CO_2 Capture

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NSTD

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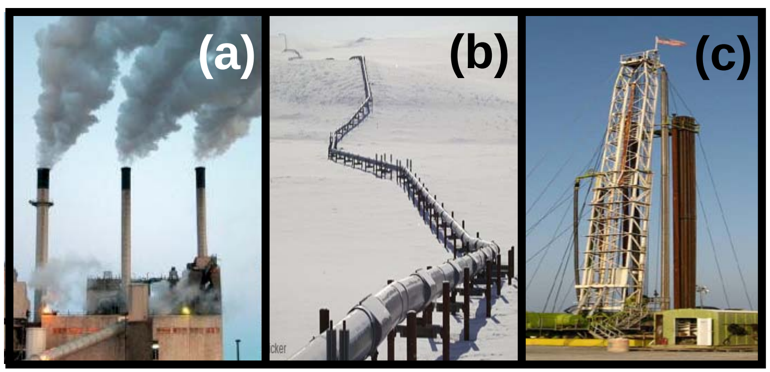
Oak Ridge National Laboratory

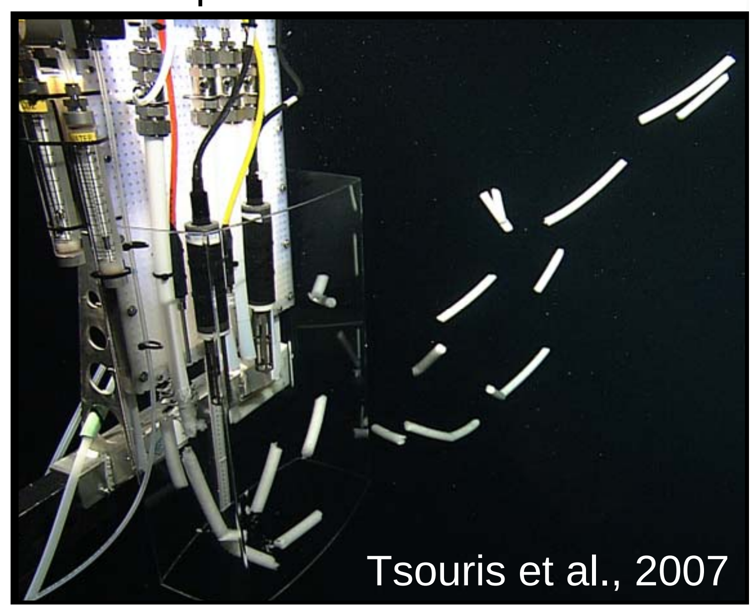
CCS Depends on a Suite of Technologies

- **Separation**[1,2]
  - Absorption, adsorption, membranes
- **Transportation**
  - Transportation via pipelines (the most viable option)
- **Storage**
  - Storage in aquifers, deep ocean, oil fields, coal seams



CO_2 is captured (a), transported (b) and stored (c)

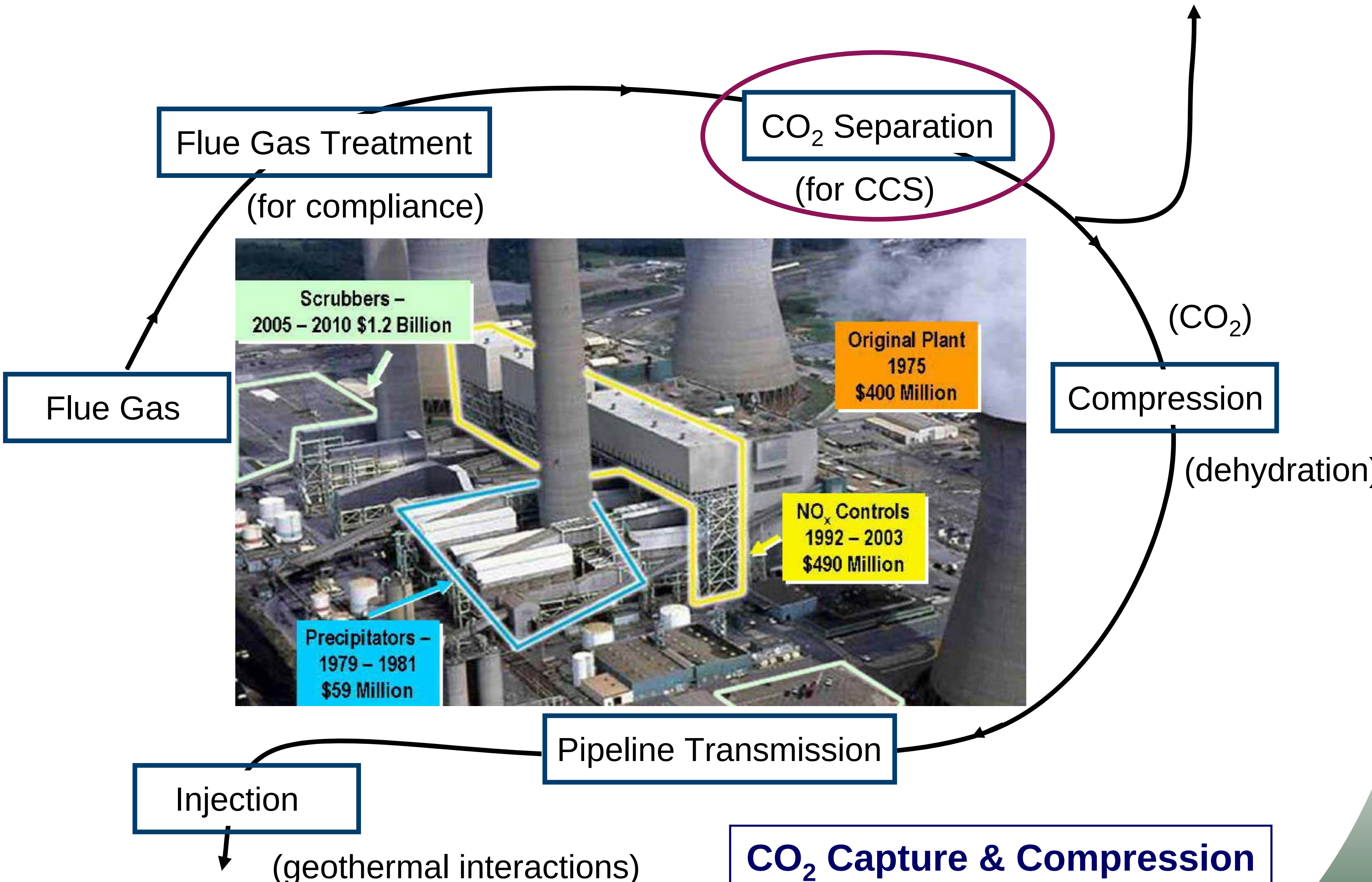
Statoil Sleipner facility: stores CO_2 in an aquifer below the North Sea



