Viability of Carbon Capture and Sequestration in Existing Coal-Fired Power Plants in the United States

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President-elect Barack Obama has proposed a cap-and-trade system to constrain carbon dioxide emissions. This policy will heavily impact the coal-fired power plant industry, emits 1.9 billion tons of carbon dioxide per year, accounting for 40% of the country’s carbon emissions, according to the EIA. Faced with the specter of paying a price for carbon, the coal industry will have to weigh various approaches for this new cost, choosing to absorb it in part or entirely or implementing measures to mitigate its carbon emissions.

Efforts to mitigate carbon emissions could be facilitated by new technologies. One such technology—viewed by many as a potential saving grace of the coal industry—is designed for carbon capture and sequestration (CCS). CCS technology allows for carbon emissions from coal-fired power plants to be captured, transported and stored in the ground. CCS could be applied to new coal plants or to existing ones, which can be retrofitted with new technologies. The technology has been demonstrated on small-scale plants, but the costs of implementing it in coal-fired power plants remain uneconomical. For this reason, CCS is not in use in the United States and has never been applied to a coal-fired power plant.

With cap-and-trade seemingly on the horizon in the United States, CCS technology could potentially become more economically viable. This paper will consider the viability of CCS in a carbon-constrained nation. We will first explain the technology behind CCS, showing its viability for the mitigation of carbon emissions and assessing the geographic potential for this technology in various states. Next, we will assess the economic viability of CCS for existing coal-fired power plants, laying out the significant costs involved with implementing this technology, with an emphasis on location and sequestration scenarios. We will run a base-case scenario to pinpoint how high the price on carbon must be in order to make implementing CCS technology economical for the coal industry. We also analyze existing and anticipated CCS projects to assess hurdles for the implementation of new projects. Finally, we will explore the political viability of a clean coal strategy in the United States.
TECHNOLOGICAL VIABILITY

To understand the economic costs of implementing CCS technology, it’s necessary to first understand the various mechanisms involved with the process of CCS in coal-fired power plants. The following analysis will focus on the technological viability of capture and sequestration as an industrial strategy for curbing carbon dioxide emissions in coal plants.

Background: The technology of U.S. coal-plants

The cost to capture CO₂ can vary dramatically based on the type of coal-fired power plant fitted with CO₂ capture technology. Either an existing coal-fired power plant or a new IGCC power plant can be retrofitted with CO₂ capture technology. The four primary PC combustion technologies include subcritical, supercritical, ultra-supercritical and circulating fluid-bed (CFB) combustion. Of the over 1,000 boilers in the US about 100 are supercritical, and the remainder is predominately subcritical [MIT]. These technologies vary in cost based on their performance. Supercritical and ultra-supercritical are designed to operate at a higher steam temperature and pressure than subcritical and CFB combustion technology to burn fuel. Thus, supercritical and ultra-supercritical have higher capital costs. But because subcritical needs to burn more fuel than the other technologies, fuel costs are the highest for subcritical.

Integrated gasification combined cycle (IGCC) is another alternative to producing electricity from coal. IGCC technology produces electricity by first gasifying coal to produce syngas, a mixture of hydrogen and carbon monoxide, which is then burned in a gas turbine. While IGCC is more expensive than any of the other four technologies, the key long-term benefit of IGCC is its ability to sequester CO₂ at a more economical price than PC combustion technology, a technology that does not have CO₂ capture capability.

Background: The Greenhouse Effect

The greenhouse effect has operated naturally for billions of years. Atmospheric constituents known as greenhouse gases intercept outgoing infrared radiation and dissipate it as heat. In this way, the atmosphere acts as a sort of blanket, retaining energy as heat to increase Earth’s surface temperature. The average temperature of Earth’s surface is around 15°C, but without the greenhouse effect it would be around -18°C. Over the past decade, a phenomenon sometimes referred to as global warming, or the enhanced greenhouse effect, has sparked international concern as the predominant environmental threat facing future generations. An enhanced greenhouse effect has been attributed to increasing concentrations of trace gases in air since the Industrial Revolution, resulting in a bigger conversation of thermal infrared light to heat, and a rising global
Carbon dioxide is a major greenhouse gas because it can absorb infrared light. A molecule absorbs light when the frequency of that light corresponds to the frequency of internal motion within the molecule. For infrared frequencies, this means the internal vibrations of the atoms of this molecule. In order for a molecule to absorb infrared light, there must be an internal shift in position of the molecules center of negative charge and center of positive charge, i.e., the molecule must possess a “dipole moment.” Symmetric molecules like nitrogen dioxide and oxygen, which make up most of the Earth’s atmosphere, do not possess dipole moments and thus do not absorb IR light. Carbon dioxide, however, can absorb IR light because it possesses a bending vibration, as well as an asymmetric stretch.

Carbon emissions from coal-fired power plants

Coal’s widespread use and long-lasting reserves mean the coal industry is a key source of American energy. But coal’s high rate of carbon emissions means this industry would be hit hard by government attempts to constrain carbon in a cap-and-trade system.

Coal is currently the world’s main fossil fuel reserve. Relative to petroleum and natural gas, coal is inexpensive to mine, transport, and is available in abundance in many regions of the world, including developing countries. As a result, the world’s 2100 coal-fired power plants are collectively responsible for approximately one-third of anthropogenic CO₂ emissions. At the current rate of consumption, coal reserves are estimated to last another 200 years. Since coal reserves will likely outlast oil and natural gas, there exists the potential for industry to fall back on coal as the main energy source of the coming century.

But relative to other fossil fuels, coal produces more CO₂ per unit of energy produced:

(coal) \[ C + O₂ \rightarrow CO₂ \]

(oil) \[ CH₂ + 1.5O₂ \rightarrow CO₂ \]

(natural gas) \[ CH₄ + 2O₂ \rightarrow CO₂ + 2H₂O \]

In the carbon-constrained world produced by a cap-and-trade policy, CCS has been touted as a potential avenue for coal plants to reduce their carbon emissions. We will now look at the science behind CCS, analyzing whether it is a technologically viable solution to the problem of carbon emissions from coal-fired power plants. Understanding the science behind CCS has ramifications for our subsequent analysis of the economic viability of this technology.
The graph above shows the amount of carbon dioxide emissions from coal-fired power plants in the US by state. As shown in the graph, carbon dioxide emissions are largely concentrated in the mid west and in Texas. This corresponds well with the location of coal regions in the US. Please see Appendix 1 for location of coal-rich regions.

