Geoengineering Part 2: Carbon Capture & Sequestration

UW PCC 588

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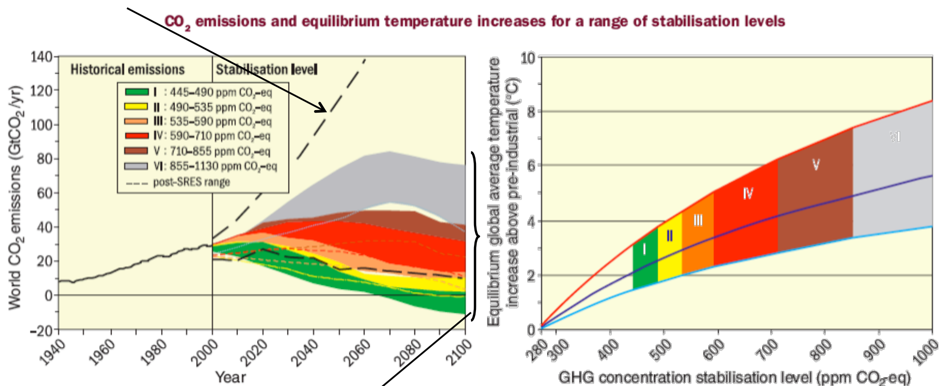
March 5, 2009

The Problem

• 2000-2006 trend



• Where emissions need to be in order to reach different target levels of atmospheric CO2, ranging from 445-1130 ppmV (comp. to 387 ppmV in 2008)

• Estimated global mean T change for the different emission scenarios
• Results for climate sensitivities of 3°C (dk. blue line), 2°C (lt. blue line), 4.5°C (red line) for CO_2 doubling

IPCC 2007 Synth. Rept. Fig. 5.1

Overview of C Capture & Sequestration Possibilities

- Capture of CO_2 Emissions from Electrical Power Plants
- Capture of CO_2 Directly from the Atmosphere
- CO_2 Burial in Spent Petroleum Reservoirs
- CO_2 Burial in Saline Aquifers
- CO_2 Disposal in the Deep Sea
- CO_2 Disposal in Basalt
- Disposal in Lakes Beneath Ice Caps
- Mineralization of Magnesium-rich Rocks
- Seafloor Disposal

Broecker (2008) *Elements* Vol. 5(4): 296-297

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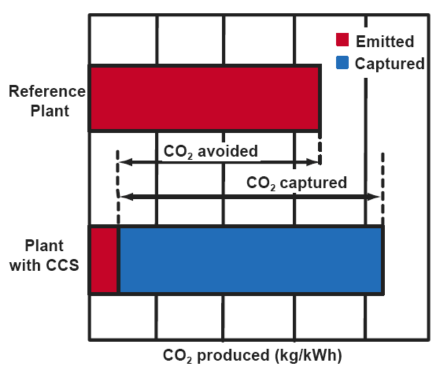
What is it & Why Focus on Power Plants?

- Removal of CO_2 before or after coal is burned to produce heat & energy
- Power plants account for about 80% of global CO_2 emissions from large stationary facilities
  - Refineries, chemical plants, cement plants, & steel mills make up the other 20%

CO_2 Capture from Power Plants: Energy Penalty



- Current commercial CO_2 capture systems can reduce CO_2 emissions by 80-90% kW/h, an efficiency of 85 – 95%
- CO_2 capture reduces overall efficiency of power generation and other processes because it requires 10-40% more energy input relative to same type of plant without capture

Adapted from Juerg Matter, LDEO

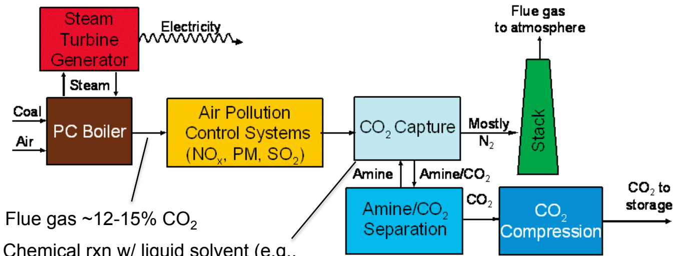
What is it? Why Focus on Power Plants?