Tsouris et al., 2007

[1]Aaron and Tsouris, 2005
[2]Li et al, 2003

Off Gas Processing for CCS



CO_2 Capture & Compression
- $1.5 billion capital

Source: Southern Company

Potential CO_2 Capture Technologies

Separation Technology	Specific Method
Absorption	Amine solvents (aqueous) Ammonia (aqueous) Alkaline salts (aqueous)
Membranes	Gas separation membrane Gas absorption membrane
Adsorption	CaO-based adsorbents Amine-based sorbents
Thermal	Cryogenic Hydrate formation
Electrical	Electrochemical separation
Biological	Biochemical separation

CO_2 R&D capture is primarily done by NETL, universities, and industry

Description of CO_2 Capture Technologies

Technology	Method Used to Capture CO_2
1. Solvent Scrubbing	Selective absorption by chemically reacting with an aqueous solution, containing an amine, alkaline salt, or ammonia. Solution is regenerated by applying heat.
2. Gas Separation Membranes	Separation of CO_2 from other gaseous components by selective permeation across a membrane under a partial-pressure gradient.
3. Gas Absorption Membranes	Permeable membrane provides a large contact area between feed gas and a liquid absorbent, which selectively captures the CO_2. Regeneration similar to a wet scrubbing process.
4. Physical Adsorption	Selective adsorption onto a solid substrate due to intermolecular forces. Regeneration by altering pressure/temperature, electrical current, or use of a regeneration gas.

Description of CO_2 Capture Technologies (continued)

Technology	Method Used to Capture CO_2
5. Solid Chemical Absorption	Selective absorption by chemically reacting with a solid sorbent. Sorbent is regenerated by applying heat.
6. Cryogenic Separation	Condensation or sublimation at low temperature and elevated pressure
7. Hydrate Formation	Forms carbon dioxide hydrates with water at low temperature and high pressure
8. Electrochemical Separation	Capture using a carbonate ion pump or proton pump
9. Biochemical Separation	Uses enzymes or photosynthesis

Absorption with a Liquid Solvent

- **Chemical interaction**
  - Solvent must be CO_2 specific for dissolution without dissolving other flue gas components
  - Solvent must be regenerable and must yield a high purity CO_2 stream
- **Regeneration**
  - Must balance solvent concentration and increased degradation rates
- **Good solvents**
  - Amine (aqueous)
  - Ammonia (aqueous): produces ammonium bicarbonate (fertilizer)
  - Designer solvents

Meisen and Shuai. Research and development issues in CO_2 capture. *Energ. Convers. Manage.* 38(Suppl), S147 – S152, 1997

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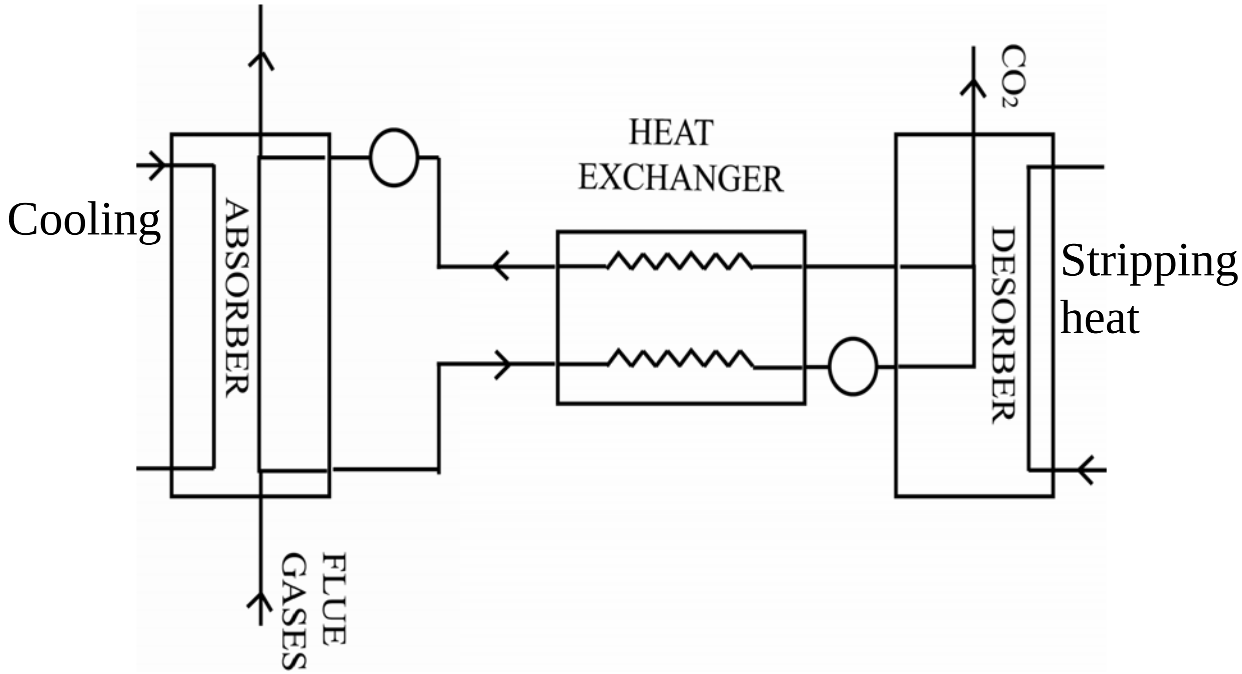
Chemical Absorption/Regeneration

