Coal Initiative Reports

White Paper Series

► A Program to Accelerate the Deployment of CO_2 Capture and Storage (CCS): Rationale, Objectives, and Costs

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Contents

Executive Summary

This White Paper analyzes one strategy for accelerating the deployment of carbon capture and storage (CCS) by the coal-fueled electricity-generation industry. This strategy involves providing reimbursement for the incremental costs of installing and operating CCS systems, with reimbursement provided for:

1. Retrofitting some existing commercial-scale (500+ MW net capacity, before installation of CCS) coal-fueled electric generation plants with CCS and operating these for five years;

2. Incorporating CCS into some new, commercial-scale (400+ MW net capacity, after installation of CCS) coal-fueled electric generation plants and operating these for five years; and

3. Launching large-scale (1 to 3 million metric tons per year) demonstrations of geologic storage of carbon dioxide (CO_2) primarily in saline formations and operating these for five years, using CO_2 from non-utility industrial sources.

The paper sets forth two alternative sets of objectives and outcomes for such a cost reimbursement program, based on program size. The objectives of the Smaller-Scale Program (10 commercial-scale demonstrations of CCS at coal-fueled electric power plants, plus five CCS demonstrations using CO_2 from other industrial sources) would be to establish reliable CCS cost and performance data, and to build experience with CCS. The objectives of the Larger-Scale Program (30 commercial-scale demonstrations of CCS at coal-fueled power plants plus 10 demonstrations of CCS using CO_2 from other industries sources) would be much more ambitious. Here the objectives are to achieve significant reductions in CO_2 capture costs and energy penalties, build broad public acceptance of CO_2 storage, and promote the timely development of CCS regulatory systems, in addition to establishing reliable cost and performance data and experience with CCS.

Given current levels of electricity generation from coal-fired plants of about 2,000 billion kWh per year, and assuming a ten-year program, "first order" cost estimates are:

- **Smaller-Scale Program:** Total cost of $8.0 to $10.2 billion. This could be funded by ten years of fees of $0.0004 to $0.0005 per kWh on coal-fueled power plants plus $0.50 per metric ton of CO_2 emitted from other industrial sources, or by some other means.

- **Larger-Scale Program**: Total cost of $23.5 to $30.1 billion. This could be funded by ten years of fees of $0.0012 to $0.0015 per kWh on coal-fueled power plants plus $1.00 per metric ton of CO_2 emitted from other industrial sources, or also by some other means.

Other options for supporting accelerated deployment of CCS are discussed in the Pew Center Coal Initiative white paper, *A Trust Fund Approach to Accelerating Deployment of CCS: Options and Considerations,* by Pena and Rubin (2007). Options considered in that paper include use of proceeds from auctions of allowances under a cap-and-trade program; provision of extra allowances to entities that store CO_2 in geologic reservoirs; and use of loans, loan guarantees, or tax credits.

The program cost estimates provided draw-on-data at the time of preparing this report. Estimates of the costs of deploying CO_2 capture with coal-fueled power plants and the attendant energy penalties are changing continually. Increasing labor costs and prices for basic materials result in upward revisions while improvements in capture technologies and system integration lead to lower cost estimates. Until the first commercial-scale CCS plants are built and in operation, all such estimates are "first order" approximations. A major benefit of the envisioned program would be a better understanding of costs, including energy penalties and reliability.

Total program costs, particularly for the Larger-Scale Program, are likely to be lower than those stated above for several reasons. As results of R&D and "learning" become incorporated into second, third, and fourth generation plants, future CO_2 capture plants would have lower costs. Second, any per kWh fees used to fund the program would decline over time if electricity generation from coal-fueled plants increases as forecast. If the Larger-Scale Program is undertaken and succeeds in significantly reducing costs, the national economic benefits would be substantial. Assuming wide-scale deployment of CCS occurs in the post-2020 time period, as a result of a mandatory national greenhouse gas-reduction program, implementing the Larger-Scale (30 Plant) Program would reduce the costs of installing CCS by $80 to $100 billion.

Introduction

This White Paper is one of a series of Pew Center papers that explores strategies for addressing CO_2 emissions from using coal to provide electricity. The strategy described in this paper involves providing reimbursement to cover the incremental costs of early deployment of CO_2 capture and storage (CCS). The paper describes objectives, possible program scales, and costs for a program that would use this strategy to remove existing barriers and thus accelerate deployment of CCS at coal-fueled electric power plants.

This paper has been written in coordination with a companion paper that considers the establishment of a CCS Trust Fund to provide the funding and institutional structure for launching and operating a program of the type described in the following pages. The Pew Center Coal Initiative white paper, *A Trust Fund Approach to Accelerating Deployment of CCS: Options and Considerations,* by Pena and Rubin (2007), also considers alternative funding options, including use of proceeds from auctions of allowances under a cap-and-trade program; provision of extra allowances to entities that store CO_2 in geologic reservoirs; and use of loans, loan guarantees, or tax credits. Additional strategies for accelerating deployment of CCS in the coal-based electricity sector are considered in the other Pew Center Coal Initiative papers. Complementary Pew Center initiatives explore options for addressing CO_2 emissions throughout the economy.

CO_2 capture and storage is currently the only technological approach that shows promise for enabling the United States to continue to rely on its vast coal reserves to provide electricity while, at the same time, achieving sufficient carbon dioxide (CO_2) emission reductions to address climate change. However, at current rates of technology progress and deployment, CCS will not be utilized by power companies at a meaningful level for many decades. This paper assumes that, at some point in time, national legislation will require steep reductions in CO_2 emissions from the electricity sector—reductions likely to be possible for coal-based electricity generation only with CCS—but makes no assumptions about the specifics of the policies that would require such reductions.

A decades-long delay in deployment of CCS will have serious negative consequences for efforts to address U.S. greenhouse gas (GHG) emissions because about one-third of U.S. emissions result from coal-fueled electricity generation (EIA, 2006). A delay may also have serious negative impacts on coal's ability to compete in the electric power sector under future climate-change policies (Pena and Rubin, 2007). Finally, a delay in deployment of CCS may result in a significant burden to the nation's economy due to the higher costs likely to be in place at the time large-scale deployment is undertaken—if the cost-reduction benefits of R&D and "learning" suggested in this paper have not been realized.

Building and operating an electricity-generation plant with CO_2 capture costs more than doing so without CO_2 capture. If commercial-scale CCS plants are to be built and operated in the near term—i.e., until policies require CCS or render it cost-competitive by constraining carbon-dioxide emissions—a mechanism is needed to enable these plants to compete with non-CCS power plants. One way to do so is to cover the incremental costs of installing and operating CCS at new or retrofitted coal-fueled power plants.

Absent an Apollo-like program, it is unlikely that the funding for installing and operating CCS at a significant number of commercial-scale electricity generation plants would be available from current or anticipated federal budgets. Thus an alternative source of funds would be needed to render support revenue-neutral.

This paper explores the costs of programs, including per plant and per kWh costs, that would reimburse the incremental costs of deploying CCS at coal-fueled power plants. An accompanying Pew Center Coal Initiative white paper, *A Trust Fund Approach to Accelerating Deployment of CCS: Options and Considerations*, by Pena and Rubin (2007), describes a per-kWh fee approach in greater detail, suggests other possible sources of funding, and presents an institutional mechanism that could be entrusted with revenues and could administer a program of the type described in this paper.

In addition to the high cost and energy penalty burdens of CCS, a series of other barriers hinder near-term adoption of CCS at coal-fueled electricity-generation plants. These barriers include lack of full-scale experience with CO_2 capture at coal-fired plants, and lack of an accepted regulatory system for CO_2 storage that reflects broad public acceptance of this option as a key greenhouse gas mitigation strategy. The ultimate goal of the program described in this paper is to help overcome all of these barriers, thus supporting accelerated deployment of CCS.

The size of a program will determine which objectives can realistically be met and which barriers can be overcome. For example, a Smaller-Scale Program would be valuable for addressing two objectives:

1. Building confidence and experience in selecting, designing and operating integrated CO_2 capture and storage systems; and

2. Establishing reliable cost and performance expectations for key generation, CO_2 capture technology, and coal-type combinations.

Ten or so demonstrations of commercial-scale CCS at coal-fueled plants, plus five demonstrations of CO_2 storage in saline formations, using CO_2 from other industrial sources, should be adequate to achieve these first two objectives.

A Larger-Scale Program, in addition to achieving the above two objectives, could have a significantly larger impact by:

1. Lowering the high capital costs of installing CO_2 capture technologies;

2. Reducing the high-energy requirements and loss-of-power-generation output resulting from operating CO_2 capture systems; and

3. Building broad public acceptance of CO_2 storage, founded on rigorous site assessment methodologies and standards.

The paper suggests that these three additional objectives could be achieved by launching approximately 30 commercial-scale demonstrations of coal-fueled power-generation units—with a total of about 12,000 MW of net capacity—plus 10 large-scale demonstrations of geologic sequestration, using CO_2 from other industrial sources.

If widespread deployment of CCS is needed starting sometime after 2020, there will be significant advantages to having built and operated 30 commercial-scale plants by that time. There is a vast body of scientific evidence that a concerted program of investment in research and large-scale demonstrations of a new technology will bring down costs, particularly if the benefits of R&D and "learning" are integrated over several generations of technology installation.

Assuming today's state of the art technology is "first generation," the author's assessment is that it will require three more "generations" of technology (about 30 commercial-scale plants) to significantly reduce CO_2 capture costs and energy penalties. Achieving such reductions within the next 10 to 15 years would enable widespread deployment of CCS to occur more rapidly and at much lower costs beyond 2020, thus providing cost savings and emission reductions that would far outweigh program costs.

Current electricity forecasts suggest that as much as 275,000 MW of new coal-fueled power-generation capacity may be required by 2050 (Kuuskraa, 2007). If such forecasts prove accurate, and national legislation requires steep reductions in CO_2 emissions from the electricity sector, a program that significantly reduces CCS costs within the next 10 to 15 years could result in cost savings of $100 billion. If a program is able to achieve less optimistic cost reductions from "learning," the savings will still be substantial, estimated at $80 billion.

The program proposed in this paper would:

1. Reimburse the costs to purchase and install CCS systems at 10 to 30 power plants and operate these systems for five years, including reimbursing power output capacity loss due to operation of CCS.

2. Ensure reimbursement for demonstrations of each of the main power generation and capture options, coal types, and geographic regions;

3. Limit reimbursement to a maximum of three plants per year to gain as much as possible from "learning by doing" and R&D advances;

4. Build confidence in geologic storage of CO_2 by supporting 5 to 10 large-scale demonstrations of CO_2 storage using CO_2 from industrial sources, with the great bulk of these in saline reservoirs;

5. Capture and store some 36 to 100 million metric tons (MMT) of CO_2 per year, depending on program scale, once 4 to 12 GW of coal-fired power capacity is installed with CCS; and

6. Cost a total of $8.0 to $10.2 billion ($U.S. 2006) for 10 demonstrations and $23.5 to $30.1 billion ($U.S., 2006) for 30 demonstrations of CCS at coal-fueled power plants (including 5 to 10 demonstrations of storing CO_2 from industrial vents).

The program includes support for CO_2 storage projects using industrial CO_2 sources (in addition to commercial-scale demonstration of CCS at coal-fired power plants) in order to gain experience with large-scale storage in saline formations at the earliest possible date. Such early experience is critical to building confidence in the viability of large-scale CO_2 storage in saline and other geologic reservoirs.

A program such as the one described in this paper, which supports commercial-scale deployment of CCS at a significant number of coal-fueled plants and other industrial sites, would complement U.S. Department of Energy initiatives, including the smaller-scale sequestration demonstrations under the Regional Sequestration Partnerships, ongoing R&D on generation and capture technologies, and FutureGen. The program could be funded, for example, by per-kWh charges on coal-fueled power plants and per-ton CO_2 emissions charges on large industrial emitters.

- A 10-plant program implemented over 10 years could be supported by fees of approximately $0.0004 to $0.0005 (4 to 5 hundredths of a cent) per kWh of electricity generated. For a 30-plant program implemented over 10 years, fees would be approximately $0.0012 to $0.0015 (slightly more than one-tenth of a cent) per kWh of electricity generated. These per-kWh fees are based on the current 2,000 billion kWh/yr of coal-fired electricity generated in the U.S.

- Approximately $0.50 to $1 per metric ton of CO_2 emitted from large industrial plants—those with CO_2 emissions of 100 million metric tons per year—would be sufficient to cover the costs of the 5 to 10 large-scale demonstrations of storing industrial CO_2, primarily in saline formations.

