

**A Technical, Economic and Environmental Assessment of Amine-based  
CO<sub>2</sub> Capture Technology for Power Plant Greenhouse Gas Control**

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## Abstract

Capture and sequestration of CO<sub>2</sub> from fossil fuel power plants is gaining widespread interest as a potential method of controlling greenhouse gas emissions. Performance and cost models of an amine (MEA)-based CO<sub>2</sub> absorption system for post-combustion flue gas applications have been developed, and integrated with an existing power plant modeling framework that includes multi-pollutant control technologies for other regulated emissions. The integrated model has been applied to study the feasibility and cost of carbon capture and sequestration at both new and existing coal-burning power plants. The cost of carbon avoidance was shown to depend strongly on assumptions about the reference plant design, details of the CO<sub>2</sub> capture system design, interactions with other pollution control systems, and method of CO<sub>2</sub> storage. The CO<sub>2</sub> avoidance cost for retrofit systems was found to be generally higher than for new plants, mainly because of the higher energy penalty resulting from less efficient heat integration, as well as site-specific difficulties typically encountered in retrofit applications. For all cases, a small reduction in CO<sub>2</sub> capture cost was afforded by the SO<sub>2</sub> emission trading credits generated by amine-based capture systems. Efforts are underway to model a broader suite of carbon capture and sequestration technologies for more comprehensive assessments in the context of multi-pollutant environmental management.

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# 1. INTRODUCTION

The control of greenhouse gases is arguably the most challenging environmental policy issue facing the U.S. and other countries. An approach that is gaining widespread interest is to control CO<sub>2</sub> emissions by capturing and sequestering CO<sub>2</sub> from fossil-fuel combustion sources (1,2). The key attraction of this option is that it can allow fossil fuels to continue to be used without contributing significantly to greenhouse warming. This would be a radical departure from conventional thinking about climate mitigation, which would require eliminating or severely limiting the use of fossil fuels. Given our high degree of reliance on fossil fuels (roughly 85% of commercial energy use domestically and globally), and the difficulties — technical, economic and social — of large-scale use of alternative options (like nuclear and renewables), the ability to use fossil energy while avoiding greenhouse gas emissions is a potentially attractive alternative that needs to be carefully studied. Coal-based power plants, which contribute about 30% of total U.S. CO<sub>2</sub> emissions, are the principal targets for this type of CO<sub>2</sub> control technology (3-5).

## 1.1. Technology Options for CO<sub>2</sub> Capture

A wide range of technologies currently exist for separation and capture of CO<sub>2</sub> from gas streams (Figure 1), although they have not been designed for power-plant-scale operations (6). They are based on different physical and chemical processes including absorption, adsorption, membranes and cryogenics (7-11). The choice of a suitable technology depends on the characteristics of the flue gas stream, which depend mainly on the power plant technology. Future coal-based power plants may be designed to capture CO<sub>2</sub> before combustion (using coal gasification systems), or they may employ pure oxygen combustion instead of air to obtain a concentrated CO<sub>2</sub> stream for treatment. Figure 2 shows the variety of power plant fuels and technologies that affect the choice of CO<sub>2</sub> capture systems.

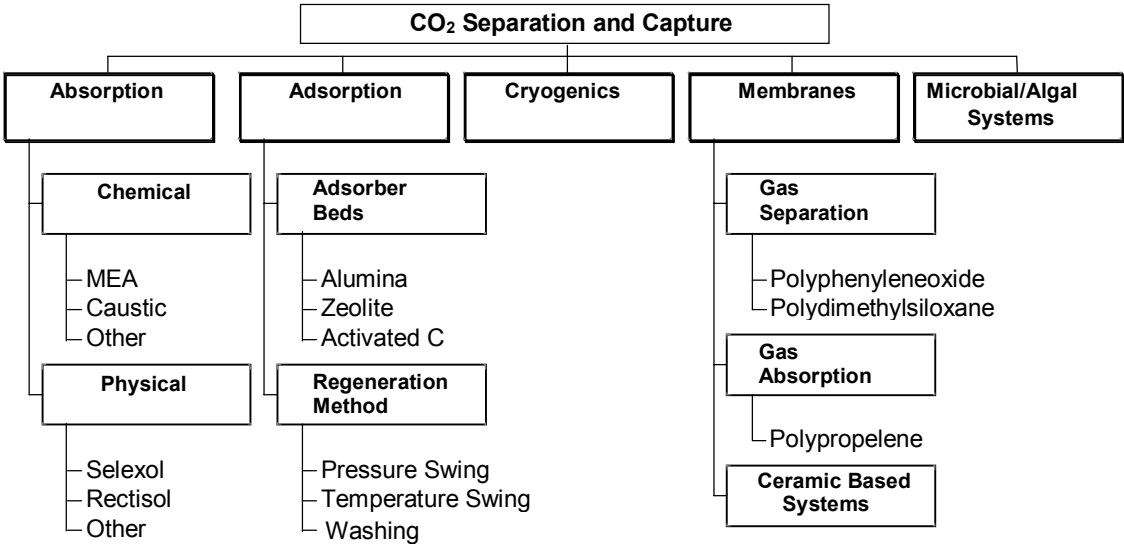


Figure 1. Technology options for CO<sub>2</sub> separation and capture



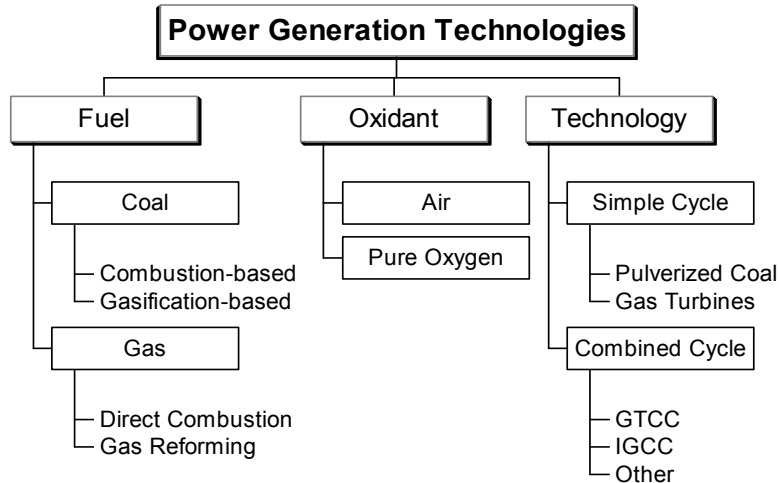


Figure 2. Technology options for fossil-fuel based power generation

## 1.2. Options for CO<sub>2</sub> Sequestration

Once the CO<sub>2</sub> is captured, it needs to be securely stored (sequestered). Again, there are a range of options potentially available. Geologic formations including deep saline reservoirs, depleted oil and gas wells, and unmineable coal seams are some of the potentially attractive disposal sites (12-14). Ocean disposal is another option being studied (15-16). The distance to a secure storage site and the availability and cost of transportation infrastructure also affect the choice of disposal option. In general, studies indicate that geologic formations are the most plentiful and attractive option for U.S. power plants (17). While the economic costs of CO<sub>2</sub> storage appear to be low, its social and political acceptability are not yet clear, especially with regard to ocean sequestration.

