The Future of Coal in a Greenhouse Gas Constrained World

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Abstract
An interdisciplinary group of MIT faculty and research staff have participated in a study to assess the contribution coal can make to the growing world energy demand during a period of increasing concern about global climate change. The study looks out to the year 2050 and assesses technologies and policies we should pursue in the short-term so that we can utilize coal in the longer-term and reduce its associated CO_2 emissions by at least 1 GtC. This paper summarizes the findings from three key components of the study: future coal use, coal conversion technologies, and CO_2 sequestration. The full report will be available over the internet in summer of 2006[2].

Keywords: CO_2, coal, power plants, capture, sequestration

Overview

In 2003, an interdisciplinary group of MIT faculty and research staff issued a report entitled *The Future of Nuclear Power* (available at http://mit.edu/nuclearpower/). That report asked the question: What should we be doing now so that in the year 2050 nuclear power can contribute about 1 gigatonne carbon (GtC) per year to greenhouse gas emissions reductions? This paper describes a follow-on study focused on coal (the final report will be available over the internet in the summer of 2006[2]). About half the interdisciplinary team that worked on the nuclear study is involved in the coal study, while the other half is new, bringing in expertise on coal and CO_2 capture and sequestration (CCS). The coal study asked the question: What should we be doing now so that in the year 2050 coal technology can contribute to reducing greenhouse gas emissions by at least 1 gigatonne carbon (GtC) per year against the business as usual case?

The MIT coal study has several major components. The three components reported on in this paper are:

- ***Future Coal Use.*** Scenarios were run using MIT's Anthropogenic Emissions and Policy Analysis (EPPA) Model. The model looked at a baseline scenario with no policies to limit greenhouse gases. It then looked at various policy scenarios which limited greenhouse gas emissions and encouraged implementation of CCS technologies.
- ***Coal Conversion Technologies.*** Coal-based power generation technologies were analyzed in detail. The focus was on Pulverized Coal (PC) and Integrated Coal Gasification Combined Cycles (IGCC). The feasibility and cost of reducing emissions through efficiency improvements and CCS technologies were analyzed. In addition, the use of coal to produce chemicals and fuels was investigated.
- ***Carbon Dioxide Sequestration.*** An assessment of geologic sequestration of CO_2 was conducted. Topics include the scientific basis for geologic sequestration, potential for leaks, capacity estimates, and measurement, monitoring, and verification needs. In addition, regulatory and liability issues were addressed.

[2] A link will be provided through http://sequestration.mit.edu/bibliography/

It is well known that developing countries must participate in any effort to control worldwide greenhouse gas emissions. Since China and India are major producers and users of coal, MIT teams made several visits to these countries to explore the circumstances which China might constrain its carbon emissions from coal significantly below the currently forecast range. However, due to space limitations, we do not report on that part of the study in this paper.

Future Coal Use

To explore the potential effects of carbon policy, three cases are formulated: a reference or *Business as Usual* (BAU) case with no emissions policy beyond the first Kyoto period, and two cases involving the imposition of a common global price on CO_2 emissions. The two policy cases, a *Low* and a *High CO_2 price* path, with the CO_2 penalty stated in terms of 1997 $US per ton of CO_2. This penalty or emissions price can be thought of as the result of a global cap-and-trade regime, a system of harmonized carbon taxes, or even a combination of price and regulatory measures that combine to impose the marginal penalties on emissions. The *Low CO_2 Price* profile corresponds to the proposal of the National Commission on Energy Policy [1] which we represent by applying its maximum or "safety valve" cap-and-trade price. It involves a penalty that begins in 2010 with $7 per ton CO_2 and increases at a rate of 5% per year thereafter. The *High CO_2 Price* case assumes the imposition of a larger initial charge of $25 ton CO_2 in the year 2015 with a rate of increase of 4% thereafter.

A global picture of coal use under these alternative CO_2 price assumptions is shown in Table 1. Under the *Low CO_2 Price* trajectory coal's contribution to 2050 global emissions is lowered from 34 $GtCO_2$ per year to around 13 $GtCO_2$ per year while total coal consumption falls to 39% of its no-policy level (though still 74% above 2000 coal use). The contribution of CCS is relatively small in this case because at this price trajectory CCS technology does not become economic until around 2035 or 2040, leading to a small market penetration by 2050. The picture differs substantially under assumption of the *High CO_2 Price* pattern. The contribution of coal to 2050 CO_2 emissions is projected to be less than half that under the lower price path, yet coal use falls by only another 9% (and still remains 59% above the 2000 level). The key factor contributing to this result in 2050 can be seen in the third line in the table. With higher CO_2 price levels early in the simulation period CCS has time to take a larger market share.

Table 1 Implications for Global Coal Use of Alternative CO_2 Price Assumptions*.