Coal-Fueled Power Plants: CO_2 Emissions and Reduction Options

No realistic strategy for addressing global warming can ignore the large volume of CO_2 emitted by coal-based electric-power generation—the "800 pound gorilla" of CO_2 emissions. A number of options are being pursued that would help reduce CO_2 emissions from the electric power sector, including stimulating greater use of renewables, nuclear energy, and energy efficiency, and building a new fleet of higher-efficiency power plants. However, if the United States is to address global climate change in a meaningful way, while continuing to rely on its vast reserves of coal to provide electricity and other forms of energy, capture and storage of CO_2 emissions from coal-fueled power becomes a primary option.

CURRENT AND PROJECTED CO_2 EMISSIONS FROM COAL-FUELED POWER PLANTS. Coal-fueled electric power plants are the largest single stationary source of CO_2 emissions in the United States, emitting nearly 2,000 million metric tons of CO_2 per year to the atmosphere (EIA, 2006), and accounting for a third of all U.S. CO_2 emissions. Moreover, in the absence of a national mandatory CO_2 reduction policy, the volume of these CO_2 emissions is expected to grow substantially, to over 2,900 million metric tons in 2030, and 3,400 million metric tons in 2050. (See Table 1).

Table 1. U.S. Carbon Dioxide Emissions by Source: Reference Case (Million Metric Tons)

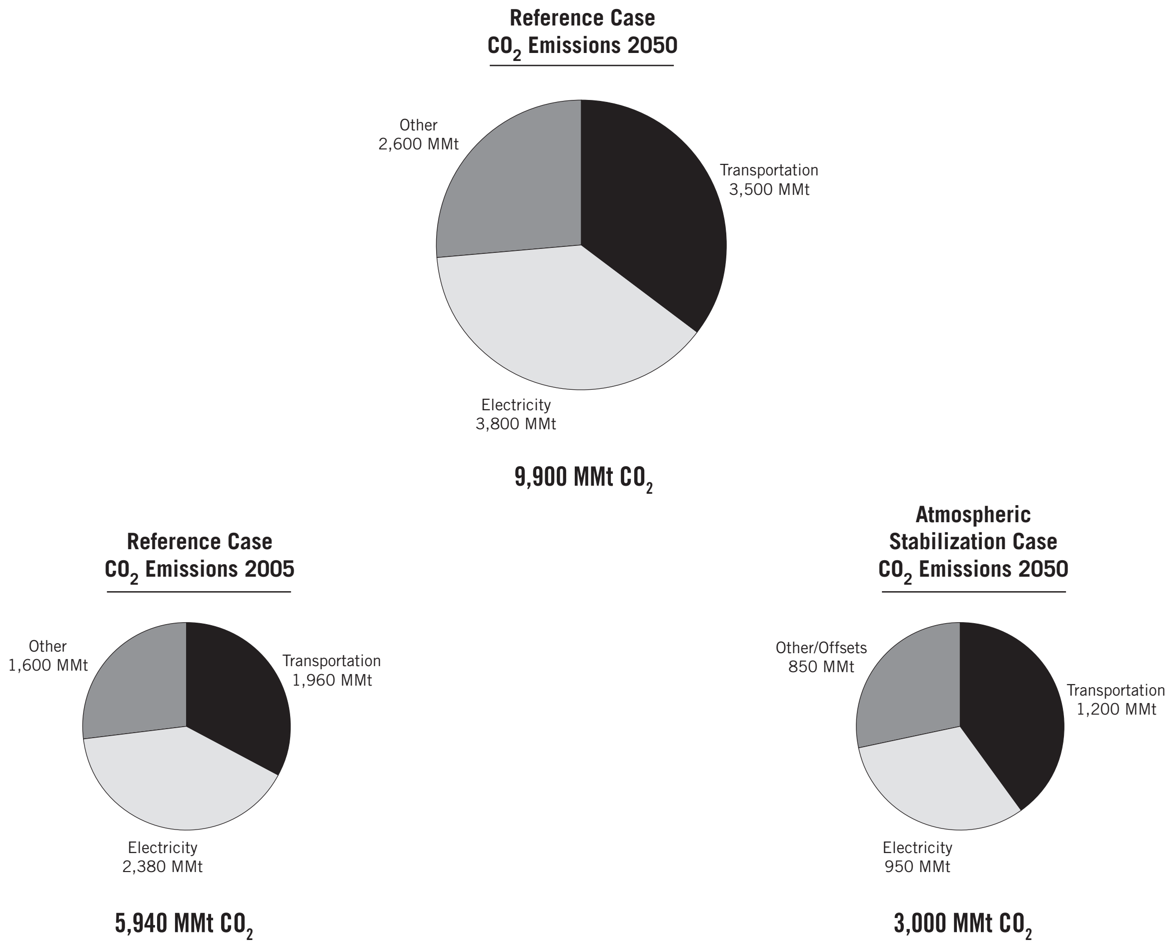
	Coal-Fueled Power Plants	Electric Power	Total U.S. CO_2 Emissions
2005	1,944	2,375	5,945
2015	2,203	2,677	6,589
2030	2,927	3,338	7,950
2050	3,400	3,800	9,900

Sources: EIA Annual Energy Outlook 2007 for years 2005-2030. Kuuskraa, V.A., and J.P. Dipietro (2007), for years 2031-2050.

If the U. S. electricity sector is to contribute its share to atmospheric stabilization of CO_2 concentrations at 550 ppm by the middle of this century[1], U.S. CO_2 emissions in the electricity sector will need to decline to below 1,000 million metric tons per year, less than half of current levels. With CO_2 emissions estimated at 3,800 million metric tons from the electricity sector in 2050, a reduction of over 2,800 million metric tons per year would be required to meet this atmospheric stabilization goal, as illustrated in Figure 1.

[1] The White Paper recognizes that considerable debate exists as to the level of reductions in U.S. CO_2 emissions that would be appropriate for achieving atmospheric stabilization of CO_2 concentrations at 550 ppm. For purposes of the analysis, this paper draws on previous work for selecting a U.S. emissions reduction target (Dipietro and Kuuskraa, 2006). Based on this previous work under the atmospheric stabilization case, total U.S. CO_2 emissions in year 2050 would be reduced in half from current levels and U.S. electric power generation would be about 70% de-carbonized.

Figure 1. Domestic CO_2 Emissions—Reference Case and Atmospheric Stabilization Case



Source: DiPietro, J.P., Kuuskraa, V.A., and Forbes, S., "Examining Technology Scenarios for Achieving Atmospheric Stabilization of GHG Concentrations: A U.S. Pathway" (updated) presented at 8th International Conference on Greenhouse Gas Technologies (GHGT-8), 19th-22nd June 2006, Trondheim Norway.

MMt=million metric tons.

A close look at the coal-based portion of the power generation sector reveals that the existing domestic coal-based power plant fleet is old and has a high CO_2 emissions intensity. Of the 315,000 MW of existing coal-based power generation capacity, one-third was installed prior to 1970. These older power plants have an efficiency factor of only 28% (HHV basis) and emit nearly 1.2 metric tons of CO_2 per MWh. In contrast, the 12,000 MW of coal-based power plants built since 1990 with newer technology have an efficiency factor of 39% and emit about 0.8 metric tons of CO_2 per MWh. Table 2 provides a snapshot of the domestic coal-based electric power plant fleet by vintage of plant installation.

Table 2. Existing Domestic Coal-Based Power Plant Fleet

Plant Installation	Capacity (GW)	Efficiency (%, HHV)	CO_2 Emissions (MMt/Yr)	CO_2 Intensity Mt/MWh
Pre-1970	109	28%	600	1.16
1970-1989	194	36%	1,280	0.90
1990-2003	12	39%	70	0.83

Source: Kuuskraa, V.A., and J.P. Dipietro (2007)

MMt = million metric tons

CO_2 CAPTURE AND STORAGE (CCS) OPTIONS FOR UTILITIES. CO_2 can be captured from coal-fueled plants either prior to or after combustion of the fuel and then stored in geologic formations. This process is called CCS. Post-combustion capture technologies are applicable to plants that combust coal using air or oxygen. Pre-combustion options are used in plants that first gasify the coal, and then separate and capture the CO_2 prior to burning a low-carbon or carbon-free H_2 fuel. Because capture technology is still evolving, and prices of materials are escalating, considerable uncertainty and debate exist as to what combination of power generation, coal type, and CO_2 capture technology will ultimately be the most cost-effective.

The current fleet of coal-fueled plants consists almost exclusively of plants that combust pulverized coal (PC) in air. Experience with oxygen-fired combustion for electric power generation is still at early stages of development, and power industry experience with coal gasification plants is limited, although fossil fuel gasification is used widely in other industries. For the next generation of plants, the CO_2 capture options will likely include advanced post-combustion capture for air-fired, super-critical PC (SCPC) plants, and pre-combustion capture for integrated gasification combined cycle (IGCC) plants.

Given current and foreseeable new plants, the three main opportunities for using CCS to lower CO_2 emissions from U.S. coal-based power generation are:

1. Re-power[2] the pre-1970 plants (109 GW of capacity);

2. Add CO_2 capture and storage (CCS) to the more modern (post-1970) coal-fired plants (206 GW of capacity); and

3. Incorporate the most cost-effective and energy efficient CO_2 capture option for the new generation of coal-fueled power plants.

[2] Re-powering a coal plant involves replacing an old, inefficient power generation unit, such as a sub-critical unit, with a higher efficiency power generation unit, such as an ultra-critical unit or an IGCC plant, while keeping much of the basic infrastructure in place.

However, capturing CO_2 from new coal-fueled plants would significantly increase the cost of electricity. Included in these higher electricity costs is the energy penalty (loss of plant efficiency, reflected as a reduction in net power output for a fixed energy input) of 25% to 30% for new air-fired PC plants and 15% to 25% for new IGCC plants (see Appendix A).

For CCS to be deployed on a significant scale, assurance is needed that adequate capacity exists in geologic formations where CO_2 can be reliably and safely stored. Current international experience with geologic storage—at Sleipner, Weyburn, and In Salah—indicates that CO_2 can be stored without leakage when a suitable reservoir has been selected. The United States has significant experience with injecting and storing CO_2 in oil fields. However, while oil (and gas) fields may provide the initial storage capacity for CO_2, saline reservoirs—the least understood of the geologic storage options—will likely be the dominant long-term option.

The United States is fortunate in having a large and diverse set of geologic options for storing CO_2. Depleted domestic oil and gas reservoirs have an estimated storage capacity of 80 gigatons (Gt) of CO_2; unmineable coal seams add another estimated 180 Gt. Deep saline formations, the largest of the CO_2 storage options, contain hundreds of Gt of capacity (NETL, 2007). Assuming the science, public acceptance, regulatory and liability issues that surround geological storage of CO_2 are favorably resolved, there is sufficient capacity to store CO_2 from U.S. coal-fueled electric generation plants in domestic geologic formations for the next several hundred years.

Other Industries: CO_2 Emissions and Reduction Options

High-CO_2 concentration releases from a variety of industrial plants constitute a smaller, but still significant, source of U.S. CO_2 emissions. These include emissions from natural gas processing plants, hydrogen plants at refineries, ammonia and fertilizer facilities, and a variety of chemical, cement, and steel plants. Adding to this list is the growing number of alternative fuel plants, including ethanol plants and plants that produce a variety of products via gasification or liquefaction of coal, coke or biomass. These releases include very high purity CO_2 sources (e.g., natural gas and H_2 plants) and somewhat lower-purity CO_2 sources (e.g., cement and aluminum plants).

CURRENT AND PROJECTED CO_2 EMISSIONS FROM OTHER INDUSTRIES. Currently, high CO_2 concentration industrial releases account for about 120 million metric tons of CO_2 emissions per year (2% of all year 2006 U.S. CO_2 emissions). These emissions are expected to increase significantly, particularly from coal-to-liquids plants, as shown in Table 3.

Table 3. High-Concentration CO_2 Emissions from Industrial Sources (Million Metric Tons)

Source of Emissions	2005	2020	2050
Natural Gas and Helium Processing	30	45	52
Ethanol	1	4	5
Hydrogen	16	21	29
Ammonia and Fertilizer	15	22	29
Cement	47	63	89
Aluminum	5	8	10
Coal Liquids and Gasification	6	40	267
TOTAL	**120**	**203**	**482**

Source: DiPietro, J.P., Kuuskraa, V.A., and Forbes, S. (2006); updated for CO_2 emissions from ethanol.

CO_2 CAPTURE, STORAGE, AND USE OPTIONS FOR INDUSTRIES. An attractive feature of CO_2 emissions from the industrial sources listed in Table 3 is that the high-concentration CO_2 is generally a normal output of the production process and in certain cases does not require much, if any, further separation. Consequently these emissions can be captured at much lower incremental costs than CO_2 emissions from power plants where CO_2 separation is an extra, and expensive, step.