- Removal of CO_2 before or after coal is burned to produce heat & energy
- Power plants account for about 30% of CO_2 emissions in the USA & 80% of global CO_2 emissions from large stationary facilities*
  - *Refineries, chemical plants, cement plants, & steel mills make up the other 20%

How is it Done?

- CO_2 capture technologies classified as:
  - Precombustion
  - Postcombustion
  - Oxycombustion
- Goal is to produce concentrated CO_2 stream for transport to sequestration site

Postcombustion Capture of CO_2



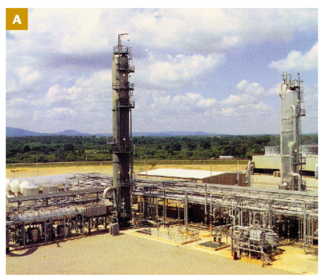
Flue gas ~12-15% CO_2

Chemical rxn w/ liquid solvent (e.g., monoethanolamine) in "absorber" vessel "scrubs" 85-90% of CO_2

"Regenerator" vessel heats solvent/CO_2 mix, releasing gaseous CO_2

CO_2 compressed to supercritical fluid for transport

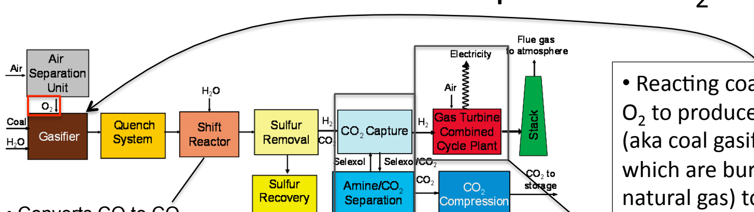
- CO_2 separated from flue gas produced from combustion of coal (or other fossil fuel) in air



- Amine-based Postcombustion CO_2 capture of flue gas from coal-fired power plant in Oklahoma

Adapted from Rubin (2008) CO_2 Capture and Transport. *Elements* Vol. 5(4): 311-317.

Precombustion Capture of CO_2



- Converts CO to CO_2 by rxn w/ steam
- Resulting gas stream ~60% CO_2, making it easier to separate

- CO_2 capture & compress as in postcombustion process
- But, high CO_2 conc. in stream allows physical sorbents instead of chem. rxn to capture CO_2

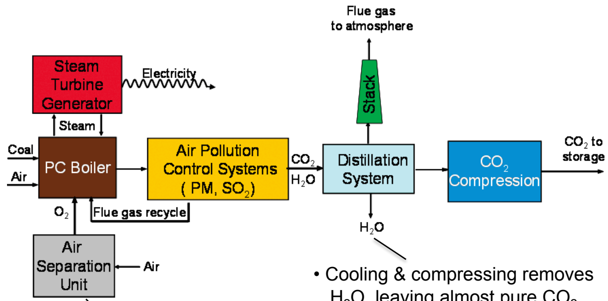
H_2 combusted to generate electricity (C-free)

- Reacting coal w/ steam + O_2 to produce CO + H_2 (aka coal gasification) which are burned (like natural gas) to make electricity

- A precombustion CO_2 capture system used to produce synthetic natural gas (syngas) from coal at the Dakota Gasification Plant in North Dakota.
- About 3 Mt/y captured CO_2 is currently transported by pipeline to the Weyburn & Midale oil fields in Saskatchewan, Canada, where it is used for enhanced oil recovery & sequestered in depleted oil reservoirs.

Adapted from Rubin (2008) CO_2 Capture and Transport. *Elements* Vol. 5(4): 311-317.