*The Science of Carbon Capture and Sequestration: Practical Aspects*

There are three technological challenges in the CCS process: separation of CO$_2$ from other gases, transport to a storage location, and sequestration. Carbon capture refers to the chemical removal of exhaust gases from major point sources, like coal-fired power plants, that would otherwise release it into the atmosphere. Capture and concentration of CO$_2$ is the most energy-intensive portion of the CCS process, requiring between one-third to one-half of the total output of the power plant to which the technology is connected. The equipment required to capture CO$_2$ is also very large, as a vast amount of air is involved in the process. As a result, capture accounts for approximately three-quarters of the cost of the CCS process, and most research and development in this area goes into finding ways to make carbon capture less energy intensive, and thus less expensive.

Currently there are three main forms of carbon capture, as well as other types undergoing research and development to become more cost effective. The three main types of carbon capture technology are called post-combustion, precombustion, and oxy-fuel combustion.

*Post-Combustion Capture*

The main advantage of post-combustion capture is its implementation through retrofitting existing
coal-fired power plants. Inside the power plant, coal is burned to generate heat, which turns into steam. This steam turns a turbine, producing electricity. The steps involved to convert the energy from heat to mechanical motion of the turbine encompass the process of combustion. When the coal is burned, CO₂ gas is produced, along with other flue gases, like H₂O, SO₂, NO₂, and, depending on the grade of the coal used, other trace gases. Post-combustion refers to separating the CO₂ gas from these flue gases after the combustion process. This process has been used in the past as a way to capture CO₂ for enhanced oil recovery, and is usually accomplished by passing the flue gases through an appropriate CO₂-absorbing solvent. The solvent is later heated, releasing steam and leaving behind concentration CO₂. These plants release flue gases through chimneys or smokestacks, and a solvent filter can be installed to capture the CO₂ as it leaves through these openings.

**Precombustion Capture**

Precombustion capture is less energy intensive than post-combustion, but it is not a retrofit for older power plant generators. In precombustion capture, coal is burned in pure oxygen, producing a flue gas mixture composed of mostly CO and H₂. This mixture is then treated with steam in a catalytic converter. Catalytic converters function to reduce pollutants to less harmful chemical species before leaving the system. In a coal-fired power plant, catalytic converters work to reduce CO₂, volatile organic compounds, and nitrous oxides. Inside a catalytic converter, there are two types of catalysts, or substances that cause a chemical reaction to accelerate without being changed by that reaction. Good converters expose a large amount of surface area to flue gases, while minimizing the amount of catalyst required. Inside the converter, the reduction catalyst reduces nitrous oxides to pure nitrogen and oxygen gases while the oxidation catalyst causes leftover hydrocarbons and carbon monoxide to be oxidized to CO₂. After leaving the converter, the mixture is mostly H₂ and CO₂, and after being passed through a CO₂ absorbing solvent, the mixture is heated and a concentrated stream of CO₂ is released.

**Oxy-Fuel Combustion**

Oxy-fuel combustion is a highly energy-intensive process. This process eliminated the separation step by fired coal in pure oxygen, producing pure CO₂ as a byproduct of combustion. Since air is only 19% oxygen by volume, the other gases must first be separated. If this process were to be implemented, power plants would have to be redesigned to use pure oxygen, as the combustion from pure O₂ produces a 3500°C flame, which is too hot for most power plant materials.
Current Research and Development

Research is ongoing to make CCS technology more efficient, in hopes of driving down costs. Several areas of research have potential for making this technology more viable.

Current capture research centers on making the process of trapping carbon dioxide and separating it from flue gases less energy-intensive, and thus less expensive. Chemical adsorption, or separating CO₂ by passing it through a solvent like an amine, can be improved by developing solvents that bind to carbon dioxide efficiently, absorbing a large amount of the gas, but require less heat to release carbon dioxide in the final separation step. Current commonly used solvents are monoethanolamine and diethanolamine. These solvents separate up to 95% of carbon dioxide from the flue gas mixture, and can be reused afterward.

Membrane separation involves separating carbon dioxide from flue gases by passing them through polymeric membranes. This type of separation technique has been used in the oil industry for over a decade, but more efficient and inexpensive membranes need be developed if it is to be implemented in coal-fired power plants.

Physical adsorption refers to separation by using certain solids, like zeolites and activated carbon, as molecular sieves to take CO₂ out of the flue gas stream. These solids have porous surfaces with holes less than 2 nanometers in diameter, allowing them to trap CO₂ and release it upon heating.

Cryogenic separation is a method of separation that exploits the fact that carbon dioxide has a higher condensation temperature than nitrogen or oxygen in the flue gas stream. As such, it can be isolated as a liquid by condensation at a low temperature and high pressure. The energy required for cryogenic separation is approximately double that of chemical adsorption.

Technology for Transporting Carbon Dioxide

It is neither efficient nor economical to transport CO₂ as an uncompressed gas, and so after the separation step of CCS, it must be converted into its supercritical liquid form for transport via pipeline. At a temperature and pressure at or beyond the critical point, CO₂ exists as a supercritical fluid, with properties between those of a gas and a liquid. CO₂ has a critical pressure of 72.9 atm and 31.3°C. Energy is required for this phase conversion, but afterward CO₂ can efficiently travel through pipeline via an air compressor.

Sequestration

After capture, CO₂ must be sequestered, or stored in a stable place for as long as it will not
compromise the goal of reducing global warming. The two main types of possible sequestration sites for CO₂ are deep ocean storage and storage in deep geological formations.

**Ocean Storage**

Carbon dioxide could plausibly be injected into the ocean as little as 200-400 meters deep. The ocean’s mixing cycles and gravity would push the injected CO₂ to lower depths, allowing it to be stored for centuries before returning to the atmosphere. If injected lower than 500 meters deep, water pressure would compress CO₂ into a liquid with a density higher than water, and it would further sink. Near the ocean floor, CO₂ would eventually react with calcium carbonate, present from sediments in seashells and other pteropods. This form of ocean storage is often labeled *ocean acidic*. In an alternate scenario, the CO₂ could first be reacted with calcium silicate, a plentiful, inexpensive mineral. The aqueous calcium bicarbonate could then be drained into ocean depths. This form of ocean storage renders CO₂ chemically inert, trapped in the bicarbonate form, and could result in thousands of years of storage. This type of ocean storage is often labeled *ocean neutral*.