Industrial CO_2 is already being captured and productively used in small-volume/short-time horizon situations by the beverage industry for carbonation of soft drinks and mineral water, in fire extinguishers, and certain other products. A few power plants capture small slip-streams of CO_2 for sale into these markets. This captured CO_2 needs to be highly pure, is transported by truck, and commands a high value. Except for demonstrating that CO_2 can be captured, purified, and transported with technology available today, this high-cost, small volume capture of CO_2 which once used is quickly released into the atmosphere, provides little value for accelerating widespread, large-scale deployment of CCS in the coal-based power sector.

Much larger volumes of industrial CO_2 are being captured and used today in the enhanced oil recovery (EOR) market. Table 4 shows that approximately 10 million tons of industrial CO_2 is being sold and productively used in the oil fields of the United States and Canada. The primary sources of this industrial CO_2 include a coal gasification plant in North Dakota, a variety of natural gas processing plants (in Michigan, Texas and Wyoming), and a fertilizer plant in Oklahoma.

Table 4. CO_2-EOR Projects Sequestering U.S. Anthropogenic CO_2

		CO_2 Supply			
State/ Province	**Plant Type**	**MMcfd**	**MMt/Yr**	**EOR Fields**	**Operator**
Texas	Gas Processing	75	1.4	Sharon Ridge, Sacroc, Others	ExxonMobil, KinderMorgan
Colorado	Gas Processing	60	1.2	Rangely	Chevron
Wyoming	Gas Processing	180	3.5	Patrick Draw, Lost Solider, Wertz, Others	Anadarko
Michigan	Gas Processing	15	0.3	Dover	Core Energy
Oklahoma	Fertilizer	35	0.6	Purdy, Sho-Vel-Tum	Anadarko, Chaparral
North Dakota	Coal Gasification	145	2.8	Weyburn (Canada)	EnCana, Apache
TOTAL		**510**	**9.8**		

Source: Kuuskraa, V.A. (2007); MMt = million metric tons; MMcfd = million cubic feet per day

According to industry sources, essentially all of the industrial CO_2 purchased and used for enhanced oil recovery (EOR) to date still remains in oil reservoirs. CO_2 is a valuable commodity and the largest single cost factor in CO_2-based EOR. Consequently, CO_2 use is tracked, and operators capture and re-inject the CO_2 that is produced with oil. Depending on operator practices, at the end of a CO_2-EOR project, most to essentially all of the originally purchased CO_2 will remain trapped in the oil reservoir. CO_2 not trapped in the reservoir may be used in a nearby oil reservoir or sold to another CO_2-EOR operator, except for small amounts that may leak or escape during oil recovery operations.

The EOR market provides a substantial potential demand for CO_2 estimated at 20 Gt given current technologies and CO_2-EOR practices, with a demand for 8 to 12 Gt of CO_2 at current oil prices (Table 4). "Next Generation" CO_2 injection and storage technology, plus incentives for storing CO_2, could expand the market for CO_2 in domestic oil fields to 40 to 50 Gt. While the price for CO_2 use (and storage) in the EOR market varies greatly, and fluctuates depending on world oil prices, it generally ranges from $20 to $30 per metric ton, delivered to the oil field at pressure. Large-scale availability of captured CO_2 needing to be stored could depress the CO_2 price offered by the CO_2-EOR market.

The domestic EOR market for CO_2 is geographically dispersed, with oil fields in Texas, California, the Rockies, and Alaska each providing significant demand for CO_2. Operators in numerous other states, such as Illinois, Kentucky and Montana, are also looking to use CO_2 for enhanced oil recovery. In the near term, industrial CO_2, which often has an advantage of proximity to favorable oil fields, will need to compete with natural CO_2 for market-share. However, natural sources of CO_2 are limited. Consequently, a viable market should continue to exist for industrial CO_2.

Table 5. Potential Market for Purchased CO_2 (Ten Basins/Areas)

	Technically Recoverable	Market for Purchased CO_2	
Basin/Area	(Billion Barrels)	Trillion Cubic Feet (Tcf)	(Billion Metric Tons)
1. Alaska	12.4	51.4	2.7
2. California	5.2	23.9	1.3
3. Gulf Coast	6.9	33.3	1.8
4. Mid-Continent	11.8	36.3	1.9
5. Illinois/Michigan	1.5	5.7	0.3
6. Permian	20.8	95.1	5.0
7. Rockies	4.2	27.5	1.5
8. Texas, East/Central	17.3	62.0	3.3
9. Williston	2.7	10.8	0.6
10. Louisiana Offshore (Shelf)	5.9	31.0	1.6
Total	**88.7**	**377.1**	**20.0**

Source: Advanced Resources International, Inc. (2006)

The Two-Part Program to Accelerate Deployment of CCS

This White Paper suggests that a program to accelerate commercial-scale installation of CO_2 capture technology and build greater public acceptance of CO_2 storage should consist of two complementary parts.

1. TACKLING THE "800 POUND GORILLA." At the heart of the first part of the program is a set of actions that would help overcome two critical barriers to commercial-scale deployment of CO_2 capture and storage at coal-fueled electric power plants. These are:

- **Lack of Experience and Reliable Cost Data.** The current experience with building and operating integrated CO_2 capture and storage systems is insufficient to build confidence in the technologies and determine realistic costs and performance data for commercial-scale CO_2 capture plants.

- **High Capital and Energy Penalty Costs.** The cost of adding CO_2 capture can increase overall power plant capital costs by 20 to 25%. The high energy requirements for operating CO_2 capture systems can reduce power generation output by 15% to 30%. Together, these can increase the total costs of electricity generated by 40 to 70% per MW.

The smaller-scale program proposed in this paper would primarily address the barriers of lack of experience and lack of reliable cost and performance data. The larger-scale program would provide experience and more reliable data and also lead to lower capital and energy penalty costs for CO_2 capture. Additional barriers to CCS and how they might be addressed are briefly discussed in the final section of this paper, and more extensively in the Pew Center Coal Initiative paper, *State Options for Low-Carbon Policy,* by Bushinsky et al. (2007).

The critical barriers described above can be overcome through a program that covers the incremental costs of:

a. Adding post-combustion CO_2 capture and storage to existing or new air-fired pulverized coal (PC) power plants;

b. Adding oxygen-firing to existing or new PC units as part of an integrated CO_2 capture system;

c. Adding pre-combustion CO_2 capture and storage to new integrated gasification combined cycle (IGCC) power facilities;

d. Adding CO_2 capture systems when older, low-efficiency PC power plants are re-powered to higher efficiency PC or IGCC facilities; and

e. Operating and maintaining such CCS systems for five years.

2. PICKING THE "LOW HANGING FRUIT." The second part of the program entails picking the "Low Hanging Fruit." Here, the objective is to take advantage of early, relatively low-cost opportunities to capture and store CO_2 from high concentration industrial releases. This would provide experience with CO_2 storage before commercial-scale coal-based plants with CCS are ready for operation and help expand the infrastructure for geological storage. Whereas significant volumes of CO_2 could be available from high CO_2 concentration industrial releases within a year of program inauguration, it is likely to take on the order of five years before commercial-scale coal-fueled electric generation plants capturing one to three MMT of CO_2 per year would be in operation.

Since many of the high-CO_2 concentration releases require only limited processing and compression to achieve "storage-ready" CO_2, the CO_2 can also be captured at lower incremental costs than CO_2 from a power plant. To build the experience base of storing CO_2 in saline reservoirs, the bulk of the industrial CO_2 storage projects supported should involve such reservoirs. For any remaining CO_2 storage projects involving industrially vented CO_2, the CO_2 could be sold into the CO_2-EOR market, helping defray some or even all of the costs.

This second component of the program would help build the technical and regulatory readiness essential for broad public acceptance of CO_2 storage in saline reservoirs. Due to expected benefits from "learning by doing," and from extending pipeline infrastructure, this second program component may also lead to lower storage system costs while reducing U.S. CO_2 emissions.

Costs of Installing CCS at Power Plants

Given the objectives set forth above, the critical question is—*how much money would be needed for a program designed to accelerate commercial-scale demonstrations of CCS?* To answer this question, one needs to know both costs per plant and the number of plants to be supported. This section provides estimates of the incremental costs of installing CCS at a power plant. The following section examines two of the many possible answers to the question of how many commercial-scale demonstrations should be supported.

At this time, no commercial-scale coal-fueled electric power plant operates with CCS. Consequently, all cost estimates are based on engineering studies. Such studies are continually undergoing review and revision as prices of basic materials such as steel rise, as labor costs rise, and as new developments in capture technologies and process designs come to the forefront. Consequently, the cost estimates provided should be viewed as "first order" estimates.

Given the urgency of the challenge and available technological options, it is important to demonstrate CO_2 capture options at commercial scale for all key generation options in a variety of locations and settings. Commercial-scale is defined as operating CCS to capture the emissions of a 400 MW plant (net electrical output, after energy consumption for CO_2 capture)[3]. For an industrial CO_2 storage project, commercial-scale is defined as a project that stores one to three million metric tons of CO_2 per year.

The first three sub-sections below discuss "baseline", alternative, and averaged estimates of the incremental capital and operating costs of CCS systems at SCPC and IGCC electric power plants. Sub-section 4 provides information on costs to transport and inject CO_2 into geologic formations. Sub-section 5 provides estimates of the incremental costs for conducting carbon storage demonstrations using other (non-utility) industrial sources of CO_2.

1. What Will Be the Cost of Adding CCS to a Commercial-Scale Coal-Fueled Power Plant? A host of studies and estimates exist on this most difficult and elusive of questions—what is the "cost" of CCS? There are large uncertainties in these studies and the cost estimates vary greatly, reflecting differing assumptions with respect to:

- Technology choices (including choice of gasifier for IGCC plants and the appropriate CO_2 capture option) and type of coal to be used).

- The capital outlay for the CO_2 capture system and annual capital charge (based on ownership and financing situation).

- The energy penalty for adding CO_2 capture to a coal-fueled power plant.

[3] The 400MW size plant (after installation of CCS) is equivalent to a 500 to 550 MW size plant before installation of CCS and represents a commercial-size unit of additional power capacity that is often added to an existing power plant facility.

- Recent cost escalations in CO_2 capture systems due to increased demand for steel, fuel, and engineering construction services.

- Expected cost reductions due to "learning by learning" (successful R&D investment) and "learning by doing" (volume of installed capacity).

- Whether CCS technology will be added to a power plant originally designed and built to operate without CCS or will be included from plant inception.

To account for these uncertainties, this paper provides estimates for both a "higher" and "lower" set of program costs. The higher cost estimate is based on studies that assume plants will add CCS after they have been built and operated for some period of time. A "low-side" estimate, based on studies that assume units are designed and built with CCS from the start, is also provided. Given the large fleet of existing coal-fueled plants, it is important that a program to accelerate CCS include demonstrations both in retrofit situations, where the higher cost estimates are more likely to apply, and in new build situations where the costs of including CCS might be lower.

2. "High-Side" Coal-Fueled Power Plant Costs and Assumptions. To provide an up-to-date estimate of the "baseline" costs of capturing CO_2 (excluding CO_2 transportation and storage), we have used the recently prepared cost study by Burns & McDonald Engineering for EPRI (EPRI, 2006). This study assumes that plants are built to operate without CO_2 capture, and that the capture system is added later. Key assumptions used in the EPRI study are shown in Table 6, with further details provided in Appendix A. Capital and O&M costs, including costs for additional fuel, are provided for a supercritical pulverized coal (SCPC) plant and an integrated gasifier combined cycle (IGCC) plant each burning Powder River Basin (PRB) coal, with and without CO_2 capture.

(a) SCPC "High-Side" Cost Reimbursement Estimate. For the "high-side" reimbursement estimate for a SCPC power plant, we start by looking at the impact of installing a post-combustion CO_2 capture facility on overall capital costs. First, the SCPC plant would need to recover the capital costs for adding a post-combustion CO_2 capture system. Second, there are costs associated with recovering the loss of electricity output (net generation capacity) due to the energy requirements for operating the CO_2 capture and compression system. In this example, the operation of the CO_2 capture and compression system lowers the efficiency of the SCPC power plant by 29%, reducing its power generation output (net capacity) from 550 MW to 390 MW.