Oxycombustion Capture of CO_2



Air separation unit req'd to produce 95-99% pure O_2

- Cooling & compressing removes H_2O, leaving almost pure CO_2
- Avoids need for postcombustion capture device

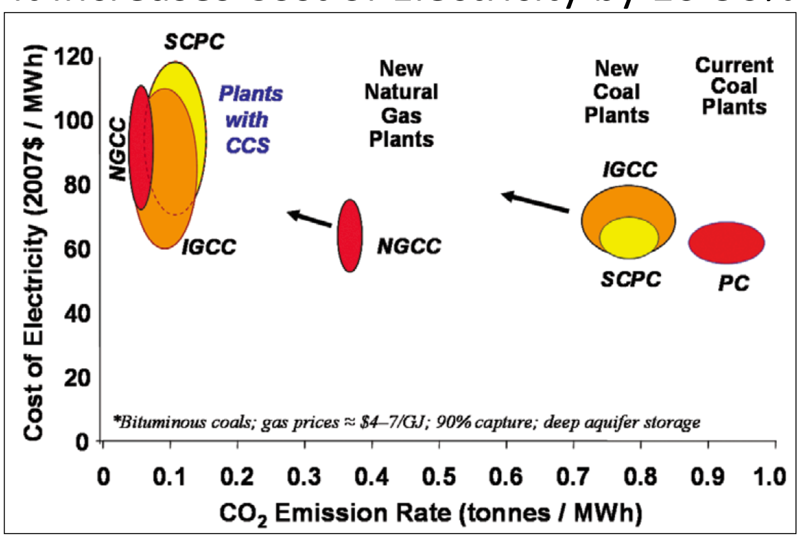
- A process that burns coal using O_2 instead of air, creating an exhaust stream of relatively pure CO_2 that can easily be captured.
- Approximately 70% of the CO_2-laden flue gas is recycled to the boiler, increasing efficiency.

- Vattenfall coal-fired Schwarze Pumpe power station in Germany, a 30 MW oxycombustion CO_2 capture system

http://www.greenbang.com/coal-fired-carbon-capture-experiment-begins/

Adapted from Rubin (2008) CO_2 Capture and Transport. *Elements* Vol. 5(4): 311-317.

It Increases Cost of Electricity by 10-90%



- These data are for the combination of C Capture + Transport + Storage (= CCS)
- However, Transport + Storage is typically < 10% of total CCS cost

Rubin (2008) CO_2 Capture and Transport. *Elements* Vol. 5(4): 311-317.

Pros & Cons of CO_2 Capture of Power Plant Emissions

- Some proven technologies
  - already in use at small scales
- Scaleable
- Rapid innovation is occurring & prices are coming down

- Doesn't deal with other 70% of CO_2 emissions (in USA)
- Increases the cost of electricity
- Still need to dispose of CO_2

CO_2 Transport

• (Above) Pipeline delivering CO_2 from precombustion capture system in North Dakota oilfield in Saskatchewan, Canada
• (Below) World's largest LNG tanker w/ 266,000 m^3 capacity

http://www.tehrantimes.com/index_View.asp?code=172852

- Except in cases where an industrial plant is located directly above a suitable geological formation, captured CO_2 must be transported from the point of capture to a sequestration site.
- In the US, pipelines are the most common method for transporting CO_2.
- Compressed CO_2 can also be economically transported by tanker similar to htose used for liquefied natural gas.

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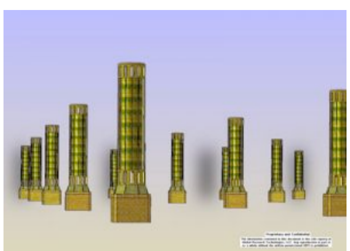
Direct Capture of CO_2 from Air

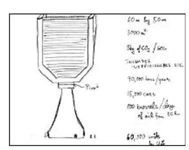


Artist's Renditions

- Klaus Lackner's "Artificial Trees" are designed to remove CO_2 from the atmosphere by reaction with a sorbent (originally NaOH…. Very caustic & dangerous)

"Global Research Technologies, LLC (GRT), a technology research and development company, and Klaus Lackner from Columbia University have achieved the successful demonstration of a bold new technology to capture carbon from the air. The "air extraction" prototype has successfully demonstrated that indeed carbon dioxide (CO_2) can be captured from the atmosphere. This is GRT's first step toward a commercially viable air capture device."

