# $CO_2$ Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change

A White Paper
Final Report

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# Disclaimer

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## 1. Executive Summary

As the world's largest emitter of $CO_2$, the US needs to develop a balanced portfolio of responses that will allow us to be an effective participant in evolving international agreements to address climate change concerns. This “climate portfolio” needs to include activities on the various aspects of the climate change problem, including better understanding the science and the potential impacts, developing technological responses for adaptation and mitigation, and formulating policies that take into account the economic costs. The purpose of this white paper is to discuss an important opportunity which we should consider as part of our technological response, namely the capture and sequestration of $CO_2$ from large stationary sources.

In the short-term, the US Department of Energy (DOE) is responding to climate change concerns by pursuing programs to promote energy efficiency. For example, the Office of Fossil Energy (FE) has a program targeted at increasing the efficiency of fossil fuel-fired power plants. However, now that the US and the international community are starting to look beyond the year 2000, additional mitigation technologies may be required. FE can respond to this longer-term outlook by investigating the continued use of fossil fuels with technologies for $CO_2$ capture and sequestration. A five year program is recommended to investigate the feasibility of such technologies and to foster their development where appropriate.

In this white paper, we will first discuss the motivation for developing $CO_2$ capture and sequestration technologies (Chapter 2) and then provide some background information, looking at both the history and economics of this mitigation option (Chapter 3). Next, we review the major technological components -- capture technology (Chapter 4), geological storage (Chapter 5), ocean storage (Chapter 6), and direct utilization (Chapter 7). Chapter 8 looks at system integration and implementation issues. In Chapter 9 we look at some other $CO_2$ mitigation technologies that FE may want to consider investigating as part of an integrated program. Finally, specific recommendations for research are summarized in Chapter 10.

Because of the potential adverse impacts from global climate change, the world community has adopted the Framework Convention on Climate Change. The urgency of their work was recently underscored when the Intergovernmental Panel on Climate Change (IPCC) issued their *Second Assessment Report* which stated that “the balance of evidence suggests a discernible human influence on global climate”. US Under Secretary of State Timothy Wirth has stated that the US will press for “an agreement that sets a realistic, verifiable, and binding medium-term emissions target” (Testimony before the US Senate Energy and Natural Resources Committee, Sept. 17, 1996).

In viewing the spectrum of responses to global climate change, there are a number of relatively low cost $CO_2$ mitigation technologies, sometimes termed “least regrets”. They include improving energy supply and end-use efficiency, switching from coal or oil to gas where possible, forestation, and inexpensive renewable energy applications. The major drawback of this group of technologies is their limited impact. They may be sufficient to meet short-term goals, but there is a general belief that they will not be able to solve the problem in the mid- and long-term. In light of their limited reduction potential, additional, but more costly mitigation technologies must be considered, specifically $CO_2$ capture and sequestration, nuclear power, and large-scale renewable energy production. All three of these mitigation technologies have the potential to substantially reduce $CO_2$ emissions at comparable costs, yet all three suffer impediments (e.g., nuclear must solve issues of safety and public acceptance and renewable energy costs must decrease). Since at least one of these options (if not all three) will be required to stabilize atmospheric levels of greenhouse gases in the mid- to long-term, it is prudent to examine all three. Compared with nuclear and renewable energy, the US research effort to-date with respect to technologies for $CO_2$ capture and sequestration has been minimal. Thus we should extend our efforts to understand $CO_2$ capture and sequestration technologies in order to better evaluate their potential and to reduce their associated costs and risks.

The main challenge regarding $CO_2$ capture technology is to reduce the overall cost by lowering both the energy and the capital cost requirements. While costs and energy requirements for today's capture processes are high, the opportunities for significant reductions exist, since researchers have only recently started to address these needs. One strategy that looks extremely promising is to combine $CO_2$ removal with advanced coal energy conversion processes that have features which will enable low energy intensive capture.

The major options for $CO_2$ storage are underground or in the ocean. Statoil is presently storing one million tonnes per year of $CO_2$ from Norwegian gas fields in an aquifer beneath the North Sea. A larger aquifer storage project may soon be undertaken by Exxon and Pertamina at their Natuna gas field in the South China Sea. Besides aquifers, geologic storage options include active oil wells (in connection with enhanced oil recovery), coal beds, and depleted oil and gas wells. The issues which need clarification include storage integrity and reservoir characterization. Ocean $CO_2$ disposal would reduce peak atmospheric $CO_2$ concentrations and their rate of increase by accelerating the ongoing, but slow, natural processes by which most current $CO_2$ emissions enter the ocean indirectly. The capacity of the ocean to accept $CO_2$ is almost unlimited, but there are questions that still need to be addressed about its effectiveness (how long will the $CO_2$ remain sequestered) and about the environmental impacts associated with increased seawater acidity near the injection point.

While there are diverse niche opportunities for industrial utilization of power plant $CO_2$, these uses are all small compared to the total quantities of $CO_2$ emitted by the power sector. Multiple small uses can be an effective, but small, part of a mitigation strategy. Large scale chemical conversion of power plant $CO_2$ to fuels such as methanol requires so much energy that it produces marginal mitigation benefit, if any. Microalgae offer the potential for conversion of power plant $CO_2$ to biomass, but research is needed to achieve improvements in productivity that would reduce land requirements and costs. Storage as carbonate minerals is another possibility, but materials handling and waste issues make practicality uncertain without further investigation. In the nearer term, limited biomass energy farming, coupled with cofiring of farmed or waste biomass with fossil fuels is an attractive option. In the much longer-term, research on bioproduction of hydrogen or on artificial photosynthesis may provide new and significant pathways for mitigation.

To address the above challenges and opportunities, we propose an initial five year research program into the capture and sequestration of $CO_2$ with the following strategic goals: encourage/accelerate near-term opportunities, assess compatibility with on-going advanced combustion and efficiency programs, assess longer-term feasibility, position the US to become a technology leader, leverage on-going international research, and stimulate private sector R&D.

To date, the cumulative research dollars spent on $CO_2$ capture and sequestration technologies in the US has been less than $10 million, limiting the research effort to small theoretical or laboratory studies. To allow needed program development, we recommend a budget that averages $50 million per year for 5 years as detailed below:

| | |
|---|---|
| FY98 | $20 million |
| FY99 | $40 million |
| FY00 | $60 million |
| FY01 | $70 million |
| FY02 | $60 million |

We envision leveraging this budget through collaboration with the private sector and through international collaboration. Approximately half of the funding should go towards collaborative projects. Specific program components, with their relative share of available funds indicated, are:

- Promotion of near-term opportunities (15%).
- Assessment and development of capture technology (25%).
- Assessment and development of storage technology (35%).
- System analysis (10%).
- Generation and assessment of longer-term technologies (15%).

To put this budget request in perspective, we can make the following comparisons:

- The limited funding to date for $CO_2$ capture and sequestration has not allowed significant program development, making it difficult to fairly assess the potential of these technologies compared to other longer-term $CO_2$ mitigation options for which substantial sums of money have been spent (e.g., switching to nuclear or renewable energy sources).

- The total US energy expenditures are approximately $500 billion annually, while the existing capital stock of the utility industry worldwide is estimated in excess of $2 trillion. It seems wise to investigate whether $CO_2$ capture and sequestration technologies can allow fossil fuels to remain a cost-effective energy source, while concurrently contributing to a significant reduction in greenhouse gas emissions.

- The proposed budget is modest in comparison to Japanese government expenditures on $CO_2$ capture and sequestration (by at least a factor of 2).

- The US now spends about $1.6 billion annually investigating various aspects of the climate change problem. Spending at that level indicates that global climate change is being taken seriously. It seems prudent to spend at just 3% of that level to investigate the flexibility of one of the few possible longer-term mitigation solutions.

## 2. Motivation and Overview

The purpose of this white paper is to discuss *new* opportunities for the US Department of Energy's Office of Fossil Energy (FE) to contribute to the solution of the climate change problem. It is important to emphasize that FE programs are already addressing a high priority opportunity for $CO_2$ mitigation -- increasing the efficiency of fossil fuel-fired power plants (see Appendix A). However, now that the US and the international community are starting to look beyond the year 2000, additional mitigation technologies may be required. FE can respond to this longer-term outlook by investigating the feasibility of technologies for $CO_2$ capture and sequestration and by fostering their development where appropriate.

Fossil fuels currently supply over 85% of the world's energy needs. They 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. This white paper proposes a research agenda to assess and develop competitive technologies that will allow us to continue to enjoy the benefits of fossil energy while significantly reducing emissions of greenhouse gases.

The potential impacts of global climate change are many and varied, though there is much uncertainty as to the timing and magnitude (Watson *et al.*, 1996). Because of the potential adverse impacts, the world community has adopted the Framework Convention on Climate Change (see Box 1). The urgency of their work was recently underscored when the Intergovernmental Panel on Climate Change (IPCC) issued their *Second Assessment Report* which stated that "the balance of evidence suggests a discernible human influence on global climate". US Under Secretary of State Timothy Wirth has stated that the US will press for "an agreement that sets a realistic, verifiable, and binding medium-term emissions target" (Testimony before the US Senate Energy and Natural Resources Committee, Sept. 17, 1996).

One of the reasons for Secretary Wirth's statement is that international attempts to reduce emissions have proven inadequate to date. The goal of stabilization of greenhouse gas emissions at their 1990 levels in the year 2000 will not be met by the vast majority of countries. Based on this experience, it is obvious that more aggressive technology responses are required to control greenhouse gas emissions.

The US is promoting policies to produce responses that are cost-effective and flexible in both space and time. This approach was very successful in controlling $SO_2$ emissions, resulting in costs more than an order of magnitude lower than originally predicted. The research conducted on $SO_2$ control options contributed to this ultimate success. By analogy, to be able to control $CO_2$ in a cost-effective manner in the future, we need to do research today on possible technological responses. The flexibility in time is needed for both an economical turnover of the existing capital stock and to develop appropriate low-cost responses (Richels and Edmonds, 1995).

Since this is a global problem, flexibility in choosing the location for mitigation programs is very appropriate. Recovering a ton of $CO_2$ in China or anywhere else in the world is equivalent to recovering a ton in the US. This is the principle behind the development of Activities Implemented Jointly (AIJ)[1]. While the industrialized world has been the major emitter of $CO_2$ to date (with the US being the largest at about 20% of the world total), countries such as China and India will be the leading emitters in the 21st century. It should be noted that both these countries are planning to utilize their large coal reserves to help develop their economies.

At this point in time, there is too much uncertainty to predict what the best technological response should be. The uncertainty lies in the science of global climate change (e.g., what is the magnitude of the problem?), the form of the policy responses, and the cost and effectiveness of the mitigation technologies themselves. However, despite the uncertainties, it is still possible to make the following statements:

- No one category of mitigation technologies will solve the problem by itself. A multi-option approach will be required. The choice of specific options will depend on local circumstances.

- There are a number of categories of relatively low cost $CO_2$ mitigation strategies, sometimes termed “least regrets”, that from an economic viewpoint could be implemented first. They include improving energy efficiency, switching from coal or oil to gas where possible, afforestation/reforestation, and inexpensive renewable energy applications. The major drawback of this group of technologies is their limited impact. They may be sufficient to meet short-term goals, but there is a general belief that they will not be able to address the problem in the mid- to long-term.

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[1] The US Initiative on Joint Implementation (USIJI), initiated in October 1993 as part of the President’s Climate Change Action Plan, is a program designed to encourage international private sector partnerships to reduce greenhouse gas emissions. Joint Implementation (JI) offers the potential to achieve greater and more cost effective emission reductions than would be likely if each country pursued only domestic actions. JI can also spur technology cooperation by increasing the market penetration of more efficient fossil generation and renewable technologies. JI projects also include fuel switching and reforestation projects. With the goal of testing criteria for joint implementation, the US supported the beginning of the international pilot phase of this program known as Activities Implemented Jointly (AIJ) at the first Conference of the Parties (COP-1) in April, 1995.

- To meet probable emissions targets in the mid- to long-term, more costly mitigation technologies must be considered, specifically $CO_2$ capture and sequestration, nuclear, and extensive use of renewable energy. All three of these technologies have the potential to significantly reduce emissions of $CO_2$, but there are limitations regarding their wide-spread implementation. As will be documented in this paper, $CO_2$ capture and sequestration has to reduce costs and demonstrate suitable methods of storage. Nuclear must address the issues of safety, waste, and public acceptance. Renewables have to overcome the problems of cost, intermittent supply, and limited geographical applicability.

Below are some reasons why research into $CO_2$ capture, use, and disposal technologies is important:

- It is a prudent measure since there are only a limited number of strategies to reduce greenhouse gas emissions. The field of $CO_2$ capture and sequestration is still in its infancy, with many questions needing to be addressed to make these technologies viable. At this time, it is judicious to explore all potential mitigation options in a balanced way, so that a broad range of strategies are available to help meet future policy goals.

