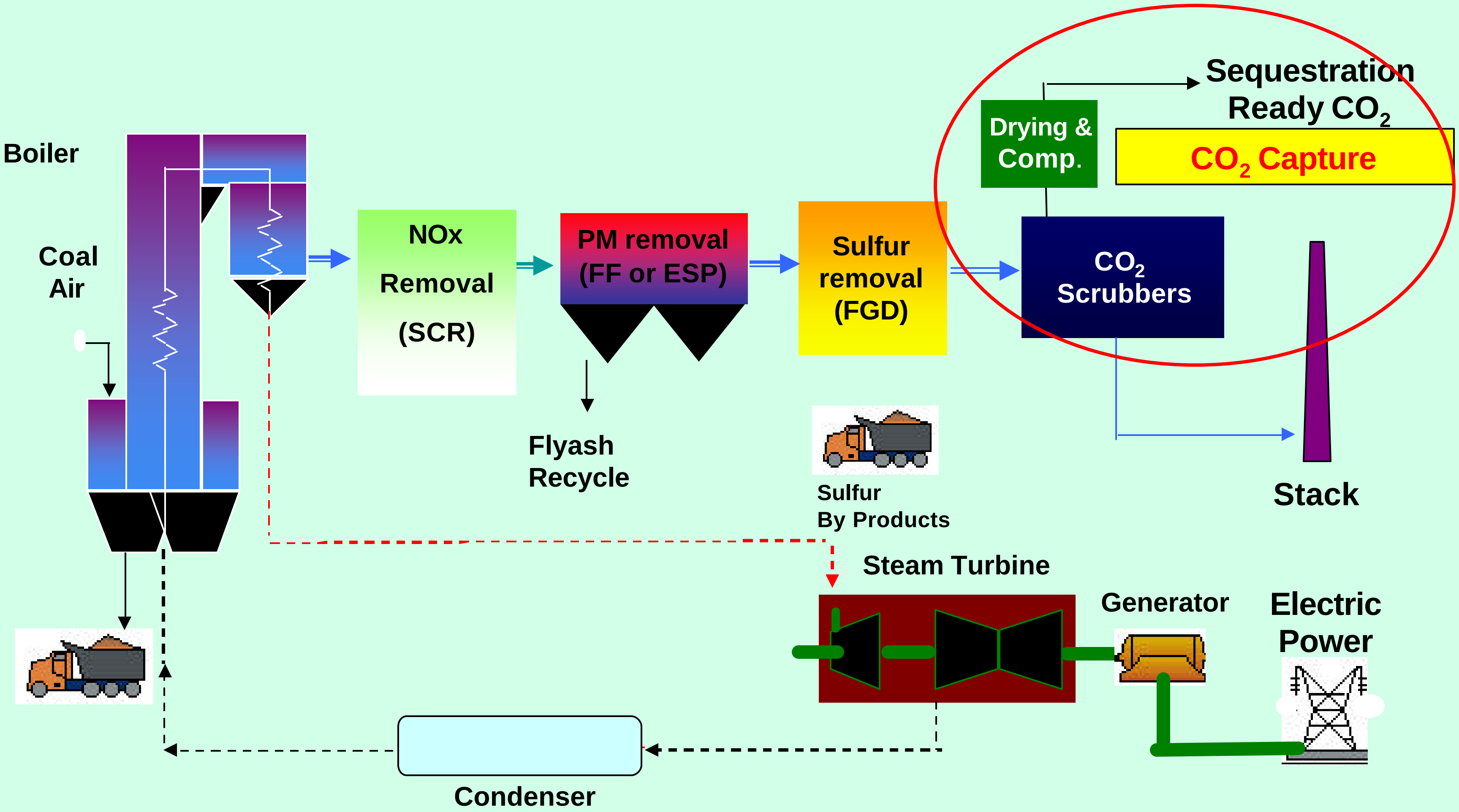
Reducing CO_2 Through Carbon Capture



Carbon Capture and Storage (or Sequestration)

- "CCS" represents the technologies to capture and store CO_2 through the following process:
  1. Separate and capture CO_2 from power plant "fuel gas" or the "flue gas"
  2. Compress the CO_2 into a liquid form
  3. Move the CO_2 via a pipeline to the location where it will be stored.
  4. Inject the CO_2 into a deep geological formation for long-term storage
- There are currently several technologies under development to capture CO_2.