-4/19/07 press release



http://www.thebreakthrough.org/blog/2008/03/from_synthetic_trees_to_carbon.shtml http://www.grtaircapture.com/

Pros & Cons of Direct Atmospheric CO_2 Capture

- Deals with all CO_2 in atmosphere (as opposed to just the 30% emitted by fossil fuel power plants)
- Scaleable

- Unproven technology
- Increases the cost of electricity
- Still need to dispose of CO_2

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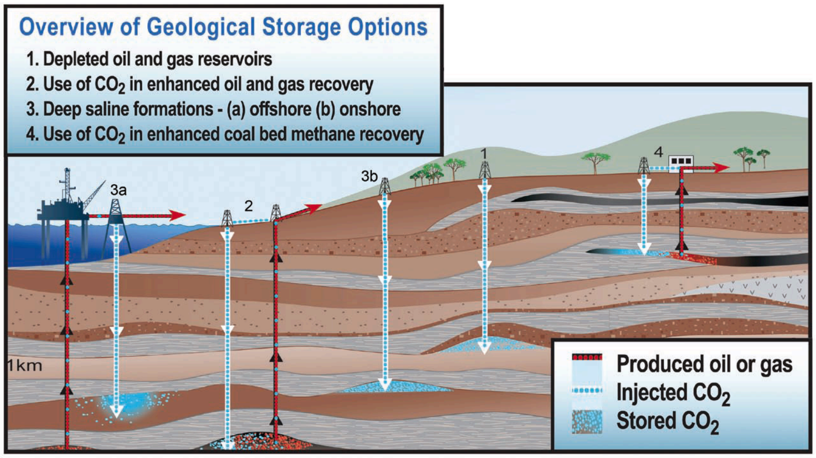
Storage of CO_2 in Geological Formations



- CO_2 already used in to improve recovery of oil & gas

Benson & Cole (2008) CO_2 Sequestration in Deep Sedimentary Formations. *Elements* Vol. 5(4): 325-331.

Many Potential Sedimentary Basins for CO_2 Storage

Benson & Cole (2008) CO_2 Sequestration in Deep Sedimentary Formations. *Elements* Vol. 5(4): 325-331.

Pros & Cons of CO_2 Storage in Deep Sedimentary Basins

- Abundant locations worldwide
- Scaleable
- Relatively inexpensive
  - $0.5-10/ton CO_2

- Unknown risk of leakage
- Unknown duration of containment
- Increases the cost of electricity

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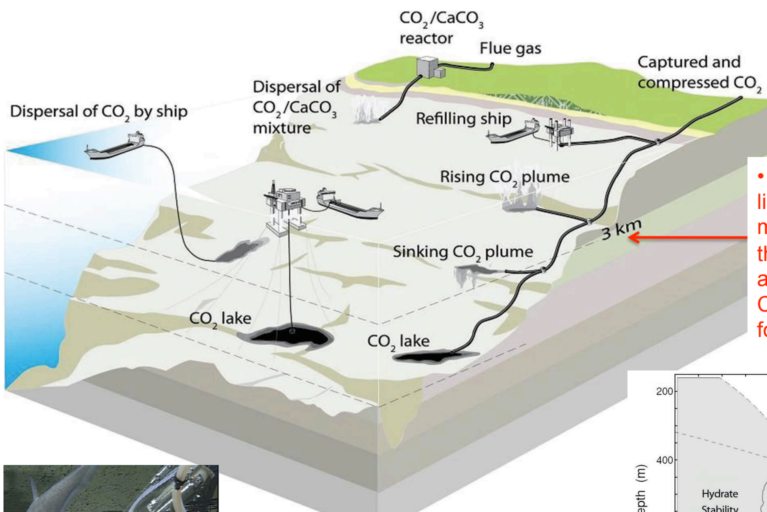
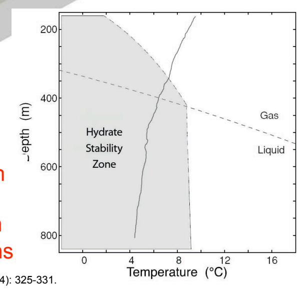
CO_2 Disposal in the Deep Ocean



• Below 3 km liquid CO_2 is more dense than seawater allowing for CO_2 lakes to be formed

• Below 0.4 km, stable CO_2 hydrates can form from that are more dense than seawater, allowing storage of CO_2 within & atop sediments, even at modest depths



Adams & Caldeira (2008) Ocean Storage of CO_2. *Elements* Vol. 5(4): 325-331.