- These technologies provide a long-term greenhouse gas mitigation option that allows for continued large-scale use of our abundant fossil energy resources.

- With continued research, these technologies have the potential to provide a cost-effective mitigation option in response to policies aimed at limiting greenhouse gas emissions and ultimately stabilizing greenhouse gas concentrations in the atmosphere.

- These technologies can be used as an alternate option in case new non-fossil energy sources like solar or present non-fossil energy sources like nuclear cannot gain sufficient market share and/or acceptance.

- These technologies could be a low cost mitigation option if hydrogen were to become a major energy carrier (see Chapter 4).

In this white paper, we will first review the background of $CO_2$ capture and sequestration, looking at both its history and economics (Chapter 3). Next, we review the major technological components -- capture technology (Chapter 4), geological storage (Chapter 5), ocean storage (Chapter 6), and direct utilization (Chapter 7). Chapter 8 looks at system integration and implementation issues. In Chapter 9 we look at some other $CO_2$ mitigation technologies that FE may want to consider investigating as part of an integrated program. Finally, specific recommendations for research are summarized in Chapter 10.

### Box 1. International Activities on Climate Change

| | |
|---|---|
| December 21, 1990 | The Intergovernmental Negotiating Committee (INC) created by the United Nations. Negotiations begin on a climate treaty. |
| June, 1992 | The Framework Convention on Climate Change (FCCC) adopted by 143 countries in Rio at the “Earth Summit”. Among its provisions is a goal to stabilize greenhouse gases at their 1990 levels by the year 2000. |
| March 21, 1994 | The FCCC comes into force 90 days after its ratification by 50 countries, including the United States. |
| March, 1995 | The first Conference of the Parties (COP-1) to the FCCC held in Berlin. The Climate Technology Initiative (CTI) is adopted. One of its provisions is to “assess the feasibility of developing longer-term technologies to capture, remove or dispose of greenhouse gases and strengthen relevant basic and applied research.” |
| February, 1996 | CTI Task Force 7 formed to accelerate international collaboration for R&D in the field of medium- and long-term technologies relating to greenhouse gas capture and disposal. |
| June 5, 1996 | The Intergovernmental Panel on Climate Change (IPCC) *Second Assessment Report* states that “the balance of evidence suggests a discernible human influence on global climate”. |
| July, 1996 | COP-2 held in Switzerland. US Under Secretary of State Timothy Wirth states that the US will press for an “agreement that sets out a realistic, verifiable, and binding medium-term emissions target.” |
| November, 1996 | In Australia, President Clinton calls “upon the community of nations to agree to legally binding commitments to fight climate change. We must stand together against the threat of global warming. A greenhouse may be a good place to raise plants; it is no place to nurture our children.” (*Washington Post*, Nov. 23, 1996) |
| December, 1997 | COP-3 scheduled to be held in Japan. On the agenda: emissions targets and timetables. |

## 3. Background

For the capture and sequestration of $CO_2$, the most cost-effective targets are large stationary sources of $CO_2$, such as fossil fuel-fired power plants. These power plants produce about one-third of US $CO_2$ emissions in the production of electricity for residential, commercial, and industrial customers. This share may increase in the future due to continued electrification of the industrial and building sectors. Also, over the longer-term, even the transportation sector may be electrified.

Avoidance of $CO_2$ emissions through physical capture of $CO_2$ from fossil fuel power plants was first proposed by Marchetti (1977), with disposal of the captured $CO_2$ in the deep ocean. In the US, preliminary studies were conducted at Brookhaven National Laboratory (Albanese and Steinberg, 1980; Steinberg, 1984). However, it was not until almost 1990 that significant research efforts were undertaken in this field. Since then, many studies have been carried out and a number of conferences have been held on options for the capture and disposal or reuse of $CO_2$ from large stationary sources.

The first gathering of the international research community investigating $CO_2$ control technologies occurred in March 1992, at the First International Conference on Carbon Dioxide Removal (ICCDR-1) (Blok *et al.*, 1992). Held biennially, ICCDR-2 was organized by the Research Institute of Innovative Technology for the Earth (RITE) in Kyoto, Japan in October, 1994 (Kondo, *et al.*, 1995). Most recently, ICCDR-3 was organized by the Massachusetts Institute of Technology (MIT) Energy Laboratory with major sponsorship from the US Department of Energy (DOE) and the Electric Power Research Institute (EPRI). As in prior meetings, over 250 delegates from over 20 countries participated. The next gathering will be in Switzerland in 1998. This conference series is now a well established forum for the exchange of scientific and technical information on this rapidly advancing field of research.

***The IEA Greenhouse GAS R&D Programme.*** In 1991, the International Energy Agency (IEA) established an Implementing Agreement for a research and development (R&D) program for greenhouse gas technologies. Initially, this program focused on analyzing technologies for capturing, utilizing, and storing of $CO_2$. The program is currently in its second 3-year phase, with support from 16 countries (including the US) and a number of commercial organizations (Webster, 1995). The scope of the program now includes other greenhouse gases (e.g., methane) as well as $CO_2$. The operating agent is the CRE Group Ltd. in Cheltenham, UK. As part of this program, two major conferences on $CO_2$ capture and disposal were held (Riemer, 1993; Riemer and Smith, 1996). Over 30 technical reports have been issued on a wide spectrum of subjects. The budget for phase 2 of this program is about one million dollars per year, with a US contribution of $180,000 per year. Plans for phase 3 are under discussion, including a proposal for the programme to facilitate the formation and management of collaborative research projects by member countries.

***The Japanese research program.*** The largest research program on $CO_2$ capture and sequestration belongs to Japan. Japan's interest in this area is twofold -- first a genuine concern for the global environment, but also an interest to develop commercial technologies which they can market worldwide. Since 1990, the Japanese government has spent 39 billion yen (about $350 million) on research. The focus of Japan's research in $CO_2$ fixation and utilization is RITE (Research Institute of Innovative Technology for the Earth). Established in July 1990 and subsidized by MITI (Ministry of International Trade and Industry), RITE is an international center for research and communication. Two large projects just being completed by RITE are $CO_2$ fixation by microalgae ($123 million) and catalytic hydrogeneration of $CO_2$, which includes research on selectively permeable membranes for $CO_2$ capture ($77 million) (Myers, 1992). A new project of similar magnitude on ocean storage of $CO_2$ is due to start in April, 1997. MITI also funds research through a system of national laboratories administered by the Agency of Industrial Science and Technology (AIST). Finally, the government also supports university research in this field.

In addition to government programs, the private sector, including electric power companies, gas companies, and heavy industries (e.g., Mitsubishi, Hitachi, IHI), has significant research programs for $CO_2$ fixation and utilization. Additional research is being conducted at the Central Research Institute of the Electric Power Industry (CRIEPI).

The Japanese research program into $CO_2$ fixation and utilization is very comprehensive. There are research projects in a variety of programs including $CO_2$ capture/cycle modifications, ocean storage, geological storage, and utilization. Ocean storage is important to Japan because of their close proximity to the deep ocean and lack of geological storage options.

***The US research program.*** The US research effort into $CO_2$ capture and sequestration technologies has spent about $10 million since 1989. The current level of funding is about one to two million dollars per year. This amount is extremely small compared to the total annual expenditure on global change research of $1.6 billion, most of which goes to understanding the science of climate change. However, the US has made significant contributions to the field, including a very well received research needs assessment. The US DOE (Fossil Energy and Energy Research) contracted with the MIT Energy Laboratory to identify, assess, and prioritize research needs for the capture and non-atmospheric sequestration of a significant portion of the $CO_2$ emitted from fossil fuel-fired electric power plants (Herzog *et al.*, 1993). While much new knowledge has been gained since that time, the conclusions still provide a useful starting point for further analysis (see Box 2). An update of this assessment is currently underway.

***Current Status.*** Today the two key challenges that must be addressed by the international research community investigating $CO_2$ removal technologies are reducing costs and finding suitable methods of sequestration. While there is much work to do, results to date give reasons for optimism.

Concerning the issue of cost, it should be noted that specific policy options aimed at reducing $CO_2$ emissions to the atmosphere are required before $CO_2$ capture and sequestration technologies can compete with other technological options in the marketplace. As noted in Chapter 2, international negotiations are now moving in this direction. At ICCDR-3, considerable progress was reported on technical research that could significantly lower costs to the levels required for the $CO_2$ capture option to successfully compete with other potential mitigation options such as renewable or nuclear energy substitutes (see Chapter 4). More discussion of the costs of $CO_2$ capture and sequestration is presented at the end of this chapter.

Since only 1-5% of the total $CO_2$ emissions from power plants could be reused effectively, technically feasible and publicly acceptable storage options are required. Two major projects, one operational and one planned, will go a long way toward demonstrating technical feasibility of large-scale storage:

- In September 1996, Statoil of Norway began storing $CO_2$ from the Sleipner West gas field into a sandstone aquifer 1000 m beneath the North Sea. The $CO_2$ 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). Earlier pilot studies showed that most of the $CO_2$ will react to form solid calcite, with some dissolving in the groundwater and some remaining as a separate phase. While Statoil has not disclosed information on the project costs, they have stated that the cost is less than the Norwegian carbon tax of $50 per tonne $CO_2$. An international research effort is being organized to monitor and document this effort so the experience can be built on by future endeavors.

- Exxon and Pertamina have recently announced plans to inject $CO_2$ from their natural gas field at Natuna into a deep aquifer 1000 m below the South China Sea floor, 375 miles east of Singapore (*Boston Globe*, p. 33, Nov. 20, 1995). Natural gas from the reservoir, one of the world's largest, will be liquefied to produce LNG for sale to the Far East, but it contains over 70% $CO_2$ by volume which must first be separated and sequestered. Averaged over a 30 year period, the 150 trillion cubic feet (about 4 trillion cubic meters) of stored carbon dioxide corresponds to the volume emitted through continuous production of 38,000 $MW_e$ of electricity from coal fired power plants.

***Comparison to other $CO_2$ mitigation options.*** In viewing the spectrum of responses to global climate change, there are a number of relatively low cost $CO_2$ mitigation technologies, sometimes termed “least regrets”. They include improving energy supply and end-use efficiency, switching from coal or oil to gas where possible, forestation, and inexpensive renewable energy applications. The major drawback of this group of technologies is their limited impact. They may be sufficient to meet short-term goals, but there is a general belief that they will not be able to solve the problem in the mid- and long-term. In light of their limited reduction potential, additional, but more costly mitigation technologies must be considered, specifically $CO_2$ capture and sequestration, nuclear power, and extensive use of renewable energy. All three of these technologies have the potential to substantially reduce $CO_2$ emissions. These points are illustrated by the data presented in Table 1. However, it is important to understand the basis and limitations of these data (see Appendix B for more details)[2]:

- For nuclear, renewable, and "least-regrets" technologies, we relied heavily on a National Academy Study (NAS, 1992), whose numbers were based on an extensive literature review. The study involved about 50 experts from academic, industrial, governmental, and public interest organizations. We supplemented the data with additional sources, which we evaluated on a comparable basis.

- For $CO_2$ capture and sequestration, we calculated the numbers based on inputs from the existing literature.

- For "least-regrets", we only considered technology as it exists today. For the other categories which are being considered for the mid- to long-term, we also made additional estimates for the year 2010 assuming advances over today's technology through research.

The data presented contain a great deal of uncertainty as seen by the large range in estimated costs and, therefore, should be used with discretion. However, the data are sufficient to support an important conclusion: the current and projected costs of $CO_2$ capture and sequestration technologies are comparable to the costs for nuclear or renewable energy options (see Figure 1). Since at least one of these options (if not all three) will be required to stabilize atmospheric levels of greenhouse gases in the mid- to long-term, it is prudent to examine all three. Compared with nuclear and renewable energy, the US research effort to-date with respect to technologies for $CO_2$ capture and sequestration has been minimal. Thus we should extend our efforts to understand $CO_2$ capture and sequestration technologies in order to better evaluate their potential and to reduce their associated costs and risks. In the chapters that follow, we document the current understanding of $CO_2$ capture and sequestration technologies and highlight some key research needs.

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[2] Except for $CO_2$ capture and sequestration technologies, it was beyond the scope of this project to fully evaluate the costs of the mitigation technologies presented in Table 1. Therefore, we had to rely on published studies in the literature. These studies were highly dependent on the assumptions used. We feel that more work needs to be done in generating a consistent set of generally accepted mitigation cost data. However, despite their shortcomings, the data presented in Table 1 are of sufficient quality to support our general conclusions.