The calculation of the reimbursement requirements for installing CO_2 capture on a SCPC power plant are set forth on Table A-1, Appendix A. This table shows that, for the 390 MW (net output) SCPC plant with CO_2 capture, the plant would need to receive $650 million of capital cost reimbursement ($1.67 million per MW) to be "held whole" compared to a 550 MW (net output) SCPC plant without CO_2 capture. A portion of the reimbursement—$300 million—would be for the capital costs of the CO_2 capture and compression system. The remainder of the reimbursement—$350 million—would be to cover the loss of power generation output (from 550 MW to 390 MW) from operating the CO_2 capture system.

Table 6. "High-Side" Assumptions and Costs of Coal-Fueled SCPC and IGCC Power Generation

	No CO_2 Capture		With CO_2 Capture	
	SCPC	IGCC	SCPC	IGCC
1. Key Assumptions				
Net Output, MWe	550	553	390	413
Plant Efficiency, HHV%	37.3	37.0	26.4	26.7
Capital Cost[1], $/MWe (thousand)	2,180	2,670	3,840[2]	4,040[2]
CO_2 Emissions, lb CO_2/MWh	1,967	1,985	278	276
Plant Capacity Factor	85%	85%	85%	85%
Coal Price, $/MMBtu	1.65	1.65	1.65	1.65
2. Cost of Electricity, $/MWh				
Capital Charge	16.6	20.3	29.3	30.7
O&M	7.6	9.5	11.4	13.6
Fuel	15.1	15.2	21.3	21.1
TOTAL	**39.3**	**45.0**	**62.0**	**65.4**

[1] Includes procurement, construction, EPC contractor indirect costs and fee and owner's indirect costs.

[2] In the "with CO_2 capture" cases the capital cost shown accounts for the loss of output due to installation of CO_2 capture.

Source: EPRI (2006).

The SCPC plant with CO_2 capture would also incur an additional $10 per MWh of electricity ($0.01/kWh) for O&M and fuel (see Table 6).

(b) IGCC "High-Side" Cost Reimbursement Estimate. Next, we examine the impact of installing a pre-combustion CO_2 capture facility on overall capital costs for an existing IGCC power plant. As above, the IGCC plant would need to recover the capital cost for adding a pre-combustion CO_2 capture system and costs due to the loss of electricity output (the energy penalty for operating the CCS system). While the energy penalty is less for an IGCC plant with capture than for a SCPC plant with capture, it is still substantial, reducing net output from 553 MW to 413 MW, or by 25% for the retrofitted plant modeled in Table 6.

The calculation of the cost and reimbursement requirements for installing CO_2 capture on an IGCC power plant are set forth on Table A-2, Appendix A. This table shows that the 413 MW (net output) IGCC plant with CO_2 capture, would need to receive $570 million of capital cost reimbursement ($1.38 million per MW) to be "held whole" compared to a 553 MW (net output) IGCC plant without CO_2 capture. A portion of the reimbursement—$200 million—would be for the capital costs of the CO_2 capture system. The remainder of the reimbursement—$370 million—would be for the loss of net power generation output (from 553 MW to 413 MW) from operating the CO_2 capture system.

The IGCC plant with CO_2 capture would also incur an additional $9 per MWh of electricity (slightly less than $0.01/kWh) for O&M and fuel (see Table 6).

(c) Average "High-Side" Cost Reimbursement Estimate. Assuming a 50/50 mix of SCPC and IGCC plants, a 550 MW (net output, before CO_2 capture and 400 MW after CO_2 capture) power plant would need to receive $610 million in capital reimbursement ($1.52 million per MW) to be "held whole" economically with a similar power plant without CO_2 capture (see Table A-3, Appendix A). In addition, assuming that this "average" power plant generates about 3 million MWh of electricity per year after installation of CO_2 capture, it would need about $30 million per year for reimbursement of incremental O&M and fuel costs. Lower levels of plant utilization and output would reduce the level of required O&M and fuel reimbursement.

For costing purposes, the program is assumed to last for ten years, and it is assumed that the O&M costs will be covered for an average of five years. Because the incremental costs for installing and operating CO_2 capture at any specific power plant are likely to vary considerably from the average costs provided in this paper, any mechanism used to reimburse incremental costs should be designed to adjust for such differences. (See the companion Pew Center Coal Initiative white paper: A Trust Fund Approach to Accelerating Deployment of CCS: Options and Considerations by Pena and Rubin (2007) for other criteria for project selection and reimbursement.)

3. "Low-Side" Cost Reimbursement Estimate. An alternative set of data were used to develop a "low-side" cost reimbursement estimate for installing CCS in conjunction with building new power plants. These costs are shown in Table 7. The data shown in this table were extracted from work by Rubin (2007) and the IPCC (2005) and converted to 2006 costs using inflation factors to account for recent increases in plant construction costs.

Table 7. "Low-Side" Assumptions and Costs of Coal-Fueled SCPC and IGCC Power Generation Based on New Plant Construction with CCS

	No CO_2 Capture		With CO_2 Capture*	
	SCPC	IGCC	SCPC	IGCC
Key Assumptions				
Net Output, MWe	513	477	390	413
Plant Efficiency, %**	39.3	37.2	29.9	32.2
Capital Cost, $/MWe (thousand)***	1,930	1,990	3,140	2,740

*New plant size assumed to be comparable with retrofitted plant size

**Case study values from Rubin, E.S., Chen, C., and A.B. Rao, (2007)

***2006 adjustment to 2002 IPCC values reported in Rubin et al (2007)

The “low-side” capital cost of including CO_2 capture in a new 390 MW (net output) SCPC plant was estimated at $240 million. In addition, to compensate for the 24% lower output (compared to a SCPC plant without capture), the SCPC plant would need to receive $240 million. Consequently, the cost reimbursement requirements for the “low-side” case SCPC plant would be $480 million, or $1.23 million per MW of net capacity, Appendix A, Table A-4.

The “low-side” capital cost of incorporating CO_2 capture and compression with a 413 MW (net output) IGCC plant (burning high rank coal) was estimated at $180 million. In addition, to compensate for the 13% lower output, the IGCC plant would need to receive $130 million. Consequently, the cost reimbursement requirements for the “low-side” case IGCC plant would be $310 million, or $0.75 million per MW of net capacity, Appendix A, Table A-5.

Assuming a 50/50 mix of SCPC and IGCC plants, the nominal 500 MW (net output without CO_2 capture, and 400 MW with CO_2 capture) power plant would need to receive $390 million in capital reimbursement ($0.98 million per MW) to be “held whole” economically compared to a similar power plant without CO_2 capture (Appendix A, Table A-6). The incremental CO_2 capture operating costs for the “low-side” case are assumed to be the same as for the “high-side” case.

4. Transportation and Storage Costs. The costs of the CO_2 transportation and storage system will vary greatly depending on the type and location of geologic storage. Assuming emissions of nearly 9,000 metric tons per day of CO_2, the capital costs of the transportation and storage systems for a 400 MW (net output) plant that needs to transport CO_2 for 50 miles would be $90 million for installing the pipeline and developing the storage site. Assuming a transportation and geologic storage cost of $5 per metric ton of $CO_{2,}$ operating the system would cost a total of $16 million per year.[4] The CO_2 transportation and storage costs used in the White Paper assume that a pipeline of 50 miles would be needed, no EOR revenues are available, and that 100% of the transportation and storage operating costs would be covered for five years.

In cases where the demonstration of CCS at a coal-fueled power plant is adjacent to an existing pipeline or a suitable reservoir, costs may be lower. In addition, when a plant is able to sell CO_2 for EOR, the revenues could be used to offset overall costs.

The CO_2 transportation and storage costs used in the White Paper assume that a pipeline of 50 miles would be needed, no EOR revenues are available, and that 100% of the transportation and storage operating costs would be covered for five years.

5. CO_2 from Other Industrial Sources: Cost Reimbursement Estimate. The least expensive way of building confidence in large-scale storage of $CO_{2,}$ particularly in the early years of the program, would be to utilize high CO_2 concentration releases emitted from industrial sources. For purposes of the program proposed in this paper, large-scale is defined to be a demonstration project that stores one to three million metric tons of CO_2 emissions per year. For costing purposes, the demonstrations of storing high concentration CO_2 from industrial sources are assumed to average two million metric tons of CO_2 per year. The program is assumed to pay for the incremental capital costs plus 100% of operating costs for 5 years. At an average cost of $10

[4] These cost estimates are based on internal Advanced Resources International cost models and actual experience in designing CO_2 transportation, injection and storage systems.

per ton of CO_2 for CO_2 compression, transportation and storage, each of these demonstrations would cost $100 million.

The program would support all of the incremental capital and operating costs for demonstrations when using deep saline formations as the geological storage site. When an oil field with enhanced oil recovery (EOR) is the CO_2 storage objective, the program would be designed to negotiate an appropriate level of cost reimbursement.

Demonstration Program: Objectives, Scale, Costs and Coverage

OBJECTIVES AND SCALE. This White Paper provides costs for a program at two scales, corresponding to the two distinct sets of objectives proposed. Information provided in the previous section can be used to calculate program costs at other scales.

The authors suggest that a program at the 10-plant scale would be adequate for establishing reliable cost and performance data for CCS. A program smaller than 10 plants would not provide demonstrations of the full range of generation-capture-coal type-location pathways for which cost and reliability information is essential for deployment of CCS across the United States. However, if the objective of a program is to significantly reduce CO_2 capture costs and energy penalties and to build broad public acceptance of CO_2 storage, a program at the 30-plant scale would be needed.

PROGRAM COSTS: SMALLER-SCALE PROGRAM. The smaller-scale program involves installing CCS at 10 coal-fueled electric generation plants plus conducting 5 demonstrations of storage in saline reservoirs, using CO_2 from non-utility industrial sources. Based on the average incremental costs of adding CO_2 capture to a coal-fueled power plant, the costs for supporting 10 demonstration plants with 4,000 MW of net power generation capacity and 5 demonstrations of storage of CO_2 from other industrial sources would be $8.0 to $10.2 billion. Of this:

- The largest portion, $3.9 to $6.1 billion, would be for capital outlays to cover the costs of installing the CO_2 capture system and reimbursing the power company for loss of generation output ($390 to $610 million per plant times 10 plants).

- Approximately $1.5 billion would be for reimbursing the costs of operating these CCS power plant demonstrations for five years ($30 million per plant per year times 5 years times 30 plants).

- In addition, $1.7 billion would be needed to reimburse the costs of transport and storage of CO_2 from the demonstration plants. This includes $0.9 billion for capital costs ($90 million per plant times 10 plants) plus $0.8 billion for operating the transportation and storage system for five years ($16 million per plant per year times 5 years times 10 plants).

- An estimated $0.5 billion would be for reimbursing the costs of demonstrating CO_2 capture from other (non-utility) industrial sources and storing this CO_2 in saline formations.

- Finally, assuming a cost equal to 4 to 5 percent of total outlays to operate and manage a program of this type, ten years of operation would cost about $0.4 billion. Included in this operating and management cost would be an extensive program of CO_2 capture technology and geologic storage assessments, front-end feasibility studies, in-depth performance assessments of the CCS demonstrations, and technology transfer.

PROGRAM COSTS: LARGER-SCALE PROGRAM. The larger-scale program involves installing CCS at 30 electric generation plants plus 10 demonstrations of storage using CO_2 from non-utility industrial sources. Based on the average incremental costs of adding CO_2 capture to a coal-fueled power plant, the costs for supporting 30 demonstration plants with 12,000 MW of net power generation capacity would be $23.5 to $30.1 billion. Of this:

- The bulk of the funds, $11.7 to $18.3 billion, would be for capital outlays to cover the costs of installing the CO_2 capture system and reimbursing the power company for loss of generation output ($390 to $610 million per plant times 30 plants).

- Approximately $4.5 billion would be for reimbursing the costs of operating these CCS power plant demonstrations for five years ($30 million per plant per year times 5 years times 30 plants).

- In addition, $5.1 billion would be for reimbursing the costs of transport and storage of CO_2 from the demonstration plants, including $2.7 billion for capital costs ($90 million per plant times 30 plants) and $2.4 billion for operating the transportation and storage system for five years ($16 million per plant per year times 5 years times 30 plants).

- An estimated $1.0 billion would be for reimbursing the costs of demonstrating CO_2 capture from other industrial sources and storing this CO_2 in saline (as well as other geological) formations.

- Finally, assuming a cost equal to 4 to 5 percent of total outlays to operate and manage a program of this type, ten years of operation would cost about $1.2 billion. Included in this operating and management cost would be an extensive program of CO_2 capture technology and geologic storage assessments, front-end feasibility studies, in-depth performance assessments of the CCS demonstrations, and technology transfer.