## 2. SCOPE OF THIS STUDY

This research is motivated by a desire to better understand the technological options for CO<sub>2</sub> capture and sequestration and their possible role in climate mitigation policy. Because the topic is fairly new, some of the key research questions that need to be addressed include: What kind of technologies may be used for capture and storage of CO<sub>2</sub>? What are the key parameters that affect the performance, cost and environmental acceptability of different options? How do the alternative options compare in terms of these considerations? What are the uncertainties associated with different options? What are the benefits of R&D to reduce key uncertainties?

To begin addressing such questions, this paper focuses on current coal combustion systems. Today the 300 GW of coal-fired power generation capacity in the U.S. provides 51% of all power generation and accounts for 79% of carbon emissions coming from electric utilities. Even with the expected growth in natural gas for new generating capacity, coal's share of the electricity supply is still projected to be about 44% in 2020, and higher in absolute capacity compared to today (18). Thus, any new policies to significantly reduce CO<sub>2</sub> emissions during the next two or three decades must consider not only the technology options for new power plants (which is the case typically discussed in the literature), but also the retrofitting of existing coal plants which will continue to operate for several decades to come. Such medium-term intervention to reduce CO<sub>2</sub> emissions has received relatively little attention to date. Hence, the present study examines the feasibility of post-combustion carbon capture at existing power plants as well as new facilities.

In this context, past studies have shown that amine-based CO<sub>2</sub> absorption systems are the most suitable for combustion-based power plants for the following reasons

- These systems are effective for dilute CO<sub>2</sub> streams, such as coal combustion flue gases, which typically contain only about 10%-12% CO<sub>2</sub> by volume.
- Amine-based CO<sub>2</sub> capture systems are a proven technology that is commercially available and in use today.
- Amine-based systems are similar to other end-of-pipe environmental control systems used at power plants. These units are operated at ordinary temperature and pressure.
- A major effort is being made worldwide to improve this process in the light of its potential role in CO<sub>2</sub> abatement. Thus, one can anticipate future technology advances.

A number of previous studies have reported some cost and/or performance data for specific amine-based systems, including hypothetical applications to coal-fired power plants (19-23). However, detailed models of such processes are not generally available. Cost data reported in different studies also tend to be limited and often incomplete. Therefore the first objective of this study has been to develop a preliminary model of performance and cost of amine-based systems based on available information, including a characterization of key uncertainties, as reflected in the current literature.

The second objective is to apply the model to study the feasibility and cost of carbon capture and sequestration at both new and existing coal-based power plants. This analysis incorporates multi-pollutant interactions between CO<sub>2</sub> control, criteria air pollutants (especially SO<sub>2</sub> and NO<sub>x</sub>), and air toxics (especially mercury). These aspects of CO<sub>2</sub> mitigation policy analysis are seldom addressed in other studies.

Finally, a third objective is to examine the impact of possible process improvements resulting from R&D. This will help to characterize the role of technological change in looking at future options and costs for CO<sub>2</sub> control.

### **3. OVERVIEW OF AMINE-BASED CO<sub>2</sub> CAPTURE SYSTEMS**

The idea of separating CO<sub>2</sub> from flue gas streams started in the 1970s, not with concern about the greenhouse effect, but as a potentially economic source of CO<sub>2</sub>, mainly for enhanced oil recovery (EOR) operations. Several commercial CO<sub>2</sub> capture plants were constructed in the U.S. in the late 1970s and early 1980s (24,25). CO<sub>2</sub> was also produced for other industrial applications such as carbonation of brine and production of products like dry ice, urea and beverages. Some of these CO<sub>2</sub> capture plants are still in operation today, but all these plants are much smaller than a typical power plant. The first commercial CO<sub>2</sub> sequestration facility started in Norway in September 1996 in response to a Norwegian carbon tax. Since then, Statoil has been storing CO<sub>2</sub> from the Sleipner West gas field in a sandstone aquifer 1000 m beneath the North Sea (1). The international research community is closely monitoring this facility.

All these plants capture CO<sub>2</sub> with processes based on chemical absorption using a monoethanolamine (MEA)-based solvent. MEA is an organic chemical belonging to the family of compounds known as amines. It was developed over 60 years ago as a general, non-selective solvent to remove acidic gas impurities (e.g. H<sub>2</sub>S, CO<sub>2</sub>) from natural gas streams (21). The process was then adapted to treat flue gas streams for CO<sub>2</sub> capture. Fluor Daniel Inc., Dow

Chemical Co., Kerr-McGee Chemical Corp. and ABB Lummus Crest Inc., were some of the initial developers of MEA-based technology for CO<sub>2</sub> capture. Typically, about 75% to 90% of the CO<sub>2</sub> is captured using this technology, producing a nearly pure (>99%) CO<sub>2</sub> product stream.

### 3.1. Process Description

A continuous scrubbing system is used to separate CO<sub>2</sub> from the flue gas stream. As illustrated in Figure 3, the system consists of two main elements: an absorber where CO<sub>2</sub> is removed, and a regenerator (or stripper), where CO<sub>2</sub> is released (in concentrated form) and the original solvent is recovered. The Supplementary Information appendix contains additional details of the process chemistry and design of this system (27-32).

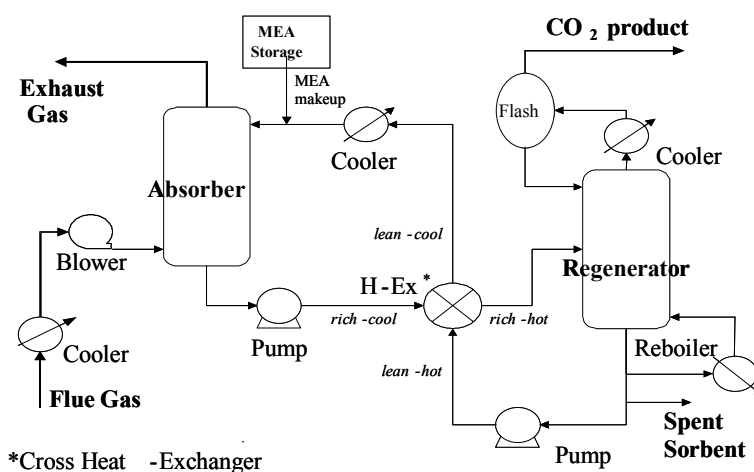


Figure 3. Flowsheet for CO<sub>2</sub> capture from flue gases using amine-based system

A key feature of amine systems is the large amount of heat required to regenerate the solvent. This heat is typically drawn from the steam cycle and significantly reduces the net efficiency of the power plant. Substantial electrical energy also is needed to compress the captured CO<sub>2</sub> for pipeline transport to a storage site. As shown later in this paper, the overall energy penalty of this process has a major impact on system performance as well as cost.