**Geological Storage**

The most promising sites for geological storage of CO₂ are oil and gas bearing formations, saline aquifers, and deep coal seams. Depleted oil and gas reservoirs can be used to store CO₂ deep underground. These reservoirs are thought to be stable because they have held oil and natural gas for millions of years. Oil and gas beds should be able to hold CO₂ underground for thousands of years. Saline aquifers are deep underground formations of porous rocks saturated with salt water. Injected CO₂ molecules would eventually dissolve into brine that occupies the porous spaces. Carbon dioxide may also be injected into coal seams that lie too far underground to be mined.

**Environmental Risks Associated with Sequestration**

Long-term storage of carbon dioxide in geological formations or the deep ocean beds poses a number of risks to the area surrounding the injection site. Deep ocean storage raises concern among the environmental community because of ocean acidification, a threat to the structural integrity of coral reefs, as well as local fauna. Ocean neutral storage should eliminate the potential for ocean acidification as the carbon dioxide should complex with other chemical species on the ocean bed, rendering it immobile. If molecules of carbon dioxide were to diffuse freely, however, the excess would disrupt the ocean’s natural buffering system. As more carbon dioxide is added to ocean water, it depletes bicarbonate and releases protons. This causes the pH of the water to drop, as well as degradation of carbonate-containing organisms. The main
threat geological storage poses is carbon dioxide leakage, which would compromise the efficacy of CCS as a global-warming mitigation technology, as well as threaten surrounding ecosystems. Among proponents of CCS, leakage is generally considered to be a small risk, as geological formations like empty oil and coal reservoirs held their previous contents for many millennia. Carbon dioxide is also nonflammable and nontoxic, so it poses little threat as an explosive or biohazard. As detailed above, the longer carbon dioxide remains in these formations, the more it becomes immobilized by various trapping mechanisms that allow for long-term storage over thousands of years.

Overall, the technological options assessed above are capable of removing the majority of carbon dioxide from the exhaust gases emitted by coal-fired power plants. While these options are technologically viable, their use in industry depends on whether or not the process of carbon capture can be cost effective. The following section investigates the potential for CCS technologies to be economically viable in American coal-fired power plants.

**ECONOMIC VIABILITY**

In this section, we will analyze the economic viability of carbon capture sequestration for existing coal-fired power plants in the United States. Since more than 50% of the electricity produced in the US comes from the current fleet of coal-fired power plants in the United States it is important to determine how the economics of these plants will be effected in a carbon constrained world. To do this, we will first determine the cost for such a plant to capture, transport and sequester carbon. Next we will select a base case scenario. Finally, we will run sensitivity analysis to ascertain how high the price of carbon would have to be in order for CCS to be economically viable.

*Cost to Capture Carbon Dioxide and Efficiency Penalty*

The cost to install equipment at an existing coal-fired power plant varies based on the plant's characteristics and design, including its age, size and efficiency. Generally, an older coal-fired power plant will have less sophisticated equipment than a coal-fired power plant that is more new. Thus, more capital costs are required to retrofit an older plant. As more equipment is added to a plant to capture carbon dioxide the more electricity is needed to operate the additional equipment. This results in more coal being burned than would have otherwise occurred and additional capital expenditures on equipment to ensure the same net electricity output. Furthermore, since coal-fired power plants have different performance characteristics, heat rates percentage changes as well as the amount of additional capital expenditures will vary depending on whether carbon dioxide is captured or not. As heat rates change, this will affect the amount of additional fuel consumed to capture carbon dioxide.
Cost to Transport Carbon Dioxide

Historically, coal-fired power plants have been located as close to coal regions as possible to reduce the costs of transporting coal. Please see appendix 1 for a map of coal regions within the United States. With the potential to sequester carbon dioxide, it is important to determine if existing coal-fired power plants are located near suitable sequestration sites.

The cost of transporting carbon dioxide includes labor, materials, right of way and miscellaneous charges for building a carbon dioxide transportation network. Costs are incurred during construction to set up a transportation network and during operations to inspect and monitor the pipeline. The cost to transport carbon dioxide is a function of the mode of transport, distance and quantity transported. Generally, carbon dioxide transportation costs are minimized when an existing carbon dioxide pipeline is used, a CCS plant is built close to a sequestration site, and carbon dioxide is transported in large quantities on the order of 10 million tonnes of carbon dioxide per year.

While carbon dioxide can be transported in limited quantities via truck, rail, and ship, moving enormous quantities of carbon dioxide over large distances requires an interstate pipeline network. Pipelines can sustain a large amount of carbon dioxide and pipelines are currently the most common method for transporting large quantities of carbon dioxide over long distances. Furthermore, for purposes of this paper we assume transport will occur onshore because offshore pipelines are twice as expensive as onshore pipelines [McKinsey].

Carbon dioxide can be transported using a point-to-point configuration either directly to a sequestration site or to an existing carbon dioxide pipeline transportation network. Altogether, approximately 5,800 kilometers (3,600 miles) of carbon dioxide pipeline operate mostly for enhanced oil recovery (EOR) today in the US (U.S. Dept. of Transportation). Please see Appendix 2 for a chart of existing major carbon dioxide pipelines in the United States. A point-to-point configuration is more costly than a hub and spoke system, a system that will begin to take more shape in about 20 years once more CCS plants are built in the US [McKinsey].

For a typical 500 MW power plant (emissions of approximately 2–3 million tonnes per year), transport cost could range from $0.15/ton for a 10 km pipeline to $4.06/ton for a 200 km pipeline based on a 100% capacity factor [McCoy and Rubin]. Carbon dioxide transportation costs are also highly non-linear for the amount transported. An MIT study found that transporting carbon dioxide across 100km can range from
approximately $0.50/ton to $2/ton for a mass flow rate of approximately 20 million tonnes of carbon per year to 1 million tonnes of carbon dioxide per year, respectively [MIT, p. 75].