As industry gains and shares experience from these initial demonstrations and from DOE's R&D/Technology Program in Carbon Sequestration, the large energy penalties and costs of CO_2 capture systems should decline. As costs per plant decline, the program could expand the number of demonstrations or support O&M costs for a longer-time period. If the program is funded by per kWh fees on electricity generated, another option would be to reduce annual fees.

OVERALL PROGRAM COSTS. The range of costs for the two program of the scope described above are set forth in Table 8.

Table 8. Initial Estimate of Carbon Trust Fund Costs

	Per Plant (in millions)	For 10 Plants (in billions)	For 30 Plants (in billions)
A. POWER PLANT DEMONSTRATIONS			
1. Incremental Capital Costs			
a. Capture System	$390 to $610	$3.9 to $6.1	$11.7 to $18.3
b. Transportation and Storage System	$90	$0.9	$2.7
Sub-Total	$480 to $700	$4.8 to $7.0	$14.4 to $21.0
2. Incremental Operating Costs*			
a. Capture System	$30/yr	$1.5	$4.5
b. Transportation and Storage Systems	$16/yr	$0.8	$2.4
B. OTHER INDUSTRIAL CCS**	$100	$0.5	$1.0
C. TRUST FUND ADMINISTRATION***	4 to 5%	$0.4	$1.2
TOTAL		**$8.0 to $10.2**	**$23.5 to $30.1**

*Assumes 5 years of reimbursement at 100%.

**Assumes 5 projects for the smaller-scale program and 10 projects for the larger-scale program.

***Assumes 10 years of Trust Fund management and operation.

PROGRAM COVERAGE. The considerable number of combinations of power generation technology, CO_2 capture technology, and coal types relevant to deployment of CCS across the United States calls for CCS demonstrations distributed among a number of categories. Illustrative initial plans for distributing demonstrations among the key CCS pathways are described below, As a program proceeds, any initial distribution plan should be revisited and revised based on knowledge gained. In all cases, both new and already-operating plants should be eligible for funding under the program envisioned in this paper. The categories and illustrative distribution are:

- Three demonstrations for the smaller-scale program, ten demonstrations for the larger-scale program, of post-combustion (or oxyfuel) CO_2 capture and storage in the eastern region of the United States. Plants should be divided roughly equally between plants burning eastern bituminous coal and plants burning sub-bituminous coal.

- Two demonstrations for the smaller-scale program, five demonstrations for the larger-scale program, of post-combustion (or oxyfuel) CO_2 capture and storage in the western region of the United States. Plants should be divided between plants burning western bituminous coal and plants burning sub-bituminous coal.

- Two demonstrations for the smaller-scale program, five demonstrations for the larger-scale program, of pre-combustion CO_2 capture and storage at IGCC (or multi-product gasification) plants located in the eastern region of the United States, gasifying bituminous coals.

- Three demonstrations for the smaller-scale program, ten demonstrations for the larger-scale program, of pre-combustion CO_2 capture and storage at IGCC (or multi-product gasification) plants located in the western region of the United States, gasifying sub-bituminous or lignite coals.

Tables 9A and 9B provides a summary of the suggested distribution of plants for both the 30-plant and the 10-plant program.

Table 9A. Proposed Distribution of CCS Demonstrations at Coal-fueled Power Plants—Larger Scale Program

Type of Capture Technology/Coal Resource	Geographic Location	
	East of Mississippi	West of Mississippi
1. Post Combustion (PC/Oxyfuel)*		
• Bituminous Coal	5	2
• Sub-Bituminous Coal	5	3
2. Pre-Combustion (IGCC)		
• Bituminous Coal	5	-
• Sub-Bituminous/Lignite Coal	-	10
TOTAL	**15**	**15**

*Includes demonstrations of oxy-fuel combustion in the program's later years.

Table 9B. Proposed Distribution of CCS Demonstrations at Coal-fueled Power Plants—Smaller-Scale Program

Type of Capture Technology/Coal Resource	Geographic Location	
	East of Mississippi	West of Mississippi
1. Post Combustion (PC/Oxyfuel)*		
• Bituminous Coal	1	1
• Sub-Bituminous Coal	2	1
2. Pre-Combustion (IGCC)		
• Bituminous Coal	2	-
• Sub-Bituminous/Lignite Coal	-	3
TOTAL	**5**	**5**

*Includes demonstrations of oxy-fuel combustion in the program's later years.

Cost Reductions Achievable by the Larger-Scale Program

Much of the rationale for and benefits of the Larger-Scale Program are based on expectation that the costs of CO_2 capture can be reduced significantly. While considerable uncertainty surrounds this expectation, the historical data and work by energy researchers and modelers provide confidence that major cost reductions are achievable given:

- A robust program of commercial-scale CCS demonstrations;
- Staged demonstrations to incorporate lessons learned in successive "age class";
- A strong, underlying R&D program.

Our judgment, based on EIA-NEMS modeling and "learning curve" studies by other energy experts (as further discussed below), is that a demonstration program involving at least 30 plants over a period of ten to fifteen years (with 12,000 MW of net installed capacity involving four successive age classes or "generations") will be required to approach the cost reduction goals set forth in this White Paper.

1. Cost Reductions in the EIA-NEMS Electricity Markets Module. The EIA-NEMS Electricity Markets Module reveals that after a sufficient number of plants (four in the model) are installed to establish an initial base of reliable cost information for CO_2 capture, capital cost reductions of 20 percent and energy penalty reductions of about 10 percent would be achieved for each doubling of installed capacity for up to three doublings of capacity (Phase 1 of deployment).

Assuming that four plants, each with 400 MW of net capacity (after installation of CCS), provide the first generation base, it will take a total of three additional generations of CCS technology (about 30 plants with 12,000 MW) to achieve significant initial cost reductions. This White Paper refers to the initial four generations (age-classes) of CO_2 capture plants as Phase I (commercial-scale demonstrations are carefully staged to incorporate lessons from each age class and results of intensive R&D into subsequent demonstrations). After achieving Phase I cost reductions, EIA modeling reveals that CO_2 capture costs would further decline during a second phase (Phase II), characterized by more rapid installation of commercial-scale CO_2 capture. During Phase II, capital cost reductions of 10 percent and energy penalty reductions of 5 percent would be achieved for each subsequent doubling of capacity for up to five additional doublings of capacity. The "optimistic" 40 percent cost reduction expectation from a Phase 1 type deployment program set forth in this paper is consistent with the EIA-NEMS model.

2. Cost Reduction Studies by Energy Researchers. This White Paper also draws on work on "learning curves" and cost reduction expectations by other energy researchers. For example, Nakicenovic (2006), drawing on an extensive series of case studies, shows that 2 to 7 doublings of capacity are required to achieve cost reductions of 50 percent for a number of technologies. Nakicenovic also sets forth a two-phased model of learning curves. Further information Nakicenovic's work on learning-based cost reductions is provided in Appendix B.

Recently, Rubin, et al. (2007) assembled a wealth of historical data on learning-based cost reduction rates for a number of relevant energy and environmental technologies. This work included historical data on the cost histories for flue gas desulfurization (FGD), selective catalytic reductions (SCR), gas turbine combined cycle (GTCC), and hydrogen production (SMR). Rubin et al. found that the "factors contributing to real long-term declines in the capital and O&M costs for these relevant energy technologies were due to improvements in technology design, materials, product standardization…" They found that the level of cost reduction for each doubling of capacity ranged from 10 percent to 27 percent for capital costs and from 6 percent to 27 percent for O&M costs, with most of the technologies having cost reductions toward the lower end of the range.

Learning rates in the Rubin et al. study fall within the range reported in the literature for energy-related technologies (McDonald and Schrattenholzer, 2001). However, the learning rates in the Rubin et al. study are, on average, systematically lower than those reported by Nakicenovic or included in the EIA-NEMS model. The somewhat more "pessimistic" level of 33 percent cost reduction achievable with a Phase 1 type deployment program entailing 12,000 MW of CCS set forth in this White Paper are consistent with work by Rubin, et al. It is important to note that Rubin et al. do not make a distinction between Phase I and Phase II in their learning rate study.

3. Cost Reduction Expectations of the CO_2 Capture Project. The CO_2 Capture Project (CCP) is a consortium of eight major oil companies, led by BP. The goal of this consortium is to reduce the costs of CO_2 capture by 50% to 75% compared to the cost situation at the time of the formation of the consortium. During the initial phase of the project, the CCP identified a series of new technologies that could significantly reduce the costs of CO_2 capture, including:

- Development of a hydrogen membrane reformer applied to pre-combustion capture of CO_2 from a natural gas-fired power plant which showed potential for a 60% reduction in overall CO_2 capture costs;

- Application of process integration, flue gas recycle and advanced amines to post-combustion capture of CO_2 from a natural gas-fired power plant which showed potential for a 54% reduction in overall CO_2 capture costs;

- Use of ionic transport membranes and flue gas recycle with oxyfuel-based capture of CO_2 from an oil refinery which showed potential for reducing CO_2 capture costs by 48%.

During the current phase of the project, the CO_2 Capture Project is further pursuing and verifying these and other cost-reduction opportunities. Appendix B provides additional detail on the accomplishments of the CO_2 Capture Project.

4. "Learning-Based" Cost Reductions Used in the White Paper. This White Paper uses two sets of "learning-based" cost reduction values, to reflect the variety of values derived from studies and models. During Phase I ("learning by learning"), the paper assumes capital cost reductions of 10% ("pessimistic") and 20% ("optimistic"), plus energy penalty reductions of 10%, for each of the three doublings of capacity after initial demonstrations establish real-world costs and energy penalties. During the subsequent Phase II ("learning by doing"), the paper assumes capital cost reductions of 10% and energy penalty reductions of 5%, for each doubling of capacity for the next five doublings. The range of cost savings reported in this paper reflects the difference between "pessimistic" and "optimistic" expectations for Phase I CO_2 capture cost reductions.

Benefits and Drawbacks of Alternative Program Scales

Ultimately the utilities, the public, interested stakeholders, and U.S. legislators will have to decide how to prepare for widespread deployment of CCS. This preparation can be pursued through an approach which would rely on modest augmentation of federal budget resources or through a more aggressive approach which would require tapping major new sources of funds. Both program scales proposed in this paper would require new sources of funds. The benefits and drawbacks of the two program scales considered in this report are examined below.

SMALLER-SCALE PROGRAM. The Smaller-Scale Program would address some of the key concerns impeding use of CCS in the coal-based power industry. It would provide realistic data about costs and energy penalties, as well as information on system reliability and performance for the key CO_2 capture technology, coal type and geographic location combinations. The primary advantage of undertaking a Smaller-Scale Program is its lower cost.

However, considerable effort will need to be invested to establish a program and its funding mechanism, including an institutional framework to operate the program and agreements on fee structure and fund dispersal criteria. This raises the question of whether, once this investment of time and energy is made—might it not be better to run the program at a scale that would also produce significant cost and energy-penalty reductions?

LARGER-SCALE PROGRAM. The primary advantage of a Larger-Scale Program would be that, in addition to addressing the issues incorporated in the Smaller Scale Program, it would significantly bring down costs and energy penalties, prior to widespread deployment of CCS. A second advantage of the Larger-Scale Program is that it would also sequester significant amounts of CO_2 emissions in the near term and build broad public support for CO_2 storage.

The primary disadvantage of a Larger-Scale Program is the higher cost. However, the fees per kWh needed to support even the Larger-Scale Program are quite modest, and once a program supporting commercial-scale CCS demonstrations were in place, it might be wise to use it to achieve significant cost reductions. The advantages to the public of achieving significant cost reductions in CO_2 capture technology prior to widespread deployment of CCS are likely to be substantial. As explained in the following paragraphs, a \$23.5 to \$30.1 billion dollar program that supports 30 CCS demonstrations might reduce post-2020 costs of deploying CCS by \$80 to \$100 billion (in real \$2006).

The \$80 to \$100 billion estimate of cost savings results from comparing two possible technology pathways for implementing CO_2 capture from coal-fueled power plants: (1) the business as usual (BAU) pathway and (2) the Larger-Scale Program pathway (involving 30 coal-fueled plants placed in operation in the next 10 to

15 years); and use of the "high-side" CCS cost estimates. Proportionately similar benefits would accrue by using "low-side" CCS cost estimates. Each pathway assumes that 275,000 MW of new coal-fueled power generation capacity with CCS will be needed by 2050, based on the above discussed Atmospheric Stabilization Case set forth in CarBen2 (Kuuskraa, 2007).