- Flue gas and solvent enter absorber
- CO_2 dissolves into solution
- CO_2-rich solution to desorber
- Desorber strips CO_2 from solution



In the absorber
T = 40°C
P = 2 atm

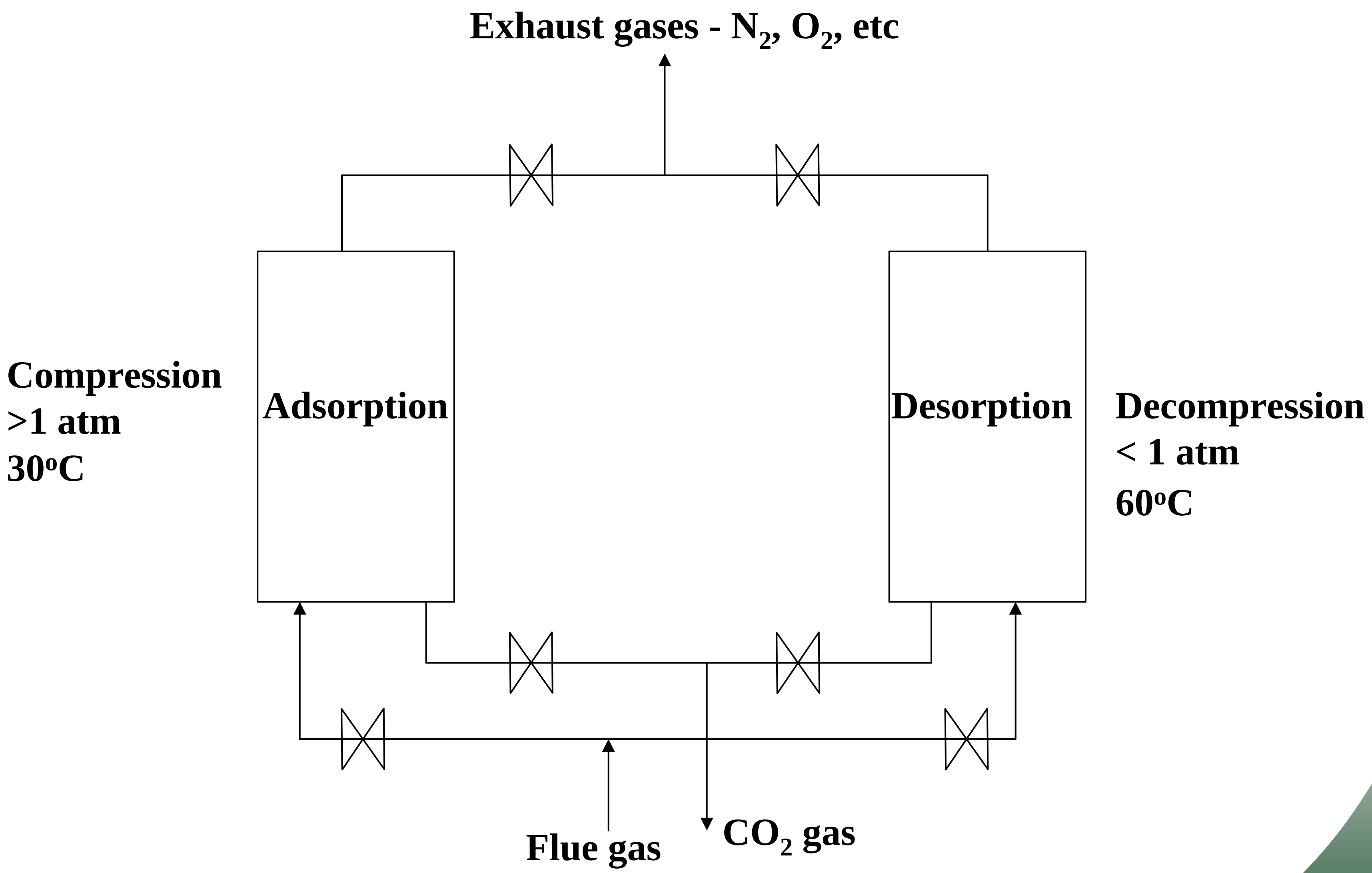
In the desorber
T = 120°C
P = 1 atm

Fisher *et. al*. Integrating MEA regeneration with CO_2 compression to reduce CO_2 capture costs. Presented at Fourth Annual Conference on Carbon Capture and Sequestration, Alexandria, VA, 2-5 May, 2005