**Table 1. Potential and Cost of Various CO$_2$ Mitigation Options for the US**
**(see Appendix B for sources and other details)**

| **CO$_2$ Mitigation Option** | **Reduction Potential (million tonnes CO$_2$)** | **Net Cost (1990 $) ($/tonne CO$_2$ avoided)** | |
|---|---|---|---|
| *CO$_2$ capture and sequestration technologies* | | | |
| | | *High* | *Low* |
| Capture with utilization | 20 | 5 | 0 |
| Capture with enhanced oil recovery | 50 | 45 | 10 |
| Capture (industrial sources) with storage | 80 | 76 | 24 |
| Capture with geological storage | 900 | 91 | 31 |
| Capture with ocean storage | 600 | 91 | 31 |
| *Energy supply technologies* | | | |
| | | *High* | *Low* |
| Nuclear | 1500 | 61 | 13 |
| Hydroelectric | 30 | 38 | 25 |
| Biomass | 130 | 42 | 8 |
| Geothermal | 69 - 235 | 144 | 0 |
| Wind | 30 | 125 | 0 |
| Solar photovoltaic | 400 | 400 | 23 |
| Solar thermal | 540 | 178 | 24 |
| *"Least-regrets" options* | | | |
| | | *High* | *Low* |
| Energy (end-use) efficiency | 425 - 620 | 6 | -84 |
| Supply efficiency | 99 | 2 | 0 |
| Fuel switching to gas | 850 | 46 | 17 |
| Forestation | 242 | 10 | 3 |

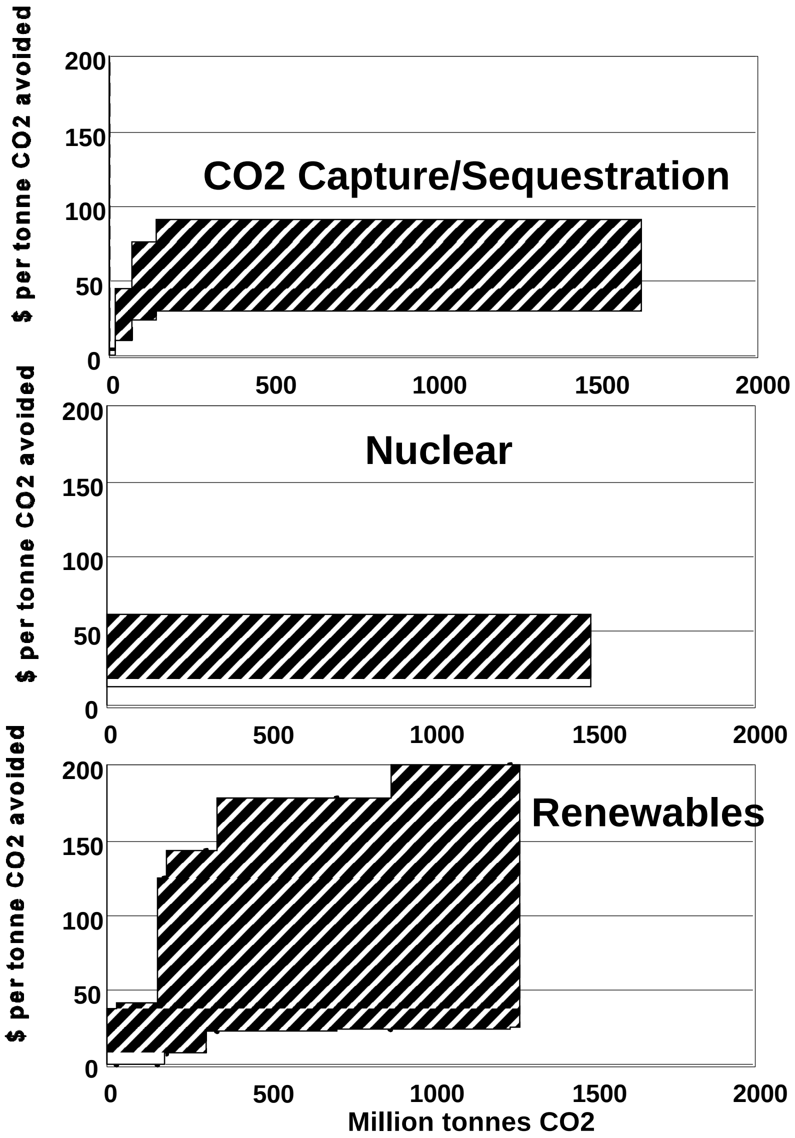


**Figure 1.** Comparison of US mitigation potential and cost (in 1990 $) of $CO_2$ capture and sequestration technologies with other leading mid- to long-term options.

**Box 2. Conclusions of the 1993 DOE/MIT Research Needs Assessment**

1. To implement $CO_2$ capture and sequestration on a national scale will decrease power plant net efficiencies and significantly increase the cost of electricity. To make responsible societal decisions, accurate and consistent economic and environmental analysis of all alternatives for atmospheric $CO_2$ mitigation are required.

2. Commercial $CO_2$ capture technology, though expensive and energy intensive, exists today.

3. The most promising approach to more economical $CO_2$ capture is to develop power plant systems that facilitate efficient $CO_2$ capture.

4. While $CO_2$ disposal in depleted oil and gas reservoirs is feasible today, the ability to dispose of large quantities of $CO_2$ is highly uncertain because of both technical and institutional issues. Disposal into the deep ocean or confined aquifers offers the potential for large quantity disposal, but there are technical, safety, liability, and environmental issues to resolve. Therefore, the highest priority research should focus on establishing the feasibility of large scale disposal options.

5. Land or ocean disposal will require research to better understand environmental impacts. Even with such information, the public may be reluctant to accept some disposal options.

6. While transportation of compressed, liquid $CO_2$ has been demonstrated, important issues involving cost, safety, liability, and institutional barriers to large scale deployment remain.

7. Individual options for using captured power plant $CO_2$ in an alternate fuel, as an industrial feedstock, or as an agricultural growth enhancer are not promising for sequestration of significant amounts of $CO_2$.

## 4. Capture Technology

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".

Historically, $CO_2$ 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 (see Box 3). Table 2 shows typical energy penalties associated with $CO_2$ capture -- both as the technology exists today and how it is expected to evolve in the next 10-20 years. Both conventional coal and gas use similar capture technologies, but because gas is less carbon intensive than coal, it has a lower energy penalty. As will be discussed below, the relatively low energy penalty for advanced coal can be attributed to features in its process that allow for less energy intensive capture methods.

**TABLE 2. Typical Energy Penalties due to $CO_2$ Capture**

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

To reduce the energy requirements and bring the cost of $CO_2$ capture to acceptable levels will require a combination of the following:

- increased base power plant efficiencies. This once again highlights the importance of existing FE efficiency programs.
- reduced capture process energy needs.
- integration of the capture process with the power plant.

To date, all commercial $CO_2$ capture plants 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). As shown in Figure 2, the process allows flue gas to contact an MEA solution in the absorber. The MEA selectively absorbs the $CO_2$ and is then sent to a stripper. In the stripper, the $CO_2$-rich MEA solution is heated to release almost pure $CO_2$. The lean MEA solution is then recycled to the absorber.

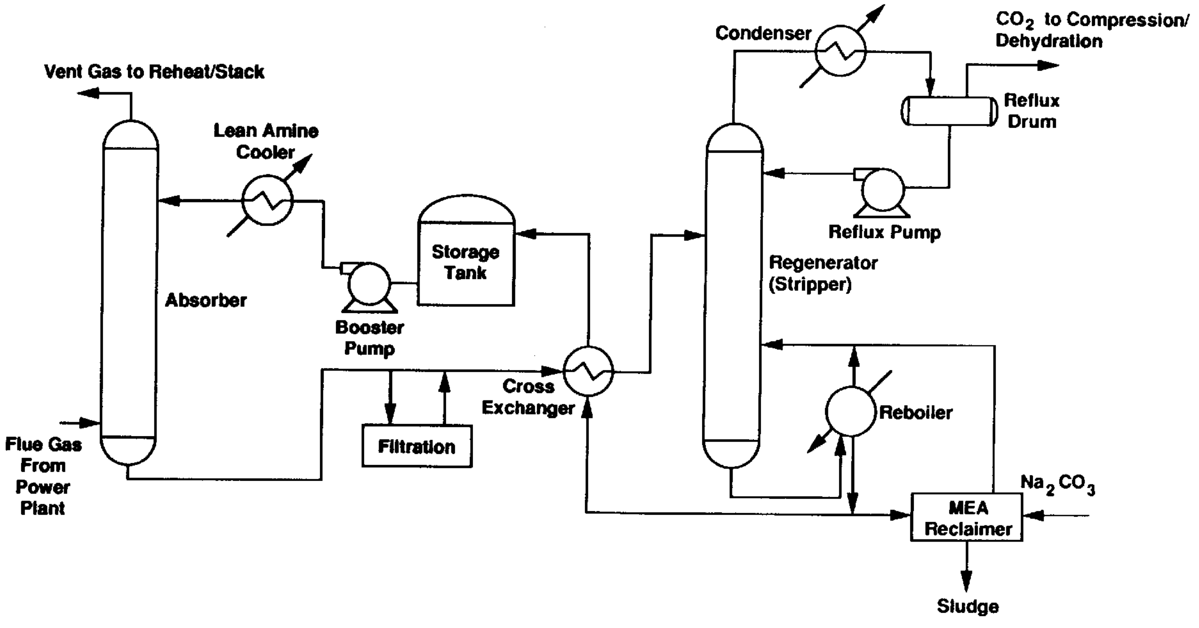


**Figure 2.** Process flow diagram for the amine separation process.

Other processes have been considered to capture the $CO_2$ from the flue gas of a power plant -- e.g., membrane separation, cryogenic fractionation, and adsorption using molecular sieves -- but they are even less energy efficient and more expensive than chemical absorption. The reason can be attributed to the very low $CO_2$ partial pressure in the flue gas. Therefore, a high priority research need is to formulate new solvents that can significantly reduce the energy penalty associated with chemical absorption. The most extensive research on improved solvents has taken place in Japan, including the Tokyo Electric Power Company and Hitachi (Arashi *et al.*, 1997) and the Kansai Electric Power Company (Mimura *et al.*, 1997). Pilot plant studies have shown that by developing new solvent technology and integrating the steam requirements for the $CO_2$ stripper with the power plant turbines, the energy penalty for $CO_2$ capture and compression can be lowered to 10-11% for gas and 15% for conventional coal (Mimura *et al.*, 1997).

Another way to reduce cost in chemical absorption systems is to reduce equipment size. By increasing the contacting efficiency between the $CO_2$ and the solvent, equipment sizes can be reduced significantly. Research at the University of Regina in Canada on structured packing indicates that absorber sizes can be reduced by a factor of five (Aroonwilas and Tontiwachwuthikul, 1997). Feron and Jansen (1997) of TNO Institute of Environmental and Energy Technology in the Netherlands have researched a membrane gas/liquid contactor and claim a three- to ten-fold reduction in equipment size.

An alternate approach to removing $CO_2$ from the flue gas is to use oxygen for combustion instead of air. To maintain thermal conditions in the combustion zone and prevent overheating of the furnace liner materials, some of the flue gas would be recycled to the furnace, giving this approach the name “$CO_2$ recycle technology”. Since the key to scrubbing $CO_2$ from flue gas is to separate the $CO_2$ from the nitrogen, eliminating the air removes the primary source of nitrogen, greatly simplifying the flue gas clean-up. Of course, producing the oxygen now becomes a major expense. However, using oxygen instead of air opens up new possibilities for increased combustion efficiencies. Trace impurities would end up in the $CO_2$ effluent stream and might be suitable for disposition with the $CO_2$. Since mandated $SO_2$ and $NO_x$ emission controls already add to the cost of producing electricity, these could be counted as credits toward the $CO_2$ control costs. This approach may be better suited for new plants (vs. retrofits of existing plants) because new plants can better take advantage of the improved efficiency opportunities related to oxygen use and because of questions concerning retrofits (e.g., air inleakage).

Advanced coal power plants offer many new opportunities for $CO_2$ capture. One example is to integrate $CO_2$ capture with an integrated gasification - combined cycle (IGCC) power plant (Doctor *et al.*, 1996). IGCC plants first gasify the fuel to produce a pressurized synthesis gas (mainly CO and $H_2$). Next, for $CO_2$ capture, after removal of impurities that might foul the catalyst, the synthesis gas is reacted with steam in a shift reactor to produce $CO_2$ and $H_2$. The $CO_2$ and $H_2$ are then separated, with the hydrogen being combusted to produce $CO_2$-free energy. The $CO_2$ stream is available for use or disposal. The partial pressure of $CO_2$ is sufficiently large in an IGCC plant (as opposed to pulverized coal plants) to allow use of a physical absorbent like Selexol (dimethyl ether of polyethylene glycol), which greatly reduces the energy requirements.

Currently, the biggest drawback to this approach is that IGCC power plants cost more than conventional pulverized coal-fired power plants. However, it is expected that costs of IGCC power plants will become competitive in the future.

