

**Pew Center/NCEP 10-50 Workshop**

**Contributing Paper: CO<sub>2</sub> Capture Economics**

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**I. Introduction**

CO<sub>2</sub> emissions from fossil fuel use are the principal man-made source of greenhouse gas emissions. Since the industrial revolution in the early 1800s, atmospheric CO<sub>2</sub> concentration has increased over 33% and this is accelerating with increasing fossil fuel use.

This analysis of CO<sub>2</sub> capture economics addresses reduction of carbon emissions while continuing to use carbon based fossil fuels. This could become an important option as energy intensity reductions (conservation and increased efficiency) reach their practical economic limits, and until it becomes economic to use renewables (wind, solar, nuclear) to satisfy most of our energy needs.

The economics of CO<sub>2</sub> capture, transportation and geologic storage favor utilization of very large “point sources” of man-made CO<sub>2</sub> emissions. Consequently this option is most appropriate for fossil fuel based power generation, especially coal-based power plants due to their traditional large sizes and very high CO<sub>2</sub> emissions per MWh of net power generated

**II. CO<sub>2</sub> Capture Options and Basic Issues**

There are only 3 general types of CO<sub>2</sub> capture technology:

1. Post-combustion
2. Oxygen-combustion
3. Pre-combustion

**Post-combustion** capture involves scrubbing CO<sub>2</sub> out of flue gas after the fossil fuel is combusted. This flue gas is usually at atmospheric pressure with a low concentration (5-15%) of CO<sub>2</sub> due to all the nitrogen in the air used for combustion. There are also small amounts of excess oxygen and sometimes of sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>). These factors increase the cost and energy requirements of post-combustion CO<sub>2</sub> capture. CO<sub>2</sub> capture at these low CO<sub>2</sub> concentrations and system pressure thereby very low CO<sub>2</sub> “partial pressure” (defined as concentration times system pressure) usually involves reversible chemical reactions which require heat in order to regenerate and recycle the chemicals used to capture the CO<sub>2</sub>, known as absorbents. The most common technology for capture uses a chemical amine solution to absorb the CO<sub>2</sub>, the CO<sub>2</sub> subsequently being released from the solution by heating it. The large size of the post-combustion absorbers, large absorbent circulation rates and especially the high regeneration heat requirement result in high costs for post-combustion CO<sub>2</sub> capture. This option is generally considered for existing boiler systems, especially when the flue gas is low in SO<sub>2</sub>

and NO<sub>x</sub> due to clean natural gas being used for combustion, or for flue gas from coal boilers that already have FGD (flue gas desulphurization) and SCR (selective catalytic reduction) systems that remove these gases. The large steam requirements of the amine stripper plus the power requirements of the CO<sub>2</sub> compressor (needed to deliver the CO<sub>2</sub> to pipelines) lead to a significant drop in net capacity and efficiency. This loss in net capacity and efficiency is usually in the range of 25-30% relative to the same combustion system without CO<sub>2</sub> capture. Furthermore, post-combustion CO<sub>2</sub> capture has only been demonstrated at a relatively small scale.

**Oxygen-combustion** involves using pure oxygen in place of air for combustion thereby producing a flue gas of mostly CO<sub>2</sub> and water vapor and resulting in higher concentrations of CO<sub>2</sub> but usually at low pressure. The oxygen is obtained by separating it from air prior to using it to burn the fuel. Retrofitting existing boilers for oxygen-combustion usually requires recycling some flue gas CO<sub>2</sub> to the combustion chamber in order to control the high temperatures characteristic of oxygen combustion. Some new advanced systems try to control the high oxygen-combustion temperature with water injection in place of recycling CO<sub>2</sub>. The high capital costs and large power requirements of air separation to make oxygen are the key contributor to the high cost of this approach. This option is generally considered for existing coal boilers which do not have any SO<sub>2</sub> and NO<sub>x</sub> control, in the hope that these pollutants can be captured and disposed of with the CO<sub>2</sub>. However, physical properties of gaseous SO<sub>2</sub> and NO<sub>x</sub> with supercritical (liquid-like) CO<sub>2</sub> at high pressure may require their removal from the CO<sub>2</sub> to avoid two-phase flow (liquid and gas mixture) that would make pumping and pipeline transportation more difficult. The large power requirements for oxygen production plus that of the CO<sub>2</sub> compressor power leads to a significant drop in net capacity and efficiency. This loss in net capacity and efficiency is usually in the range of 25-30% relative to the same combustion system without CO<sub>2</sub> capture. Furthermore, oxygen combustion for CO<sub>2</sub> capture as only been tested at very small-scale pilot plants.