1. Business as Usual (BAU) Cost Reduction Pathway. The Business As Usual (BAU) Pathway assumes a continued, modest investment in CO_2 capture R&D and technology[5]; through 2020. This would include pilot-scale field demonstrations of sequestration under the Department of Energy's Regional Sequestration Partnership program; and completion of the FutureGen plant, a near-commercial scale plant that is expected to be designed to test alternative capture technologies. Under this pathway it is assumed that few, if any, commercial-scale coal-fueled plants deploy CCS by 2020. Due to the lack of sufficient, commercial-scale demonstrations, under the BAU pathway costs of adding commercial-scale CO_2 capture to a coal-fired power plant remain at $1.52 million per MW of capacity through year 2020 (Table 10).

Table 10. Business As Usual: Capital Costs of CO_2 Capture Technology

Time Period	CO_2 Capture Plant Costs (Million $/MW)		
	SCPC	IGCC	Average Plant
1. Today	$1.67	$1.38	$1.52
2. Year 2020 (Starting Costs)	$1.67	$1.38	$1.52
3. Year 2050 (Last Plant)	-	-	$0.98

Starting in 2021, the BAU Pathway assumes that 275,000 MW of coal-fueled power generation capacity with CO_2 capture is installed under a rapid commercialization scenario, essentially skipping the staged "learning by learning" phase (Phase I). As a result, capital cost reductions of 10% and energy penalty reductions of 5% per doubling of installed capacity for up to five doubling of capacity would occur (i.e., cost reductions would be characteristic of Phase II—"learning by doing"—reductions).

The first CCS plant built in 2021 would have costs of $1.52 million per MW of capacity, and the last power plant built in 2050 would have costs of $0.98 million per MW (Table 10). Under this pathway, the capital costs for installing CO_2 capture at 275,000 MW of coal-based power generation capacity (including reimbursement for loss of capacity due to the CCS energy penalty) would be $274 billion.

2. Larger-Scale (30 Plant) Program Cost Reduction Pathway. The "Larger-Scale" (30 Plant) Program Pathway, which assumes several successive age classes or generations of plants, each incorporating lessons from earlier plants and from an accompanying robust R&D program in CCS, leads to significant capital and energy penalty cost redcutions by the 30th plant, as discussed in the previous section. As a consequence, the capital costs for CO_2 capture decline from $1.52 million per MW for the first plant (installed in the next few years) to $0.90 million per MW (a 41% cost reduction) or to $1.02 million per MW (a 33% cost reduction) for the

[5] Energy Bills currently under consideration in Congress may result in significant increases in funding for CCS. However, unless funding escalates to "Apollo" program levels, increases will fail to support sufficient CCS demonstrations to bring costs down significantly.

30th plant installed in 2020 depending on whether "optimistic" or "pessimistic" expectations for Phase I learning are used. (See Table 11 and Appendix C).

Table 11. 30 Plant Program: Capital Costs of CO_2 Capture Technology (Using High-Side Cost Assumptions)

Time Period	CO_2 Capture Plant Costs (Million $/MW)		
	SCPC	IGCC	Average Plant
1. Today	$1.67	$1.38	$1.52
2. Year 2020 (30th Plant)	$0.98–$1.12	$0.83–$0.93	$0.90–$1.02
3. Year 2050 (Last Plant)	-	-	$0.64–$0.71

From years 2021 through 2050, an additional 263,000 MW of coal-fueled generating capacity with CCS will be installed (275,000 MW – 12,000MW = 263,000MW). However, the rapid and large-scale installation of this additional power capacity with CCS would start at lower costs of $0.90 to $1.02 million per MW. As the cumulative volume of installed CO_2 capture capacity increases, costs decline further and costs are $0.64 to $0.71 million per MW of capacity for the last plant built in 2050, depending on use of "optimistic" or "pessimistic" expectations for Phase II learning. Under this pathway, the overall capital investment costs (including reimbursement for loss of capacity) for installing CCS at 263,000 MW of coal-based power generation are $177 to $199 billion.

A comparison of the Business As Usual Pathway with capital costs of $274 billion and the Larger-Scale (30 Plant) Program Pathways with cost of $177 to $199 billion yields a cost savings from the Larger-Scale (30 Plant) Program Pathway of about $80 to $100 billion. Achieving these savings depends on successfully achieving the results of the Larger-Scale (30 Plant) Program, with $23.5 to $30.1 billion of costs for the accelerated demonstration program (involving installation of 30 CCS plants with 12,000 MW of capacity by 2020). Subtracting out the costs of the program thus results in a net savings of some $56 to $70 billion dollars.

In addition to reducing costs, adding demonstrations of CO_2 capture and storage to 30 coal-based power plants and ten other industrial sources will reduce CO_2 emissions by about 100 million metric tons of CO_2 per year by the time all demonstrations are operating. Consequently, one of the additional contributions of the Larger-Scale Program is that it will preclude 500 million metric tons of CO_2 emissions from being vented to the atmosphere in the next 10 years.

Other Barriers to CCS in the Coal-fueled Power Industry

The current high capital costs of CO_2 capture and loss of efficiency in operating CO_2 capture systems are at the top of the list of barriers to large-scale deployment of CCS. The actions suggested in this White Paper could address these two barriers. However, several other barriers also impede timely deployment of CCS by the coal-based power industry. These include developing suitable regulatory systems and gaining public acceptance for CO_2 storage, reaching agreement on long-term liability for stored CO_2, gaining right-of-way for CO_2 pipelines, and assuring sufficient numbers of skilled employees and domestic construction capacity.

Of particular importance is the barrier that there is not yet a requirement for CO_2 reductions and therefore emitters do not incur a cost for emitting CO_2 to the atmosphere. The program envisioned in this paper is intended to help prepare the way for such a requirement, i.e., for mandatory regulation of CO_2 emissions. By providing sufficient experience with CCS technologies and reducing their costs and energy penalties, the risks and economic burden of CO_2 limitations for coal-based power generators will decrease. This can be expected to translate into greter acceptance of mandatory CO_2 regulation by coal-based industries.

A number of programs are already underway to address some of the barriers to CCS other than costs and energy penalties. The CO_2 storage pilots being sponsored by DOE's Regional Sequestration Partnerships Program are beginning to engage and inform the public and regulatory bodies on the key issues surrounding CO_2 storage, namely public safety, monitoring systems, protection of groundwater, and storage site evaluation. The U.S. EPA is helping facilitate these small-scale CO_2 storage pilots by enabling CO_2 injection wells to be certified as Class V (experimental) underground injection (UIC) wells. In addition, larger, one million metric tons CO_2 per year, storage demonstrations are being planned by DOE to address both public acceptance and regulatory issues at appropriate scale.

State bodies are beginning to grapple with the issues of long-term liability for CO_2 storage (e.g., Texas) and eminent domain for right-of-way for CO_2 pipelines and storage (e.g., Montana). A more in depth review of the wide range of state initiatives to overcome barriers to deployment of CCS at utilities is provided in the Pew Center Coal Initiative white paper: State Options for Low-Carbon Coal Policy by Bushinsky et al. (2007). However, new regulatory structures and authorities and a large body of case law will be required before CO_2 storage can be implemented efficiently at commercial scale across the nation.

The engineering and construction market is currently "very tight". This tight market plus the growth in demand for steel and other commodities has been escalating power plant and CO_2 capture facility costs, as reflected in the high capital costs for the SCPC and IGCC plants discussed in this paper. In addition the pool of expertise needed for site characterization, modeling, and monitoring the fate of injected CO_2 is limited. The primary options for overcoming these barriers are: (a) to enact mandatory U.S. climate policy that assures a long-term demand for CO_2 capture and storage facilities so markets and the educational system can plan for adequate capacity; and (b) to standardize CO_2 capture systems and their components so that economies of scale and volume can help bring down costs, as they have done historically in many other industrial sectors.

Summary and Conclusions

If large-scale implementation of CO_2 capture and storage is to be efficiently and successfully implemented in the coal-based power industry, the time to prepare is now.

This White Paper sets forth a near-term program that would accelerate CCS deployment. A smaller-scale version of this program would provide an essential base of experience with CCS technologies, while a larger-scale version could, in addition, significantly lower capital costs and energy penalties. The program would also address high CO_2 concentration emissions from industries, helping to build infrastructure and acceptance for large-scale geological storage of CO_2, particularly in saline formations.

The primary near-term action needed to establish a program of the type described in this paper is the creation of a mechanism, such as a CCS Trust Fund, to raise funds and reimburse power and industrial companies for the extra costs of installing and operating CO_2 capture and storage systems. The mechanism would support some 10 to 30 commercial-scale demonstrations of CCS at coal-fueled power plants over a ten to fifteen year period, plus 5 to 10 large-scale demonstrations of storage (primarily in saline formations). The cost of a program is estimated at some \$8 to \$30 billion (\$U.S., 2006), depending on program scale. The larger-scale program, involving 30 utility projects and the 10 industrial demonstrations (once fully implemented), would capture and store 100 million metric tons of CO_2 per year; the smaller-scale program would capture and store 36 million metric tons of CO_2 per year.

Funds to support a program of the type described in this White paper could come from a per kWh fee placed on coal-fueled power plants and a per ton CO_2 fee on industrial sources of CO_2, from proceeds from auctioning allowances under a cap-and-trade program, or via some other mechanism. Given the approximately 2,000 billion kWh/yr of coal-fired electricity generated in the United States and annual costs of \$0.8 to \$1.0 billion per year for the smaller-scale programs and \$2.5 to \$3.0 billion per year for the larger-scale program, if a per kWh fee were used, the average fee on coal-based electricity generated would be \$0.0004 to \$0.0005 per kWh for the smaller-scale and \$0.0012 to \$0.0015 per kWh for the larger-scale program. These per kWh fees would decrease as power generation from coal increases, as cost reductions in CCS systems materialize or if the program were conducted over 15 years instead of 10 years. Fees per kWh could also be lowered if cost-sharing were required and should projects be able to take advantage of opportunities to sell CO_2 into the EOR market. Given the current 100 million metric tons of CO_2 being emitted from large, high CO_2 concentration industrial sources, and an average annual cost of \$50 to \$100 million for the industrial portion of the program, the fee to industrial plants would range from \$0.50 to \$1 per metric ton of CO_2 emitted with revenues gained from selling this CO_2 into the EOR market subtracted from the costs.

In addition to lowering CO_2 emissions, a program of the scope described would provide significant benefits, by lowering the costs of deploying CCS in the coal-fired power sector. Our analysis shows that, with the experience gained from 30 demonstrations of CCS, the capital costs of wide-scale implementation of CCS in coal-fueled plants could be \$80 to \$100 billion lower than otherwise.

Most likely, a new institution will be required to implement and manage a program of the type proposed in this paper. The Pew Center Coal Initiative white paper: A Trust Fund Approach to Accelerating Deployment of CCS: Options and Considerations by Pena and Rubin (2007) examines use of a Trust Fund as one option for raising funds and managing a carefully staged deployment program, and briefly reviews other means to provide financial support for accelerating deployment of CCS.

Appendix A: CO_2 Capture and Storage Costs for SCPC and IGCC Plants

The cost information on CO_2 capture used in this White Paper is based on two sources. The "high-side" cost estimates of installing CCS as a retrofit to an existing power plant are based on the recently prepared cost study by Burns & McDonald Engineering for EPRI ("Feasibility Study for an Integrated Gasification Combined Cycle Facility at a Texas Site" (EPRI, 2006)). This study provides up-to-date costs of capturing CO_2 (excluding CO_2 transportation and storage) under the assumption that capture technologies will be added to an electric generation plant originally operating without such equipment. The "low-side" cost estimates of installing CCS, which assume CCS will be included as part of a newly built power plant, are based on the representative cost values in the IPCC (2005) report, escalated by the author to year 2006 costs. A useful tabulation of these low side costs is provided in Rubin (2007).

The "high-side" costs are for a supercritical pulverized coal (SCPC) plant and an integrated gasifier combined cycle (IGCC) plant burning low rank Powder River Basin (PRB) coal, with and without CO_2 capture. The "low-side" costs for the IGCC plant assume burning of higher rank coal. The specific cost and energy penalty values for the "high-side" cost of adding CO_2 capture to a modern coal-fueled power plant are discussed below and set forth in Tables A-1, A-2 and A-3. The specific cost and energy penalty value for the "low-side" costs are set forth on Tables A-4, A-5 and A-6.

The "high-side" costs are for nominal 550 MW facilities (400 MW after CO_2 capture), located at a Texas Gulf Coast location (greenfield) that is initially built without capture equipment and would have CO_2 capture added later. The "low-side" costs with associated lower energy penalties are for a nominal 500 MW facility (400 MW after CO_2 capture) and would have CO_2 capture included in a newly built facility.

"HIGH-SIDE" COST ASSUMPTIONS. The capital costs are based on mid-2006 costs without escalation. Sales taxes, interest during construction, financing fees and transmission lines or upgrades are not included in capital costs.