Pulverized Coal Plant with Carbon Capture



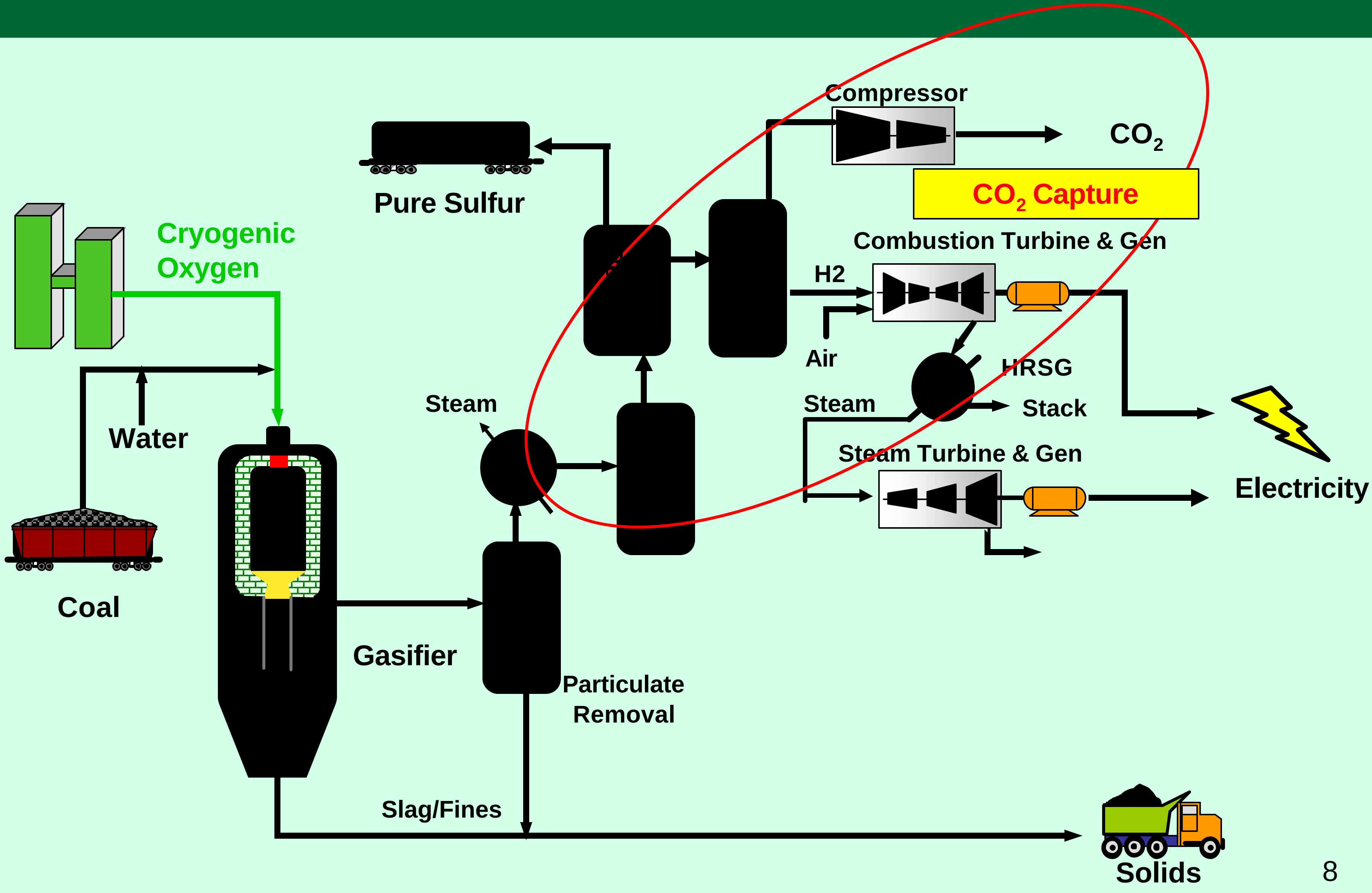
Pulverized Coal Plant with Carbon Capture

- Post-combustion capture controls can be integrated with a conventional combustion power plant to remove the CO_2 from the flue gas stream. For example, an amine solvent is used to remove the CO_2 from the other flue gases.
- The CO_2 is then stripped from the solvent and compressed for transport; the regenerated solvent is reused.
- The major barriers to this technology are high cost and high energy penalty.