Power technologies such as fuel cells or other advanced cycles are evolving and may become available to use the hydrogen rich fuel gas produced from the coal gasifier/shift-reactor/$CO_2$-separator. These technologies are likely to yield higher energy efficiencies and, therefore, further reduce the penalties associated with $CO_2$ capture.

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, as witnessed by the Sleipner West project in Norway and the proposed Natuna project in Indonesia (see Chapter 3). Finally, 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 (Williams, 1996; Kaarstad and Audus, 1997).

There are several other industrial processes, primarily the production of ammonia and ethylene, which generate nearly pure $CO_2$ streams and therefore allow relatively inexpensive recovery of $CO_2$ -- with recovery costs per tonne of $CO_2$ avoided about half those of the best power plant recovery processes. Refineries, especially those that use heavier crudes, also provide some opportunities for $CO_2$ capture and have costs for capture per tonne of $CO_2$ avoided that are comparable to or somewhat greater than similar costs for capture from power plants. Other major $CO_2$-emitting industries, including iron and steel production and the broader petrochemical industries, have $CO_2$ capture costs per tonne avoided about twice those for capture from power plants (Farla *et al.*, 1992).

***Summary.*** The key challenge regarding $CO_2$ capture technology is to reduce the overall cost by lowering both the energy and the capital cost requirements. While costs and energy requirements for today's capture processes are high, opportunities for significant reductions exist since researchers have only recently started to address these needs. The following approaches appear the most fruitful:

- Implement the easy opportunities first, such as those in the natural gas industry and industries like ammonia and ethylene.

- Improve today's commercially available chemical absorption processes. Key research needs are to develop more energy efficient solvents and reduce equipment size and cost.

- Use oxygen instead of air for combustion, producing a flue gas from which $CO_2$ is easily captured. Research needs include reducing oxygen costs, addressing the problems associated with retrofitting existing plants, and optimizing the efficiency of new plants.

- Integrate $CO_2$ capture into advanced power plants, such as IGCC or fuel cells. Research needs to address improved separation techniques (e.g., membranes), improved shift catalysts, and heat and power integration.

## BOX 3. CALCULATING THE COST OF CAPTURE

The following example demonstrates a simple and straight forward method to estimate the cost of capturing $CO_2$ from a fossil fuel-fired power plant. While the example is presented to illustrate the methodology, we did attempt to use realistic numbers for our sample calculations.

**Step 1: Calculate the cost of power without capture.**

Basis: 500 $MW_e$ pulverized coal-fired power plant (new construction) with a 65% annual capacity factor.

Calculation of generating cost:

| | $mills/kWh_e$ |
|---|---|
| Capital Cost ($1160/kW) | 23.5 |
| Fixed O&M ($14.5/kW/yr) | 2.5 |
| Variable O&M | 2 |
| Fuel | 18 |
| Generating Cost | 46 |

In addition to the generating cost, the consumer must also pay for other costs (transmission and distribution, etc.). For this example, we fix these other costs at 2¢/$kWh_e$. These costs are be assumed to be unaffected by the implementation of $CO_2$ capture.

| | |
|---|---|
| Generating Cost | 4.6¢/$kWh_e$ |
| Other Costs | 2.0¢/$kWh_e$ |
| Delivered Cost of Electricity | 6.6¢/$kWh_e$ |

**Step 2: Calculate cost of the $CO_2$ capture plant (excluding fuel). The fuel to drive the $CO_2$ capture plant comes from the power plant, so that cost was listed in Step 1. However, using this fuel for $CO_2$ capture derates the power plant, which will be accounted for in Step 3.**

Basis: 90% capture efficiency (≈9000 tonnes of $CO_2$ captured/day) and a 20% energy penalty (reduces power plant net output from 500 $MW_e$ to 400 $MW_e$). Captured $CO_2$ compressed above 100 bars.

| | $mills/kWh_e$ |
|---|---|
| Capital Cost ($270 million) | 11 |
| Fixed O&M | 1.5 |
| Variable O&M | 1 |
| Generating Cost | 13.5 |

**Step 3: Calculate cost of power with capture.**

| | $mills/kWh_e$ |
|---|---|
| Base plant generating cost | 46 |
| $CO_2$ capture plant cost (excluding fuel) | 13.5 |
| Generating Cost | 59.5 |

The cost of 59.5 mills/$kWh_e$ is based on a net generation of 500 $MW_e$ net. To account for the power plant derating:

$$\frac{59.5\text{ mills}}{kWh_e\text{ (before capture)}} \times \frac{500\ MW_e\text{ (before capture)}}{400\ MW_e\text{ (after capture)}} = 74.4\text{ mills}/kWh_e\text{ (after capture)}$$

| | |
|---|---|
| Generating costs (with capture) | 7.44 ¢/$kWh_e$ |
| Other costs | 2 ¢/$kWh_e$ |
| Cost of electricity (with capture) | 9.44 ¢/$kWh_e$ |

Increase in cost of electricity = 2.84¢/$kWh_e$ (43% increase)

**Step 4: Calculate the cost of capture to compare with other mitigation options.**

| | Base | Capture |
|---|---|---|
| Cost of electricity | 6.6 ¢/$kWh_e$ | 9.44 ¢/$kWh_e$ |
| $CO_2$ emissions to atmosphere (kg/s) | 115 kg/s | 11.5 kg/s |
| Net output | 500 $MW_e$ | 400 $MW_e$ |
| $CO_2$ emissions (kg/$kWh_e$) | 0.828 kg/$kWh_e$ | 0.104kg/$kWh_e$ |

$$\text{Cost of capture} = \frac{(9.44 - 6.6)¢/kWh_e}{(.828 - .104)kg/kWh_e} = 3.9¢/kg = \$39/\text{tonne } CO_2 \text{ avoided}$$

## 5. Geological Storage Technology

Underground storage in geological formations is a major option for disposing of $CO_2$. As described in Chapter 3, geological storage is currently being demonstrated: $CO_2$ from Norwegian gas fields is presently being stored in an undersea aquifer in the North Sea, and a substantially larger project may soon be undertaken by Exxon and Pertamina at their natural gas field at Natuna in the South China Sea. The main issues are uncertainties in the volumes available for storage (see Box 4), the long-term integrity of the storage, and the costs associated with $CO_2$ transport to the storage site and the storage operation itself (Herzog *et al*., 1993; Freund and Ormerod, 1997). Storage integrity is important not only to prevent the unintended return of $CO_2$ to the atmosphere, but also for concerns about public safety and the potential liability should there be a catastrophic release. $CO_2$ gas is heavier than air and, if a large release were to occur, it could displace air at the surface and cause asphyxiation.

The main options for underground storage are (Herzog *et al.*, 1993):

- storage in active oil reservoirs
- storage in coal beds
- storage in depleted oil and gas reservoirs
- storage in deep aquifers
- storage in mined salt domes or rock caverns

The relative merits of these options are described in Table 3 and include issues of storage capacity, cost, storage integrity and feasibility.

**TABLE 3. Comparison of Geological Storage Options**

| **Storage Option** | **Relative Capacity** | **Relative Cost** | **Storage Integrity** | **Technical Feasibility** |
|---|---|---|---|---|
| Active oil wells (EOR) | Small | Very Low | Good | High |
| Coal beds | Unknown | Low | Unknown | Unknown |
| Depleted oil/gas wells | Moderate | Low | Good | High |
| Deep aquifers | Large | Unknown | Unknown | Unknown |
| Mined caverns/ salt domes | Large | Very High | Good | High |

Depleted oil and gas reservoirs appear to be the most promising land storage option, at least in the near-term (Herzog *et al.*, 1993). Because these reservoirs have already demonstrated their ability to contain pressurized fluids for long periods of time, their storage integrity is likely to be good. Currently abandoned oil and gas reservoirs in the US could hold about 2.9 billion tonnes of $CO_2$, while the ultimate reserves of oil and gas would hold roughly 100 billion tonnes of $CO_2$ (Winter and Bergman, 1996). These compare with current US power plant emissions of about 1.7 billion tonnes of $CO_2$ per year. However, most of the wells would have to be redrilled, and actual effective capacity is uncertain given that changes to the reservoir may have occurred due to water/brine intrusion or geostructural alteration. The oil and gas industry has significant experience in the management of such reservoirs, but is particularly concerned about long-term liability issues. With the exception of Texas, most oil and gas reservoirs are not located near primary sources of $CO_2$ production, so a new $CO_2$ pipeline network would be needed to connect power plants with suitable storage sites. The costs, environmental impacts and safety issues associated with such a network need to be considered in any analysis of this storage option. Due largely to differences in required pipelining, storage costs will be very site-specific. A cost study for several specific sites in Texas has been performed by Bergman *et al.* (1997).

Active oil and gas reservoirs could also be used. For example, $CO_2$ is used routinely for enhanced oil recovery (OTA, 1978; Lake, 1989). The amount of $CO_2$ that can be utilized for EOR and related applications is small compared to total $CO_2$ emissions and $CO_2$ can currently be supplied from natural sources at about one-third the cost projected for $CO_2$ captured from power plants (Herzog *et al.*, 1993). Hence there is no immediate incentive to utilize power plant $CO_2$ for this purpose. However, if credits for the avoided $CO_2$ emissions are considered, the price of power plant $CO_2$ is reduced and this option becomes very attractive. While the basic technology exists for EOR, additional research is required to modify EOR operations to optimize the storage of $CO_2$.

$CO_2$ can also be used to enhance the recovery of coal bed methane (Gunter *et al.*, 1997). Using this technology, abandoned and uneconomic coal seams become potential storage sites. Unlike EOR, where $CO_2$ break-through eventually occurs, the injected $CO_2$ becomes sorbed to the coal surface and hence remains sequestered. Estimated US coal bed methane resources are large -- ranging from 275 to 649 trillion cubic feet, with current production coming mainly from the San Juan Basin in SW Colorado and the Black Warrior basin in Alabama (Dawson, 1995). Although still in the development stage, the process has been tested in pilot scale field studies conducted by Amoco and Meridian in the San Juan Basin.

Mined salt domes or rock caverns theoretically have a large storage capacity, and have been used for the related purposes of storing petroleum, compressed air and natural gas (Tek, 1989), but the associated costs are a major impediment. Without a major breakthrough, the costs of excavating rock caverns are too high to be practical. Salt domes can be excavated at more reasonable cost by solution mining. However, in both cases large amounts of rock or brine would have to be excavated, handled and either utilized or disposed of in an environmentally acceptable manner.

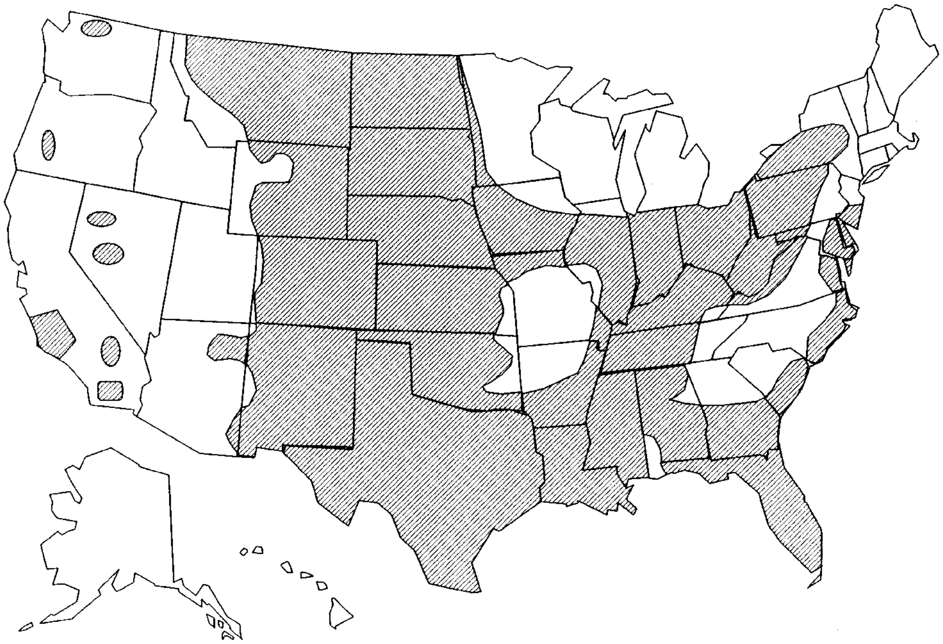


**Figure 3.** Saline aquifers in the US based on US geological survey (Bergman and Winter, 1996).

Deep aquifers may be the best long-term underground storage option. Such aquifers are generally saline and hydraulically separated from shallower aquifers and surface water supplies used for drinking water. Depending on the aquifer properties, injected $CO_2$ would displace water some of it remaining as pure $CO_2$ (Gunter *et al.*, 1993; Hitchon, 1996). The estimated storage potential of deep aquifers in the US is 5-500 billion tonnes of $CO_2$ (Bergman and Winter, 1996) compared with annual US power plant emissions of about 1.7 billion tonnes of $CO_2$. Figure 3 shows the locations of deep aquifers underlying the US. The spatial match between storage locations and $CO_2$ sources is somewhat better for deep aquifers than for gas and oil reservoirs; indeed, Bergman and Winter (1996) estimate that 65% of $CO_2$ captured from US power plants could possibly be injected directly into deep aquifers without the need for long pipelines. Because there has been less interest in them, the properties of aquifers are not as well known as those of oil and gas reservoirs, which leads to technical uncertainty. The aquifer should be located under a relatively impermeable cap, yet there should be high permeability, as well as porosity, below the cap to allow the $CO_2$ to be distributed efficiently. Effects of gravity segregation and fingering may limit the effective storage, and fractures and open peripheries can allow leakage (Lindeberg, 1997). Issues of safety associated with leakage are also a major concern (Holloway, 1997). Energy companies have proprietary information that may help clarify some of these technological concerns and provide more accurate information on aquifer locations in the US, but issues of liability will have to be resolved before industry cooperation can be expected. Experience can also be gleaned from the disposal of industrial wastes as the US currently uses over 400 wells to inject about 75 million cubic meters of industrial waste (some hazardous; some non-hazardous) into deep aquifers each year (Bergman and Winter, 1996). However, regulations on aquifer disposal vary from state to state and not all states would currently allow such disposal. DOE/PETC has initiated a study of the economic, legal, environmental and social issues surrounding the use of the Mt. Simon Aquifer, a large aquifer which underlies Illinois, Indiana, Ohio, Michigan, Kentucky and Pennsylvania.