From a multi-pollutant perspective, there are also important interactions between the CO<sub>2</sub> capture system and the control of other air pollutants, especially SO<sub>2</sub> and NO<sub>x</sub> emissions. Acid gases like SO<sub>2</sub> and NO<sub>2</sub> react with MEA to form heat-stable salts that reduce the CO<sub>2</sub> absorption capacity of the solvent. Thus, very low concentrations of these gases (on the order of 10 ppm) are desirable to avoid excessive loss of (costly) solvent. The problem is especially acute for SO<sub>2</sub> because its concentration in flue gases is typically 700 to 2500 ppm at coal-fired plants. NO<sub>x</sub> is less of a problem because most of the NO<sub>x</sub> is nitric oxide (NO), whereas only NO<sub>2</sub> (typically about 5% of total NO<sub>x</sub>) is reactive (see Supplementary Information for additional details).

## 4. PROCESS PERFORMANCE MODEL

The removal of CO<sub>2</sub> from flue gases using an amine scrubber depends on the gas-liquid mass transfer process. The chemical reactions that permit diffusion of CO<sub>2</sub> in the liquid film at the gas-liquid interface enhance the overall rate of mass transfer. Thus, the CO<sub>2</sub> removal efficiency in the

absorber is a function of various parameters that affect the gas-liquid equilibrium (e.g., flow rates, temperature, pressure, flue gas composition, CO<sub>2</sub> concentration, MEA concentration and absorber design). Similarly, the conditions and detailed design of the regenerator affect the energy requirements and overall performance of the system.

#### 4.1. Performance Parameters

A mathematical model was developed to simulate the performance of a CO<sub>2</sub> capture and storage system based on amine (MEA) scrubbing. This CO<sub>2</sub> module was then added to an existing coal-based power plant simulation model, described later in this paper. Basically, there are two types of input parameters to the CO<sub>2</sub> performance model

*Table 1. Amine System Performance Model Parameters and Uncertainties*

Performance Parameter	Units	Data (Range)	Nominal Value	Unc. Representation (Distribution Function)
CO <sub>2</sub> removal efficiency	%	Mostly 90	90	-
SO <sub>2</sub> removal efficiency	%	Almost 100	99.5	Uniform(99,100)
NO <sub>2</sub> removal efficiency	%	20-30	25	Uniform(20,30)
HCl removal efficiency	%	90-95	95	Uniform(90,95)
Particulate removal eff.	%	50	50	Uniform(40,60)
MEA concentration	wt%	15-50	30	-
Lean solvent CO <sub>2</sub> loading	mol CO <sub>2</sub> /mol MEA	0.15-0.30	0.22	Triangular(0.17,0.22,0.25)
Nominal MEA make-up	kg MEA/tonne CO <sub>2</sub>	0.5-3.1	1.5	Triangular(0.5,1.5,3.1)
MEA loss (SO <sub>2</sub> )	mol MEA/mol SO <sub>2</sub>	2	2	-
MEA loss (NO <sub>2</sub> )	mol MEA/mol NO <sub>2</sub>	2	2	-
MEA loss (HCl)	mol MEA/mol HCl	1	1	-
MEA loss (exhaust gas)	ppm	1-4	2	Uniform (1,4)
NH <sub>3</sub> generation	mol NH <sub>3</sub> /mol MEA oxidized	1	1	-
Caustic consumption in MEA reclaimer	kg NaOH/tonneCO <sub>2</sub>	0.13	0.13	-
Activated carbon use	kg C/tonne CO <sub>2</sub>	0.075	0.075	-
Cooling water makeup	m <sup>3</sup> /tonne CO <sub>2</sub>	0.5-1.8	0.8	Triangular (0.5,0.8,1.8)
Solvent pumping head	kPa	35-250	207	Triangular(150,207,250)
Pump efficiency	%	70-75	75	Uniform (70,75)
Gas-phase pressure drop	kPa	14-30	26	Triangular(14,26,30)
Fan efficiency	%	70-75	75	Uniform (70,75)
Equiv. elec. requirement	% regeneration heat	9-19	14 <sup>a</sup>	Uniform (9,19)
CO <sub>2</sub> product purity	wt%	99-99.8	99.5	Uniform (99,99.8)
CO <sub>2</sub> product pressure	MPa	5.86-15.16	13.79	Triangular(5.86,13.79,15.16)
Compressor efficiency	%	75-85	80	Uniform (75,85)

<sup>a</sup> For retrofit applications, nominal value is 25.

- *Parameters from the “base plant”*: These include the flow rate, temperature, pressure and composition of the inlet flue gas to the CO<sub>2</sub> absorber, and the gross power generation capacity of the power plant.

- *Parameters of the CO<sub>2</sub> system:* The CO<sub>2</sub> module specifies parameters of the CO<sub>2</sub> capture technology, CO<sub>2</sub> compression system, CO<sub>2</sub> product transport, and CO<sub>2</sub> storage (sequestration) method. The basic configuration is an MEA-based absorption system with pipeline transport of liquefied CO<sub>2</sub> to a geologic sequestration site. Table 1 lists the model input parameters that affect overall process performance. These parameters, along with those from the base plant, are used to calculate the solvent flow rate, MEA requirement, regeneration heat requirement, and electrical energy needs of the CO<sub>2</sub> system. Functional relationships and default values for all model parameters were developed for a typical system design based on a detailed review of the literature, discussions with process developers and other experts, and the use of detailed process simulation models (33,34). The resulting model employs fundamental mass and energy balance relationships together with empirical relationships for some key parameters. Details of the performance model are presented as an attachment (35). All of the performance parameters also affect the cost of the system.

## 4.2. Characterization of Uncertainties

This modeling effort also incorporates a stochastic simulation capability that allows any or all model inputs to be represented by a probability distribution rather than a single deterministic value. In general, such distributions may reflect uncertainty and/or variability in system design parameters. Table 1 shows the distributions used in this paper to characterize the performance parameters of the CO<sub>2</sub> capture system. These distributions reflect the current literature on amine-based (MEA) systems and (in a few cases) data and judgments provided by process developers (36). Detailed descriptions of these distributions are provided as an attachment (35).