Adsorption

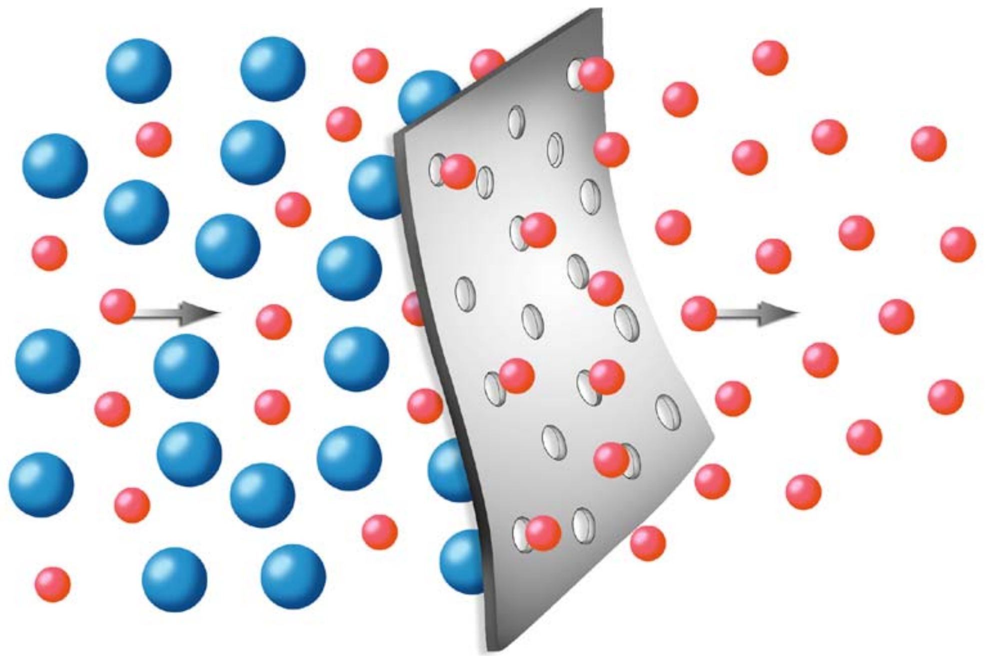
- **Physical or chemical interaction**
  - CO_2 trapped on sorbent surface including the pore surface
- **Regenerable sorbent**
  - Moderate temperature and pressure requirements for capture and regeneration
- **No current sorbent meets the three primary criteria necessary for large-scale implementation:**
  - Selectivity – exhibit high CO_2 capture with little sorption of N_2, O_2, H_2O, etc.
  - Capacity – greater CO_2 capture per sorbent mass is desirable
  - Longevity – sorbent must allow many cycles of sorption and desorption with little loss in capacity/selectivity

Pressure-Swing Adsorption



Membrane Separation

- **Physical and chemical**
  - Membrane pores and CO_2-specific chemicals separate CO_2
- **Low operating cost**
  - Promising future for higher-temperature membranes
- **Availability**
  - Most membranes do not meet selectivity, rigidity, robustness or permeability requirements (similar to adsorption)



Flue gas (~10% CO_2)

40^oC, 2.5 atm

Mostly CO_2

40^oC, 0.12 atm

Image from T. Armstrong's Fuel Cell Initiative at ORNL. *ORNL Review*. November, 2006

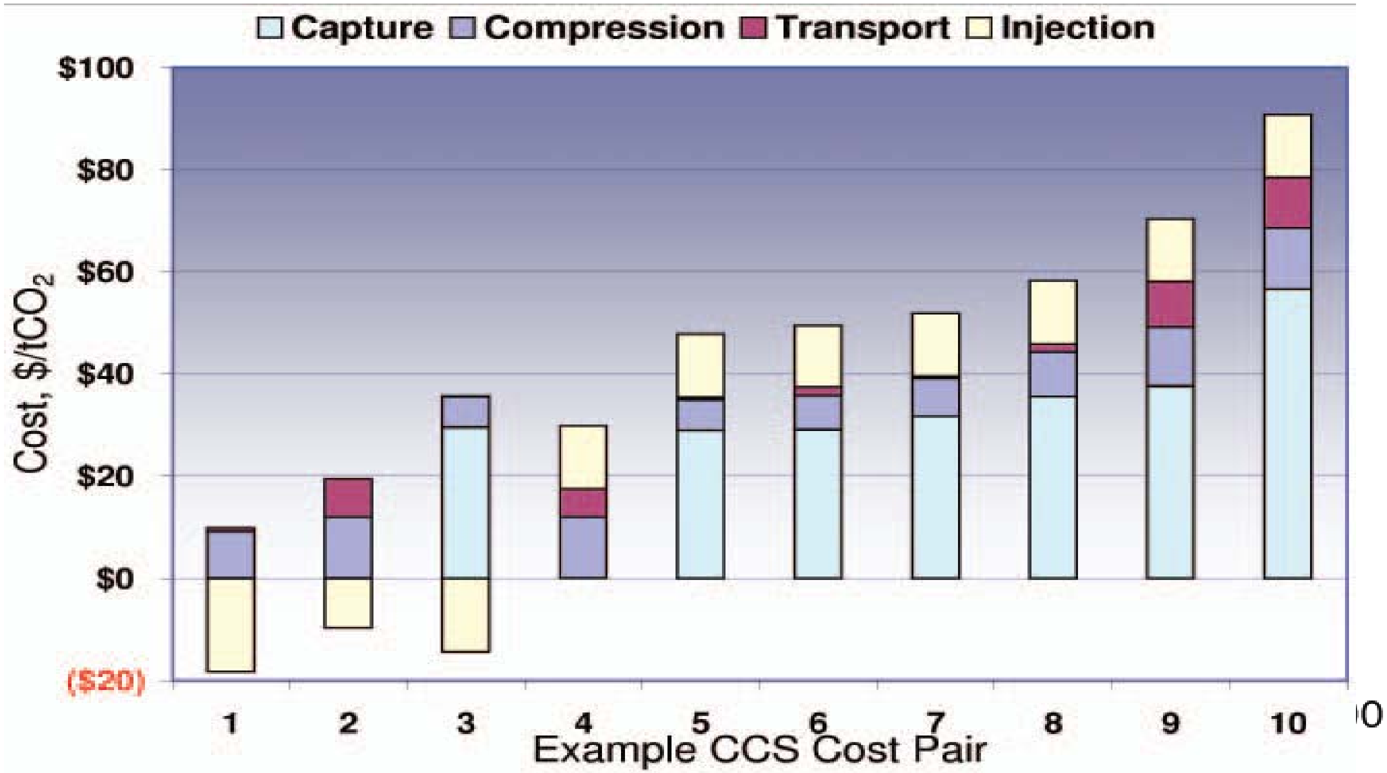
Combustion Methods and Suitable CO_2 Capture Technologies