Cost to Sequester Carbon Dioxide

In the technology portion of our paper we explored the location of carbon dioxide emissions from existing coal-fired power plant. We now would like to know if the emissions from existing coal-fired power plants could be sequestered within or near the states in question.

As mentioned previously, carbon dioxide can be sequestered using saline formations, oil and gas fields or unmineable coalfields. Sequestration options are abundant in most states. As shown in the Exhibit 1, saline aquifers offer many carbon dioxide sequestration possibilities for the states that emit the most carbon dioxide from coal-fired power plants. However, in some states—including Minnesota, Wisconsin and Nevada—coal-fired power plants would need to transport carbon dioxide emissions across state boundaries because of limited carbon dioxide storage potential.

Exhibit 1. Billion tons of potential carbon dioxide storage in saline aquifers and total potential [NETL]

The major costs of sequestering carbon dioxide include the upfront costs of site selection and drilling wells as well as the costs to monitor the sequestration site. The cost to sequester carbon dioxide will vary based on the type and size of the storage site. Additional revenue streams for production of oil or gas may also offset the cost of storage by injecting carbon dioxide into the ground.

In addition to the three different types of sequestration sites, a selected storage reservoir can vary based on characteristics such as depth, permeability, net thickness and pressure. A deep saline aquifer is generally more expensive than a saline aquifer closer to the surface and vice versa because of a reduction in drilling costs and site inspection costs.

Bock et al. estimates the low and high costs for saline and depleted oil/gases fields to be $0.4-4.5 (700-1,800m depth) and $0.5-12.2 per ton of carbon dioxide, respectively [Bock et al.]. McKinsey estimates
a base case for saline and depleted oil/gases fields to be €5 and €4 per ton of carbon dioxide, respectively, with 20% going to annual O&M costs. McKinsey uses a higher base case for saline formations because of the additional costs needed to explore and map areas where more geological data is needed to determine the site’s sequestration viability [McKinsey].

The size of a sequestration site plays an important factor in determining the economic viability of a CCS plant. The larger the sequestration site, the more costs can be distributed over larger carbon dioxide quantities. As more and more CCS plants come on line, economies of scale will drive down the costs.

EOR can also affect the economics of a CCS plant. According to the US DOE, $25-35 per ton of carbon dioxide is possible at locations. Moreover, the size of this market in the US is on the order of 7,500 million tons between now and 2030 [DOE], which means that roughly 125 500 MW coal-fired power plants that emit 3 million tons of carbon dioxide per year can benefit from EOR between now and 2030.

Base Case Scenario Assumptions

Before determining how a coal-fired power plant’s distance to a sequestration site affects its economic viability, we would first like to establish a base case with the following set of assumptions from authoritative sources and recent events that will remain constant in our analysis. For some of the variables below we selected the location Mattoon, Illinois, the site of the postponed FutureGen project, as our base case. A detailed analysis of the cost to capture, transport and sequester carbon dioxide is also included below. See Appendix 3 for an explanation behind our base case assumptions.

As a base case, we also assume a supercritical coal-fired power plant will be retrofitted with carbon capture technology. Even though there are less supercritical coal-fired power plants in the United States than subcritical coal-fired power plants, we believe that the economic cost to capture carbon dioxide is far more attractive for a supercritical power plant that already runs more efficiently than a subcritical coal-fired power plant. Furthermore, while IGCC is the most economical plant to retrofit CCS technology, we believe there are far less opportunities to retrofit an IGCC plant in the United States than another existing coal-fired power plant.

We assume that the total capital cost to capture carbon dioxide is $900 million ($22.95/MWh), additional levelized fuel costs from an efficiency penalty is $9.14/MWh and additional O&M levelized costs from capital are $11.74/MWh.
For transportation costs, we assume approximately 3 million tons of carbon dioxide will be transported a few miles to a sequestration site at 100% capacity. Based on the analysis above, we assume the capital cost required to transport carbon dioxide is $40 million. We also assume O&M transportation costs are approximately 1% of capital cost [McKinsey].

For sequestering carbon dioxide we use FutureGen's proposed sequestration site, Mt. Simon Sandstone, as our base case. Mt. Simon Sandstone is a regional deep saline formation with thicknesses up to 2,000 feet and a base estimated to be 8,350 feet deep. With these characteristics, we assume a base case of $200 million in capital costs to sequester carbon dioxide, with O&M costs of roughly 20%.

**Base Case Scenario Results**

We determine that a carbon dioxide price of $43/ton would need to be established in the marketplace in 2013 for a supercritical coal-fired power plant to consider retrofitting its plant with CCS technology. At this price the net present value achieved is equal to zero. If $43/ton becomes a reality, this would result in an annual payment borne by ratepayers of approximately $142 million beginning in 2013 and increasing annually at US inflation.

**Sensitivity Analysis for Capturing Carbon Dioxide**

As noted above, existing coal-fired power plants have different characteristics such as age and technology. Thus, the cost of capturing carbon dioxide can be significantly different between existing coal-fired power plants. We assume a cost range for capital cost and O&M cost determined by MIT in the table below.

<table>
<thead>
<tr>
<th></th>
<th>Subcritical</th>
<th>Supercritical</th>
<th>Ultra-supercritical</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost ($/MWh)</td>
<td>21.2 - 32.5</td>
<td>17.6 - 26.6</td>
<td>37.5 - 38.8</td>
<td>8.2 - 12.0</td>
</tr>
<tr>
<td>O&amp;M ($/MWh)</td>
<td>12.1 - 16.1</td>
<td>11.3 - 12.1</td>
<td>8.5 - 10.0</td>
<td>2.0 - 2.7</td>
</tr>
<tr>
<td>Heat Rate w/o Capture (Btu/kWh)</td>
<td>9,950</td>
<td>8,870</td>
<td>7,880</td>
<td>8,891</td>
</tr>
<tr>
<td>Heat Rate with Capture (Btu/kWh)</td>
<td>13,600</td>
<td>11,700</td>
<td>10,000</td>
<td>10,942</td>
</tr>
<tr>
<td>CO2 Emitted w/o Capture (kg/h)</td>
<td>466,000</td>
<td>415,000</td>
<td>369,000</td>
<td>416,000</td>
</tr>
<tr>
<td>CO2 Emitted with Capture (kg/h)</td>
<td>637,000</td>
<td>546,000</td>
<td>469,000</td>
<td>512,000</td>
</tr>
</tbody>
</table>