Pulverized Coal Plant with Carbon Capture RD&D Needs

- RD&D Needs to Reduce Costs:
  - Better solvents (i.e. amines and chilled ammonia) to remove the CO_2 from the flue gas
  - Less energy intensive CO_2 capture systems
- Timing:
  - Three small plants in operation in U.S. today
  - Several small scale (10 MW) pilot projects planned and in development
  - Several large scale (over 300 MW) demos being explored

IGCC with Carbon Capture



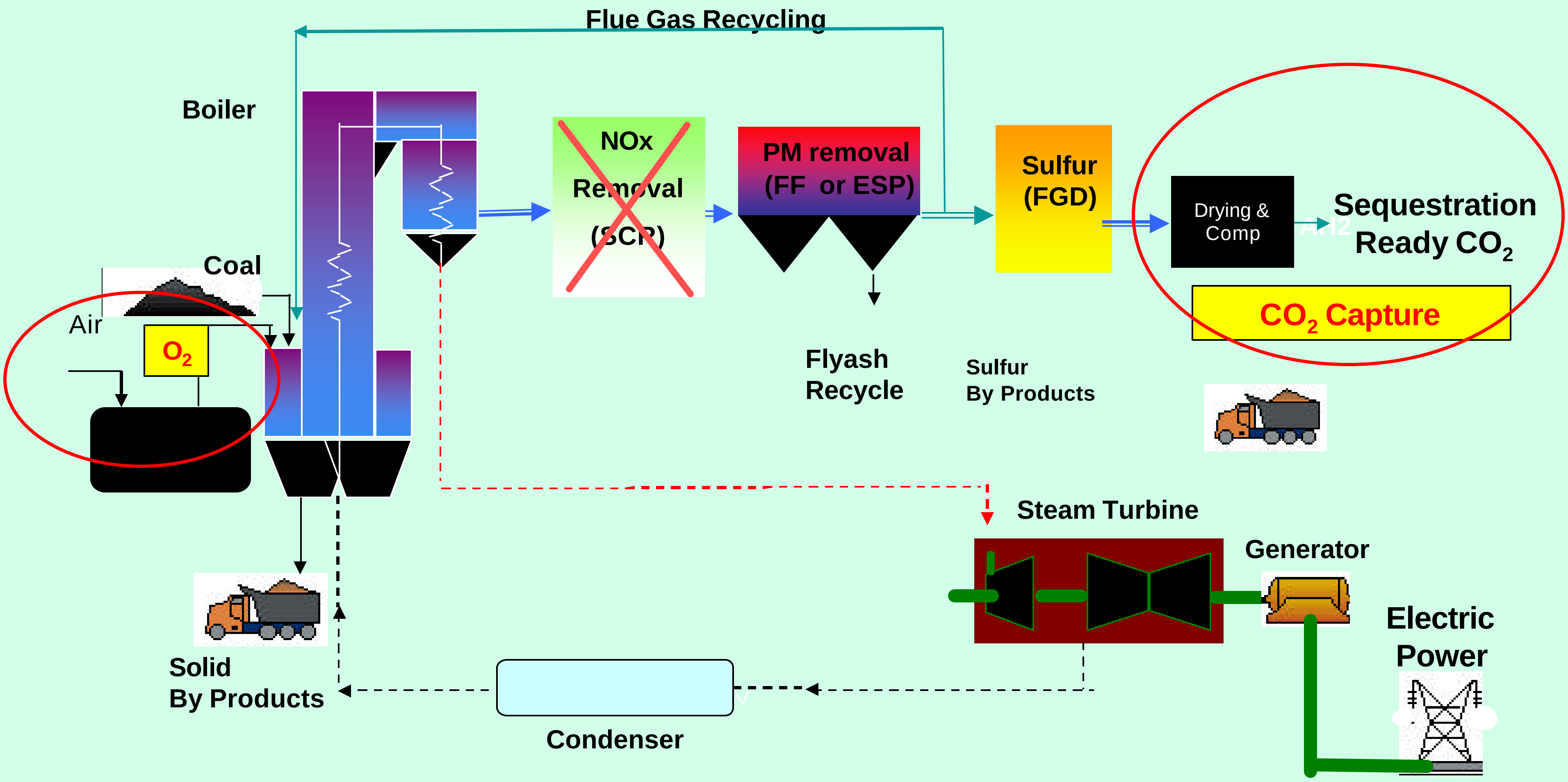
IGCC with Carbon Capture

- Pre-combustion capture can be achieved via integrated gasification combined cycle (IGCC) technology by introducing a water shift reactor to modify the syngas from the gasifier.
- The shift reactor converts the carbon monoxide in the syngas to hydrogen and CO_2.
- This modified syngas is almost all hydrogen and CO_2, which can be separated with physical sorbents.
- The hydrogen is then combusted in a gas turbine and the CO_2 is captured and pressurized.