- **Post-combustion**
  - Burn coal or natural gas traditionally using air or oxygen (oxy-combustion) and then separate CO_2 from exhaust flue gas
  - Separate CO_2 from N_2, H_2O, O_2, etc
  - Suitable capture technology: absorption with amine solvents
- **Pre-combustion**
  - Combined cycle technologies for coal gasification (IGCC) and natural gas (NGCC)
  - Turn fuel into synthesis gas mixture of CO and H_2, then perform water-gas shift to provide CO_2 and more H_2
  - Separate CO_2 from H_2, store CO_2 and burn H_2
  - Suitable capture technologies: membranes or absorption

Estimated CO_2 Capture Requirements

- **Post-combustion [primary method for pulverized coal (PC) facilities]**
  - Installation of carbon capture systems adds ~75% to the capital cost of PC facilities
  - Energy penalty: 30-44%
- **Pre-combustion**
  - Installation of Carbon capture systems adds ~40% to the capital cost of IGCC facilities
  - Energy penalty: 18-23%
- **CO_2 capture adds cost and energy penalty**
  - Requires 10-12 acres additional area
  - Doubles water requirements

Cost of CCS for Various Industries

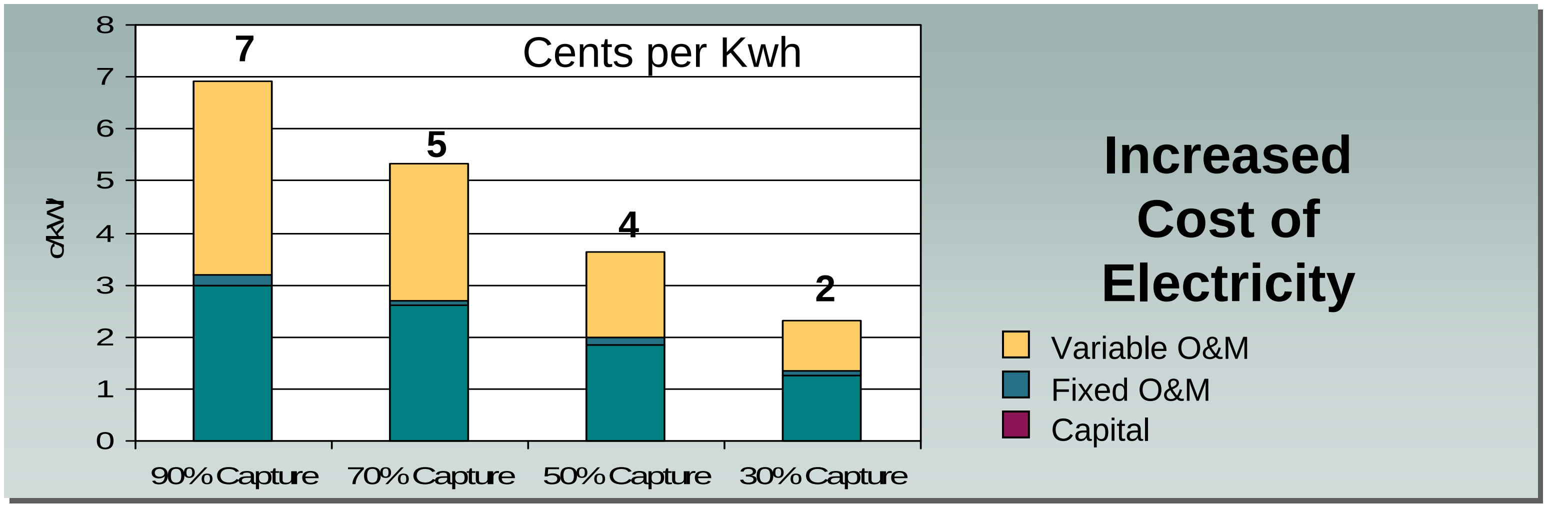


Dooley et al., 2006

1 High purity ammonia plant / nearby (<10 miles) EOR opportunity
2 High purity natural gas processing facility / moderately distant (~50 miles) EOR opportunity
3 Large, coal-fi red power plant / nearby (<10 miles) ECBM opportunity
4 High purity hydrogen production facility / nearby (<25 miles) depleted gas field
5 Large, coal-fired power plant / nearby (<25 miles) deep saline formation
6 Coal-fired power plant / moderately distant (<50 miles) depleted gas field
7 Iron & steel plant / nearby (<10 miles) deep saline formation
8 Smaller coal-fired power plant / nearby (<25 miles) deep saline basalt formation
9 Cement plant / distant (>50 miles) deep saline formation
10 Gas-fired power plant / distant (>50 miles) deep saline formation