*Exhibit 2. Capital and O&M costs to capture carbon dioxide [MIT]*

The capital cost required for IGCC is the lowest because the technology is capture ready. On the other hand, subcritical, supercritical and ultra-supercritical technologies require a higher capital investment because of higher integration costs. O&M and fuel costs are also significantly higher for these technologies because of the greater inefficiencies in producing electricity and the additional equipment required to run the equipment to capture carbon dioxide.
As shown in the chart below (x-axis: change in price of carbon capture technology (%), y-axis: price of carbon ($/ton)), a change in price of carbon capture technology has a significant effect on the price of carbon that is needed by an existing coal-fired power plant to achieve a net present value of zero. A downward trend in the price of carbon capture technologies will have a greater effect on subcritical, supercritical and ultra-supercritical than IGCC and will allow subcritical, supercritical and ultra-supercritical technologies to purchase CCS equipment at a lower carbon price set in the marketplace.

Exhibit 3. Sensitivity analysis showing a change in carbon capture (%) vs. carbon price ($)

Sensitivity Analysis for Transporting and Sequestering Carbon Dioxide

For purposes of running carbon dioxide transportation sensitivity, we assume transport capital costs to range from $0.25/ton to $5/ton. The low end costs represents projects that have the following characteristics: 1) The project is either very close to sequestration sites or to an existing carbon dioxide pipeline network; 2) The mass flow rate of carbon dioxide is approximately 10 million tonnes of carbon dioxide per year. The high cost range represents projects with the opposite characteristics.

A transportation cost of $5/ton of carbon dioxide represents existing coal-fired power plants that are approximately 200 km from a suitable sequestration site. As our previous analysis showed, the majority of states in the US have an abundant amount of carbon dioxide storage potential. Furthermore, since each state varies in area, and our economic analysis covers the variability of distance, we also included total carbon dioxide storage potential and carbon dioxide emissions from coal-fired power plants by area in Appendix 4. We conclude from these graphs that with the exception of a few states, the distance to a sequestration site is not a key determinant in siting a plant because there are abundant possibilities to sequester carbon dioxide within each state.
For purposes of running carbon dioxide sequestration sensitivity, we assume sequestration costs will range from $5 to $15 per ton of carbon dioxide. The low-end cost represents a sequestration site that is a depleted oil/gas field where lots of carbon dioxide can be stored and where a significant amount of geological data is already known. High costs to sequester carbon dioxide will have opposite characteristics.

Exhibit 4. Sensitivity analysis showing a change in carbon capture, transport and sequestration (%) vs. carbon price ($) for our base-case supercritical coal-fired power plant

From Exhibit 5 (which varies capital costs (%) and price of carbon to achieve a net present value of zero for existing coal-fired power plants), we see that a change in the price to capture carbon dioxide dominates the economic viability of retrofitting a coal-fired power plant with CCS technology. So a 60% decrease in transportation costs, for instance, from $40 million to $16 million would represent a 2% decrease in the total CCS cost and reduce a carbon price to achieve a net present value of zero from $43/ton to $42/ton. So a 60% decrease in sequestration costs, for instance, from $200 million to $80 million would represent an 11% decrease in the total CCS cost and reduce a carbon price to achieve a net present value of zero from $43/ton to $39/ton.

Due to the high costs of CCS, no CCS coal plants currently exist. There are, however, several projects that have tested elements of the technology. We will examine currently operating projects outside the US along with several projects being planned currently in the United States. By comparing various aspects of these projects, we will analyze what hurdles such projects in the U.S. are facing and how they might be overcome.

There are no operational projects of CCS as of now in the United States. The five compiled below are planned projects. These five projects stand out as significant because they intend to sequester at least 700,000 tons of carbon dioxide annually.

Current projects in planning in the United States
There are no operational projects of CCS as of now in the United States. The five compiled below are significant ones being planned to inject at least 700,000 tons of carbon dioxide annually. The exact numbers for Praxair and Tenaska are unavailable, but they were noted to be major projects by the Scottish Centre for Carbon Storage (whose information was last updated November 21, 2008).

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Technology</th>
<th>Power (MW)</th>
<th>CO₂ captured (mtons/yr)</th>
<th>Cost (US$m)</th>
<th>Initiated</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FutureGen</td>
<td>Mattoon, IL</td>
<td>IGCC</td>
<td>275</td>
<td>1 - 2.5</td>
<td>1,800</td>
<td>2005</td>
<td>2012</td>
</tr>
<tr>
<td>Hydrogen Energy California (HECA)</td>
<td>Kern County, CA</td>
<td>IGCC</td>
<td>390</td>
<td>2</td>
<td>Not available</td>
<td>2007</td>
<td>2014</td>
</tr>
<tr>
<td>Basin Electric - Powerspan</td>
<td>Beulah, ND</td>
<td>ECO₂ (Post-combustion with ammonia)</td>
<td>120</td>
<td>1</td>
<td>150 - 200</td>
<td>2007</td>
<td>2012</td>
</tr>
<tr>
<td>Praxair</td>
<td>Jamestown, NY</td>
<td>Oxy-coal</td>
<td>50</td>
<td>Not available</td>
<td>145</td>
<td>2007</td>
<td>2013</td>
</tr>
<tr>
<td>Tenaska</td>
<td>Nolan County, TX</td>
<td>Post-combustion with amine absorption</td>
<td>600</td>
<td>Not available</td>
<td>1,500</td>
<td>2008</td>
<td>2014</td>
</tr>
</tbody>
</table>

Source: Project and company websites

1. **FutureGen**

Below is the diagram demonstrating FutureGen’s proposed project which will carry out the role of coal gasification, power generation as well as carbon capture, transportation and storage. The project selected Mattoon, IL for its final site because the CO₂ injection well is proposed to be on the site, and thus, no CO₂ corridor would be necessary. However, the project is currently put on hold due to budget concerns.
1. **Hydrogen Energy California**

At the heart of HECA is a gasification unit and carbon capture facility where petroleum coke (or blends of petroleum coke and coal, as needed) is transformed into hydrogen and CO2. This process is designed to capture approximately 90% of the CO2 from the fuel source and transport it by pipeline for enhanced oil recovery in local oil fields and permanent and secure storage in deep geological formations. Kern County has been identified as an ideal location for a new hydrogen fueled power station due to its proximity to oil production facilities, appropriate geology for CO2 storage and the necessary infrastructure, including roads, non-potable water resources and electrical transmission lines.