## 4.3. Model Outputs

The key outputs of the amine system performance model include

- *MEA requirement.* This depends mainly on the mass flow rate of CO<sub>2</sub> in the flue gas, the desired CO<sub>2</sub> capture efficiency, the MEA concentration, and CO<sub>2</sub> loadings in the solvent. Depending on the level of impurities in the flue gas, there is additional loss of solvent associated with removal of other acid gases such as SO<sub>x</sub> and NO<sub>2</sub>.
- *Energy requirements.* Heat requirements for solvent regeneration depend mainly on the lean sorbent loading and other system parameters. This heat is provided by low-pressure steam within the power plant, thus decreasing the net power generation efficiency. In addition, electrical energy is required for CO<sub>2</sub> product compression, solvent circulation, and other system requirements. The total amine system energy requirement is one of the most important model results, as it dictates the net power plant output, and hence the net cost of power generation and CO<sub>2</sub> avoidance.
- *Environmental emissions.* The CO<sub>2</sub> control system generates several new waste products that are accounted for in the model, principally ammonia gas (generated by degradation of MEA) and reclaimer bottoms (a potentially hazardous solid waste generated during recovery of spent sorbent from the process). On the other hand, the CO<sub>2</sub> capture system also reduces emissions of particulate matter and acid gases like SO<sub>2</sub>, HCl and NO<sub>2</sub>. Removal of trace metals like mercury and other air toxics is not well-characterized for these systems, but is anticipated to be similar to other wet scrubber systems. A complete accounting of multi-pollutant emissions is provided by the IECM framework in which the CO<sub>2</sub> module is embedded, as discussed below.

#### 4.4. The IECM Framework

The Integrated Environmental Control Model (IECM) is a power plant simulation model developed by Carnegie Mellon University for the U.S. Department of Energy (USDOE) (37, 38). It includes a menu of technological options for controlling criteria air pollutants (SO<sub>2</sub>, NO<sub>x</sub>, and particulates), mercury (an air toxic), and solid wastes. The new CO<sub>2</sub> module has been integrated into the existing IECM modeling framework, allowing the analysis of alternative CO<sub>2</sub> capture and sequestration technologies in complex plants involving multi-pollutant emission controls. (This newly integrated version is designated IECM-CS.)

### 5. PROCESS COST MODEL

The CO<sub>2</sub> capture and sequestration system cost model is directly linked to the process performance model described earlier. The cost model follows the framework used in the IECM to ensure consistency in plant-level economic calculations (35). There are four types of cost calculated by this model based on available data (8,19,23,26,30,39-42).

#### 5.1. Capital Cost

The total capital requirement (TCR) of a system is the sum of direct equipment costs (which depend on one or more performance variables that determine the size or capacity of a component), plus various indirect costs that are calculated as fractions of the total process facilities cost (PFC), following the EPRI cost estimating guidelines (43). Table 2 lists the elements of capital cost, showing the nominal parameter values plus the uncertainties used later for probabilistic analyses. For the MEA system, the absorber capital cost depends mainly on the flue gas flow rate. The cost of the regenerator section and the CO<sub>2</sub> compressor scale mainly with the mass flow rate of CO<sub>2</sub> captured. Indirect cost factors are estimated based on available data for amine systems and similar technologies.

Table 2. MEA Cost Model Parameters and Nominal Values

Capital Cost Elements	Nom. Value*	O&M Cost Elements	Nom. Value*
Process Area Costs (9 areas) <sup>a</sup>		<b>5.2. Fixed O&amp;M Costs (FOM)</b>	
Total Process Facilities Cost	PFC <sup>b</sup>	Total Maintenance Cost	2.5 % TPC <sup>j</sup>
Engineering and Home Office	7 % PFC <sup>c</sup>	Maintenance Cost	40 % of total maint. cost
General Facilities	10 % PFC <sup>d</sup>	Allocated to Labor	
Project Contingency	15 % PFC <sup>e</sup>	Admin. & Support Labor	30 % of total labor cost
Process Contingency	5 % PFC <sup>f</sup>	Cost	
Total Plant Cost (TPC) = sum of above		Operating Labor	2 jobs/shift <sup>k</sup>
Interest During Construction		<b>Variable O&amp;M Costs (VOM)</b>	
	calculated	Reagent (MEA) Cost	\$1250/tonne MEA <sup>l</sup>
Royalty Fees	0.5 % PFC <sup>g</sup>	Water Cost	\$0.2/m <sup>3</sup>
Pre-production Costs	1 month <sup>h</sup> VOM & FOM	CO <sub>2</sub> Transport Cost	\$0.02/tonne CO <sub>2</sub> /km <sup>m</sup>
Inventory (startup) Cost	0.5 % TPC <sup>i</sup>	CO <sub>2</sub> Storage/Disposal Cost	\$5/tonne CO <sub>2</sub> <sup>n</sup>
Total Capital Reqmt (TCR) = sum of above		Solid Waste Disposal Cost	\$175/tonne waste <sup>b</sup>

\*Uncertainty distributions are given below. <sup>a</sup>The individual process areas modeled are: flue gas blower, absorber, regenerator, solvent processing area, MEA reclaiming, steam extractor, heat exchanger, pumps, CO<sub>2</sub> compressor. The sum of these is the total process facilities cost (PFC). The uncertainty distributions used are: <sup>b</sup>Normal (1.0,0.1), <sup>c</sup>Triangular (5,7,15), <sup>d</sup>Triangular (5,10,15), <sup>e</sup>Triangular (10,15,20), <sup>f</sup>Triangular (2,5,10), <sup>g</sup>Triangular (0,0.5,0.5), <sup>h</sup>Triangular (0.5,1,1), <sup>i</sup>Triangular (0.4,0.5,0.6), <sup>j</sup>Triangular (1,2.5,5), <sup>k</sup>Triangular (1,2,3), <sup>l</sup>Uniform (1150,1300), <sup>m</sup>Triangular (0.004,0.02,0.06), <sup>n</sup>Triangular (-10,5,8)

### 5.3. O&M Costs

Operating and maintenance (O&M) cost elements are also listed in Table 2. Major variable cost items include the cost of sorbent (MEA) and the costs of CO<sub>2</sub> transport and storage. Fixed costs include the costs of maintenance and labor. Energy costs are handled internally in the model by derating the overall power plant based on the calculated energy requirement. This increases the cost per net kilowatt-hour delivered by the plant.

### 5.4. Cost of Electricity

The IECM framework calculates the cost of electricity (COE) for the overall power plant by dividing the total annualized plant cost (\$/yr) by the net electricity generated (kWh/yr). Results are expressed in units of \$/MWh (equivalent to mills/kWh). Two key parameters in this calculation are the levelized fixed charge factor (used to amortize capital expenses), and the plant capacity factor. The fixed charge factor is based on the plant lifetime (book life) and after-tax discount rate (or interest rate, or rate of return), while the capacity factor reflects the average annual hours of plant operation. The incremental cost of electricity attributed to CO<sub>2</sub> control is then the difference in COE between plants with and without the CO<sub>2</sub> capture and storage system.

