THE ECONOMICS OF CO_2 CAPTURE[1]

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ABSTRACT

We have conducted a comparison of published studies that analyzed the economics of capturing CO_2 from the flue gas of power plants. For these studies, we have put the results on a common basis and conducted a sensitivity analysis. Three types of power plants were reviewed: pulverized coal plants, integrated gasification combined cycle plants, and natural gas combined cycle plants. Based on our analysis, we summarize the costs of CO_2 capture using today's technology. In addition, we have identified where technological improvements can significantly lower costs. We conclude that with new developments, CO_2 capture and sequestration can become a cost-effective mitigation pathway.

INTRODUCTION

Fossil fuels currently supply over 85% of the world's energy needs and will remain in abundant supply well into the 21st century. They have been a major contributor to the high standard of living enjoyed by the industrialized world. We have learned how to extract energy from fossil fuels in environmentally friendly ways, controlling the emissions of NO_x, SO_2, unburned hydrocarbons, and particulates. Even with these added pollution controls, the cost of fossil energy generated power keeps falling. Despite this good news about fossil energy, its future is clouded because of the environmental and economic threat posed by possible climate change, commonly referred to as the "greenhouse effect". The major greenhouse gas is carbon dioxide (CO_2) and the major source of anthropogenic CO_2 is combustion of fossil fuels. However, if we can develop technology to capture and sequester the fossil fuel CO_2 in a cost-effective and environmentally sound manner, we will be able to enjoy the benefits of fossil fuel use throughout the next century.

The idea of capturing CO_2 from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO_2, especially for use in enhanced oil recovery (EOR) operations where CO_2 is injected into oil reservoirs to increase the mobility of the oil and, therefore, the productivity of the reservoir. Several commercial CO_2 capture plants were constructed in the late 1970s and early 1980s in the US (Arnold *et al.*, 1982; Hopson, 1985; Kaplan, 1982; Pauley *et al.*, 1984). The North American Chemical Plant in Trona, CA, which uses this process to produce CO_2 for carbonation of brine, started operation in 1978 and is still operating today. However, when the price of oil dropped in the mid-1980s, the recovered CO_2 was too expensive for EOR operations and all of the other CO_2 capture plants were closed. Several more CO_2 capture plants were subsequently built (Barchas and Davis, 1992; Sander and Mariz, 1992) to take advantage of some of the economic incentives in the Public Utility Regulatory Policies Act (PURPA) of 1978 for "qualifying facilities" and to provide CO_2 for sale commercially.

In addition to power plants, there are a number of large CO_2-emitting industrial sources that could also be considered for application of capture and sequestration technologies. In natural gas operations, CO_2 is generated as a by-product. In general, gas fields contain up to 20% (by volume) CO_2, most of which must be removed to produce pipeline quality gas. Therefore, sequestration of CO_2 from natural gas operations is a logical first step in applying CO_2 capture technology. In the future, similar opportunities for CO_2 sequestration may exist in the production of hydrogen-rich fuels (e.g., hydrogen or methanol) from carbon-rich feedstocks (e.g., natural gas, coal, or biomass). Specifically, such fuels could be used in low-temperature fuel cells for transport or for combined heat and power. Relatively pure CO_2 would result as a byproduct (Socolow 1997).

The first commercial CO_2 capture and sequestration facility started-up in September 1996, when Statoil of Norway began storing CO_2 from the Sleipner West gas field into a sandstone aquifer 1000 m beneath the North Sea. The

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CO_2 is injected from a floating rig through five pipes at a rate of 20,000 tonnes/week (corresponding to the rate of CO_2 produced from a 140 MW_e coal fired power plant). The economic incentive for this project is the Norwegian carbon tax of $50 per tonne CO_2. Costs of the operation are approximately $15/tonne of CO_2 avoided (Olav Kaarstad, Statoil, personal communication). An international research effort is being organized to monitor and document this effort so the experience can be built on by future endeavors.