![Diagram of HECA process](image)

2. **Powerspan**

This project jointly led by Powerspan and Basin Electric is planning to feed its captured carbon dioxide into an existing CO2 compression and pipeline system owned by Basin Electric’s wholly owned subsidiary, Dakota Gasification Company (Dakota Gas), which has been in operation since 2000. This pipeline leads to oil fields in Saskatchewan, Canada.

3. **Praxair**

Praxair in cooperation with the Jamestown Board of Public Utilities is pursuing carbon capture using oxy-coal technology. It will be a small demonstration project. Again, due to financial sponsorship difficulties the project is making sluggish progress. As of June 2008, the project has only gained around $7 million in state
funds. Also, no details have been given as to where the storage site will be and how they will transport the captured carbon dioxide.

4. Tenaska

85 to 90 percent of the carbon dioxide produced by the Tenaska Trailblazer Energy Center is anticipated to be captured, dehydrated, compressed and delivered via pipeline to Permian Basin oil fields for use in enhanced oil recovery (EOR) projects and reinjected into geologic storage from day one of this project.
# Current operational projects elsewhere around the world

<table>
<thead>
<tr>
<th>Projects</th>
<th>Location</th>
<th>Technology</th>
<th>Power (MW)</th>
<th>CO\textsubscript{2} captured (metric tons / year)</th>
<th>Cost</th>
<th>Initiated</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weyburn - Midale</td>
<td>Weyburn and Midale in Saskatchewan, Canada</td>
<td>IGCC</td>
<td>900</td>
<td>2.5</td>
<td>CAD 1.5 billion</td>
<td>1998</td>
<td>2009</td>
</tr>
<tr>
<td>Sleipner West</td>
<td>Sleipner West oil field, North Sea</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
<td>EUR 350 million</td>
<td>1996</td>
<td>Ongoing</td>
</tr>
<tr>
<td>In Salah</td>
<td>In Salah, Algeria</td>
<td>N/A</td>
<td>N/A</td>
<td>1.2</td>
<td>USD 25 million</td>
<td>2004</td>
<td>Ongoing</td>
</tr>
<tr>
<td>K-12B</td>
<td>Dutch sector of the North Sea</td>
<td>N/A</td>
<td>N/A</td>
<td>0.2 (demo stage) 0.31 – 0.48 (final stage)</td>
<td>EUR 4 million</td>
<td>2004</td>
<td>Ongoing</td>
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<tr>
<td>Otway Basin</td>
<td>Otway, Australia</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1</td>
<td>AUD 40 million</td>
<td>2005</td>
<td>2010</td>
</tr>
</tbody>
</table>

*Source: Project and company websites*

1. **Weyburn-Midale Project**

EnCana’s Weyburn field and Apache’s Midale field, located in southeast Saskatchewan, Canada, host the world’s leading project studying CO\textsubscript{2} geological storage. EnCana began injecting first at 5000 tons per day during the first phase of the project (2000-2004). For the current (final) phase, Apache joined to inject 1800 tons of carbon dioxide per day while EnCana is increasingly injecting at 7000 tons per day. The main objective is for enhanced oil recovery and the target is to sequester 20 million tons of CO\textsubscript{2} over the lifetime of the project. The CO\textsubscript{2} used by the project comes from the Dakota Gasification Company (Great Plains Synfuels Plant) near Beulah, North Dakota. There, the gas is captured after coal gasification, liquefied by compression and pipelined 320 km north to the oil fields in Canada. This is noted for being the first man-made source of CO\textsubscript{2} being used for enhanced oil recovery. Much of the injected CO\textsubscript{2} is pumped to the surface together with oil and water, then separated and reinjected. At the end of the enhanced oil recovery period, virtually all injected and recycled CO\textsubscript{2} is permanently stored. The above-seen Powerspan and Basin Electric project will be incorporating their captured carbon in this same pipeline.

2. **Sleipner West**
About 3,000 tons of carbon dioxide are separated daily from Sleipner West's gas production and injected into the Utsira sandstone formation (saline aquifer). To date, the project has sequestered over 7.5 million tons and the project is estimated to sequester 20 million tons over its lifespan. We note that this project is using naturally produced carbon dioxide from gas fields, not CO2 produced artificially through burning coal.

3. **In Salah**

Similar to Sleipner West, In Salah project led by BP, Statoil and Sonatrach stores the carbon dioxide that they separate from the natural gas they retrieve from 8 different gas fields in the Ahnet-Timimoun Basin in the Algerian Central Sahara. Approximately 10% of the gas in the reservoir is made up of CO2. The project currently compresses the captured carbon and injects it in wells 1,800 meters deep into a lower level of the gas reservoir where the reservoir is filled with water. Such sequestration is considered gas field storage. Around 1 million metric tonnes of CO2 are injected into the reservoir annually. The project is estimated to sequester 17 million tonnes of CO2 over its lifespan with a daily injection rate of 3,000 to 4,000 tonnes.

4. **K-12B**

Since 1987, the K-12B gas field in the North Sea has been producing natural gas with a relatively high CO2 content. Prior to transporting the gas to shore, the carbon dioxide is separated and stored into the depleted gas field, at a depth of approximately 4,000 meters.

5. **Otway Basin**

The Buttress-1 well in Australia which was drilled in 2002 with the intention of producing natural gas was found rich in CO2. CO2CRC researchers initiated the Otway Basin project to extract the carbon dioxide rich gas from the well, compress it and pipe it to a deeper depleted natural gas field (Naylor). Over two years starting 2008, up to 100,000 tonnes of the CO2-rich gas stream at supercritical state will be injected via the CRC-1 well to a depth of 2,050 meters. The pipeline which connects the natural gas field to the depleted storage site was installed between December 2007 and January 2008. It is 2.25 kilometers long and made of stainless steel.