### 5.5. Cost of CO<sub>2</sub> Avoided

Analysts commonly express the cost of an environmental control system in terms of either the cost per tonne of pollutant removed or the cost per tonne “avoided.” For an energy-intensive system like amine scrubbers there is a big difference between the cost per tonne CO<sub>2</sub> removed and the cost per tonne CO<sub>2</sub> avoided based on *net* plant capacity. Since the purpose of adding a capture unit is to reduce the CO<sub>2</sub> emissions per net kWh delivered, the cost of CO<sub>2</sub> avoidance (relative to a reference plant with no CO<sub>2</sub> control) is the economic indicator most widely used. It can be calculated as

$$\text{Cost of CO}_2 \text{ Avoided (\$/tonne)} = \frac{(\$/\text{kWh})_{\text{capture}} - (\$/\text{kWh})_{\text{reference}}}{(\text{tonne CO}_2/\text{kWh})_{\text{reference}} - (\text{tonne CO}_2/\text{kWh})_{\text{capture}}}$$

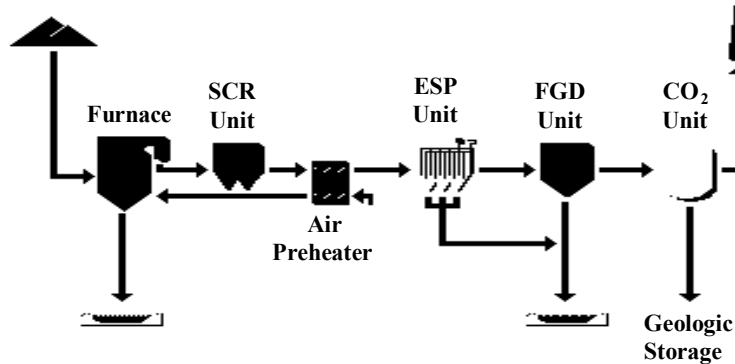


Figure 4. Schematic of an NSPS plant including CO<sub>2</sub> capture unit

## 6. CASE STUDY RESULTS FOR A NEW PLANT

The IECM-CS simulation framework models a complete coal-fired power plant with multi-pollutant environmental controls, including CO<sub>2</sub> capture and sequestration. The reference case is assumed to be a new 500 MW unit (gross) burning low-sulfur western U.S. coal, and meeting current federal New Source Performance Standards (NSPS) for SO<sub>2</sub>, NO<sub>x</sub> and particulates (44). The CO<sub>2</sub> capture case adds an MEA scrubber. Figure 4 shows a schematic of the plant and its environmental control systems, including the CO<sub>2</sub> capture unit. Table 3 lists key plant design parameters and the uncertainties assumed for probabilistic analysis.

Table 3. Design Parameters for Case Study of New Pulverized Coal Plant

Parameter	Value	Parameter	Value
Gross plant size (MW)	500	Emission standards	2000 NSPS <sup>d</sup>
Gross plant heat rate (kJ/kWh)	9600 <sup>a</sup>	NO <sub>x</sub> Controls	LNB <sup>e</sup> + SCR <sup>f</sup>
Plant capacity factor (%)	75 <sup>b</sup>	Particulate Control	ESP <sup>g</sup>
		SO <sub>2</sub> Control	FGD <sup>h</sup>
		CO <sub>2</sub> Control	MEA <sup>i</sup>
<i>Coal characteristics</i>			
Rank	Sub-bit.	CO <sub>2</sub> capture efficiency (%)	90
HHV (kJ/kg)	19,346	CO <sub>2</sub> product pressure (kPa)	13,790 <sup>j</sup>
% S	0.48	Distance to storage (km)	165
% C	47.85		
Mine-mouth cost (\$/tonne)	13.73	Cost year basis (constant dollars)	2000
Delivered cost (\$/tonne)	23.19 <sup>c</sup>	Fixed charge factor	0.15 <sup>k</sup>

<sup>a</sup>Nominal case is a sub-critical unit. Uncertainty case includes supercritical unit. The uncertainty distributions used are: <sup>Unc</sup> = Uniform(9230,9600); <sup>b</sup>Unc = Triangular(65,75,85); <sup>c</sup>Unc = Triangular(15.94,23.19,26.81); <sup>d</sup>NO<sub>x</sub> = 65 ng/J, PM = 13 ng/J, SO<sub>2</sub> = 70% removal (upgraded to 99% with MEA systems); <sup>e</sup>LNB = Low- NO<sub>x</sub> Burner; <sup>f</sup>SCR = Selective Catalytic Reduction; <sup>g</sup>ESP = Electrostatic Precipitator; <sup>h</sup>FGD = Flue Gas Desulfurization; <sup>i</sup>MEA = Monoethanolamine system; <sup>j</sup>See Table 1 for uncertainty. <sup>k</sup>Corresponds to a 30-year plant lifetime with a 14.8% real interest rate (or, a 20-year life with 13.9% interest); <sup>Unc</sup> = Uniform(0.10,0.20)



## 6.1. Deterministic Results

We run the model first for the reference power plant (without CO<sub>2</sub> capture) and then for the same plant including CO<sub>2</sub> capture. Table 4 quantifies the impact of the CO<sub>2</sub> unit on plant performance, plant discharges and plant costs. Figure 5 shows graphically the relationship of electricity cost to CO<sub>2</sub> emissions for the two cases; the slope of the line connecting the two points represents the cost of CO<sub>2</sub> avoided, which is \$59/tonne for this case. Most of this cost (79%) is associated with the CO<sub>2</sub> capture process (including gas compression). CO<sub>2</sub> transport (8%) and storage (13%) account for the remainder.

Table 4. Deterministic Results for a New 500 MW Plant

Parameter	Units	Reference Plant	w/CO <sub>2</sub> Control
Net plant capacity	MW (net)	462	326
CO <sub>2</sub> emission rate	g CO <sub>2</sub> /kWh (net)	941	133
SO <sub>2</sub> emission rate	g SO <sub>2</sub> /kWh (net)	2.45	0.0003
NO <sub>x</sub> emission rate	g NO <sub>x</sub> /kWh (net)	0.45	0.58
CO <sub>2</sub> sequestered	10 <sup>6</sup> tonne CO <sub>2</sub> /yr	-	2.58
Cost of electricity	\$/MWh (net)	49.2	97.0
CO <sub>2</sub> mitigation cost	\$/tonne CO <sub>2</sub> avoided	-	59.1