To date, all commercial plants to capture CO_2 from power plant flue gas use processes based on chemical absorption with a monoethanolamine (MEA) solvent. MEA was developed over 60 years ago as a general, non-selective solvent to remove acid gases, such as CO_2 and H_2S, from natural gas streams. The process was modified to incorporate inhibitors to resist solvent degradation and equipment corrosion when applied to CO_2 capture from flue gas. Also, the solvent strength was kept relatively low, resulting in large equipment sizes and high regeneration energy requirements (Leci, 1997). Therefore, CO_2 capture processes have required significant amounts of energy, which reduces the power plant's net power output. For example, the output of a 500 MW_e (net) coal-fired power plant may be reduced to 400 MW_e (net) after CO_2 capture. This imposes an "energy penalty" of 20% (i.e., (500-400)/500). The energy penalty has a major effect on the overall costs. Table 1 shows typical energy penalties associated with CO_2 capture -- both as the technology exists today and as it is projected to evolve in the next 10-20 years.

METHODOLOGY

We have conducted a comparison of published studies from the past several years that analyzed the economics of capturing CO_2 from the flue gas of coal fired power plants (see Table 2). These studies fall into three categories -- capture from Pulverized Coal (PC) power plants, capture from Integrated Gasification Combined Cycle (IGCC) power plants, and capture from Natural Gas Combined Cycle (NGCC) power plants. MEA scrubbing was used in the PC and NGCC plants, but IGCC plants allow the use of more energy efficient scrubbing processes involving physical absorption. All studies were made using commercially available technology and include the cost of compressing the captured CO_2 to about 2000 psia for pipeline transportation. In all cases, except the Fluor PC case, we relied entirely on the data presented in the original reports. For some of these cases, additional calculations were required to report the results on a common basis. In the Fluor PC case, only data on the MEA process were presented. We augmented these data with power plant and compressor data from the EPRI PC case.

The Argonne study is used to illustrate our methodology. Two cases are compared, a power plant with no capture and the same plant with capture. In both cases, the gross (i.e., before capture) capacity and fuel requirements are the same. From the report, we extracted the following data:

- For the base (no capture) case, the power cost is 5.83¢/kWh_e for 411 MW_e net output with 0.8 kg CO_2 emitted/kWh_e.
- For the capture case, the power cost is an additional 0.62¢/kWh_e (based on the 411 MW_e gross output). The net output is 373 MW_e with 0.2 kg CO_2 emitted/kWh_e.

The first step is to calculate the net power cost for the capture case. This is done by adding the base power cost to the incremental cost of capture and adjusting for the reduced net output, as follows:

$$(5.83 + 0.62)\ \text{¢}/kWh_e \times (411\ MW_e)/(373\ MW_e) = 7.10\text{¢}/kWh_e$$

The cost of capture is then calculated by dividing the increase in the cost of power by the amount of CO_2 avoided:

$$[(7.10 - 5.83)\text{¢}/kWh_e] / [(0.8\text{-}0.2)\ \text{kg}\ CO_2\ \text{emitted}/kWh_e] = 2.1\text{¢/kg}\ CO_2\ \text{avoided} = \$21/\text{tonne}\ CO_2\ \text{avoided}$$

The energy penalty is simply the difference in the net power outputs divided by the base case power output:

$$[(411 - 373)\ MW_e] / 411\ MW_e = 9.2\%$$

RESULTS

The results of the analysis are summarized in Table 2. To find the total mitigation cost, the capture cost must be added to the sequestration cost (i.e., the cost of transporting and injecting the CO_2 into the ground or ocean). Assuming a nominal sequestration cost of \$10 per tonne of CO_2 avoided, the mitigation costs are plotted versus the energy penalties in Figure 1. Note that the capture cost was calculated by comparing a CO_2 capture power plant to a "no capture" power plant of the same type. To take account of the fact that an IGCC plant is more expensive than a PC plant, the mitigation costs for the IGCC capture plants compared to a PC base plant are also plotted. The line in Figure 1 is the level of the carbon tax in Norway. All points below the line become economically attractive when subjected to such a tax.

Some observations on Figure 1:

- In general, the lower the energy penalty, the lower the cost.