**Analysis of existing projects**

What we notice right away from the information provided is the fact that most of the current operational CCS projects are ones that capture and sequester naturally produced carbon dioxide from gas.
fields. They are only extracting the CO₂ from natural gas using the already widespread amine absorption, membrane separation technology. The Weyburn-Midale project is the sole one incorporating CCS of man-made carbon dioxide from coal burning. Hence, we can safely assume that the United States is not particularly “falling behind” in CCS of coal plants. It is important to note that the actual capture of carbon dioxide through IGCC in the Weyburn-Midale project is executed in the U.S., not in Canada.

However, we also need to take into account that the U.S. cannot be considered a pioneer either based on the status of its current coal plant CCS projects. The current U.S. projects noted above are progressing very slowly. Most have been lingering in their initial stages for quite some time without much advancement. Also, there project completion dates are all many years into the future. This demonstrates little confidence in their proposals and leaves much room for uncertainty. The proposals themselves possess many blanks and question marks. They provide us little detail regarding the methods they will use for transportation and sequestration of the carbon they capture. All of them are still in the stage of obtaining their permits and approvals. No tangible construction has begun yet and all we have are broad overviews of what these projects hope to achieve once they have fully taken off. All they are marketing to the public is the fact that they will not be emitting whatever carbon dioxide they would be thanks to their initiative.

The main reason for the hold up of these projects is the costs and funding. The government and state bodies are not willing to invest wholeheartedly into these projects. This is a direct reflection of how CCS still has a long way to go to be fully well received by politicians as well as the general public as a solid alternative way of conserving energy and protecting the climate. On top of this, the recent economic crisis is making things hard for these projects to advance. Cost projections which have been announced quite a while ago are now inaccurate and budgets need to be revised accordingly. Rising costs lead to more difficulty for financial sponsorship.

An additional interesting point that we should not overlook is that the carbon storage site does not need to be bound by proximity to the capture site. Weyburn and Midale are in no way as close to North Dakota as the selected storage sites of the U.S. projects are to their respective capture sites. Yet it is still one of the largest and most successful operational projects in the world. What we learn from the Weyburn-Midale project is that there is no need for the carbon storage site to be always in close proximity to the capture site if other infrastructure, mainly the carbon transportation, is cost effective and stable.

**POLITICAL VIABILITY**

*Government Support*

Politically, carbon capture and sequestration technology has been supported by the federal
government under the Bush administration as a way for the nation to mitigate carbon emissions but continue to rely on its plentiful supply of coal. The political problem for CCS has largely surrounded gathering funding to support the commercialization of this technology—not political acceptance of the idea of CCS itself.

CCS research and development has received symbolic and fiscal support from the federal government during the Bush administration. In 2003, the US became a member of the Carbon Sequestration Leadership Forum, a coalition of 22 nations to promote carbon capture and sequestration. That same year, it looked like the United States might lead the way for the commercialization of CCS technology on coal-fired power plants, when it committed $1 billion to demonstrating this technology in the FutureGen project. But when costs escalated, the Department of Energy (DOE) revamped the initiative to dedicate the funding to several smaller-scale projects rather than one large project, a strategy that Barack Obama said he supported in a late November address.

In addition, the federal government has sought to provide organizational support to regional projects that aim to pave the way for the commercialization of CCS technology. DOE has created a network of seven Regional Carbon Sequestration Partnerships that team states with industry and academia, all of whom must contribute funding to the projects. In accordance with these efforts, and as part of their own efforts, some states are expressing support for CCS by preparing the regulatory framework that will need to accompany use of this technology. Wyoming has already passed measures to address land rights during sequestration. Another major regulatory question will include liability issues in instances of escaped carbon. However, since commercial use of CCS technology remains nothing more than anticipated, state-wide efforts to pass such legislation is partly a symbolic show of support for CCS (WSJ).

Industry Reactions to CCS

Industry-led funding of CCS projects has been minimal (but not non-existent). Some analysts see this as likely to change as cap-and-trade becomes more likely (WSJ). In late October, for example, Goldman Sachs invested in a company that funds CCS projects.

Despite providing minimal funding for such projects, the coal industry has seized on the idea of clean coal as a public relations argument. Clean coal—an umbrella term for technologies, including CCS, which reduce the environmental impact of coal—is a lynchpin in the industry’s pro-coal argument.

Considering the economic viability of coal, why does the industry have to worry about public relations? Though environmental impact might not be a deterrent to coal use by the American consumer—who would continue to consume the most economical form of energy regardless of environmental impact,
according to many analyses (WSJ)—the coal industry does face the threat of legislation, which could severely limit its activities.

As a result, clean coal—and now carbon capture and sequestration—have figured heavily into the coal industry’s public relations campaigns. Coal and utilities companies spent $35 million during the last election cycle on public relations—and clean coal was a major component of the argument (Post). For example, the coal industry-funded group Americans for Balanced Energy choices launched a campaign commercial that invoked CCS: “Today, energy companies are working with the federal government to develop, demonstrate, and deploy the next generation of advanced technologies that will make it possible to reduce regulated emissions even further (to near-zero levels) and capture and store greenhouse gases” (America’s Power).

Nevertheless, the coal industry isn’t powerless before the federal government. The industry has ample political clout. During the final weeks of the Presidential campaign, when Barack Obama seemingly expressed ambivalence toward the coal industry, industry officials and government representatives from coal-rich states pressed for clarification, leading to a flurry of outspoken support for clean coal from Obama’s campaign.

It may be likely that cap-and-trade will pass: Obama has reiterated his commitment to this system even after being elected and even in the wake of the financial crisis, and he is likely to find support in a Democratically-controlled Congress. Plus, there is speculation that Obama could bypass congressional debate altogether and establish cap-and-trade through regulation at the Environmental Protection Agency (Atlantic). Nevertheless, since coal plays such a major role in the U.S. economy, the institution of a cap-and-trade program will surely be developed in a way that would not cripple the coal industry.