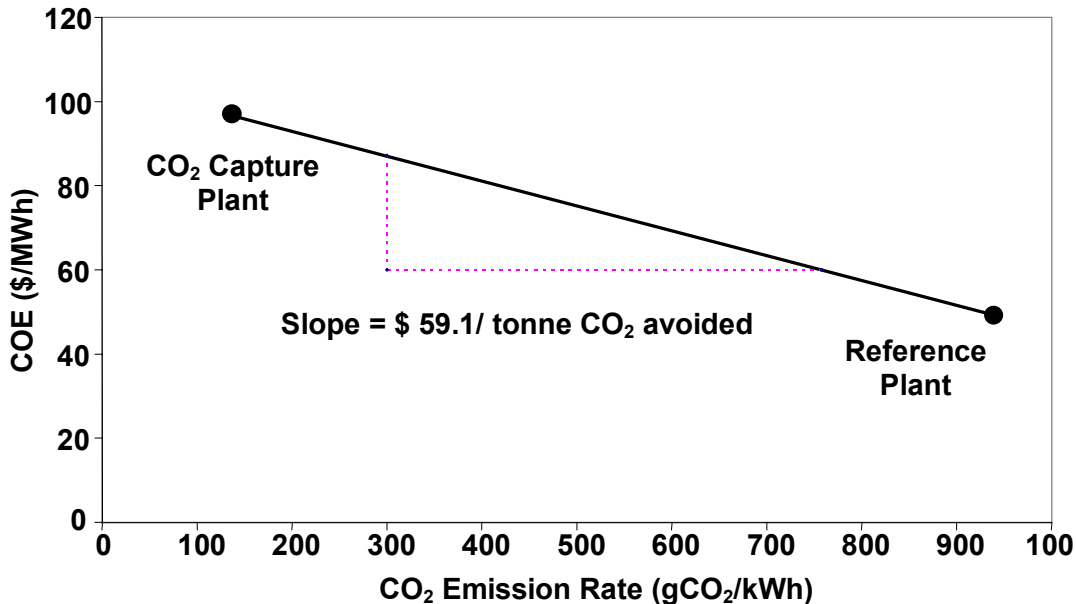


Figure 5. Nominal CO<sub>2</sub> avoidance cost for the case study coal plant (New 500 MW, Low-S coal, 75% CF)

Addition of the CO<sub>2</sub> capture system increases the total plant capital cost from \$571M (for the reference plant) to \$705M. Energy requirements consume about 27% of gross plant capacity,

mostly for solvent regeneration (49% of total) and CO<sub>2</sub> product compression (34% of total). Solvent circulation and fan power account for the remaining share (17% of total). MEA makeup requirements contribute about 10% to the cost of CO<sub>2</sub> capture. The presence of SO<sub>2</sub> impurities can substantially increase these reagent costs, so the cost of CO<sub>2</sub> avoidance is sensitive to the SO<sub>2</sub> removal efficiency of the FGD unit located upstream of the MEA system. Tradeoff studies showed that overall plant costs were minimized by reducing the SO<sub>2</sub> concentration to about 10 ppm inlet to the MEA absorber. Therefore, in this case study the SO<sub>2</sub> removal system was upgraded to 99% removal with CO<sub>2</sub> controls, as against only 70% SO<sub>2</sub> removal in the reference case. The costs of this upgrade were charged to the CO<sub>2</sub> unit.

## 6.2. Probabilistic Results

Different assumptions about power plant design, coal properties, plant operation and CO<sub>2</sub> control system design can have a significant effect on CO<sub>2</sub> mitigation costs, and are responsible for many of the cost differences found in the literature. To systematically characterize the effects of different assumptions, parameters that vary across design studies are represented here by probability distributions, with values selected based on the current literature (35) and (in some cases) the authors' judgment. Note that the term "uncertainty" is used loosely here to include parameter variability.

Figure 6a first shows the effect of considering uncertainties and design variability only in the performance parameters of the MEA system (from Table 1). The resulting distribution for cost of CO<sub>2</sub> avoidance has a 95-percentile range of \$43-72/tonne. The main contributors to this range are the lean solvent CO<sub>2</sub> loading (which determines the reboiler duty) and equivalent electrical penalty of the regeneration steam requirement. Figure 6b shows the additional uncertainty contributed by CO<sub>2</sub> cost model parameters, including the costs of the CO<sub>2</sub> capture unit, pipeline transport and geologic storage (see Table 2). Now the overall cost of CO<sub>2</sub> avoided shows a much wider range of \$33-73/tonne (95% probability interval). The dominant factor here is the assumed cost of CO<sub>2</sub> storage. The high end of the distribution corresponds to a disposal cost of up to \$8/tonne CO<sub>2</sub> stored, while the low end reflects a cost credit (revenue) of up to \$10/tonne when CO<sub>2</sub> is used for enhanced oil recovery (EOR).

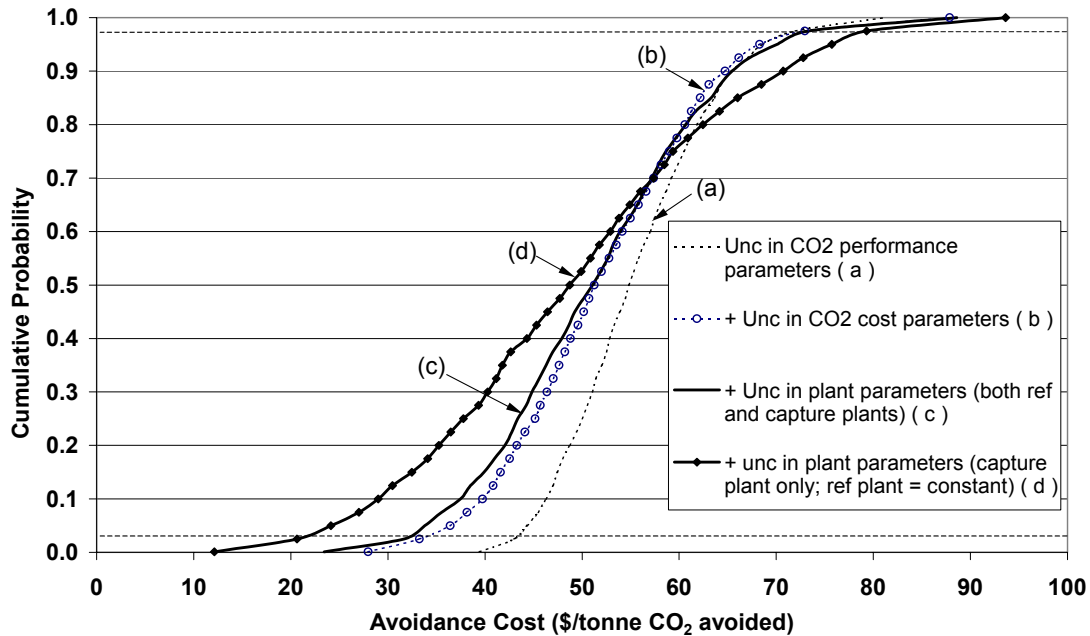


Figure 6. . Uncertainty in the cost of CO<sub>2</sub> avoided, decomposed into three parameter categories. The shaded areas at the top and bottom of the graph demark the 95% probability interval.