Pros & Cons of CO_2 Storage in Deep Ocean

- Massive buffering capacity of ocean
- Scaleable

- Lowers the pH of seawater
  - 0.3 units for 5600 Gt CO_2—i.e., 200 yr of current emissions
- Unknown consequences to marine life
- Unknown duration of containment
- Relatively expensive
  - $5-30/ton CO_2
- Increases the cost of electricity

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Mineral Carbonation of CO_2

Potential mineral hosts of CO_2: (a) calcite, (b) dolomite, (c) magnesite, (d) siderite

- Mineral carbonation = the fixation of CO_2 into carbonate minerals such as calcite, dolomite & magnesite
- Very stable, long-term storage mechanism for CO_2
- Feasibility demonstrated by proportion of terrestrial C bound in these minerals: > 40,000x more in the atmosphere
- Many challenges in mineral carbonation must be resolved:
  - overcoming the slow kinetics of mineral–fluid reactions
  - dealing with the large vol. of source material required
  - reducing the energy needed to hasten the carbonation process.

Oelkers et al. (2008) Mineral Carbonation of CO_2. *Elements* Vol. 5(4): 325-331.

How does it work? – *ex situ*

- Mineral carbonation requires combining CO_2 with metals to form carbonate minerals
- With few exceptions, the required metals are divalent cations, including Ca^{2+}, Mg^{2+} and Fe^{2+}
- A major challenge is obtaining sufficient quantities of these cations
- The most abundant cation source is silicate minerals.
- Carbonate phases are energetically favored to form from the interaction of CO_2 with such silicate phases as forsterite & anorthite as follows:

$$Mg_2SiO_4 + 2CO_2 = 2MgCO_3 + SiO_2$$

forsterite *magnesite* *quartz*

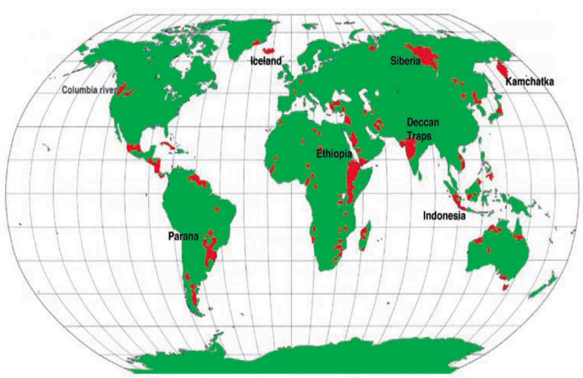
$$CaAl_2Si_2O_8 + CO_2 + 2H_2O = CaCO_3 + Al_2Si_2O_5(OH)_4$$

anorthite *calcite* *kaolinite*

- About 6-20 tons of the silicate rocks are req'd to sequester 1 ton of CO_2
- Minerals are ground to increase surface area, reacted with acids (or base) to release cations, & heated in a reactor to speed the carbonation reaction

Oelkers et al. (2008) Mineral Carbonation of CO_2. *Elements* Vol. 5(4): 325-331.

How does it work? – *in situ*



Locations of continental basalts that could serve as *in situ* mineral carbonation sites

- Inject CO_2 directly into porous rocks in the subsurface where it can react directly with host rock
- Eliminates the need for transport of reactants in and end products out
- May provide heat to accelerate the carbonation process
- Host rock must contain easily dissolved metal cations & have sufficient permeability & pore volume to store injected CO_2 and carbonate-mineral products

Oelkers et al. (2008) Mineral Carbonation of CO_2. *Elements* Vol. 5(4): 325-331.