The Cost of CO_2 Capture Varies with Capture Efficiency

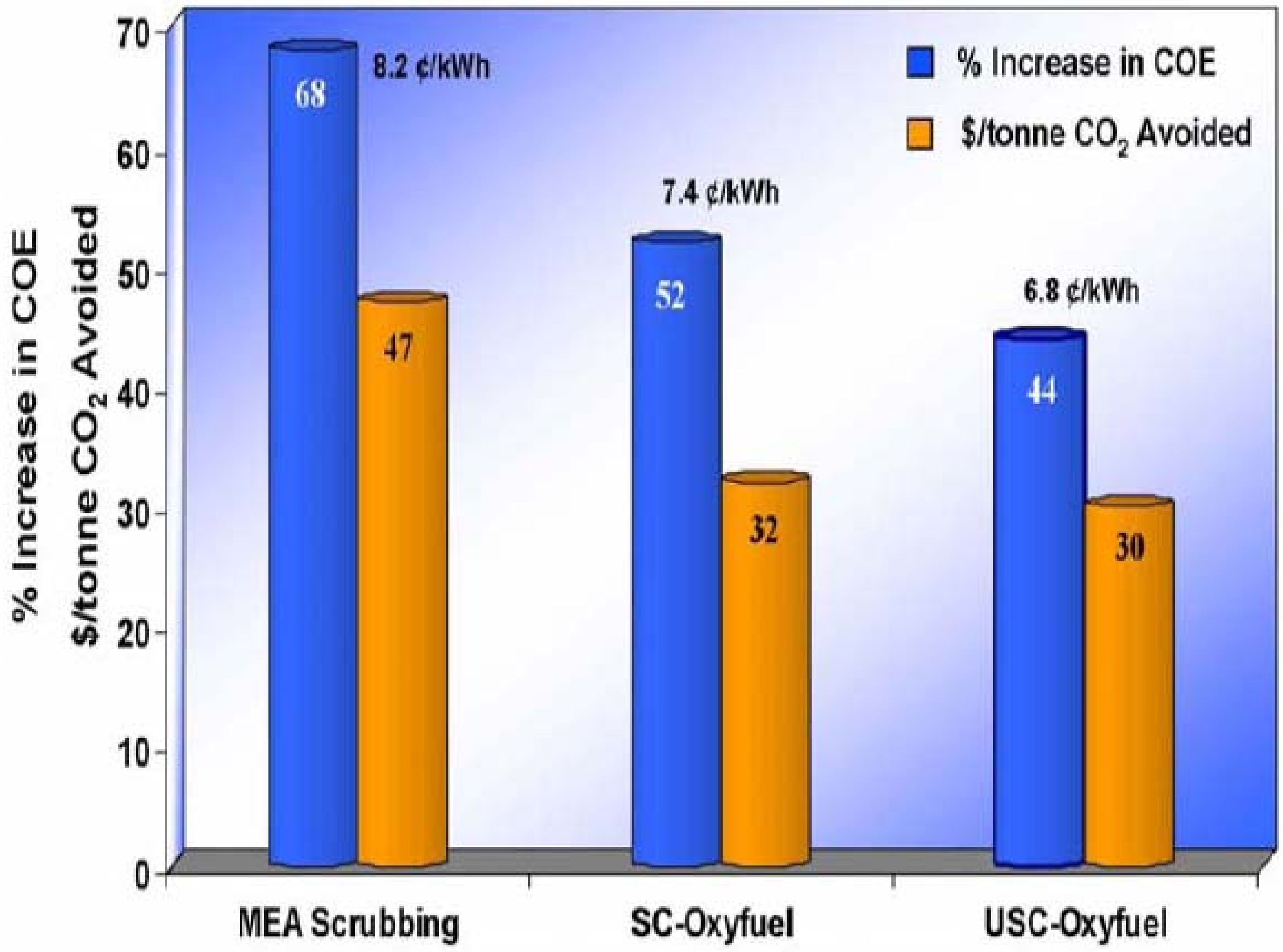
- Cost of amine CO_2 scrubbing



- Economically, it is better to treat less gas with higher capture efficiency

Ciferno, 2008

CO_2 Capture Costs with MEA / Oxy-Fuel



MEA Scrubbing: Air Fired SC Boiler, Econamine FG+ CO_2 Capture

Ciferno, 2008

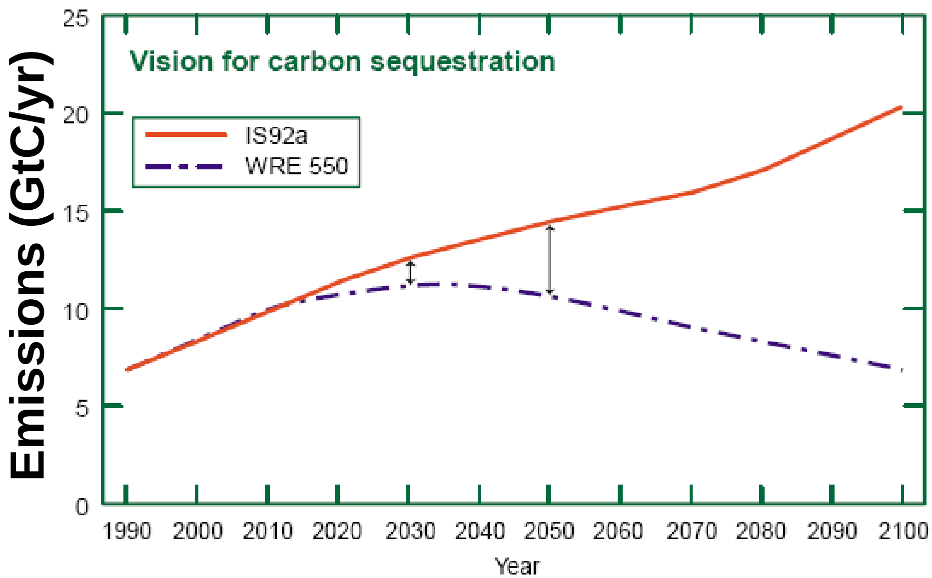
The High Cost of CO_2 Capture

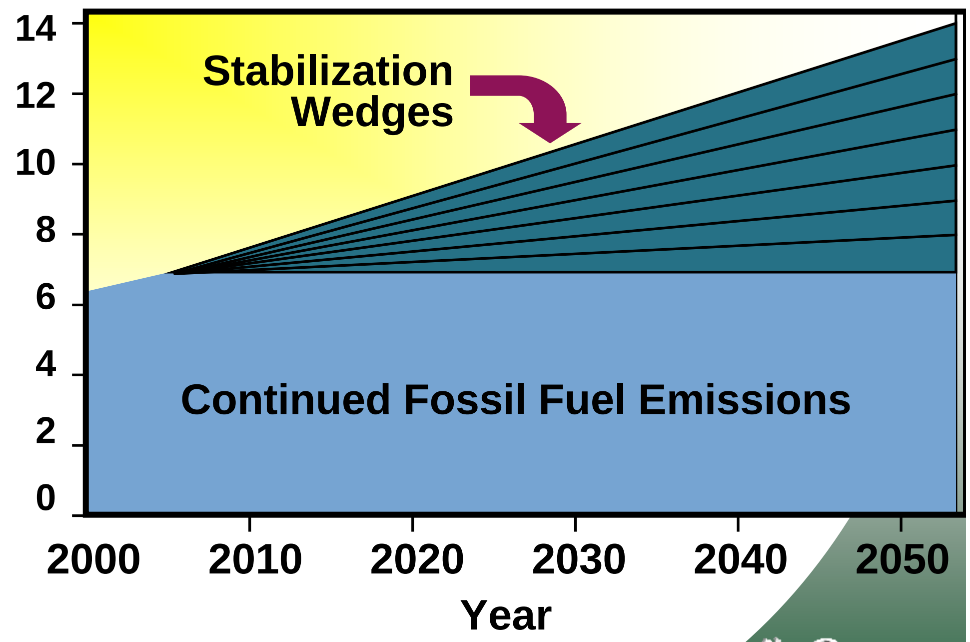
- **Summary of costs (from IPCC report)**

Technology	Low Cost ($/ton CO_2)	High Cost ($/ton CO_2)	Rep. Cost ($/ton CO_2)	Notes
IGCC (pre-combustion)	13	37	23	
Amine (post-combustion)	29	51	41	New PC plant
Amine (post-combustion)	45	73	59	Retrofitted PC plant
NGCC	37	74	53	
Oxy-fuel combustion	27	72	47	Low-confidence data
Transport	0	6	4	From 0 km to 250 km
Geo-storage	0.6	8.3	5	Includes monitoring
Carbonation	50	100	75	High due to mineral dehydration
Total cost from IPCC				
PC	30	71	51	For 250 km transmission
Oxy-fuel combustion	28	86	56	Low-confidence data
IGCC	14	53	33	
NGCC	38	91	62	

Relative Importance of CCS Cost

- Calculated the resources needed for CCS to stabilize CO_2 emissions
- Used this “pool” of money to build, maintain, operate, and decommission alternative energy installations (Virtual CCS)
- Based calculations on the Pacala and Sokolow (2004) seven-wedge stabilization triangle





175 GtC must be sequestered over 50 years!

Model Input Data for Comparison of CCS, Wind Power, and Nuclear Power

- Data taken from the literature determine the scale of CCS and alternative solutions:

CO_2 emissions in 2005	CO_2 emissions increase	Cost of CCS[1]
(GT)	(GT/year)	(\$/ton CO_2)
25.67	0.513	55

- These data lead to a total, one-wedge cost of $5.14 trillion over a period of 50 years
- Cost and revenue data for wind and nuclear energy:

Wind installed cost	Wind revenue	Nuclear installed cost[2]	Nuclear revenue
($/kW)	($/kW-yr)	($/kW)	($/kW-yr)
5667	394.2	5046	433.4

[1]IPCC Report [2]Waste disposal cost included

Economic Evaluation of CCS Shows Other Alternatives are Better Options

- With the current economics of CCS, wind energy, and nuclear energy, CCS is not the best option for carbon avoidance in atmospheric emissions:
  - If instead of CCS, we used wind energy, for the lifetime of wind mills, we could avoid 2.1 times the amount of CO_2 that we would avoid with CCS
  - If instead of CCS, we used nuclear energy, for the lifetime of plants, we could avoid 4.9 times the amount of CO_2 that we would avoid with CCS
  - Wind power and Nuclear power would have a revenue from power sales, while CCS would not have any revenue

Revenue for a $5.14-trillion investment (1 wedge*)

CCS	Wind	Nuclear
~$0	$8.9 trillion	$23.3 trillion

1 wedge = 25Gt Carbon (91.67Gt CO_2) avoided over 50 years

CCS Expected to be Implemented

- CCS is an essential element of fossil energy
- Without CCS, fossil energy will be phased out if we want to stabilize the atmospheric CO_2 concentration at 450 or even 550 ppm
- Phasing out fossil energy is not politically acceptable; it will remove the biggest energy source from the few options we currently have
- There are government incentives promoting new fossil energy plants with CCS capabilities
- NETL has invested billions of dollars on in-house and university R&D and on industrial demonstrations by seven partnerships
- CCS will help address CO_2 emissions by other industries such as the steel industry, cement industry, refineries, etc.
- Thus, CCS R&D, demonstration, and deployment are expected to continue

How We Can Improve CCS?

- For post-combustion technologies, the maturity level and cost of technologies suggest that R&D focus should be primarily on CO_2 capture

	Maturity	Cost
Capture and Compression	Lab, pilot, field	~75%
Transport	Field	~5%
Storage	Lab, pilot, field	~20%

- Additional R&D on storage should address the fate of CO_2 and potential risks

DOE/NETL CCS Program Goals

By 2020, have available for commercial deployment, technologies and best practices for achieving:

- **90% CO_2 capture**
- **99%+ storage permanence**
- **Pre-combustion Capture (IGCC)**
  - **< 10% increase in cost of electricity (COE)***
- **Post-and Oxy-combustion Capture**
  - **< 35% increase in COE***

* Includes 50 mile pipeline transport and saline formation storage, 100 years of monitoring

(J. Ciferno, 2007)

NETL Cost Reduction Strategies

OBJECTIVE 1 – Lower Specific Capital Costs of CCS
Improve CCS Process Technologies
Develop Alternative Materials of Construction
Process Intensification
Reduce Equipment Volumes