The SCPC unit is assumed to operate with steam conditions of 3,500 psig and 1,050°F/1,050°F and to contain wet flue gas desulfurization (FGD) for SO_2 control, SCR for NO_x control, and a baghouse for particulate control. The SCPC unit is assumed to have an operating factor of 85% (7,446 hrs/yr).

The IGCC facility assumes the use of the Shell gasification process,[6] which has certain advantages for using low rank PRB coal, linked to a GE 7FB gas turbine. The IGCC has an 85% operating factor (7,446 hrs/yr) with two cold starts per year. The IGCC facilities do not include a spare gasifier to increase the operating factor or to provide operational flexibility. The assumption of the 85% operating factor in the Burns & McDonald

[6] A slurry feed gasifier, as a water quenched version of the Shell gasifier, may be more favorable if the primary option is to capture CO_2.

Engineering study for EPRI may be optimistic based on past performance. A lower operating factor or the addition of a spare gasifier would increase the IGCC cost set forth in this study.

While a number of solvent-based CO_2 capture technologies are available for post-combustion capture, including MHI's tertiary amine solvent called KS-1 and the ammonia-based CO_2 capture process being tested by Alstom, EPRI, and Wisconsin Energy, the capital costs in the Burns & McDonald Engineering study for EPRI are based on installing Fluor's Econoamine FG Plus ^{SM} CO_2 capture technology. Other post-combustion processes, should they be less energy intensive, would lead to lower costs. Additional capital is required for compression, FGD modifications and enlarged cooling capacity. The captured CO_2 would be compressed to 2,000 psig.

Similarly, while a number of pre-combustion capture options are available, the capital costs in this study are based on using the UOP SELEXOL unit which includes absorber and stripper towers, stripper reboiler, rich/lean solvent exchange and flash drums) and costs for CO_2 compression, modifying the acid gas recovery (AGR) and syngas treatment units, and making other modifications. The captured CO_2 would be compressed to 2,000 psig.

"LOW-SIDE" COST ASSUMPTIONS. The reader is pointed to the IPCC (2005) report and to the excellent overview paper on the costs and performance of power plants with CCS by Rubin (2007) for support and elaboration on the "low-side" cost assumptions. A key of this paper assumption is that year 2006 capital costs for CCS are judged to be 50% higher than the year 2002 costs set forth in the IPCC (2005) report. O&M and fuel costs, however, were assumed to be the same as in the "high-side" cost case.

Table A-1. High-Side Capital Costs for Adding Current Commercial-Scale Post-Combustion CO_2 Capture Technology—SCPC Plant (Initial Plant)

	SCPC Plant Without Capture	SCPC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	550	390
Base Cost ($US, 2006)	$1,200 million	$1,200 million
Incremental Cost ($US, 2006)	-	$300 million
Cost per MW ($US, 2006)	$2.18 million	$3.85 million
II. Calculation of Reimbursement		
1. Capture System		$300 million
2. Loss of Net Capacity		
Capacity Loss		160 MW
Reimbursement (@ $2.18 million/MW)		$350 million
3. Total Reimbursement		$650 million
Per MW		$1.67 million

Table A-2. High Side Capital Costs for Adding Current Commercial-Scale Pre-Combustion CO_2 Capture Technology—IGCC Plant (Initial Plant)

	IGCC Plant Without Capture	IGCC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	553	413
Base Cost ($US, 2006)	$1,470 million	$1,470 million
Incremental Cost ($US, 2006)	-	$200 million
Cost per MW ($US, 2006)	$2.67 million	$4.04 million
II. Calculation of Reimbursement		
1. Capture System		$200 million
2. Loss of Net Capacity		
Capacity Loss		140 MW
Reimbursement (@ $2.67 million/MW)		$370 million
3. Total Reimbursement		$570 million
Per MW		$1.38 million

Table A-3. High-Side Average Incremental Costs of Adding CO_2 Capture

	SCPC Plant With Capture	IGCC Plant With Capture	Average Plant* With Capture
1. Additional Capital Costs			
Total ($ million)	$650	$570	$610
MWe (net capacity)	390	413	401.5
$/MWe (millions)	$1.67	$1.38	$1.52
2. Additional O&M/Fuel Costs			
O&M ($/MWh)	3.8	3.8	3.8
Fuel ($/MWh)	6.2	5.2	5.7
TOTAL ($/MWh)	10.0	9.0	9.5

*Assuming an equal number of SCPC and IGCC plants.

Table A-4. Low-Side Capital Costs for Integrated Installation of Current Commercial-Scale Post-Combustion CO_2 Capture Technology—SCPC Plant (Initial Plant)

	SCPC Plant Without Capture	SCPC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	513	390
Base Cost ($US, 2006)	$990 million	$990 million
Incremental Cost ($US, 2006)	-	$240 million
Cost per MW ($US, 2006)	$1.93 million	$3.14 million
II. Calculation of Reimbursement		
1. Capture System		$240 million
2. Loss of Net Capacity		
Capacity Loss		123 MW
Reimbursement (@ $1.93 million/MW)		$240 million
3. Total Reimbursement		$480 million
Per MW		$1.23 million

Table A-5. Low-Side Capital Costs for Integrated Installation of Current Commercial-Scale Pre-Combustion CO_2 Capture Technology—IGCC Plant (Initial Plant)

	IGCC Plant Without Capture	IGCC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	477	413
Base Cost ($US, 2006)	$950 million	$950 million
Incremental Cost ($US, 2006)	-	$180 million
Cost per MW ($US, 2006)	$1.99 million	$2.74 million
II. Calculation of Reimbursement		
1. Capture System		$180 million
2. Loss of Net Capacity		
Capacity Loss		64 MW
Reimbursement (@ $1.99 million/MW)		$130 million
3. Total Reimbursement		$310 million
Per MW		$0.75 million

Table A-6. Low-Side Average Incremental Costs of Integrated Installation of CO_2 Capture

	SCPC Plant With Capture	IGCC Plant With Capture	Average Plant* With Capture
1. Additional Capital Costs			
Total ($ million)	$480	$310	$395
MWe (net capacity)	390	413	401.5
$/MWe (millions)	$1.23	$0.75	$0.98
2. Additional O&M/Fuel Costs **			
O&M ($/MWh)	3.8	3.8	3.8
Fuel ($/MWh)	6.2	5.2	5.7
TOTAL ($/MWh)	10.0	9.0	9.5

*Assuming an equal number of SCPC and IGCC plants.

**For purposes of the analyses, the O&M/fuel costs have been kept the same for both the high-side and the low-side cases. The additional O&M/fuel costs may be lower for an integrated power system with CO_2 capture.

Appendix B: Learning Curves and Cost Reductions

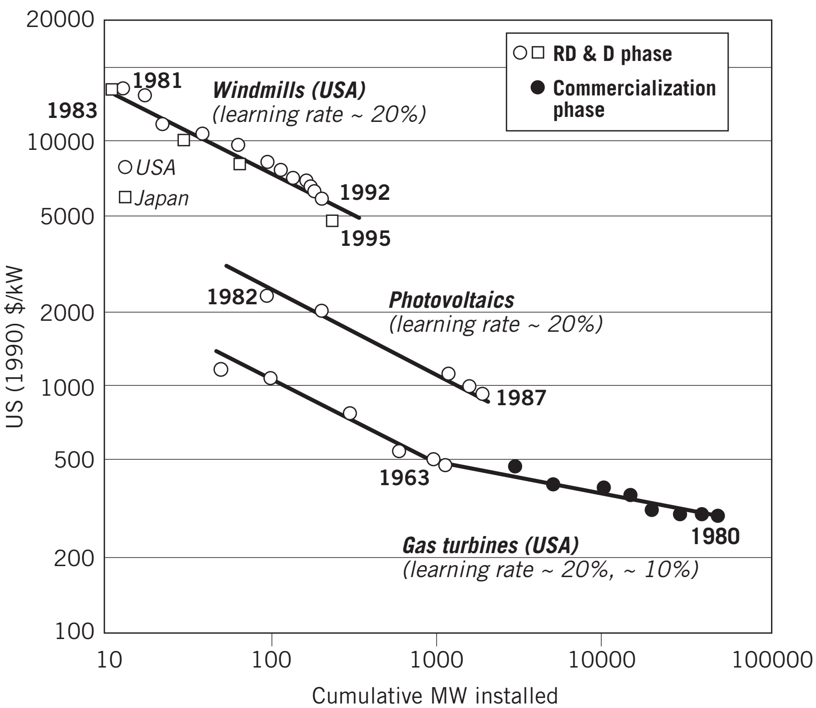
An important premise of this report is that technological change and progress will significantly improve CO_2 capture technology, including providing cost reductions in CO_2 capture equipment and improvements in energy efficiency for operating the CO_2 capture process. The premise that costs decrease with robust RD&D investment and increasing commercial installations is based on time-proven experience with "learning curves" and is a widely seen characteristic of all successful technologies.

1. Learning Curve Work by Nakicenovic. The learning curve work by Nakicenovic partitions the cost reductions process into two phases:

- Phase One: The initial R&D ("learning by learning") phase during which costs decline by 20% (as measured by the price to consumers) for every doubling of installed capacity; and

- Phase Two: The subsequent commercialization ("learning by doing") phase, during which time cost declines by 10% (as measured by the price to consumers) for every subsequent doubling for installed capacity.

Figure B-1. Learning Curves for Energy Technologies

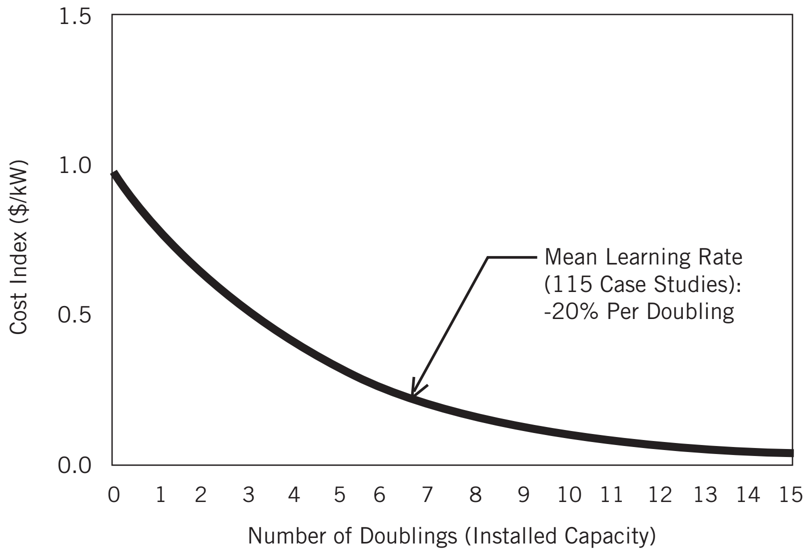


These curves illustrate the well-established phenomenon that technology costs tend to decline with cumulative production.

Source: Nakicenovic, N., Grubler, A., and MacDonald, A., "Global Energy Perspectives", ISBN-10: 0521645697, Cambridge University Press (1998).

Figure B-1 provides the historical data on the "learning curve" for three technologies—photovoltaics, windmills and gas turbines. For gas turbines, the RD&D ("learning by learning") phase provided significant initial cost savings, equal to a 20% reduction in capital costs per doubling of cumulative MWs installed. The cost reductions for gas turbines slowed but still remained substantial during the commercialization ("learning by doing") phase, equal to a 10% reduction in capital costs per doubling of cumulative MWs installed.

Figure B-2. Historical Cost Reduction Rates from Learning-by-Doing



A larger sample of historical learning cost reductions, as reported by Nakicenovic for 115 case studies of distinct technologies (Figure B-2), shows that the significant potential for learning-based cost reductions are not unique to gas turbines. The work by Nakicenovic (as well as the incorporation of his work in the EIA/NEMS electricity module) provides the basis for the upside (50%) cost reductions expected from the larger-scale CO_2 capture and storage demonstration set forth in the White Paper.

2. Cost Reduction Goals of the CCP. The CO_2 Capture Project (CCP) was launched in 2000 to address key technical and cost issues in CO_2 capture and storage from industrial sources. The first phase of the CCP (completed in 2004) identified the potential for significant cost reductions from a variety of new CO_2 capture technologies, shown in the table and chart on the following page. Cost savings, compared to initial baseline cost estimates, ranged from relatively small increments to very large savings (14% to 60%). The potential for cost savings was found to be significant because CO_2 capture was (and still is) a relatively new technology in large-scale energy applications.

