Geoengineering Part 2: Carbon Capture & Sequestration

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The Problem

- **2000-2006 trend**
  - CO₂ emissions and equilibrium temperature increases for a range of stabilisation levels

- **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 CO₂ doubling

IPCC 2007 Synth. Rept. Fig. 5.1
Overview of C *Capture & Sequestration Possibilities*

- Capture of CO\textsubscript{2} Emissions from Electrical Power Plants
- Capture of CO\textsubscript{2} Directly from the Atmosphere
- CO\textsubscript{2} Burial in Spent Petroleum Reservoirs
- CO\textsubscript{2} Burial in Saline Aquifers
- CO\textsubscript{2} Disposal in the Deep Sea
- CO\textsubscript{2} Disposal in Basalt
- Disposal in Lakes Beneath Ice Caps
- Mineralization of Magnesium-rich Rocks
- Seafloor Disposal

**What is it & Why Focus on Power Plants?**

- **Removal of CO₂ before or after coal is burned to produce heat & energy**
- **Power plants account for about 80% of global CO₂ emissions from large stationary facilities**
  - Refineries, chemical plants, cement plants, & steel mills make up the other 20%

**CO₂ Capture from Power Plants: Energy Penalty**

- Current commercial CO₂ capture systems can reduce CO₂ emissions by 80-90% kW/h, an efficiency of 85 – 95%
- CO₂ 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 Jürg Matter, LDEO
What is it? Why Focus on Power Plants?

- Removal of CO₂ before or after coal is burned to produce heat & energy
- Power plants account for about 30% of CO₂ emissions in the USA & 80% of global CO₂ emissions from large stationary facilities*
  – *Refineries, chemical plants, cement plants, & steel mills make up the other 20%

How is it Done?

- CO₂ capture technologies classified as:
  – Precombustion
  – Postcombustion
  – Oxycombustion
- Goal is to produce concentrated CO₂ stream for transport to sequestration site
Postcombustion Capture of CO₂

Flue gas ~12-15% CO₂
Chemical rxn w/ liquid solvent (e.g., monoethanolamine) in "absorber" vessel "scrubs" 85-90% of CO₂
"Regenerator" vessel heats solvent/CO₂ mix, releasing gaseous CO₂
CO₂ compressed to supercritical fluid for transport

Precombustion Capture of CO₂

Reacting coal w/ steam + O₂ to produce CO + H₂ (aka coal gasification) which are burned (like natural gas) to make electricity
H₂ combusted to generate electricity (C-free)

A precombustion CO₂ capture system used to produce synthetic natural gas (syngas) from coal at the Dakota Gasification Plant in North Dakota.
About 3 Mt/y captured CO₂ 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.

Oxycombustion Capture of CO₂

- A process that burns coal using O₂ instead of air, creating an exhaust stream of relatively pure CO₂ that can easily be captured.
- Approximately 70% of the CO₂-laden flue gas is recycled to the boiler, increasing efficiency.

Vattenfall coal-fired Schwarze Pumpe power station in Germany, a 30 MW oxycombustion CO₂ capture system

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


It Increases Cost of Electricity by 10-90%

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

Pros & Cons of CO₂ Capture of Power Plant Emissions

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

**Cons**
- Doesn’t deal with other 70% of CO₂ emissions (in USA)
- Increases the cost of electricity
- Still need to dispose of CO₂

CO₂ Transport
- Except in cases where an industrial plant is located directly above a suitable geological formation, captured CO₂ must be transported from the point of capture to a sequestration site.
- In the US, pipelines are the most common method for transporting CO₂.
- Compressed CO₂ can also be economically transported by tanker similar to those used for liquefied natural gas.

Overview of C \textbf{Capture} \& \textbf{Sequestration} Possibilities

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Direct Capture of CO$_2$ from Air

- Klaus Lackner's \textit{"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

Pros & Cons of Direct Atmospheric CO₂ Capture

- Deals with all CO₂ 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 CO₂

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Storage of CO\(_2\) in Geological Formations

- CO\(_2\) already used in to improve recovery of oil & gas

Many Potential Sedimentary Basins for CO\(_2\) Storage

Pros & Cons of CO\textsubscript{2} Storage in Deep Sedimentary Basins

- Abundant locations worldwide
- Scaleable
- Relatively inexpensive – $0.5-10/ton CO\textsubscript{2}
- Unknown risk of leakage
- Unknown duration of containment
- Increases the cost of electricity

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CO₂ Disposal in the Deep Ocean

- Below 3 km, liquid CO₂ is more dense than seawater, allowing for CO₂ lakes to be formed.
- Below 0.4 km, stable CO₂ hydrates can form from that are more dense than seawater, allowing storage of CO₂ within & atop sediments, even at modest depths.


Pros & Cons of CO₂ Storage in Deep Ocean

- Massive buffering capacity of ocean
- Scaleable
- Lowers the pH of seawater
  - 0.3 units for 5600 Gt CO₂—i.e., 200 yr of current emissions
- Unknown consequences to marine life
- Unknown duration of containment
- Relatively expensive
  - $5-30/ton CO₂
- Increases the cost of electricity
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Mineral Carbonation of CO$_2$

- 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.


Potential mineral hosts of CO$_2$: (a) calcite, (b) dolomite, (c) magnesite, (d) siderite
How does it work? – ex situ

- Mineral carbonation requires combining CO₂ with metals to form carbonate minerals.
- With few exceptions, the required metals are divalent cations, including Ca²⁺, Mg²⁺, and Fe²⁺.
- 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 CO₂ with such silicate phases as forsterite & anorthite as follows:
  
  \[
  \text{Mg}_2\text{SiO}_4 + 2\text{CO}_2 = 2\text{MgCO}_3 + \text{SiO}_2
  \]
  forsterite    magnesite    quartz

  \[
  \text{CaAl}_2\text{Si}_2\text{O}_8 + \text{CO}_2 + 2\text{H}_2\text{O} = \text{CaCO}_3 + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4
  \]
  anorthite    calcite    kaolinite

- About 6-20 tons of the silicate rocks are req’d to sequester 1 ton of CO₂.
- Minerals are ground to increase surface area, reacted with acids (or base) to release cations, & heated in a reactor to speed the carbonation reaction.


How does it work? – in situ

- Inject CO₂ 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 CO₂ and carbonate-mineral products.

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