OBJECTIVE 2 – Lower Specific Operating Costs of CCS
New or improved Solvents, Sorbents, Membranes
Improve CDR Operability & Reliability

OBJECTIVE 3 – Improve Energy Efficiency of CCS
Reduce Sorbent/Solvent Regeneration Energy
Reduce CO_2 Capture Requirement
Process Intensification & System Integration
Raise System Mechanical/Electrical Efficiencies

(J. Ciferno, 2007)

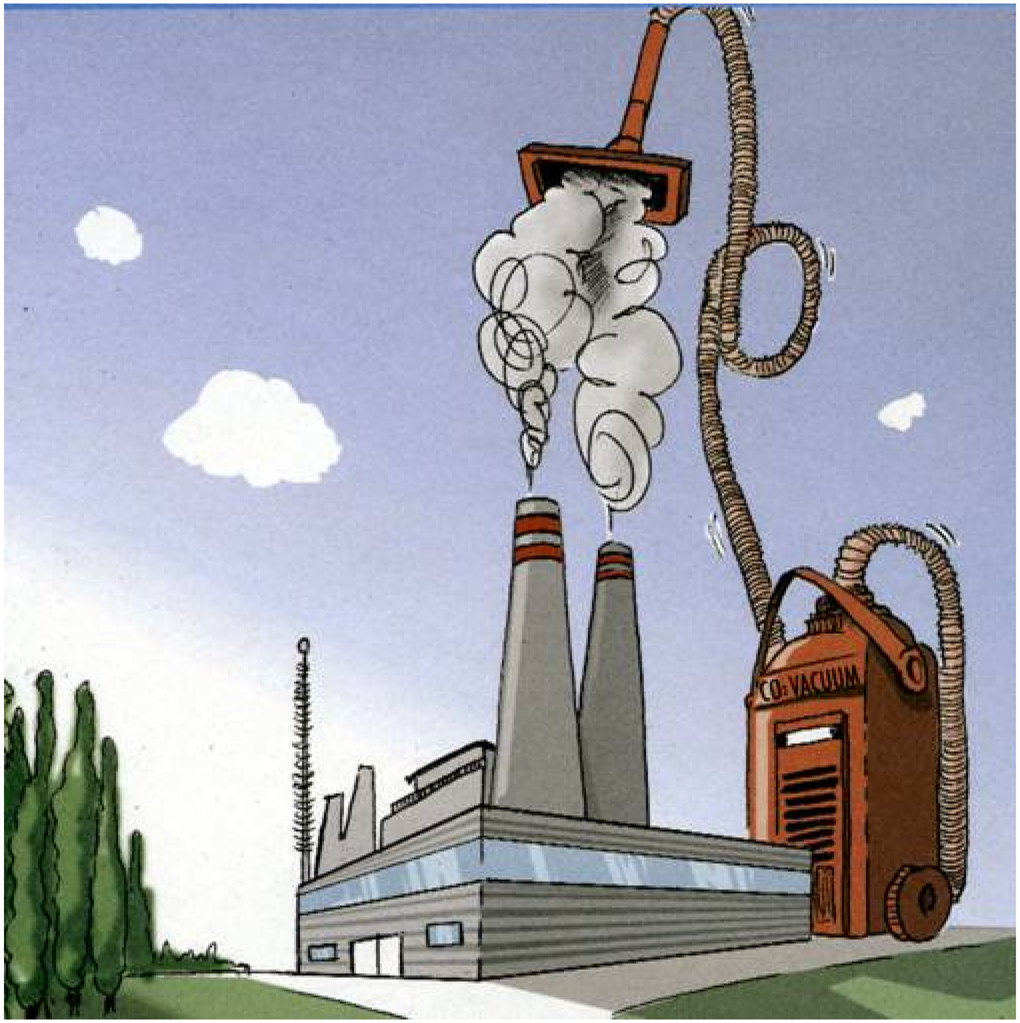
OBJECTIVE 4 – Lower Specific Retrofit Costs
Process Synthesis
Reduce Engineering, Design, Installation Costs

OBJECTIVE 5 – Increase On-Site Steam & Power Generation
Supply CDR Parasitic Load with Waste Heat
Increase Boiler Capacity
Add Supplemental Boiler for Steam Generation

Target Materials and Processes for CO_2 Capture

- **Adsorbents**
  - Selectivity
  - Capacity
  - Longevity
- **Membranes**
  - Selectivity
  - Rigidity
  - Robustness
  - Permeability
- **Absorbents**
  - Selectivity
  - Capacity
  - Longevity
  - Low vapor pressure
    - Avoid entrainment of solvent in emissions that will increase cost for further gas treatment
    - Ionic liquids

CO_2 Capture and Storage – Not Nearly this Simple



Source: IPCC, 2006

CO_2 Capture is Challenging - ORNL Can Contribute

Capture Technologies	ORNL's Opportunity Areas	ORNL's Potential Technology Role(s)
Materials for advanced separations processes	Materials and Processes	• Materials R&D to enable – High-T oxyfiring – Chemical Looping Combustion • Advanced Separations • Partnering on demonstrations with regional industry leaders (TVA, Alstom, etc.)
Innovative Solutions	Catalysis R&D Separations	• Algae to Fuels and other products • CO_2 to Syn Fuels via F-T + Nuclear hydrogen • Photocatalytic Reduction of CO_2 • Air Capture
Evaluation of Alternatives	Economic Analysis	• Integrated analysis of future energy systems

Source: David DePaoli

Potential Collaborators on CO_2 Capture Technologies

- **Universities (for materials development)**
  - University of Cincinnati
  - University of Wyoming
  - University of British Columbia
  - University of Tennessee
- **EPRI**
- **TVA**
- **SECARB (South East Carbon Sequestration Partnership)**
- **Industry**
  - Eastman
  - Southern Company