**Pre-combustion** capture involves converting a fossil fuel into hydrogen (H<sub>2</sub>) and CO<sub>2</sub> usually via gasification. Electricity is then generated by combusting hydrogen in a gas turbine and further efficiencies are gained by using waste heat to power a steam turbine. Oxygen is generally used for combustion in gasification systems, but compared to oxygen-combustion of pulverized coal, gasification requires significantly less oxygen per unit of fuel feedstock or net power output. Furthermore, when CO<sub>2</sub> is captured via pre-combustion, the CO<sub>2</sub> is at very high partial pressure (high system pressures times the high concentrations). These are critical issues because they greatly reduce the capital costs of the CO<sub>2</sub> absorber, the rate of absorbent circulation, and especially the energy requirements for absorbent regeneration. In fact, processes that use physical solvents rather than chemical absorbents become effective at the high CO<sub>2</sub> partial pressures of gasification. This enables CO<sub>2</sub> recovery in a dry condition, at moderate pressure and little or no use of steam, significantly reducing the CO<sub>2</sub> compressor capital and power requirements, and resulting in a noticeably smaller loss of net capacity and efficiency than post-combustion and oxygen-combustion. An added advantage of pre-combustion CO<sub>2</sub> capture is that it involves production of hydrogen giving it strategic flexibility for future energy trends such as fuel cells and potentially the “hydrogen economy”. The key issues impeding deployment of pre-combustion CO<sub>2</sub> capture is that gasification is a complex chemical process in comparison to more familiar, mechanical, steam boiler technologies; and it can be both more expensive and less

reliable than traditional steam boiler power plants. Although gasification of fossil fuels to H<sub>2</sub> with CO<sub>2</sub> capture is commercially used throughout the ammonia and oil industries, it is foreign to the power industry, which is also a factor leading to electric utility skepticism and hesitancy.

### III. Present Economics of CO<sub>2</sub> Capture in Electric Power Generation

The most important issue when considering CO<sub>2</sub> capture as an option in electric power generation is the increase in price of electricity associated with the cost of CO<sub>2</sub> capture. Calculating an increase requires that a baseline cost of traditional fossil fuel power generation without CO<sub>2</sub> capture be established. Furthermore, retrofits of existing fossil power plants will usually have a loss in net power output unless additional fuel is consumed to meet the energy demands of CO<sub>2</sub> capture and compression.

For new power plants, the most appropriate baseline is the cost of electricity from new state-of-the-art NGCC (natural gas combined cycle) plants which have CO<sub>2</sub> emissions of about 0.34 metric ton CO<sub>2</sub> per MWh. For existing power plants, a typical 20-25 year-old pulverized coal (PC) unit is used to establish baseline costs as this type of unit is responsible for most of the U.S. power industry's CO<sub>2</sub> emissions and almost 10% of global man-made CO<sub>2</sub> emissions. Since these old PC units have amortized (paid-off) most of their original capital costs, the costs of electric power (\$/MWh) are low, in the range of only \$10-20/MWh or 1-2 cents per kWh. Old PC units have relatively low thermal efficiency which, together with the fact that coal has a higher carbon content per unit of energy than natural gas, results in emissions of about 0.91 metric tons CO<sub>2</sub> per MWh.

Table 1 summarizes the costs of electric power for natural gas and coal with and without CO<sub>2</sub> capture for new power plants. Electric power costs increase from about \$43/MWh with no CO<sub>2</sub> control to \$61-79/MWh with control depending on the option. These power costs are at the power plants gate and do not include additional power transmission and distribution costs. The costs of CO<sub>2</sub> avoidance range from \$67-190/ton CO<sub>2</sub>. CO<sub>2</sub> avoidance cost (in \$/ton) is defined as the increase in electricity cost (in \$/MWh) between a base case and a specific CO<sub>2</sub> capture option, divided by the reduction in CO<sub>2</sub> emitted to the atmosphere (in tons CO<sub>2</sub>/MWh) for the same two cases.

**Table 1. Costs of Carbon Capture compared to Base Cases**

Type of Plant	Capital cost \$/kW	Electricity Cost \$/MWh	Difference \$/kW	Difference \$/MWh
NGCC: no CO <sub>2</sub> control	506	42.8		
NGCC: with control	<i>1,057</i>	<i>66.0</i>	551	23.1
CGCC: no CO <sub>2</sub> control	1,376	45.5		
CGCC with CO <sub>2</sub> control	<i>1,807</i>	<i>61.4</i>	431	15.9
New PC: no CO <sub>2</sub> control	1,276	42.8		
New PC: with CO <sub>2</sub> control	<i>2,351</i>	<i>78.7</i>	1,075	36.0

Note: Costs shown in italics are costs with CO<sub>2</sub> control. Assumptions: Coal price is \$1.00 per MM Btu HHV; Gas price is \$4.30 per MM Btu HHV; plants operate at 80% annual load and capital cost amortization is 15% /yr.

Table 2 compares the costs of electric power from existing mostly paid-off coal fired power plants to the costs of electric power under various CO<sub>2</sub> reduction options. The electric power costs increase from about \$17/MWh to \$58-65/MWh depending on the CO<sub>2</sub> reduction options. The costs of CO<sub>2</sub> avoidance ranged for \$55-165/ton CO<sub>2</sub>.