Figure 6c and Figure 6d show the effect of additional uncertainties (or variability) for the assumed power plant efficiency (heat rate), capacity factor, coal price, and fixed charge factor (see Table 3). If these parameter values are identical for the reference plant and capture plant (Figure 6c), the range in the CO<sub>2</sub> avoidance cost increases slightly (\$32-73/tonne), although the COE of each plant is strongly affected. However, if the capture plant is different from the reference plant (Figure 6d) the CO<sub>2</sub> mitigation cost now broadens to a much wider range of \$21-79/tonne CO<sub>2</sub> avoided (95% probability interval). The dominant factors here are the fixed charge rate and plant capacity factor, which strongly influence the COE for the overall plant, and thus the cost of CO<sub>2</sub> avoided.

Note that the tails of the overall distribution span an order of magnitude in the cost of CO<sub>2</sub> avoided. Note too that the distributions in Figure 6 are not symmetric about the deterministic value of avoided cost shown in Figure 5. This is a consequence of the distributions assumed for key model parameters like lean sorbent loading, CO<sub>2</sub> transportation and disposal cost and power plant heat rate. The median and mean cost (Figure 6c) are both \$51/tonne CO<sub>2</sub> avoided.

## 7. APPLICATIONS TO CO<sub>2</sub> RETROFITS

As discussed earlier, a large number of existing coal-fired power plants may be candidates for CO<sub>2</sub> retrofits under a sufficiently stringent climate policy. Because of multi-pollutant interactions, the cost of CO<sub>2</sub> mitigation will be affected by policies for other pollutants, especially SO<sub>2</sub>. Considering that most (~ 70%) of the current coal-based capacity in the U.S. does not have SO<sub>2</sub> scrubbers, several cases were modeled to analyze the impacts of adding post-combustion CO<sub>2</sub> capture systems to existing coal plants (see Table 5).

Table 5. Scenarios for Retrofit Studies of a 500 MW Plant

CASE	A	B	C	D
<b>Coal Type</b>	Low-S	Low-S	Low-S	High-S
<b>Existing SO<sub>x</sub> control</b>	<i>None</i>	<i>None</i>	FGD (70% removal)	FGD (~ 90% removal)
<b>Existing NO<sub>x</sub> control</b>	LNB	LNB	LNB	LNB
<b>CO<sub>2</sub> Retrofit Option</b>	MEA system	MEA system plus new FGD	MEA system plus FGD upgrade	MEA system plus FGD upgrade

Cases A and B are for a plant burning low-sulfur western coal (0.48% S, as in Table 3) with no other SO<sub>2</sub> emission controls. It complies with federal standards for plants constructed before July 1978. To reduce CO<sub>2</sub> emissions the plant can either retrofit an MEA system (Case A), or install both MEA plus a new FGD system (Case B) to reduce the input of sulfur impurities to the MEA unit. In Case C the low-sulfur coal plant is already equipped with an FGD system that meets federal New Source Performance Standards (NSPS), which in this case is 70% SO<sub>2</sub> removal. This plant has the option of upgrading the existing SO<sub>2</sub> scrubber (to 99% removal) in addition to installing an MEA system. Case D is similar to Case C except that the plant burns high-sulfur (3.25% S) eastern bituminous coal. Federal standards in this case require about 90% reduction in potential SO<sub>2</sub> emissions, achieved with a wet FGD system.

In contrast to the new plant analysis presented earlier, the retrofit scenarios assume, as a bounding case, that all existing capital equipment has been fully amortized. The cost of electricity is then determined only by plant O&M costs, plus any new capital expenditures for CO<sub>2</sub> control. The latter includes the costs of any new sulfur removal systems that are installed to minimize the cost of CO<sub>2</sub> avoidance. We also credit the CO<sub>2</sub> unit for the market value of additional SO<sub>2</sub> allowances that are generated and traded under the national acid rain control program. The remaining plant life is assumed to be at least 15 years. The base capital cost of the CO<sub>2</sub> capture unit is the same as for a greenfield site, but we then consider an additional retrofit cost premium to account for site-specific retrofit difficulties. We also assume higher plant heat rates and energy penalties in providing steam to the MEA system (see Table 1).

### 7.1. Results for Low-Sulfur Coal Plants

Figure 7 shows the deterministic results for the cost of electricity versus CO<sub>2</sub> emission rate for the three low-sulfur coal plant retrofit cases (A, B, C), plus the new plant case shown earlier. Without CO<sub>2</sub> capture, the fully amortized reference plant produces electricity at a cost that is 60-65% lower than the new plant. This lower COE reduces the cost of CO<sub>2</sub> capture when the energy-intensive MEA unit is added to the plant. The analysis also shows that for an existing facility without SO<sub>2</sub> control (Cases A and B), the addition of an SO<sub>2</sub> scrubber along with the CO<sub>2</sub> scrubber significantly reduces the cost of carbon mitigation. For a plant that already has FGD (Case C), upgrading the existing system to achieve higher sulfur removal efficiency further reduces the cost of carbon capture. These results are consistent with the design premises of other studies (26, 39, 40) that include SO<sub>2</sub> removal prior to an amine scrubber.