Costs for geological storage of $CO_2$ may vary from \$1-8 per tonne $CO_2$ depending on local circumstances. Transportation costs via pipeline have been estimated at \$1-3 per tonne $CO_2$ per 100 km (Hendriks, 1994). The range of costs for disposal (including transportation) used in the analysis in Chapter 3 was \$5-15 per tonne $CO_2$.

Based on the above discussion, several steps need to be implemented to further the development of land-based $CO_2$ storage. It should be emphasized that some of the needed information is actually available, but not accessible due to proprietary and anti-trust considerations; these obstacles must be overcome in order to avoid costly duplication. The needs include:

- Perform a quantitative assessment of storage volume at depleted gas and oil field sites in the US. The study should be national in scope and include input from the American Petroleum Institute, the American Gas Association and the National Petroleum Council.

- Assess the storage integrity characteristics of depleted fields and their suitability for re-opening to inject $CO_2$. Also, determine how best to "finish" currently producing wells for future $CO_2$ storage.

- Establish a methodology for assessing the long-term integrity and ecological impacts of storage, as well as the safety risk for underground reservoir types.

- Test modifications in EOR operations to maximize $CO_2$ sequestration as well as oil recovery.

- Continue testing the use of $CO_2$ to increase coal bed methane production and explore synergies whereby coal bed methane, produced with the enhancement of waste $CO_2$, could fuel power plants resulting in no net $CO_2$ emissions.

- Finally, because deep aquifer storage holds the best long-term promise, but is also the least certain, this option deserves special consideration:

- Conduct basic theoretical and laboratory research concerning the fluid, thermal and geological properties of deep aquifers in order to refine technical feasibility criteria.

- Conduct a comprehensive survey of industrial and government data on the location and nature of deep aquifers throughout the US (including off-shore aquifers) that meet the feasibility criteria. Much of the needed data does not exist and will need to be collected.

- Conduct an economic analysis of capital and operating costs for this option with specific attention to identified sites in the US.

- Conduct a domestic field demonstration project.

### Box 4. Worldwide Storage Potential for CO$_2$

The IEA Greenhouse Gas R&D Programme estimated the worldwide storage potential in billion tonnes of CO$_2$ (Ormerod, 1994). As reflected in the large ranges below, this task is very difficult given all the uncertainties:

| | |
|---|---|
| • Deep Ocean | 5,100 - >100,000 |
| • Deep Aquifers | 320 - 10,000 |
| • Depleted Gas Reservoirs | 500 - 1100 |
| • Depleted Oil Reservoirs | 150 - 700 |

Since the world produces about 22 billion tonnes of CO$_2$ annually from energy production, it is clear that the theoretical capacities are more than adequate. Research is required to help narrow these ranges and determine what portion of this potential can be practically exploited.

## 6. Ocean Storage Technology

The ocean represents the largest potential sink for anthropogenic $CO_2$ (see Box 4) and it already contains the estimated equivalent of 140,000 billion tonnes of $CO_2$ (compared with annual worldwide anthropogenic emissions of about 22 billion tonnes of $CO_2$). Furthermore, discharging $CO_2$ directly to the ocean would accelerate the ongoing, but slow, natural processes by which over 90% of present-day emissions are currently entering the ocean *indirectly* (Sarmiento, 1993). As indicated schematically by Figure 4, discharging $CO_2$ directly to the ocean would reduce both peak atmospheric $CO_2$ concentrations and their rate of increase. However, $CO_2$ concentrations in the atmosphere and ocean will equilibrate over time scales of 1000 years or more, regardless of where the $CO_2$ is discharged. The ocean storage concept was first mentioned by Marchetti (1977) who conceived of piping $CO_2$ into the outflow of the Mediterranean Sea, where it would sink deeper into the Atlantic. Some follow-up work was undertaken in the late 1970s (e.g., Hoffert *et al.*, 1979; Baes *et al.*, 1980), but most research has taken place in the past six years, principally by researchers in Japan, Norway and the United States.

Figure 5 illustrates five methods for the direct injection of $CO_2$ into the ocean:

- dry ice released at the ocean surface from a ship (Nakashiki *et al.*, 1991).
- liquid $CO_2$ injected at a depth of about 1000 m from a pipe towed by a moving ship and forming a rising droplet plume (Ozaki *et al.*, 1995).
- liquid $CO_2$ injected at a depth of about 1000 m from a manifold lying on the ocean bottom and forming a rising droplet plume (Liro *et al.*, 1992).
- a dense $CO_2$-seawater mixture created at a depth of between 500 and 1000 m forming a sinking bottom gravity current (Haugan and Drange, 1992).
- liquid $CO_2$ introduced to a sea floor depression forming a stable "deep lake" at a depth of about 4000 m (Ohsumi, 1995).

The relative merits of each scenario involve issues of sequestration efficiency, cost and technical feasibility, and environmental impact (see Table 4).

Sequestration efficiency relates to how long the $CO_2$ will remain in the ocean before ultimately equilibrating with the atmosphere (Figure 4). As shown through the use of global circulation models, sequestration efficiency is clearly site-specific (Bacastow and Dewey, 1996). If the injected $CO_2$ can be incorporated in the general oceanic deep water circulation, a residence time of approximately 1000 years can be anticipated.

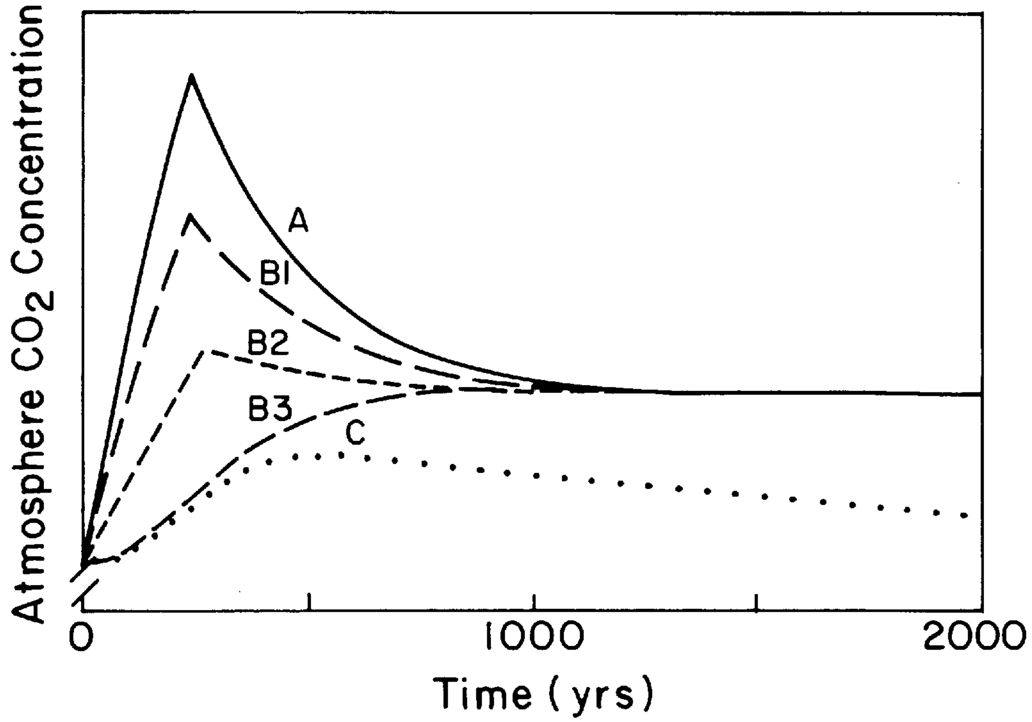


**Figure 4.** Qualitative illustration of the effect of ocean disposal on atmospheric $CO_2$ concentrations, based on a constant $CO_2$ emission rate for 250 years and then no further emissions. Line A represents business-as-usual emissions to the atmosphere. Because the atmosphere and ocean are out of equilibrium, atmospheric concentrations will decrease after emissions stop until an equilibrium is achieved at around 1000 years. Lines B1, B2, B3 show the effect of ocean storage with either increasing quantity of $CO_2$ injected to the ocean or increasing depth of disposal, leading to longer residence times. Line C shows the potential effect of carbonate chemistry (or solid deposition on the ocean floor) whereby some of the $CO_2$ becomes permanently sequestered, never to return to the atmosphere. (after Wilson, 1992.)

Costs and feasibility are functions of the distance and depths between $CO_2$ capture and injection. Shorter distances favor pipelines, with $CO_2$ compressed as a supercritical (dense phase) fluid, while longer distances favor barge transport as a refrigerated liquid (Golomb, 1997). In the case of dry ice, significant additional expenses would be incurred in solidifying the $CO_2$. Conventional pipe-laying technology has not been applied to depths much beyond 1000 m as would be required for a deep lake, though the reasons appear to reflect current needs of the oil and gas industry rather than any fundamental ocean engineering limitations (Palmer, 1997). Only scant experience with the technology for pipes towed from moving ships exists from OTEC research and incipient design work in Japan (Ozaki *et al.*, 1995; Ozaki, 1997). The dense gravity

**TABLE 4. Comparison of Ocean Storage Options**

| Option | Development Required | Cost | Environmental Impact | Leakage to Atmosphere |
|---|---|---|---|---|
| Dry Ice | Lowest | High | Low | Low-Medium |
| Towed Pipe | Medium | Low-Medium | Lowest | Medium |
| Droplet Plume | Low | Low | Low-Medium | Medium |
| Dense Plume | Medium | Lowest | Highest | Medium |
| $CO_2$ Lake | Highest | High? | Low | Lowest |

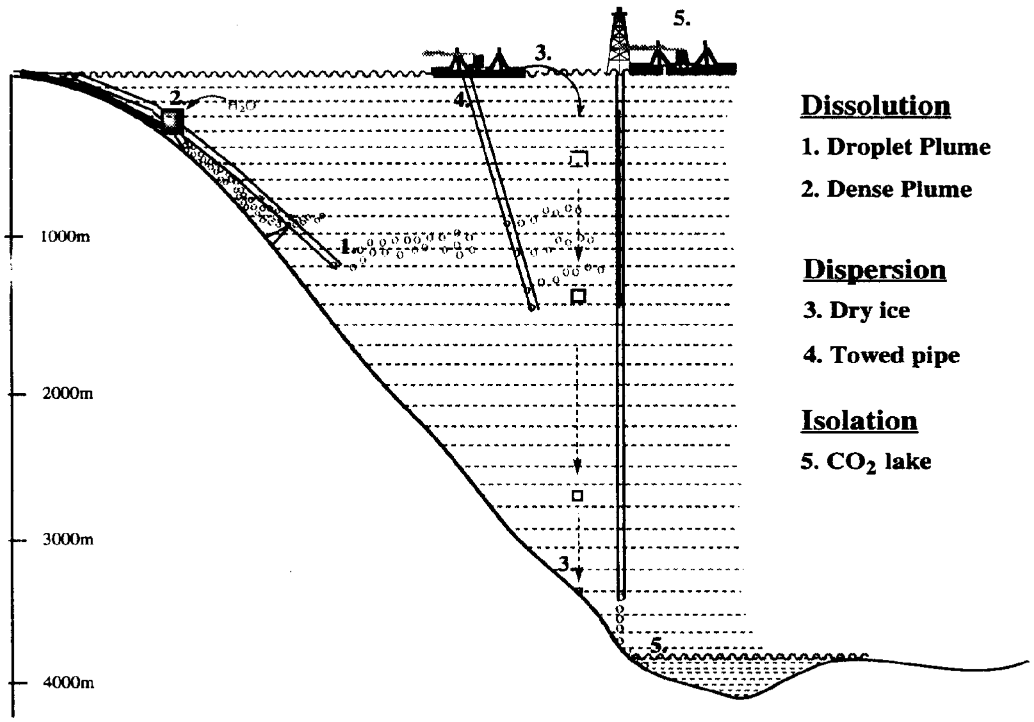


**Figure 5.** Five injection scenarios have been the focus of recent research. The scenarios are shown schematically above. A consensus is developing that the towed pipe and droplet plume scenarios offer the best approach for the near future.

current would require a suitable site with appropriate slope and design of a mixing device to concentrate the $CO_2$ (Adams *et al.*, 1995; Kajishima *et al.*, 1995) in order to generate sufficient negative buoyancy. Therefore, injection as a droplet plume from a bottom pipe is the only option which is feasible with proven technology, but even this option has uncertainties associated with the physical/chemical behavior of $CO_2$ as it mixes with seawater. Costs for ocean disposal of $CO_2$ (including transportation) have been estimated as low as $1-6 per tonne $CO_2$ (Freund and Ormerod, 1997), but based on our work (Herzog *et al.*, 1995) we feel that $5-15 per tonne $CO_2$ is a more realistic estimate.