CCP2 (CO_2 Capture Project Phase 2) continued in 2004 with even more ambitious goals of 75% cost reductions from year 2000 baseline costs. CCP2, working with international funding agencies and premier researchers in their fields, is planning to demonstrate one or more of the promising CO_2 capture technologies from its extensive portfolio of improved CO_2 capture options.

The CCP staff reviewed the potential for CO_2 capture cost reductions set forth in the White Paper. Their assessment is that the proposed assumptions on cost and energy penalty reductions are reasonable.

CO_2 CAPTURE PROJECT RESULTS

Conclusion

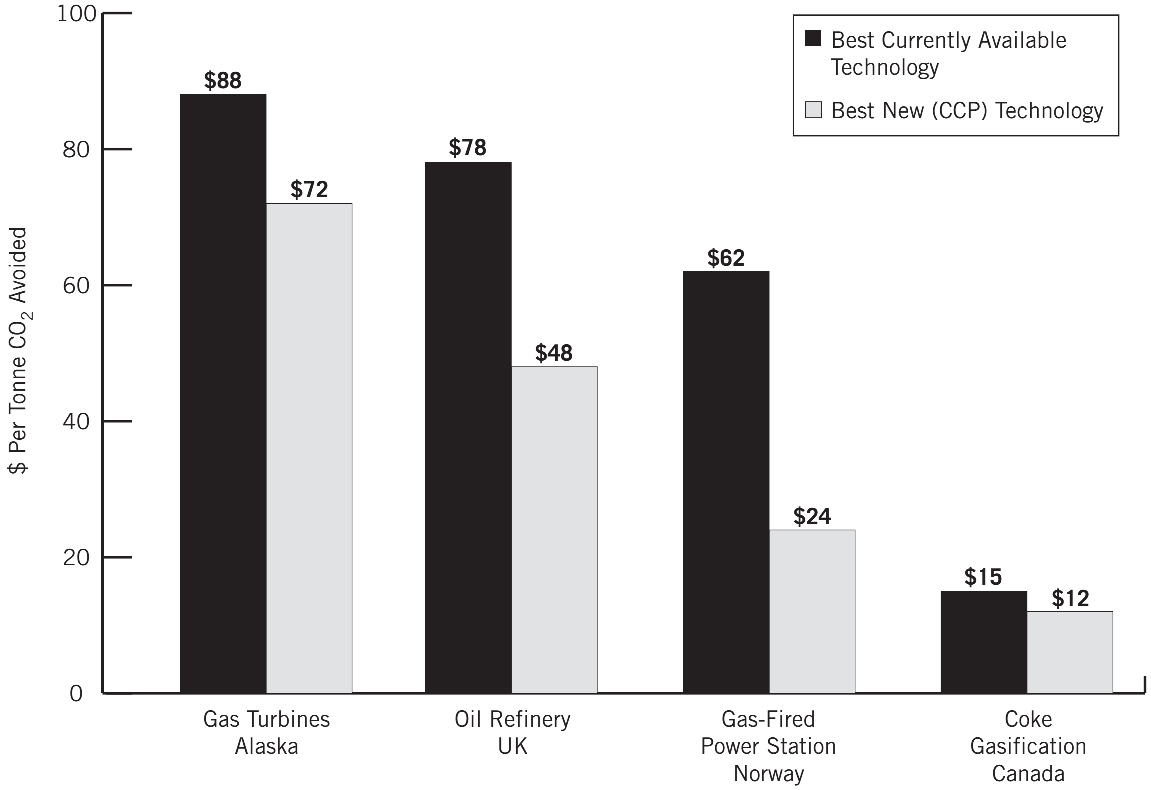
Once the capture technologies being developed by the CCP had been taken to proof of concept stage, the most promising were subjected to a more detailed cost assessment. The results have shown significant potential savings for all scenarios, ranging from 16% for the coke gasification scheme to 60% for the gas-fired power station.

While different technologies are at different stages of development, the wide range identified by the CCP means that they could be suitable for many of the world's major emissions sources. Techniques developed for gas-fired power generation for example could also be used for coal-fired power generation, if combined with the gasification of coal.

Pre-combustion capture, where some of the most significant advances have been made, is applicable to all fossil fuel sources and may also offer the opportunity to produce large amounts of hydrogen cost effectively, helping to stimulate the development of a hydrogen based energy economy in the future.

With continued public-private partnership, the next step will be to work towards the commercial scale demonstration of the most promising technologies developed by the CCP as well as the achievement of further cost reductions. This is helping to bring forward the day when society could benefit from cleaner energy from fossil fuels.

Potential Cost Savings of Best CO_2 Capture Technologies



Potential Cost Savings of CCP Capture Technologies	Alaska Distributed Gas-Fired Power Generation	UK Oil Refinery	Norway Natural Gas Power Station	Canada Coke Gasification
Baseline Cost (best currently available technology) $ per tonne of CO_2 avoided	$88.2	$78.1	$61.6	$14.5
CCP Developed Technologies Cost / $ Per Tonne of CO_2 Avoided (% variation from baseline)				
Pre-Combustion Capture Technology				
Membrane Water Gas Shift (GRACE & DOE-membrane)		$48.1 (-38%)		
Membrane Water Gas Shift (GRACE & Pd-membrane)		$52.4 (-33%)		
Sorption Enhanced Water Gas Shift	$71.8 (-19%)			
Sorption Enhanced Water Gas Shift – O2ATR			$42.7 (-31%)	
Sorption Enhanced Water Gas Shift – AirATR			$34.4 (-44%)	
Very Large Scale Auto Thermal Reformer	$76.0 (-14%)			
Hydrogen Membrane Reformer			$24.4 (-60%)	
Advanced Coke Gasification				$12.2 (-16%)
Post-Combustion Capture Technology				
Nexant Integrated Baseline Design			$35.1 (-43%)	
MHI Solvent (KSI) with Kvaerner Membrane			$47.5 (-23%)	
Best Integrated Technology (Nexant BL Integrated & MHI-KSI)			$28.2 (-54%)	
Oxyfuel Capture Technology				
Oxyfiring with Flue Gas Recycle & Ionic Transport Membranes (ITM)		$41.0 (-48%)		
Oxyfiring with Flue Gas Recycle & ASU		$48.7 (-38%)		

Cost reduction determined using Common Economic Model with generic (US Gulf Coast) material costs and standardized energy prices.

Source: www.co2captureproject.org.

Appendix C: Cost Savings and Benefits for Larger-Scale Program

This Appendix sets forth the calculations of cost-savings that would accrue from launching a large-scale integrated program of research, development and commercial-scale demonstration of CO_2 capture and storage (CCS).

Table C-1 shows, for a SCPC plant, the capital costs for the CO_2 capture facility at the 30th plant assuming an "optimistic" decrease in CO_2 capture capital costs (plus reductions in the energy penalty). Incremental capital costs decline from the currently estimated \$1.67 million per MW (Table A-1) to an estimated \$0.98 million per MW.

Table C-2 shows similar information for an IGCC plant with CO_2 capture, where the incremental capital costs for CO_2 capture decline from the currently estimated \$1.38 million per MW (Table A-2) to an estimated \$0.83 million per MW at the 30th plant.

Table C-3 shows the average capital costs for CO_2 capture (for a combined 30th SCPC and IGCC plant) with an "optimistic" cost reduction expectation of 41% in CO_2 capture capital costs. Average capital costs decline from \$1.52 million per MW (Table A-3) to an estimated \$0.90 million per MW.

Table C-4 shows, for a SCPC plant the costs for the CO_2 capture facility at the 30th plant, assuming a "pessimistic" decrease in CO_2 capture capital costs (plus reductions in the energy penalty). Incremental capital costs decline from the currently estimated \$1.67 million per MW (Table A-1) to an estimated \$1.12 million per MW.

Table C-5 shows similar information for an IGCC plant with CO_2 capture, where the incremental capital costs for CO_2 capture decline from the currently estimated \$1.38 million per MW (Table A-2) to an estimated \$0.93 million per MW at the 30th plant.

Table C-6 shows the average capital costs for CO_2 capture (for a combined 30th SCPC and IGCC plant) with a "pessimistic" cost reduction expectation of 33% in CO_2 capture capital costs. Average capital costs decline from \$1.52 million per MW (Table A-3 to an estimated \$1.02 million per MW.

Table C-1. High-Side Capital Costs for Adding Advanced Commercial-Scale, Post-Combustion CO_2 Capture Technology: 30th SCPC Plant with "Optimistic" Capital Cost Reduction Expectations

	SCPC Plant Without Capture	SCPC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	550	430
Base Cost ($US, 2006)	$1,200 million	$1,200 million
Incremental Cost ($US, 2006)	-	$160 million
Cost per MW ($US, 2006)	$2.18 million	$3.16 million
II. Calculation Of Reimbursement		
1. CO_2 Capture System		$160 million
2. Loss of Net Capacity		
Capacity Loss		120 MW
Reimbursement (@ $2.18 million/MW)		$260 million
3. Total Reimbursement		$420 million
Per MW		$0.98 million

Table C-2. High-Side Capital Costs for Adding Advanced Commercial-Scale, Pre-Combustion CO_2 Capture Technology: 30th IGCC Plant with "Pessimistic" Capital Cost Reduction Expectations

	IGCC Plant Without Capture	IGCC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	553	453
Base Cost ($US, 2006)	$1,470 million	$1,470 million
Incremental Cost ($US, 2006)	-	$110 million
Cost per MW ($US, 2006)	$2.67 million	$3.49 million
II. Calculation Of Reimbursement		
1. CO_2 Capture System		$110 million
2. Loss of Net Capacity		
Capacity Loss		100 MW
Reimbursement (@ $2.67 million/MW)		$270 million
3. Total Reimbursement		$380 million
Per MW		$0.83 million

Table C-3. Average High-Side Capital Costs for Adding Advanced Commercial-Scale, CO_2 Capture Technology: 30th Plant with "Optimistic" Phase I Cost and Energy Penalty Savings

	SCPC Plant With Capture	IGCC Plant With Capture	Average Plant* With Capture
1. Additional Capital Costs			
Total ($ million)	$420	$380	$400
MWe (net capacity)	430	453	442
$/MWe (millions)	$0.98	$0.83	$0.90

*Assuming an equal number of SCPC and IGCC plants.

Table C-4 High-Side Capital Costs for Adding Advanced Commercial-Scale, Post-Combustion CO_2 Capture Technology: 30th SCPC Plant with "Pessimistic" Capital Cost Reduction Expectations

	SCPC Plant Without Capture	SCPC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	550	430
Base Cost ($US, 2006)	$1,200 million	$1,200 million
Incremental Cost ($US, 2006)	-	$220 million
Cost per MW ($US, 2006)	$2.18 million	$3.30 million
II. Calculation Of Reimbursement		
1. CO_2 Capture System		$220 million
2. Loss of Net Capacity		
Capacity Loss		120 MW
Reimbursement (@ $2.18 million/MW)		$260 million
3. Total Reimbursement		$480 million
Per MW		$1.12 million

Table C-5. High-Side Capital Costs for Adding Advanced Commercial-Scale, Pre-Combustion CO_2 Capture Technology: 30th IGCC Plant with "Pessimistic" Capital Cost Reduction Expectations

	IGCC Plant Without Capture	IGCC Plant With Capture
I. Key Assumptions		
Net Capacity (MW)	553	453
Base Cost ($US, 2006)	$1,470 million	$1,470 million
Incremental Cost ($US, 2006)	-	$150 million
Cost per MW ($US, 2006)	$2.67 million	$3.58 million
II. Calculation Of Reimbursement		
1. CO_2 Capture System		$150 million
2. Loss of Net Capacity		
Capacity Loss		100 MW
Reimbursement (@ $2.67 million/MW)		$270 million
3. Total Reimbursement		$420 million
Per MW		$0.93 million

Table C-6. Average High-Side Capital Costs for Adding Commercial-Scale, CO_2 Capture Technology: 30^{th} Plant with "Pessimistic" Capital Cost Reduction Expectations

	SCPC Plant With Capture	IGCC Plant With Capture	Average Plant* With Capture
1. Additional Capital Costs			
Total ($ million)	$480	$420	$450
MWe (net capacity)	430	453	442
$/MWe (millions)	$1.12	$0.93	$1.02

*Assuming an equal number of SCPC and IGCC plants.

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This paper analyzes strategies for accelerating the deployment of carbon capture and storage at coal-fueled electric power plants. It is part of a Pew Center on Global Climate Change Coal Initiative, a series of reports examining and identifying policy options for reducing coal-related GHG emissions. The Pew Center brings a cooperative approach and critical scientific, economic, technological, business and policy expertise to the global climate change debate at the state, federal and international levels.

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