Challenges Facing the Use of Coal in a Carbon Constrained World: What the Biologists Should be Thinking About"
Factors that may impact the biological utilization of CO₂

- CO₂ concentration
- Nitrogen fertilization
- Inhibition by impurities: H₂S, SO₂, toxic elements,…
- Heat integration
- Constraints on water access and land area

What might the Biologists wish to know?

- What is coal?
- Why coal?
- How is coal utilized to-day?
- How is coal use being impacted by carbon constraints?
- Are there potential synergies between biological utilization of CO₂ and the operation of coal-fired power plant?
Coal is not simply carbon. It consists of substituted polybenzenoid moieties. The number of rings in the polybenzenoids moieties increases with rank of coal: roughly 1 or 2 for lignites, 3 to 5 for bituminous coal, larger numbers for anthracites.

Model of bituminous coal by Peter Solomon (1990). Concentration of nitrogen in coal varies in a narrow range about 1.4%. Sulfur concentrations vary much more widely with part of the sulfur organically bound and the remainder in mineral sulfides.
Occurrence of Elements and Inorganic Compounds in Coal
Clay and Calcite Inclusions, Padia
Pyrites Inclusions, Padia
After combustion the mineral constituents in coal form ash most in the 1 to 50 micron size range but with about one percent in submicron aerosols produced by vaporization and condensation.
Residual Particles

20 microns

Coal Ash

Coal Ash Plerosphere

About 45% of ash is used for the production of concrete. For this application, the carbon content in the ash must be below 4%. Significant amounts of ash are stored in ash ponds, recently receiving public attention with the TVA spill at the Kingston, TN plant. An opportunity?
Size dependence of elements (Kauppinen)

Can the contaminants in coal be used to augment capture of CO₂?

“Coal Burning FGD Flue Gas Yields Superior Algal Growth!” Studies at the Ashkelon Power Station in Israel by Abi Ben-Amotz, November 20, 2008
Why Coal?

Major Domestic Energy Resource
(Reserves/Production = 234 years)

Provides about 50% of energy for electricity production in the US
The cost of electricity is generally lower for states in which coal generation dominates (National Mining Association, 2009)
How is coal utilized to-day?

USGS estimates that 136 million gallons/day of freshwater withdrawals for thermoelectric generation second only to agriculture to cover demands for cooling towers, make up boiler water, steam temperation, ash ponds, scrubbers,…

Coal combustion and steam generation
Boiler Population (Plant shown is typical with a capacity of 500 MWₑ)

There are about 1,1150 boilers in US with installed capacity of 330 GWₑ (Replacement cost 1 to 3 trillion dollars)

A 500 MWₑ may burn 250 tons/hr coal, uses over 12 million gallons/hr of water (265,000 gallons/hr consumptively) (Feeley et al., 2005)

Ameren Sioux Power Plant (Burners from different plant)
Evolution of Air Pollution Control Equipment
Regulations have driven impressive reductions in emissions of criteria pollutants despite a great increase in coal use since passage of the Clean Air Act in 1970 (Feeley, 2002)

These have been met by technological developments (adapted from Marion, 2005).

Incremental costs
- Capital $215/kWₑ (vs historical $1000/kWₑ)
- Cost of Electricity 0.93c/kWhr (vs base of ~4c/kWhr)

What are the prospects for biological treatment of NOₓ and SOₓ in addition to CO₂ capture?
How is coal use being impacted by carbon constraints?
Past Announcements of Capacity Additions vs. Actual

Historically, actual capacity has been shown to be significantly less than proposed capacity. For example, the 2002 report listed 11,455 MW of proposed capacity for the year 2005 when actually only 329 MW were constructed.

J. Strakey, DOE, NETL (2008)
OPPOSITION: Demonstrators march through Abington, Va., last month to protest a proposed coal-fired power plant. Legal clashes over coal are rivaling those over nuclear power decades ago.

“We hope to clog up the system”

David Bookbinder, Sierra Club Chief Climate Counsel
Recent Statements by Public Interest Groups

• Reality’s definition (from their web site) of what is "Clean" Coal: “For a coal power plant to be clean… its CO₂ emissions must be captured and safely stored so that they cannot enter the atmosphere.”

David Hawkins, Director, Climate Center, Natural Resources Defense Council (NRDC) on March 10, 2009

“NRDC is calling for all new coal plants to be built with carbon capture and sequestration (CCS) technologies, which are deemed to be ready for deployment today by NRDC”
What are technologies for carbon capture and sequestration available in the near term?
Sorbent (e.g., monoethanolamine or MEA) absorption/simple stripping. (Rochelle, 2007)

Technology is well established. Industry has experience with scrubbers. However, high costs are driven by large energy requirement for steam stripping of amine, cost of amine replacement, and capital costs. Major installations at Sleipner, Norway and In Salah, Algeria for scrubbing CO₂ in natural gas.
Oxy-Fuel Combustion: Oxygen diluted with Recycled Flue Gas mimics combustion air (Stromberg, 2004). Dry combustion products will be primarily CO$_2$.

Vatttenfall: 30MW$_t$ pilot facility operational at Schwarze Pumpe. 250 MW$_e$ tentatively planned at Jänschwalde by 2015.
Air separation unit is a major cost for the operation. Operators like the familiarity of boiler operation.