Environmental impacts may be the most significant factor determining the acceptability of ocean storage, since the strategy is predicated on the notion that impacts to the ocean will be significantly less than the avoided impacts of continued emission to the atmosphere. Several reviews have identified potential impacts (Magnesen and Wahl, 1993; Kollek, 1993; Auerbach *et al.*, 1996), with the most significant deriving from lowered pH resulting from the reaction of $CO_2$ with seawater. Carbonate dissolved in seawater and in benthic sediments at shallow depths will provide a buffer, but depending on the method of release, pH can be expected to vary from as low as 4 very near the injection point, to its ambient value of about 8. Impacts would occur principally to non-swimming marine organisms (e.g., zooplankton, bacteria and benthos) residing at depths of about 1000 m or greater and their magnitude will depend on both the level of pH change and the duration of exposure (Auerbach, 1996). However, available data suggest that mortality associated with pH change can be completely avoided if the injection is properly designed to disperse the $CO_2$ as it dissolves (Caulfield, 1996).

At global scales, anthropogenic emissions of $CO_2$ that are occurring today will cause a gradual decline in average ocean pH of about 0.5 units over the next several centuries. Direct injection of $CO_2$ to the ocean will perturb the system by less than another 0.1 pH unit. However, the increased acidity due to the direct addition of $CO_2$ will occur primarily in the deep ocean, while acidification of the more productive surface waters would actually be mitigated (Haugan and Drange, 1995).

The viability of ocean storage as a greenhouse gas mitigation option will also hinge on social and political considerations. In view of public precaution toward the ocean, the strategy will require that all parties (private, public, non-governmental organizations) be included in ongoing research and debate.

Based on the above, we summarize the following research needs in the area of ocean storage:

- ***Physical-chemical interactions between $CO_2$ and seawater***, including the likelihood of hydrate formation on surfaces of $CO_2$ droplets contained in droplet plumes, and the interaction between $CO_2$-enriched seawater and stratified receiving water. Hydrates will affect mass transfer between $CO_2$ and seawater, and hence the elevation within the water column at which $CO_2$ is dissolved (Masutani *et al.*, 1995). Plume/ambient interaction will affect the elevation at which the $CO_2$-enriched seawater is ultimately sequestered and, in particular, whether or not the plume will impact more environmentally sensitive benthic organisms.

- ***Ocean circulation and mixing.*** Mortality of marine organism in the near field (<25 km from the injection point) has been shown to be very sensitive to horizontal diffusivity (Caulfield, 1996), yet most available data are from near surface experiments. Better quantification of vertical mixing is also needed because such mixing helps control the residence time of $CO_2$ within the water column. To help in site selection and to better understand sequestration times, it is important to further the development, intercomparison, and field validation of three-dimensional circulation models for the far field (>300 km from the injection point), including better ways to couple regional and global scale models.

- ***Biological impacts.*** Environmental assessments to-date have been based on bioassays using surface organisms exposed to constant levels of pH. More tests are needed on organisms found at depths of order 1000 m, and with time-varying exposure. Also, data are required to evaluate chronic effects of existing and potential future trends in varying pH.

- ***Ocean engineering.*** The feasibility of laying deep $CO_2$ pipelines (greater than 1000 m), towing pipes from a moving ship, and creating a deep $CO_2$ lake has yet to be demonstrated. Such demonstration might allow discharge scenarios with less environmental impact and greater sequestration potential to be realized.

Many of these issues will require a combination of experimental and theoretical research. Laboratory research has progressed remarkably well over the last six years, especially in Japan (Ohsumi, 1995). However, many of the important physical, chemical and biological processes cannot be scaled, which means that more experimental research must eventually be conducted in the field. We believe this research should take place in three steps:

- small scale, short-term tests of physical/chemical perturbations conducted at an open ocean site. The US DOE is currently engaged in the planning of such an experiment -- a month-long field study conducted in collaboration with the Japanese at an open site such as the Kona coast of Hawaii.

- longer-term tests of acute and chronic biological impacts conducted at a semi-enclosed site such as a fjord.

- full scale testing using a prototype power plant outfitted for $CO_2$ capture.

## Box 5. IEA Ocean Disposal Workshops

Between August 1995 and October 1996 the IEA Greenhouse Gas R&D Programme sponsored four workshops in which international experts convened to discuss the necessary steps toward demonstrating the feasibility of ocean disposal. The major conclusions of these workshops were:

***Workshop 1 -- Ocean Circulation.*** Sequestration efficiency and large scale environmental impacts will depend on predictions from ocean global circulation models (OGCMs). To improve their reliability we must:

- involve the ocean modeling community more widely in the ocean storage concept.
- initiate an OGCM inter-comparison exercise on point sources of $CO_2$ in the deep ocean.
- support measurement programs which can provide validation data.

***Workshop 2 -- Environmental Impacts.*** The concept of ocean storage requires that impacts to the marine environment be substantially less than avoided impacts of continued emissions to the atmosphere. To better quantify marine impacts we must:

- develop basic guidelines for biological acceptability.
- improve understanding of the physiological response of organisms through laboratory experiments under pressurized conditions and ultimately through *in situ* field experiments.
- collaborate with relevant existing marine biology research programs.
- research the impact of the business-as-usual scenario.

***Workshop 3 -- International Links and Concerns.*** Global change is a worldwide problem requiring worldwide mitigation efforts and worldwide acceptance of these efforts. To facilitate this acceptance, we should:

- establish an international strategic advisory group consisting of science and technology experts, including representatives from other interest groups.
- involve other ongoing programs (e.g., International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), IPCC).
- define processes for seeking legal and public acceptance.
- identify and involve stakeholders.
- learn from past examples.

***Workshop 4 -- Practical and Experimental Approaches.*** In order to advance the concept of ocean disposal to the level of demonstrated technology, we must:

- develop experimental programs on biological impact (to gain understanding and acceptability) and near field plume behavior (to validate impact modeling).
- improve global/regional modeling to quantify benefits and identify sites.
- develop engineering solutions to refine injection options (sites, modes of discharge) and quantify costs and impacts.
- develop legal case and educate public.
- forge links with existing international science programs.

## 7. Direct Utilization Technologies

Recycling or reuse of $CO_2$ emitted or captured from power plants would seem to be an attractive alternative to the disposal options discussed in the two preceding chapters. However, the problem is finding enough uses to sequester a significant amount of the $CO_2$ generated. Today, the total industrial use of $CO_2$ in the US is about 40 million tonnes per year -- only about 2% of the 1.7 billion tonnes produced annually from our power plants. About 80% of this use is in enhanced oil recovery (EOR) and is supplied from $CO_2$ gas wells at prices much cheaper than power plant $CO_2$. Therefore, the challenge is to find new and larger uses that will consume the $CO_2$ or otherwise sequester it from the atmosphere. The candidate uses fall into three main categories: industrial uses, chemical conversion to fuels, and biological conversion to fuels.

***Industrial uses.*** To illustrate the mismatch in quantities between power plant emissions and industrial use potential for $CO_2$, assume that $CO_2$ was substituted for fossil fuel feedstocks in all US plastics production. This total transformation of the US plastics industry to $CO_2$ feedstocks would require less than 100 million tonnes of $CO_2$ per year, about 5% of the 1.7 billion tonnes produced annually from US power plants. There are a number of other fairly small-scale industrial applications that could use captured $CO_2$ (Aresta and Tommasi, 1997). In a vigorous $CO_2$ mitigation effort, many small industrial activities could be converted to power plant $CO_2$ feedstreams, but the potential total impact would be much less than 1% of the total power plant $CO_2$ generated.

In a greenhouse gas-constrained world, it is likely that the industrial sector could reduce its own $CO_2$ emissions by identifying processes that produce relatively pure $CO_2$ streams and then either capturing and sequestering $CO_2$ or strategically linking it to another processing operation requiring $CO_2$ as a feedstock. There are numerous specific opportunities to reuse $CO_2$ in industrial processes, and certain processes such as ethylene and ammonia production produce high concentration $CO_2$ streams that are often currently released to the atmosphere. The standard way of producing hydrogen today is through steam reforming of methane which can be regulated to produce a $CO_2/H_2$ mixture which is easily separable.

$$CH_4 + 2H_2O = CO_2 + 4H_2 \qquad (7\text{-}1)$$

This $CO_2$ could be sequestered or utilized in another process. With increasing interest in the use of hydrogen as an energy carrier and fuel in the future, this $CO_2$ source is likely to grow and create an opportunity for additional mitigation. Even today, $CO_2$ from ammonia production is often used as a feedstock for urea production. Such streams would serve as a good feedstock for plastics production, production of inorganic carbonates, etc. Industrial combustion processes, like power plants, will have lower concentration streams of $CO_2$, making $CO_2$ capture more expensive as a way to mitigate emissions.

New applications might be found if further research is done on interesting potential reaction pathways. Since $CO_2$ is a very stable molecule, considerable energy is required to transform it into products where the C-O bonds are broken, such as in recycling to fuels as discussed in the next section. Transformation into carbonates, carbamates, or other forms that retain or shift bonds is less energy intensive and the products also tend to be more stable. For example, a room temperature exothermic exchange reaction using $CO_2$ was recently reported on in *Chemical and Engineering News* ("Carbon Dioxide Fixation," p. 8, Nov. 11, 1996) for converting germanium or tin bisamides to industrially useful isocyanates and other products. However, in spite of the many diverse possibilities, the industrial sector still has only limited capacity for utilization of the large quantities of $CO_2$ that are generated by the power sector.

***Carbonate minerals.*** Another possibility is to use $CO_2$ to make stable solid products like carbonate minerals that can be returned to the environment. This concept really could be considered as another form of geological storage. Weathering of alkaline rocks (especially calcium and magnesium silicates) is a natural method of $CO_2$ sequestration (Kojima *et al.*, 1997). To enhance the rate of the natural process, the authors suggest that olivine sand and wollastonite could be pulverized, dissolved, and reacted with power plant $CO_2$ to form magnesium and calcium carbonates. Energy needs for the pulverization generate $CO_2$ that is from 1 to 15% of the $CO_2$ sequestered. While the process seems feasible, large amounts of rock must be transported and handled -- several times the weight of the $CO_2$ sequestered -- as well as significant amounts of makeup hydrochloric acid. Lackner and Butt (1997) have done some preliminary calculations on this concept that suggest its potential for significant $CO_2$ mitigation at costs of about $30 per tonne of $CO_2$ sequestered (not including costs of capture) and they note that the scale of the operations would be somewhat smaller than the present scale of coal mining activities in the US. While further research is needed to support these preliminary estimates, this is an interesting possibility.

Dunsmore (1992) suggested the possibility of using underground brines rich in chlorine and sulfate, such as those in Canada's Elk Point salt basin, to produce carbonates. The brines could be pumped to a $CO_2$ contacter and the precipitate slurry could be reinjected. An *in situ* processing option also exists. Per tonne of $CO_2$ reacted, about 2.2 tonnes of precipitate would be formed. The residual brine would be highly acidic and about 0.5 tonnes of excess brine would be produced for reinjection or *in situ* reaction. The suitable brines are available in only a few locations and the environmental management of the acidic wastes presents a major problem. The quantities of solid materials that require handling, the large waste streams, and the transport distances to bring power plant $CO_2$ to the disposal site probably make this an impractical option for mitigation.