Indicator	**BAU**		**Low CO_2 Price**	**High CO_2 Price**
	2000	**2050**	**2050**	**2050**
Coal CO_2 emissions ($GtCO_2$/yr)	9	34	13	5
Coal Consumption (EJ/yr)	100	441	174	159
% Coal w/ CCS	0	0	6	66

* Universal, simultaneous participation, limited nuclear & EPPA-Reference Gas Price.

The point to take from Table 1 is that CO_2 mitigation policies at the level tested here will limit the expected growth of coal and associated emissions but not necessarily constrict the industry below today's level. Also, the long-term future for coal use, and the likely achievement in CO_2 emissions abatement, are sensitive to the development and public acceptance of CCS technology and the timely provisions of incentives to its commercial application.

Coal Conversion Technologies
We analyzed the technologies that are either currently commercial or will be commercial in the near term for electricity generation from coal, without and with CO_2 capture. It focuses primarily on the USA, although the analysis is more broadly applicable. Power generation from coal is subject to a large number of variables which impact technology choice, operating efficiency, and cost of electricity (COE) produced. Our approach was to pick a set of conditions in this very broad parameter space at which to compare each of the generating technologies. It is the results of this analysis that we present in this paper. In the full report, we analyzed how changes from this point set of conditions, such as changing coal type, impact the design, operation, and cost of electricity (COE) for each technology.

For our reference power plant, we chose a supercritical pulverized coal (SCPC) power plant operating on Illinois #6 bituminous coal with a net power plant thermal efficiency of 38.5% (Higher Heating Value). For the SCPC, we considered capture via oxyfuel-combustion as well as post-combustion capture with amines. We also considered integrated gasification combined cycle (IGCC) power plants with pre-combustion capture. In analyzing these cases, we relied on published studies [2-8], expert validation (including many of the major vendors), and our own modeling effort. In all cases, we use technology that is available today. However, we did assume n^{th} plant costs (i.e., we ignore the problem-burdened costs that one would expect to find in first-of-a-kind plants).

Table 2 shows the impact of CO_2 capture and compression to 100 atm. in terms of capital cost and power output. The capital investment is the difference in total investment between a power plant with capture and one without, assuming the same coal feed rate in each case. Because capture technologies require parasitic power (see discussion below), adding capture reduces the plant net power output. The impact on capital costs in $/kW is simply a combination of these two terms (capital investment divided by power output). For the post-combustion SCPC case, investment increases 23% while output decreases 24%. Therefore, the impact on capital costs in terms of $/kW is simply 1.23 divided by (1-.24) which equals 1.62 or a 62% increase.

Table 2 Capital Costs for CO_2 Capture and Compression.

Power Plant	**Capture Technology**	**Capital Investment**	**Power Output**	**$/kW**
SCPC	Post-Combustion	+23%	-24%	+62%
SCPC	Oxyfuel-Combustion	+14%	-20%	+42%
IGCC	Pre-Combustion	+7%	-19%	+32%

Reducing the parasitic energy load associated with CO_2 capture and compression will lower capture costs in two ways. In addition to lowering fuel costs, it will also lower the additional capital cost as seen in Table 2. Therefore, understanding the source and magnitude of these energy requirements is essential for lowering costs. In the post-combustion PC case, the biggest energy requirement is steam needed to regenerate the absorbent used to capture CO_2. In our analysis, it is assumed that back-pressure steam is extracted from the steam turbine, which is the most energy efficient source of the steam. If the steam were generated from a stand-alone boiler, its impact on net power output could double. The breakdown for loss of net power output in post-combustion capture from a SCPC is as follows:

- 13% for steam to regenerate sorbent
- 9% for power for compressors
- 2% for power to blow flue gas through CO_2 absorber

In oxyfuel combustion capture, the major parasitic power requirement is for the oxygen production. Note that some of the power losses are mitigated by efficiency gains in the boiler from using oxygen instead of air plus the somewhat speculative assumption that we no longer need flue gas desulfurization (FGD) because the SO_x will be co-sequestered with the CO_2. The breakdown for loss of net power output in oxyfuel-combustion capture from a SCPC is as follows:

- 17% for power for oxygen production
- 9% for power for compressors
- -6% (gain) from boiler efficiency improvements, removal of FGD, other smaller changes

In pre-combustion capture from an IGCC, the losses associated directly with the CO_2 capture and compression systems are greatly reduced. This is due to the high partial pressure of CO_2 in the gas stream, allowing the use of less energy-intensive sorbents (e.g., Selexol in place of amines) for capture. Compression energy is lowered because CO_2 is produced at pressures above atmospheric. However, there is a large energy requirement in producing a high partial pressure CO_2 stream because of the steam needed for shifting $CO + H_2O$ to $CO_2 + H_2$. The breakdown for loss of net power output in pre-combustion capture from an IGCC is as follows:

- 11% for steam for shift plus other smaller process changes
- 6% for power for compressors
- 2% for power for CO_2 capture

Table 3 compares the cost of electricity (COE) for the various cases analyzed. Using a SCPC without capture as the reference, the relative COEs are presented for an IGCC without capture and the three different capture plants. While an IGCC without capture produces more expensive electricity than a SCPC without capture, the ranking is reversed when capture is considered. Furthermore, given today's technology, oxyfuel combustion seems more economical than post-combustion capture. Note that these results are just for a single set of conditions. For example, if a lower-ranked coal was used as the basis, PCs with capture would be more competitive relative to IGCCs with capture. Also note that there is very little commercial operating data to verify the data used in the literature studies and technology will change over time. Therefore, it is premature to say that the rankings presented in Table 3 are robust over the wide range of conditions found around the world. All of these technologies deserve further development. The information presented above helps identify the opportunities and challenges each of these pathways present.