Opposition to CCS

Despite federal funding and symbolic industry support, CCS isn’t universally accepted. Some environmentalists see the logic in CCS, but argue that commercialization of the technology is too far off for this to serve as a solution to carbon emissions from coal-fired power plants. Further, some environmental groups—including those sometimes categorized as “extreme,” such as Green Peace—point to potential environmental risks posed by escaped carbon as an argument against CCS. Studies of public perception of CCS have been largely identified a lack of knowledge of the technology, along with some positive feedback when subjects became more informed (EPA).
Conclusion

With cap-and-trade potentially on the horizon, existing coal-fired power plants will potentially seek ways to curb their carbon dioxide emissions. The enormous costs of implementing CCS and the dearth of successful CCS projects have so far stifled the commercialization of these methods. CCS also seems to be politically viable, with the parting and incoming Presidential administrations supporting the idea. However, whether R&D will receive sufficient funding in the short-term to commercialize this technology remains in question. And even if cap-and-trade is instituted, the significant costs of CCS may mean that use of this technology will not be economically viable unless the price of carbon is rather high. In our base case we calculated that an existing coal-fired power plant would not invest in CCS technology until the price of carbon reaches $43/ton. Assuming that our base case plant of 500 MW is identical across the existing fleet of coal-fired power plants in the United States (330 GW), this would translate to a cost of approximately $83 billion per year in today’s dollars. This amount would be approximately 25% of the existing revenues the total electricity industry received in 2006 [EIA]. CCS technology today is not economical to implement in the existing fleet of coal-fired power plants. Even with a price of carbon dioxide set at $30/ton for EOR, a coal-fired power plant would not invest in CCS technology. For CCS to be more economical it will be important for the cost to capture carbon dioxide to come down significantly. Government funding to support capture technology is an attractive possibility to bring this cost down. Thus, the prospect of the industry investments in CCS technology across the existing base of coal-fired power plants in the near term is very doubtful.

A useful research agenda for further examining the viability of CCS technology would analyze, from a technological standpoint, how to make this technology more efficient and thus more economical. New literature on the economics of implementing this technology will have to take into account the specific regulations set by a cap-and-trade policy, if one is set. Further analysis of the economic viability of CCS should also compare the costs of implementing these capabilities on new power plants such as IGCC versus the existing fleet. From a political angle, further analysis should provide an estimation of the amount of R&D funding that would be needed to break the threshold and lead to commercialization of this technology. Such an estimate should draw on historical instances of R&D breakthroughs leading to commercial products. It would also be useful to assess whether such funding would be politically realistic in the short-term.
Appendix 1

Coal Regions and Coal Fields

Source: Coal Transportation: Rates and Trends. 2004. EIA.
http://www.eia.doe.gov/cneaf/coal/page/trans/ratesntrends.html
Appendix 2

Appendix 3

### Construction period

We assume 48 months as the time to construct a CCS plant. This is based on AEP’s estimate to build a 629 MW IGCC electric generating plant in West Virginia.

### Engineering data

We use MIT’s report “The Future of Coal” as our primary source for providing engineering data. In this report, MIT assumes a base case plant capacity of 500 MW, a design heat rate of 8,897 without CO2 capture, a design heat rate of 10,942 Btu/kWh with CO2 capture, a capacity factor of 85%, CO2 emissions without CO2 capture of 11,800 lb/MMBtu, CO2 emissions with CO2 capture of 546,000 lb/MMBtu.

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<thead>
<tr>
<th>Timing Data</th>
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<td>Beginning of Construction</td>
<td>01 Jan 2009</td>
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<tr>
<td>Construction Period</td>
<td>48 months</td>
<td></td>
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<tr>
<td>Economic Life</td>
<td>30 years</td>
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<td>US Inflation</td>
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<thead>
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<th>Engineering Data</th>
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<tr>
<td>Net Electric Power Capacity</td>
<td>500 MW</td>
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<tr>
<td>Heat Rate w/o Capture</td>
<td>8,870 Btu/kWh</td>
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<tr>
<td>Heat Rate with Capture</td>
<td>11,700 Btu/kWh</td>
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<tr>
<td>Capacity Factor</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Fuel Heat Value</td>
<td>11,800 Btu/lb</td>
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<tr>
<td>CO2 Emissions w/o Capture</td>
<td>415,000 kg/hr</td>
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<tr>
<td>CO2 Emissions with Capture</td>
<td>546,000 kg/hr</td>
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<td>CO2 Capture</td>
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<td>Fuel Transportation Cost</td>
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<td>Mortgage Style Loan</td>
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<td>Debt Ratio</td>
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<tbody>
<tr>
<td>Income Tax Rate</td>
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<td>Depreciation Schedule (Years)</td>
<td>10 Years</td>
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<td>Investment Tax Credit</td>
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<tr>
<td>Loan Guarantee</td>
<td>80%</td>
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<table>
<thead>
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<th>Project Return</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount Rate</td>
<td>7.00%</td>
<td></td>
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</table>
without capture of 416,000 kg/hr, CO2 emissions with capture of 512,000 kg/hr and a CO2 capture rate of 90% [MIT].

In Mattoon, Illinois, we assume the FutureGen project would have used Illinois Basin coal. Illinois Basin coal has a heat value of 11,800 Btu/lb.

*Fuel cost data*

We assume delivered fuel cost for Illinois Basin coal to the FutureGen project would have been $2.10/mmBtu. This is based on the average cost of coal delivered to electricity generation in the US in August 2008, $2.17/mmBtu, and the average cost of coal delivered to electricity generation in Illinois in August 2008, $1.75/mmBtu [EIA].

*Financing data*

We assume a 30-year mortgage style loan at an 8% interest rate before a government loan guarantee. With a loan guarantee from the government covering 80% of the loan, and assuming the guaranteed portion of the loan will have an interest rate of 4%, we assume an effective interest rate of 4.8%. We also assume a debt ratio of 70%.

*Tax data*

We assume a MACRS depreciation schedule of 10 years for gasification projects. We assume a federal tax rate of 35%. We also assumed an investment tax credit (ITC) from the government of 20%.

*Price of carbon*

The price of carbon is calculated by setting NPV equal to zero. We assume existing coal-fired power plants and new IGCC plants will be able to benefit from a price for carbon starting in year 2013 and thereafter increase annually at US inflation. This will allow developers enough time to construct necessary CCS installations.
Appendix 4

Source: http://www.natcarb.org [NETL]
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Figures: 1) CO2 dipole moment, 2) CO2 phase diagram