***Chemical conversion to fuels.*** A large use that could begin to match power plant emissions of $CO_2$ is to "recycle" the $CO_2$ back to a fossil fuel that could reduce the use of virgin fossil fuels. Unfortunately, reducing $CO_2$ back to carbon requires at least 80% of the energy that is generated from burning a typical coal, and when processing losses are considered, there may be no net gain or even a loss of energy. Unless this energy comes from non-fossil sources, additional $CO_2$ is generated. And if non-fossil energy is available, in most cases it would be better used to substitute for the burning of coal in the first place.

Much interest has been generated in the possibility of converting $CO_2$ to a transportation fuel, such as methanol, using hydrogen.

$$CO_2 + 3H_2 = CH_3OH + H_2O \qquad (7\text{-}2)$$

In this reaction, each molecule of $CO_2$ is reacted with three molecules of hydrogen to produce one molecule of methanol. But energy is required to produce hydrogen. The most efficient pathway to hydrogen today is through steam-methane reforming (see Eq. 7-1) which is about 80% efficient. Production from coal gasification is about 50% efficient; production from electrolysis of water, about 30% efficient (Rosen and Scott, 1996). In a simple example (Herzog *et al.*, 1993), it can be shown that about six units of solar (or other non-fossil) energy would be needed to recycle the $CO_2$ generated from producing one unit of energy in a coal-fired power plant, if the $H_2$ came from electrolysis of water. For that case, replacing the original coal energy by the non-fossil energy source is a much better solution from the standpoint of efficient energy utilization. If $H_2$ is available, the most energy efficient solutions will probably involve its direct use, such as in fuel cells, rather than as a reactant to recycle $CO_2$ to methanol.

Nevertheless, there is considerable research in progress, especially in Japan and Korea, on improved catalysts and catalytic pathways, both liquid and gas phase, to achieve high conversion and minimal energy loss in using $H_2$ to convert $CO_2$ to methanol. However efficient the conversion, the fundamental energy requirements to recycle $CO_2$ to methanol still make the conversion of very limited usefulness from an energy utilization viewpoint.

To produce as much methanol as possible per unit of $CO_2$, three molecules of methane are needed for each molecule of flue gas $CO_2$ and four molecules of methanol are then produced.

$$CO_2 + 3CH_4 + 2H_2O = 4CH_3OH \qquad (7\text{-}3)$$

This means that only one molecule of $CO_2$ is being recycled and that three additional molecules of methane are being used and will emit additional $CO_2$ when the methanol is burned. Considering that the production of methanol is only about 60% efficient, it might be better to burn the natural gas in the power plant in the first place, or go to methane as an automotive fuel. This conclusion is similar to that of Audus and Oonk (1997) who conclude, based on a carbon-to-hydrogen ratio analysis, that producing methanol from $CO_2$ and $H_2$ (instead of by steam reforming of $CH_4$) is unlikely to make a significant contribution to a reduction in $CO_2$ emissions to the atmosphere (see Box 6).

An alternative route to producing hydrogen is by cracking the methane (Steinberg, 1996).

$$CH_4 = C + 2H_2 \qquad (7\text{-}4)$$

With support from the Environmental Protection Agency, research on the thermal decomposition of methane is continuing. The residual carbon might be sequestered or used to replace current uses for carbon black from virgin coal. The technologies involved are in early stages of development and it still is too early to see whether the efficiencies can be improved to the point where the process is feasible.

***Biological conversion to fuels.*** Photosynthesis is the process by which plants, including algae, use solar energy to convert $CO_2$ to biomass. With about 500 billion tonnes per year of $CO_2$ fixed by terrestrial plants, the terrestrial biological carbon cycle is about twenty times larger than the production of $CO_2$ from fossil fuel combustion. Biomass is considered a renewable fuel because, upon burning, the $CO_2$ evolved matches the quantity of $CO_2$ recently removed from the atmosphere through the growth of the biomass. However, some additional energy may be needed to plant, fertilize, irrigate, harvest and process the biomass fuel crop. Biomass can be used to replace fossil fuels (e.g., combustion of wood fuels or agricultural residues) or can be processed to biofuels (e.g., gasifier gas, pyrolysis oils, ethanol, biodiesel, methane, hydrogen).

It was recently estimated that in the next century biomass fuels could mitigate 4 to 16 billion tonnes of $CO_2$ emissions annually (Sampson *et al.*, 1992). Most of these opportunities are indirect processes, independent of $CO_2$ production (see Chapter 9). Microalgae systems present the best biological technology for the direct capture and utilization of $CO_2$ emitted by power plants. The efficiency of conversion of solar energy to biomass is only around 1-3% for typical plant growth. However, there is much potential for improving the efficiency by up to an order of magnitude through the use of bioengineered species and low-cost/low-energy “biofarming” practices. Plant growth is thought to be enhanced by higher $CO_2$ concentrations, so some limited potential might exist for combining $CO_2$ rich streams captured from power plants with a greenhouse farming scheme.

Benemann (1997) has reviewed the possibilities in a recent paper that analyzes the different options and suggests fruitful areas for further research. Microalgae are of particular interest because of their rapid growth rates (up to ten times that of trees) and potential for significantly higher efficiency solar conversion than land plants. These microscopic plants would be grown in large open ponds, into which power plant flue gas or pure $CO_2$ (captured from power plants) is introduced as small bubbles. The estimated mitigation costs for this type of scheme would be up to \$100 per tonne $CO_2$ recycled (with significant opportunities for further cost reduction); a pond area of about 50 - 100 square kilometers would be needed for a 500 $MW_e$ power plant (Benneman and Oswald, 1996). After harvesting, the biomass would be converted to a fossil fuel replacement, preferably a high value liquid fuel such as biodiesel. Microalgae systems require a combination of land, water, and climate resources seldom found in conjunction with power plants. These factors currently constrain the likely reductions by microalgae systems in the US to a few tens of millions of tonnes of $CO_2$ per year -- perhaps 1% of present fossil $CO_2$ emissions. Again, this could be one element of a diverse set of utilization options that contribute to mitigation.

Until recently, there has not been much R&D effort on microalgal $CO_2$ utilization/recycling systems. There are some interesting possibilities when such systems are integrated in a synergistic manner with wastewater treatment systems. Work in Japan is concentrating on photobioreactors (Usui and Ikenouchi, 1997) and on new strains of microalgae and growing conditions. Work at the US National Renewable Energy Laboratory (Kadam, 1997) concludes that, although the costs are likely in the mid-term to be about $100 per tonne $CO_2$ recycled, the ponds would produce a lipid feedstock that could be used for biodiesel production at costs similar to the current crude soybean oil prices.

***Summary.*** Although utilization does not seem to offer large scale opportunities for mitigation, it is important to recognize that a large number of small uses can play an important part of an overall mitigation strategy. Further, if $CO_2$ can be used as a feedstock for useful products, it provides a credit against capture costs and avoids incurring land or ocean storage costs. An overview of the status of utilization opportunities at present is:

- Many diverse industrial niche opportunities exist for use of power plant $CO_2$, for linking of industrial processes to minimize $CO_2$ emissions, or for inexpensive capture of $CO_2$-rich streams.

- Increased production of hydrogen for use as a fuel offers additional inexpensive $CO_2$ capture opportunities.

- Microalgae conversion of $CO_2$ to biomass is the leading candidate for direct biological utilization of power plant $CO_2$ and has potential for significant improvements in conversion productivity.

- Longer term prospects for potential storage of power plant $CO_2$ as minerals are interesting but uncertain as to practicality.

- Large-scale conversion of power plant $CO_2$ to fuels, such as methanol, appears unattractive based on the criteria of effective energy utilization.

## Box 6. Suggested Feasibility Criteria for Evaluating Utilization Options

*Audus and Oonk (1997) present the following criteria for evaluating the usefulness of potential utilization processes for significant $CO_2$ mitigation:*

1. A reduction in net emissions of $CO_2$: Does the process consume carbon? (i.e., is the molar C/H ratio of the stable products greater than that of the raw materials?)

2. A reasonable energy input for conversion: The heat of reaction for the process should not be more than 1.25 times the heat of combustion of the reference fuel. (This rule of thumb gives good agreement for chemicals which are predominately carbon and hydrogen; but may give conflicting results with other chemicals).

3. When alternate utilization processes are being compared, the better choice will usually involve:
    - A reduction in the number of processing steps
    - Milder operating conditions
    - Fewer discontinuities in operating conditions
    - Improved possibilities for process integration

4. Favorable reaction equilibrium chemistry: Negative or slightly positive free energy change ($\Delta G$) indicates that the equilibrium for the reaction favors the desired product.

5. Effectiveness:

    - Significant storage lifetime (time scales of 100 to 1000 years or more)
    - Market size sufficient to sequester at least 10 million tonnes $CO_2$ per year
    - Availability of co-reagents to process at least 10 million tonnes $CO_2$ per year

*Two examples of applying these criteria are presented in their paper, with the following conclusions:*

- Fixation of $CO_2$ in inorganic carbonates seems a feasible method of reducing $CO_2$ emissions to the atmosphere.

- In terms of reducing $CO_2$ emissions, producing methanol from steam reforming of methane is a better process route than production of methanol from $CO_2$ and $H_2$.

## 8. System Implementation Issues

The preceding chapters have looked at technologies for capturing $CO_2$ from fossil fuel-fired power plants and for sequestration by geological storage, ocean storage, and utilization. This chapter will discuss the potential integration of these technologies and the barriers and opportunities related to their implementation. There appears to be no single solution to the sequestration issue in the event that a major $CO_2$ mitigation program is implemented. Therefore, $CO_2$ mitigation will require a systems approach that must be integrated on a still higher level with other $CO_2$ mitigation options such as improved efficiency, increasing use of non-fossil fuels, and indirect means of atmospheric $CO_2$ reduction (see Chapter 9). Within the fossil fuel sector, energy efficiency improvements are usually double winners, both from the economic viewpoint of reduced fuel costs and from the reduction in $CO_2$ emissions, which also reduces the costs of capture and sequestration.

However, in developing additional strategies for selecting the most effective national portfolio of power plant $CO_2$ capture and sequestration systems, there are a number of important factors:

- ***Full cost analysis.*** For each major power plant (or industrial) source, the system costs include the costs of capture or reuse of the $CO_2$, costs of transportation to a storage or reuse point, the costs associated with the storage or reuse, and the costs associated with losses and inefficiencies. Such studies provide a rational basis for assessing tradeoffs between local environmental impacts and global impacts.

- ***Externality analysis.*** Full fuel cycle analysis requires the inclusion of external environmental and societal costs that are often neglected in traditional cost analyses. DOE and the Commission of the European Communities (CEC) have looked at externality valuation for fossil and non-fossil technologies (ORNL, 1994). The DOE and the IEA Greenhouse Gas R&D Programme have also attempted to evaluate the external costs of greenhouse gas emissions (Saroff, 1996; Audus, 1996).

- ***Sequestration effectiveness.*** Different modes of sequestration remove $CO_2$ from the atmosphere for different periods of time. Looking at possible future use of fossil fuels over periods of several hundred years, geologic storage appears relatively permanent. Ocean storage may be effective over time scales up to 1000 years or longer but is dependent on injection technologies and other factors.

- ***Uncertainty analysis.*** It is evident that sequestration methods vary considerably in the amount of uncertainty associated with their likely costs and effectiveness. Areas of large potential, but large uncertainty, are prime candidates for active research programs that are designed to identify key factors that will help in future strategy development and in the targeting of the most promising future research and development efforts.

- ***Legal and regulatory analysis.*** From global agreements that may drive national initiatives, to potential opportunities for actions implemented jointly by multilateral agreements, to issues of local and state regulations and jurisdiction, to laws of the sea, and other issues such as interstate transportation, a good understanding of the legal frameworks that may facilitate or impede implementation of desirable $CO_2$ mitigation technologies or policies is very important

- ***Public participation and education.*** At present, the US public is not very aware of the issues associated with global climate change and even less aware of the technological options for $CO_2$ capture and sequestration. These involve a range of environmental, land use, economic and societal impacts that will require the support of knowledgeable citizens and their political representatives. As the program evolves, clear dissemination of information, opportunities for interaction among diverse experts at workshops, workshop reports, and other opportunities for inputs and feedback will be important for the acceptability of alternative options.

One of the major challenges associated with full cost pathway analyses or externality analyses is to identify least cost and impact opportunities, which will vary on a site by site basis depending on the nature of the $CO_2$ source and distances from storage or use locations that appear to be suitable.