IGCC with Carbon Capture RD&D Needs

- Timing:
  - Some existing **non-power** gasification plants use CO_2 capture today
  - Several large-scale IGCC with CO_2 capture demos being explored
- R&D Needs to Reduce Costs:
  - Refractory improvements (ceramic liner for gasifier)
  - Ion transport membranes (improved systems to produce oxygen)
  - Warm gas clean up (to remove H_2S)
  - Hydrogen turbine development

Oxy-Coal Combustion Plant With Carbon Capture



Oxy-Coal Combustion Plant With Carbon Capture

- Oxy-combustion is an emerging technology that produces a concentrated CO_2 stream that can then be more readily captured for storage or use.
- While similar to conventional PC generation, oxy-combustion uses pure oxygen instead of air in the boiler. This significantly reduces the dilution of carbon dioxide in the exhaust gas stream by removing nitrogen (80% in air) from the system.

No Commercial Power Plants Use Oxy-Combustion Today, BUT

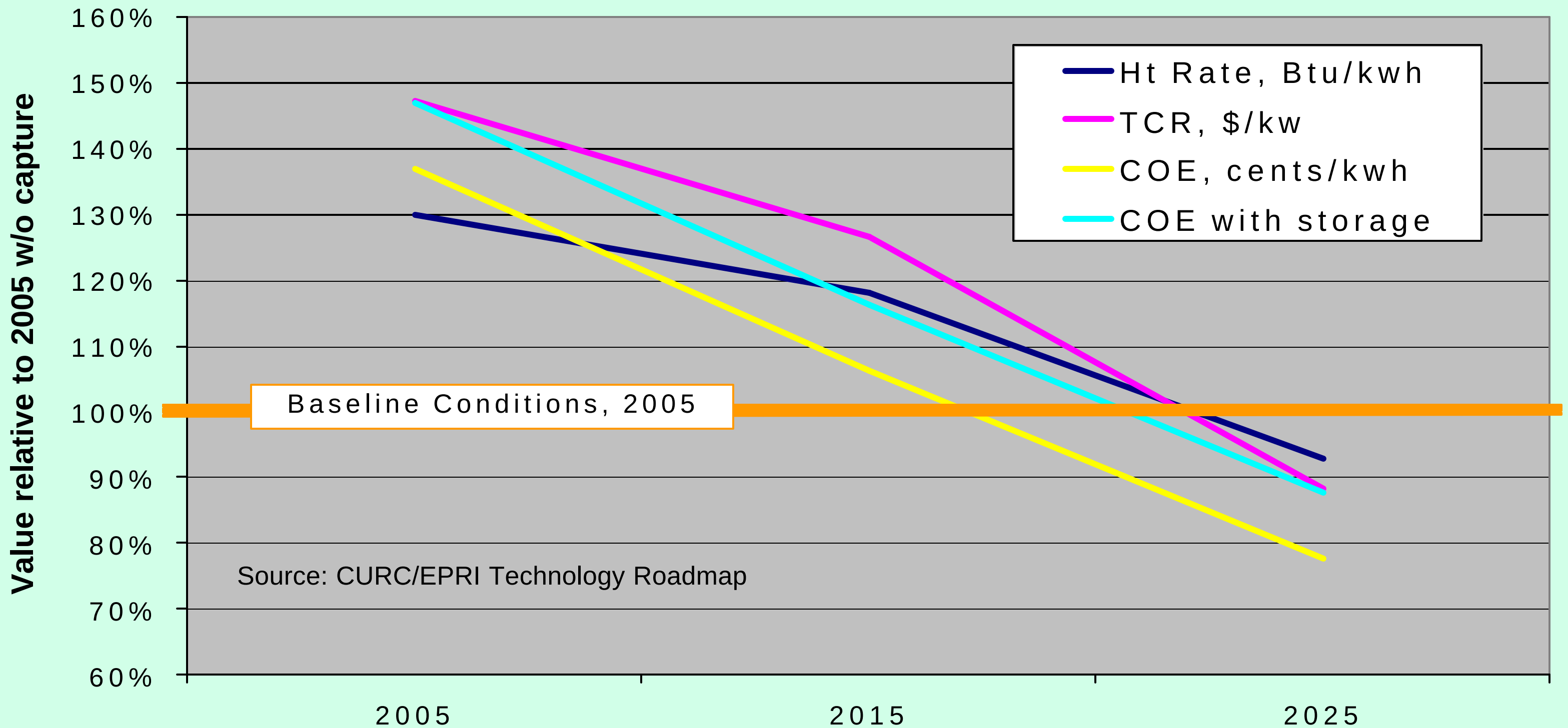
- Timing:
  - Several small scale (1 to 3 MW) projects underway
  - Two large demonstrations announced (10 to 30 MW)
  - Larger scale (200-300 MW) demonstrations being explored by AEP and SaskPower
- R&D Needs to Reduce Costs:
  - Reduced cost oxygen separation systems
  - Lower cost CO_2 pressurization
  - Integration of oxy-system with rest of plant