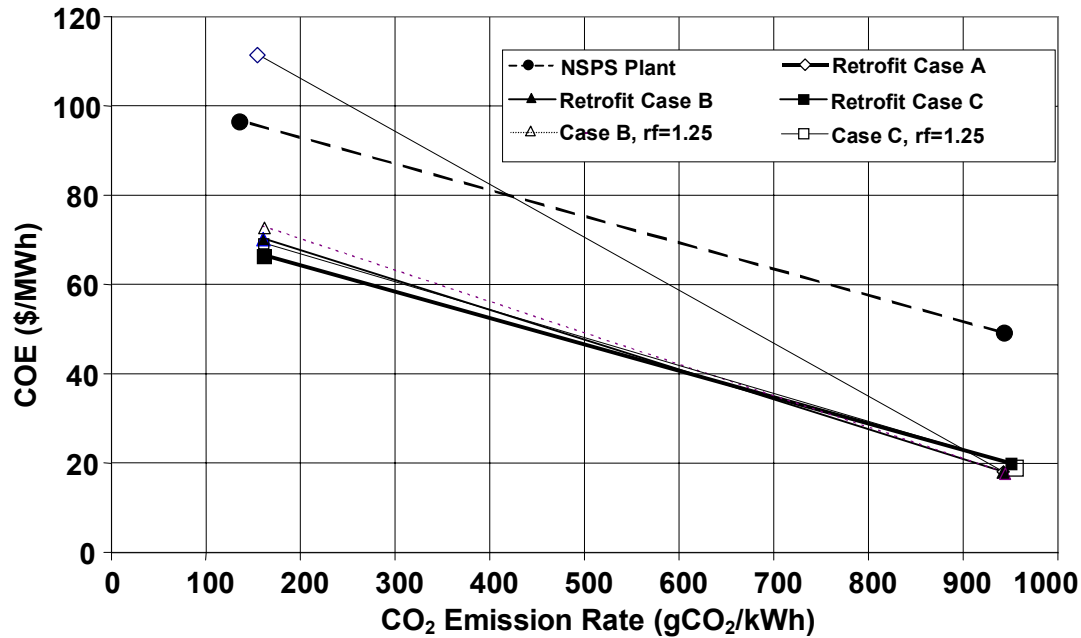


Figure 7. Estimation of CO<sub>2</sub> avoidance cost for low-S coal plants

In all cases, retrofitting the power plant with an MEA system results in substantial added reductions in SO<sub>2</sub> emissions, which is an additional environmental benefit. The interaction between SO<sub>2</sub> and CO<sub>2</sub> controls is shown in Table 6. If credits for SO<sub>2</sub> reductions at recent market prices are taken into account, the carbon mitigation cost decreases slightly, by about \$1-1.5/tonne CO<sub>2</sub> avoided. Even with SO<sub>2</sub> credits, however, the CO<sub>2</sub> mitigation cost for the retrofit plant is likely to be higher than for a new plant. This is mainly because of the much higher energy penalty resulting from limitations in efficient heat integration. Retrofit costs also are likely to be higher because of site-specific difficulties of installing new equipment at an existing plant location. Assuming a 25% capital cost premium for retrofit applications (Cases B and C with rf = 1.25 in Figure 7), adds about \$3-5 per tonne of CO<sub>2</sub> avoided. Still, the overall COE for the retrofitted plant (Cases B and C) is less than the new plant COE because of the amortized capital. Other schemes that can reduce the energy penalty costs (e.g., an auxiliary boiler system fired by low-cost natural gas) could potentially improve the economics of retrofit applications.

Table 6. Effect of SO<sub>2</sub> Controls on Carbon Mitigation Costs for the Low-Sulfur Retrofit Scenarios

Quantity	Reference Plant (no CO <sub>2</sub> control)	Case A (MEA only)	Case B (MEA + FGD)	Case C (MEA + FGD upgrade)
Net power (MW)	470	288	275	275
COE (\$/MWh)	18.0	111.8	70.4	66.7
SO <sub>2</sub> emission rate (g/kWh)	4.51	0.04	0.0004	0.0004
Total SO <sub>2</sub> emission (tonne/yr)	13,916	69	0.7	0.7
New SO <sub>2</sub> capture in FGD (tonne/yr)	0	0	13,777	7,451
New SO <sub>2</sub> capture in MEA (tonne/yr)	0	13,847	138	138

Total new SO <sub>2</sub> capture (tonne/yr)	0	13,847	13,915	7,589
Mitigation cost (\$/tonne CO <sub>2</sub> avoided)				
No SO <sub>2</sub> credit	-	118.8	67.0	59.2
\$150/tonne SO <sub>2</sub> credit	-	117.4	65.5	58.4
No SO <sub>2</sub> credit, Retrofit factor = 1.25	-	123.2	70.5	62.7

## 7.2. Results for High-Sulfur Coal Plants

CO<sub>2</sub> mitigation costs for Case D (3.25 % S coal) were again minimized by adding new FGD capacity to achieve 99% SO<sub>2</sub> removal. The COE for the fully amortized plant was 27 \$/MWh without CO<sub>2</sub> control and 75 \$/MWh with controls, yielding a nominal CO<sub>2</sub> mitigation cost of \$64/tonne avoided. The effects of SO<sub>2</sub> credits and retrofit cost premiums were similar to those for the low sulfur coal cases in Table 6.

## 8. BENEFITS OF R&D

R&D programs that improve the performance of current amine-based system can reduce the future cost of CO<sub>2</sub> capture. The Supplementary Information includes a hypothetical example in which improvements in MEA system performance, and reductions in uncertainties, produce a substantial reduction in the cost of CO<sub>2</sub> avoided. New or improved sorbents, lower regeneration heat requirements, and overall process optimization are some of the potential sources of cost reduction. Government-sponsored R&D efforts, together with industrial initiatives like the CO<sub>2</sub> Capture Project (45), are actively pursuing such goals. Our future modeling research will seek to realistically estimate potential process improvements, and apply those results to quantify potential R&D benefits and priorities.

## 9. DISCUSSION

The present study has established a framework for quantifying the impacts of carbon capture and sequestration technology on power plant performance, emissions and economics. For amine (MEA)-based absorption systems applied to coal-fired power plants, the cost of carbon avoidance was shown to depend strongly on assumptions about the reference plant design, details of the CO<sub>2</sub> capture and storage system designs, and interactions with other pollution control systems. Climate mitigation policy models that overlook or oversimplify these factors may produce misleading results regarding the feasibility and cost of CO<sub>2</sub> capture and sequestration options.

The presence of acid gas impurities like SO<sub>2</sub> and NO<sub>2</sub> in power plant flue gas was seen to adversely affect the performance and cost of the CO<sub>2</sub> removal system. Adding or upgrading an FGD unit to remove SO<sub>2</sub> was essential to minimize the cost of carbon mitigation. The presence of NO<sub>x</sub> had a much smaller effect on CO<sub>2</sub> capture costs since most NO<sub>x</sub> is NO, not NO<sub>2</sub>. Because of such interactions, more stringent future regulation on SO<sub>x</sub>, NO<sub>x</sub> and other emissions (e.g., for control of PM<sub>2.5</sub>, ozone, air toxics or acid rain) could make subsequent carbon capture less expensive (at the margin), thus integrating local and regional air pollution policies with the global issue of climate change.

An analysis of retrofit options found that the large energy requirements of CO<sub>2</sub> capture lead to a more substantial loss of plant capacity compared to a new plant affording better heat integration. Site-specific difficulties may further increase the capital cost of a retrofit installation. Thus, the overall cost of CO<sub>2</sub> capture is likely to be greater than that of a new plant, despite the lower cost of electricity for plants that are fully or partially amortized, or the potential credits for new SO<sub>2</sub> reductions accompanying CO<sub>2</sub> controls.

The large plant derating resulting from amine-based CO<sub>2</sub> controls also will significantly affect the capacity planning decisions of electric utilities if this technology is widely implemented. Analysis of these system-wide effects on future capacity requirements, technology choices, demand projections, costs, and CO<sub>2</sub> emissions require a more comprehensive modeling framework (46), but must be part of any large-scale policy analysis of CO<sub>2</sub> capture and sequestration technologies.

Finally, an important feature of the study is that it takes into account the uncertainties and variability in key performance and cost parameters that influence the cost of carbon mitigation. Understanding the nature of these uncertainties, and the potential for reducing them, is crucial to projecting future costs and capabilities of new technologies for carbon capture and sequestration. A characterization of potential R&D benefits is the subject of ongoing analysis.

## 10. SUPPLEMENTARY INFORMATION

Additional details accompanying this paper can be found in an attachment (referenced as [45] throughout the report). The attachment is in draft form and will be resubmitted in final form when it is completed..

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