- The Utrecht cases predict much lower costs than the other studies. Part of the reason is their use of lower discount rates.

- PC plants need significant developments to become economic in a situation like Norway today. However, NGCC and IGCC plants may be economic in Norway today with only small improvements on existing technology. That is why Norway is currently considering building an NGCC power plant with CO_2 capture within the next few years.

- For IGCC power plants, the economics can be greatly enhanced by improving the performance of the base (no capture) power plant.

SENSITIVITY ANALYSIS

To try to understand what are some of the key variables required to reduce costs, we conducted a sensitivity analysis. As base cases, we used the EPRI PC and the Argonne IGCC cases. These cases represented high and low sensitivity cases, respectively. The results below are presented as a percentage change in cost per percentage change in the sensitivity parameter:

- ***Decrease the heat rate (increase base plant efficiencies).*** This has a very significant effect on cost, lowering costs between 1-1.2% per a 1% improvement in heat rate. The range of study was 9750 Btu/kWh_e (35% efficiency) to 6830 Btu/kWh_e (50% efficiency).

- ***Lower the energy penalty.*** Lowering the energy required for capture and compression can significantly reduce costs. For every percent reduction in the energy required for capture, costs were lowered between 0.7-1%. The range of study was 0-75% reduction in energy requirements. As seen in Table 1, studies have shown how energy requirements can be cut by 50%.

- ***Lower the fuel cost.*** This variable had very little impact on cost. For each percent drop in the fuel price, the cost of capture only changes by 0.1%.

FUTURE OUTLOOK

One should not judge the viability of CO_2 capture power plants based on today's relatively expensive technology. There is great potential for technological improvements that can significantly lower costs. As shown in the above sensitivity studies, improving the heat rate of fossil plants or reducing the energy penalty for CO_2 capture can significantly reduce costs. For coal-fired power plants, a 50% thermal efficiency (i.e., 30% decrease in heat rates) is achievable, resulting in a 30% decrease in capture costs. Table 1 indicates the energy penalty could be cut in half with only evolutionary developments, thereby cutting capture costs about 40%.

Even larger costs reductions are possible in the future with new technologies. For example, we can develop new types of power plants and power cycles. Results can be dramatic as seen with the more economical capture from

IGCC plants versus PC plants. At the same time, we can make breakthroughs in capture technologies. Two examples follow:

- A separation process based on hydrates is being developed to capture CO_2 from an IGCC plant. Initial work shows a potential to reduce the energy penalty to 6% and cut costs to the order of $10 per tonne of CO_2 avoided (Spencer, 1998).

- Toshiba Corporation has developed new ceramic materials that can absorb and store up to 400 times its volume with CO_2. The use of this ceramic to absorb CO_2 using a temperature swing adsorption process (absorb at 450-700^oC, desorb >700^oC) is currently being investigated (GECR, 1998).

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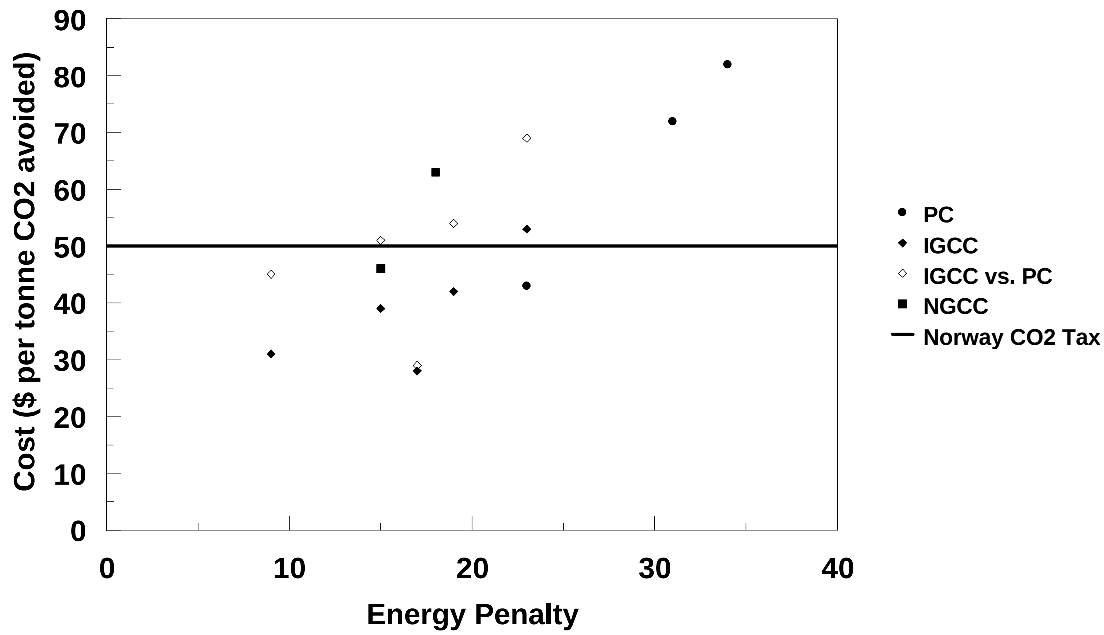