Table 3 Relative Cost of Electricity for Various Plant Designs.

Power Plant	**Capture Technology**	**Without Capture**	**With Capture**
SCPC	Post-Combustion	1	1.61
SCPC	Oxyfuel-Combustion		1.46
IGCC	Pre-Combustion	1.07	1.36

Taking the CO_2 capture and compression costs from Table 3 and combining them with transport and sequestration costs of \$5/tCO_2 yields the mitigation costs shown in Table 4. This table implies that an equivalent carbon price of about \$29/tCO_2 (just over \$100/tC) is needed to make CCS commercially viable for coal-fired power plants using today's technology.

Table 4 Mitigation Costs for CCS*.

Type of Capture Plant	Cost (\$/tCO_2 avoided)
Post-Combustion SCPC	45
Oxyfuel-Combustion SCPC	35
Pre-Combustion IGCC	29

* Assumptions: Base case is Supercritical PC; Uses technology available today; Assumes an nth plant (versus 1st of a kind); Transport/storage cost is \$5/tCO_2

A key finding from this part of the study is: *It is premature to select one coal combustion technology as the preferred route for cost-effective electricity generation combined with CCS. At present, the estimates indicate that, with CCS, IGCC is cheaper than air- or oxygen- driven SCPC, but this conclusion depends upon coal type and could be reversed by future technical advances. Other conversion/combustion technologies should not be ruled out today and deserve R&D at the process development scale.* Furthermore, we recommend that *the federal government should provide assistance for 3 to 5 "first-of-a-kind" coal utilization demonstration plants with carbon capture. The scale of these should be on the order of 250 to 500 MW_e power plants, or the product equivalent.*

While coal to fuels is currently receiving attention, we do not foresee this as a significant use of coal before 2030. We do make the following observations:

- When crude prices are greater than about \$45/bbl and natural gas greater than about \$7.00/MMBtu, the coal conversion to fuel becomes an economic possibility. Without CCS, such synfuels would more than double CO_2 emissions per unit of fuel used because of the additional emissions from the conversion plant. CCS will increase the cost of coal-to-liquid fuels by about 20%. This relatively low additional cost is due to the fact that synthetic fuel plants are designed to use oxygen, operate at high pressure, and separate the CO_2 from the synthesis gas as an integral part of the process.
- For IGCC plants designed to produce electricity, the production of fuels or chemicals (polygeneration) will usually be unattractive for a power producer. However, for synthesis gas plants designed to produce fuels and/or chemicals, power production for internal plant use (almost always) and for the merchant market (sometimes) will be attractive.

Carbon Dioxide Sequestration

Once the CO_2 is captured, it still must be sequestered. We focused on geologic sequestration in this report because it appears to be the most promising large-scale approach for the 2050 timeframe.

Large volumes of CO_2 may be injected underground into depleted oil and gas fields, saline aquifers, and deep (unmineable) coal seams for greenhouse gas storage. Current understanding of science and technology for geological carbon sequestration supports these key conclusions:

- Sequestration can be executed safely
- In time, sequestration could effectively mitigate substantial emissions (>1 GtC/yr) for many years
- Initial demonstration of sequestration, at scale, should be deployed with the highest priority.

Uncertainties do remain about CCS. Many of these uncertainties should be resolved with straightforward investigative programs and an accelerated scientific research agenda addressing the following objectives:

- An accurate estimate of both total CO_2 sequestration capacity and annual injectivity.
- Development of protocols to select sites for injection based on the class or target reservoir.

- Development, demonstration, and test of the appropriate technologies to monitor both injected CO_2 at depth and potential fugitive CO_2 emissions at the surface.
- Enhance current abilities to accurately and quantitatively assess leakage risk.

The priority need is to embark on large-scale injection projects (order of 1 Mt CO_2/year). The large scale is necessary to establish the viability of broad successful deployment of CCS facilities, to ensure that key geological thresholds are reached, and to demonstrate sequestration engineering practice. These projects require a parallel scientific effort aimed at providing insight into the key questions and needs discussed above. The projects should encompass enough key basins, nations, and geological variance to represent adequately the most important injection opportunities. If adequate resources are committed to these projects, the major uncertainties surrounding geologic sequestration should be resolved within 10-15 years.

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