Technologies Currently in R&D for Advanced CO_2 Capture

CO_2 Removal Technology	Development Stage	Process Type
Ammonia-Based Process For Multicomponent Removal From Flue Gas	Pilot in Engineering	Chemical Absorption
Liquid Absorbant For CO_2 Capture	Lab	Chemical Absorption
Oxygen Membrane For Oxyfuel Combustion	Lab	Cryogenic Separation
Advanced Oxyfuel Boilers	System studies	Cryogenic Separation
Oxygen-Based PC Boiler	Theoretical Development	Cryogenic Separation
Oxygen Firing In Circulating Fluidized Bed Boilers	Theoretical Development	Cryogenic Separation
Carbon Dioxide Separation With Microporous Metal Organic Frameworks	Theoretical Development	Adsorption based
Solid Sorbents For CO_2 Capture From Postcombustion Gas Streams	Lab	Adsorption based
CO_2 Adsorption On Solid Amine Sorbent	Theoretical Development	Adsorption based
Carbon Dioxide Capture From Flue Gas Using Dry Regenerable Sorbents	Pilot Scale Testing	Adsorption based
Absorption With Potassium Carbonate	Pilot Scale Testing	Adsorption based
Dry Regenerable Sorbent	Lab	Adsorption based
Metal Monliths For CO_2 Capture	Lab	Adsorption based
Microporous Metal Organic Framworks For Removal Of CO_2 From Flue Gas	Lab	Adsorption based
Microporous Inorganic Siliceous Matrix With Amine Groups Physically Bonded On The Membrane	Lab	Membrane
Enzyme Based Membrane	Lab	Membrane
Membrane Separation Process	Lab	Membrane
Ionic Liquids As Novel Absorbents		Membrane
Hydrogen Selective Silica Membranes	Lab	Membrane
Ionic Liquids Based Membranes	Lab	Membrane
Molecular Design Of High Capacity CO_2 Adsorbents	Lab	Adsorption based
Carbon Dioxide Separation With Microporous Metal Organic Frameworks	Theoretical Development	Adsorption based
Solvents For CO_2 Capture	Lab	Chemical Adsorption
Solid Sorbents For CO_2 Capture From Precombustion Gas Streams	Lab	Adsorption based
CO_2 Hydrate Process For Gas Separation From A Shifted Synthesis Gas	Bench Scale	Adsorption based
Membrane For Pre-Combustion Separation Of CO_2	Lab	Membrane

Source: NETL/DOE

With RD&D, Today's Costly CO_2 Capture Systems Can Become Cost-Competitive



Necessary Technologies

	2015	2025
IGCC	-Improved refractory -Demonstrated C storage -Ion Transport Membrane (O_2) -Hydrogen turbine	-Warm gas cleanup -Membrane CO2 separation -Multi-pollutant disposal
PC	-Advanced steel alloys -Advanced Sorbents for CO2 capture (e.g., chilled ammonia) -Oxy-Firing	-Advanced sorbents -Chemical looping

Important Issues for Coal CO_2 Solutions

- We need a portfolio of options
  - Different coals may require different solutions
  - It is too early in the technology development process to “pick a winner”
- Retrofit solutions will be more costly than new plant solutions due to space limitations, and relatively low initial power plant efficiencies.
- Some improvements are “learn by doing”; others require development of new components or materials.

With continued RD&D, the costs for both advanced IGCC and advanced PC plants with and without CO_2 capture can go down

Retrofits Require a Lot of Space

June 1990

December 2006

CO_2 capture plant for 500-MW unit occupies 6 acres, i.e. 510 ft x 510 ft

Source: Electric Power Research Institute

Options for Reducing CO_2 from Coal Plants

Generating Technology	CO_2 Approach	Challenges
IGCC	**Improve Efficiency** **Capture CO_2**	**Cost & Integration of IGCC** **Storage**
Pulverized Coal	**Improve Efficiency** **Capture CO_2**	**Integration of CO_2 Capture** **Penalty of Capture CO_2** **Storage**
Oxy Firing	**Improve Efficiency** **Capture CO_2**	**Cost of oxygen production** **Storage**

CO_2 Storage Policy a Challenge for all Technologies

Source: Electric Power Research Institute