Figure 1: Mitigation cost plotted vs. energy penalty and type of power plant for the studies analyzed. The mitigation cost is the sum of the capture costs in Table 2 plus an additional $10/tonne CO_2 avoided to account for the sequestration costs.

Table 1. Typical Energy Penalties Associated with CO_2 Capture

Power Plant Type	**Today**	**Future**
Conventional Coal (PC)	27 - 37% (Herzog and Drake, 1993)	15% (Mimura *et al.*, 1997)
Gas (NGCC)	15 - 24% (Herzog and Drake, 1993)	10 - 11% (Mimura *et al.*, 1997)
Advanced Coal (IGCC)	13 - 17% (Herzog and Drake, 1993)	9% (Herzog and Drake, 1993)

Table 2. Results of the Economic Analysis

Study	Argonne	EPRI	Utrecht	IEA GHG	Essen	EPRI	Utrecht	Fluor	IEA GHG	Trondheim
Reference	**Doctor 1996**	**Condorelli 1991**	**Hendriks 1994**	**Audus 1995**	**Pruschek 1996**	**Smelser 1991**	**Hendricks 1994**	**Mariz 1995**	**Audus 1995**	**Bolland 1992**
Plant Type	**IGCC**	**IGCC**	**IGCC**	**IGCC**	**IGCC**	**PC**	**PC**	**PC**	**NGCC**	**NGCC**
CO_2 emitted without capture (kg/kWh_e)	0.80	0.87	0.80	0.78	0.69	0.91	0.80	0.91	0.41	0.40
CO_2 emitted with capture (kg/kWh_e)	0.20	0.10	0.10	0.17	0.09	0.14	0.10	0.14	0.075	0.046
Percent reduction in CO_2 emissions	75%	88%	88%	78%	87%	85%	88%	85%	82%	89%
Plant efficiency (HHV) without capture	36.6%	35.4%	43.6%	39.9%	45.0%	34.8%	41.0%	34.8%	50.0%	47.4%
Plant efficiency (HHV) with capture	33.2%	28.5%	36.3%	34.0%	34.7%	22.9%	31.5%	24.0%	41.0%	40.4%
Energy penalty	9%	19%	17%	15%	23%	34%	23%	31%	18%	15%
Cost basis	1995$	1990$	1990$	1993$	199?$	1990$	1990$	199?$	1993$	1992$
Effective capital charge rate	11.1%	12.8%	7.1%	9.4%	?	12.3%	7.1%	12.3%	10.5%	8.6%
Electricity price (busbar) no capture (¢/kWh_e)	5.8	5.7	3.8	5.9	6.8	4.6	3.7	4.6	3.6	3.1
Electricity price (busbar) w/capture (¢/kWh_e)	7.1	8.2	5.1	7.6	9.4	10.1	6.1	9.4	5.4	4.4
Cost of Capture ($/tonne CO_2 avoided)	$21	$32	$18	$29	$43	$72	$33	$62	$53	$36