**Table 2. Costs compared to old PC plants**

Type of Plant	Capital Cost \$/kW	Electricity Cost \$/MWh
Base Case: old PC	102	17.7
NGCC with control	1,151	65.3
CGCC with control	1,687	58.4
PC retrofit (O <sub>2</sub> firing)	1,119	58.9
PC (scrubbers)	1,101	66.7

Note: Capital costs shown in Table 2 differ from those shown in Table 1 because parts of the existing facilities can be reused in the retrofit.

#### **IV. Challenges to Adoption of Carbon Capture Technologies**

There are 3 basic barriers to CO<sub>2</sub> capture in fossil-fuel based electric power generation:

1. The high costs of capital and electricity, especially relative to continued life extension of our large fleet of cheap paid-off existing coal-fired power plants.
2. Government policies which continue to provide economic incentives to continued life extension of old existing coal-fired power plants
3. The need for successful full-scale regional demonstrations to convince the power industry that massive amounts of CO<sub>2</sub> can be effectively captured and geologically stored for hundreds of years at sites near power plants.

Currently the large fleet of old coal-fired power plants represents about 40% of the entire United States and 10% of worldwide man-made CO<sub>2</sub> emissions. The average age of this 300,000 MW of existing coal capacity is 31 years (MW weighted). Thus there is a large opportunity for CO<sub>2</sub> capture and reductions as this old capacity is replaced.

Recent changes in the Clean Air Act (CCT) and specifically the New Source Reviews (NSR) makes it easier to refurbish existing coal-fired power plants without emission reductions for another 8-10 years. This economically encourages continued life extensions of the over 300,000 MW of old and relatively inefficient coal-fired power plants.

Over the next 10 years, EIA projects power generation CO<sub>2</sub> emissions will significantly increase mostly due to increased use of the existing coal power plant capacity. Government policy changes would be required to discourage this. Economic analysis shows a carbon tax would have little impact because the existing paid-off coal-powered plants have such low costs that it would be cheaper to pay the tax than build replacement plants with low CO<sub>2</sub> emissions.

Over the next 10 years, the best opportunity for advancing CO<sub>2</sub> capture is to support and encourage a number of regional, large-scale, CO<sub>2</sub> capture and storage demonstrations at fossil-

fuel power plants. Demonstrations involving retrofits of natural gas plants or coal gasification repowering (i.e. on-site replacement of pulverized coal combustion plants with gasification systems) of existing very old coal plants are likely to be the best options. These approaches avoid the large capacity and efficiency losses that attend retrofits using flue gas CO<sub>2</sub> scrubbers or oxygen-combustion. If a carbon-constrained world develops, natural gas prices are likely to increase. Therefore, coal gasification repowering is likely to prove the more important option.

Coal gasification demonstration with CO<sub>2</sub> capture will also help the traditional coal-based utilities get over their fears and concerns about gasification. Specifically they must realize gasification is a complex chemical process, requiring chemical and oil industry skills to be successful, and they must have opportunities to become acquainted with these processes and skills. There are currently over 20 commercial gasification plants, which make ammonia and pure hydrogen and capture CO<sub>2</sub>. Furthermore, General Electric gas turbines have over 450,000 hours of successful operating experience using hydrogen-rich fuel gas. The only issue should be costs, which can be addressed through experience. Electric utility experience, albeit with a much simpler chemical process (flue gas desulfurization), has demonstrated significant cost reductions and improved reliability over the last 20 years through “learning by doing”.

The 20-30 year time frame will be the critical period for CO<sub>2</sub> capture. In this time frame most of the large fleet of existing coal power plants in the United States will need to be replaced. Therefore, it is essential that CO<sub>2</sub> capture and storage technologies have been fully and successfully proven before these replacements begin. The additional cost and performance improvements associated with advancing technologies and “learning by doing” in the demonstrated plant over the next 10-20 years will be critical to achieving this goal.

Our ability to accurately predict technological change 50 years out is terrible. Nevertheless, there are several important technical and economic issues to consider relative to CO<sub>2</sub> capture. Existing coal fired power plants are the largest source of CO<sub>2</sub> emissions and are key large “point sources” for effective large scale CO<sub>2</sub> capture. Furthermore, the large reserves and low cost of coal will likely assure its continued use 50 years from now. The two dominant consuming countries of coal will likely remain the United States and China. China’s massive growth in coal-based electric power generation is generally following that of the United States but it is about 20-30 years behind. This means that 50 years from now China will have a massive fleet of old paid-off coal fired power plants that will need to be replaced. The United States has the opportunity during the next 10-30 years to develop and demonstrate the best technical and economic options for CO<sub>2</sub> capture from coal-based power plants both for U.S. needs in the 20-30 year time-frame and for China’s needs in the 50 year time-frame.