Energy Flows for the case of Oxy-Fuel Firing Showing Losses with Air Separation Unit and CO₂ Compression (Stromberg, ’04)

- Original electricity output: 865 MW - 42.7%
- Net electricity output: 689 MW - 34.0%
- CO₂ compression: 71 MW - 3.5%
- Air separation: 137 MW - 6.8%
- Auxiliaries: 45 MW - 2.2%
- Cooling: 1084 MW - 53.5%

Efficiency penalty, as a percentage loss, decreases with increasing operating temperature:
- 36% subcritical (16 MPa, 540°C)
- 41% supercritical (25 MPa, 600°C)
- 44% ultra-supercritical (35 MPa, 700°C)
Gasification can be used for power (Integrated Gasification Combined Cycle or IGCC) and chemicals (Siirola, 2008). NH₃ is a relevant by-product of gasification, H₂S is a possible contaminant.

\[
\text{H}_2\text{O} + \text{CO} = \text{CO}_2 + \text{H}_2 \quad \text{Water gas shift reaction can be used to vary H}_2/\text{CO for chemicals and fuels or H}_2 \text{ for combined cycle operation (gas turbine for IGCC)}
\]
Comparative Costs of CO₂ Capture, % Efficiency Loss, and Increase In Cost of Electricity (COE) for Amine Scrubbing, Ox-Fuel Combustion, IGCC

Costs have increased since the time of publication. Recent estimates place cost of an Nth plant at about $60 to $65/tonne of CO₂ avoided and the increase in cost of electricity generation to $40 per MWhr or 4c/kWhr (Herzog, 2009)

(MIT Coal Study, Deutch & Moniz, 2007)
Major CO$_2$ Sequestration Options are in Enhanced Oil Recovery and in Deep Saline Formation (Mudd/Cooke 2006)

Sequestration costs are secondary to capture (< 20%) (NETL, 2005). Problems of public acceptance and long term fiduciary responsibility need to be addressed but capture costs present the current bottle neck to large scale use of capture and sequestration.

Enhanced oil recovery offsets cost of capture but capacity is limited. In USA the capacity of deep saline formations $> 3,700$ GtCO$_2$ vs total coal-fired emissions of $\sim 1.2$ GtCO$_2$/year (Deutch & Moniz, 2007)

Sleipner, Nor.  In Salah, Algeria  Weyburn, Canada

$> 1$ MtCO$_2$/year
What is needed to facilitate adoption of CCS technologies?

Reduced cost

Legislation
Chemical looping air

Technologies with potential of reducing cost of capture are being developed, e.g., chemical looping. $M$ is oxygen carrier e.g., metal (e.g. Ni), CaS, oxides with multiple valence states (e.g. Cu$_2$O)

Chemical reactions:

1. $M + \frac{1}{2}O_2 \rightarrow MO$
2. $MO + Coal \rightarrow CO_2, H_2O + M$

Diagram:

Air

$N_2, O_2$

Coal (CH$_{0.7}$O$_{0.3}$)

$CO_2, H_2O$
Costs of Electricity vs Carbon Price for 1. Technologies near commercialization, 2. Advanced Technologies

COE (cost of electricity) for conventional boiler with payment of CO₂ price

COE for technologies with CO₂ capture near commercialization

COE for advanced technologies with CO₂ capture

Adapted from Marion et al., 2004
Legislation is critical for the adoption of CCS: Waxman-Markey bill “American Clean Energy and Security Act of 2009.”

Comparison of Legislative Climate Change Targets in the 110th Congress, 1990-2050
As of December 8, 2008

- reductions of 3% by 2012, 17% by 2020, 42% by 2030, and 83% by 2050 from 2005 levels

For a full discussion of underlying methodology, assumptions and references, please see [http://www.wri.org/usclimatetargets](http://www.wri.org/usclimatetargets). WRI does not endorse any of these bills. This analysis is intended to fairly and accurately compare explicit carbon caps in Congressional climate proposals and uses underlying data that may differ from other analyses. Price caps, circuit breakers and other cost-containment mechanisms contained in some bills may allow emissions to deviate from the pathways depicted in this analysis.
At first, a cap-and-trade system will not be sufficient for deployment of CCS (Herzog, 2009)
Is it technically feasible to meet the goals of 42% reduction proposed in legislation by 2030 and if so how? (EPRI PRISM Analysis, Specter, 2009)
Concluding Comments

- **Coal is not just carbon.**
  - Control of pollutants by provides opportunities for as well as for CO₂ capture.
  - The products of conversion of the minor elements in coal can be the sources of nutrients or be toxic to biomass.

- **Current generation of power plants**
  - Energy generation requires significant quantities of water both for make up in the boiler and for cooling so that power plants are in locations with ready access to water, although they are under increasing pressure to reduce consumption and environmental impacts.
  - Ample quantities of low temperature energy are available if needed.

- **Constraints on carbon emissions**
  - Few new coal-fired plants will be constructed without carbon capture and sequestration.
  - The cap and trade provisions of pending legislation if passed would impose escalating costs on carbon that would not result in significant adoption of CCS until after 2030. CO₂ capture by algal growth would offset the costs of carbon in the absence of CCS.
  - The effluent of CCS plants when these are adopted will provide a different environment for algal growth both in terms of concentration and chemical composition of the effluents.
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