***Regional issues.*** The choice of a $CO_2$ sequestration technology is likely to be dependent on siting because of transportation costs. Power plants are distributed throughout the US, with major concentrations near large population and industrial centers. Largest concentrations are in the northeast area in a band stretching from New York through Missouri. Other concentrated locations are in the southeast and in Texas (see Box 7).

Ocean storage will favor coastal locations that are near a suitable disposal site. For the US, offshore distances to reach 1000 m depths vary considerably. Subsea pipeline costs are expected to be in the order of $2 million or more per mile. While some general studies have commented on potential ocean storage sites for the US, no definitive study on specific $CO_2$ ocean disposal sites exist. A definitive study must investigate proximity of disposal sites to the power plant, transportation considerations, the ultimate fate of the injected $CO_2$, environmental considerations, and costs.

Storage in depleted oil and gas wells is another option, but US wells are of limited capacity and are mostly located in Texas and a couple of neighboring states (Winter and Bergman, 1996). These authors estimate that existing abandoned reservoirs could hold a total of about 2.9 billion tonnes of $CO_2$ (US power plants generate about 1.7 billion tonnes annually). Because wells are owned privately and are often abandoned with significant residual inventory due to economic reasons, it is difficult to inventory the true capacity. An estimate of total volume available from depletion of *all* US oil and gas reserves is 100 billion tonnes of $CO_2$. For power plants in Texas, the potential for disposal of significant quantities of $CO_2$ in depleted oil and gas wells appears attractive. Pipelines would be required as part of the system, and with pipeline costs in rural areas at about $750,000 per mile, there are strong incentives to minimize transport distance. In more congested areas pipeline costs increase to around $1 million per mile or more. Pipeline distances from these mid-US power plant locations to suitable ocean disposal sites would be much greater and costs would likely be prohibitive.

The EPA already allows disposal of liquid industrial wastes into aquifers if a retention time of greater than 10,000 years can be proven. However, regulations on aquifer disposal vary from state to state and not all states would currently allow such disposal. Aquifers underlie large portions of the US -- about 65% of the US power plant $CO_2$ emissions are produced in these areas. Bergman and Winter (1996) estimate potential capacities of 5-500 billion tonnes of $CO_2$. This broad range reflects the uncertainties in the estimates! Further, very little is known about the behavior of $CO_2$ if it were injected into an aquifer. The $CO_2$ has different properties than the brine that is present in such aquifers and how it interacts and reacts with the brine and with various rock matrices is only a subject of conjecture at the present time.

Other storage and utilization options will also be geographically distributed and the best matches with $CO_2$ emission sources will require analysis on a system level that includes capture, transportation, and sequestration.

***Barriers and Opportunities to Implementation.*** In the short-term (next 10 years), there are several significant barriers to implementing $CO_2$ capture and disposal technologies. The cost of capture is significant and must be reduced. Availability of viable utilization or storage options is also lacking. Finally, practical considerations regarding the ability to retrofit or repower existing power plants (e.g., is there enough land to add a capture plant?) need to be considered.

However, if one takes a medium-term (10-30 years) view, the opportunities for implementing $CO_2$ capture and sequestration technologies are much more positive. Research seems promising to significantly reduce the cost of capture. New power plants can more efficiently integrate $CO_2$ capture and sequestration technologies. Also, new power plants can be sited with $CO_2$ sequestration as a criteria, taking into account the transportation costs of both electricity and $CO_2$. In other words, $CO_2$ capture and sequestration technologies will allow one to build new fossil fuel power plants without generating significant greenhouse gases.

Environmental impacts of sequestration alternatives will need further elucidation, particularly for sequestration in aquifers and the oceans. Public education and involvement will be important in future decisions involving land use issues and environmental and social tradeoffs among alternatives.

From the above discussion, we conclude the following:

- In the short-term (up to 10 years), $CO_2$ capture and sequestration technologies will be viable only in niche applications, such as oil and gas operations (e.g., Sleipner West, Natuna), or fulfilling a commercial need for $CO_2$ (e.g., EOR).

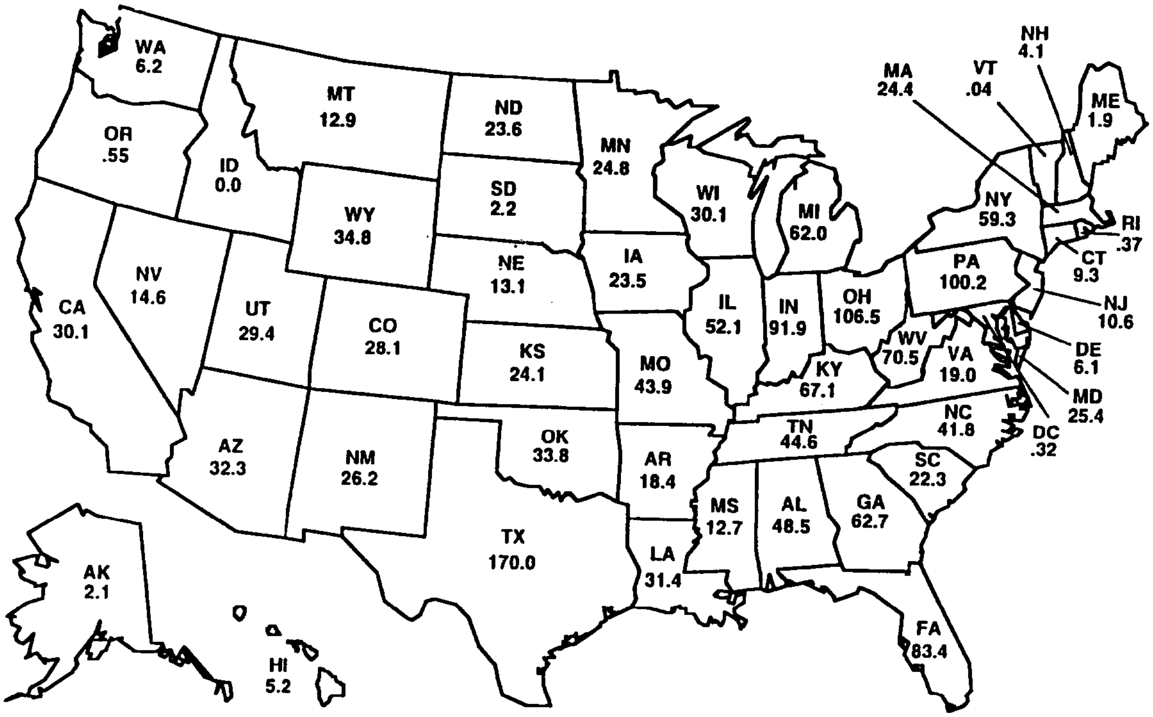
- In the medium-term (10-30 years), $CO_2$ capture and disposal technologies can be used to retrofit existing plants that have good alternatives for $CO_2$ disposal or use. In addition, new plants can be designed and sited to take advantage of integrated $CO_2$ capture and disposal opportunities.

- In the longer-term (30 years plus), we may see most new power plants include $CO_2$ control technology, just as today's power plant designs include technology to address the issues of $SO_2$, $NO_x$, and particulate control. If one of the broader energy strategies involves large scale use of hydrogen produced from natural gas, this technology also offers opportunity for inexpensive $CO_2$ capture and integration into sequestration systems.

## Box 7. CO$_2$ PRODUCTION FROM US POWER PLANTS (1990)

(in millions of metric tonnes)

(Herzog *et al.*, 1993)



**TOTAL = 1689**

## 9. Other Approaches to $CO_2$ Reduction

As a short-term mitigation strategy, the US DOE is vigorously pursuing energy efficient technology development. This report has so far focused on technologies for $CO_2$ capture and sequestration for the mid- to longer-term. Additionally, there are a variety of other possibilities that may be of interest to the fossil fuel industry if they seek technologies for $CO_2$ swaps or offsets. As such, these programs would be of interest to others, including the US DOE Offices of Fossil Energy, Energy Research, and Energy Efficiency, plus other governmental agencies as they develop programs to meet mid- to longer-term mitigation goals.

***Forestation.*** Trees and woody plants sequester $CO_2$ during their growth periods. Destruction of forests, especially with burning of residues, releases stored $CO_2$ back into the atmosphere. The forestation options include prevention of deforestation, afforestation (converting land back to forest), and reforestation (planting to create a new forest). During the life of a typical forest, biomass productivity is about 3-10 dry tonnes per hectare per year (about equivalent to fixing the same weight of $CO_2$) . As the forest matures over 100 years or so, some of the sequestered $CO_2$ can be released back to the atmosphere through decay of fallen trees or through forest fires. Once the forest is mature, additional carbon uptake is minimal. Planting costs are in the range of \$1000 - \$2000 per hectare in accessible areas (Yokoyama, 1997). If an area of 370 million hectares were reforested (about one half the size of the Amazon basin), about 3.6 billion tonnes of $CO_2$ could be captured annually until the forest matures (Jarvis, 1989). If no other costs are required for land acquisition, soil remediation, or irrigation, this provides initial $CO_2$ mitigation at a cost of \$1 to 2 per tonne captured. The IPCC (Bruce *et al.*, 1996) estimates afforestation costs in the range of \$3 - \$10 per tonne of $CO_2$ sequestered, but notes that costs rise with the scale of activity. Real costs might be substantially higher if land costs and forest management are included, and if allowance is made for release of some of the $CO_2$ back to the atmosphere. Audus and Saroff (1995) present a full life cycle evaluation of an afforestation option in a temperate European country and estimate costs of around \$26 per tonne of $CO_2$ avoided.

Several arguments beyond cost can be raised against major reforestation schemes. $CO_2$ sequestration into forests is limited and would diminish over the next century when needs for $CO_2$ mitigation are likely to be even more acute. The long-term fate of carbon sequestered in forests is somewhat uncertain as some ends up sequestered in the soil and some eventually returns to the atmosphere as $CO_2$. Carbon balances for various types of biomass are not well known. Also, widespread reforestation removes land from economic utility and requires that the mature forest not be utilized in the future in a manner that fosters release of the sequestered $CO_2$ to the atmosphere. However, reforestation of low productivity land may be useful, as is use of planting trees for shade and shelterbelts around buildings as an energy conservation measure. Also, reforestation might offer recreational benefits, could aid biodiversity if this were a parallel goal, and might be designed for protection of watersheds. It may also serve as a stepping stone towards more active sustainable utilization of the wood as biofuel for fossil fuel replacement or cofiring.

***Bioenergy farming.*** A more active and sustainable approach to reforestation is the farming of biomass for a fossil fuel replacement. If trees or plants can be used as a fuel that displaces fossil fuel use, then a net reduction in $CO_2$ emissions occurs. Yokoyama (1997) indicates that the potential reforestation area available worldwide (for land that does not require major investments in soil improvement or irrigation) is about 340 million hectares. If all this land were developed for energy plantations, he computes a theoretical potential for mitigating 5.1 billion tonnes of $CO_2$ per year using Eucalyptus trees with a six year rotation. For comparison, the total area of Brazil is 850 million hectares. However, biomass energy involves additional costs in farm management, harvesting, and transportation. If transportation distances exceed 50 - 75 km, transportation energy becomes a significant portion of the energy gathered in the biomass. The best applications for biomass energy farming appear to be in smaller growing areas serving a medium size power plant or for use as a cofiring fuel with coal.

***Utilization of biomass fuels.*** Biofuels presently make up about 4% of the primary energy used in the US and are used primarily in the forest products industries. Available forestry and agricultural wastes and residues could supply about twice this energy, if there were incentives for utilization (Robertson and Shapouri, 1993). Municipal solid waste generates about 2,000 $MW_e$ in the US today. However, the wood power industry is in trouble, with plants in California and the Northeast being shut down for economic reasons, mainly from continuing falling fossil fuel and electricity prices, potentially worsened further by the deregulation of the electric power industry.

The efficient utilization of biomass in replacing fossil fuels should be a major part of any broad $CO_2$ mitigation program. To make biomass a more attractive fuel, technology improvements in combustion efficiency are needed. Currently, stand-alone biomass power plants have efficiencies of about 20-25% (on a higher heating value basis) compared to fossil fuels, which are typically used with 30-40% efficiencies. Thermochemical gasification may have potential for achieving improved efficiencies, but still requires considerable development to overcome problems with tar and alkali deposition, as well as with hot gas cleanup. Improved technologies are also being developed to allow the drying and combustion of entire trees, and for better handling of ash and slag in combustion chambers (Wiltsee *et al.*, 1993). Investment in improved biomass combustion technologies may serve as a bridge to more widespread use of biomass energy in the future.

The potential for producing liquid fuels from biomass is more limited. Starch or oil crops, used for conversion to ethanol or biodiesel, are expensive, energy intensive, and produce only moderate (or sometimes negative) $CO_2$ mitigation. While there may be niche uses because of the desirability of liquid fuels, the greatest potential for reducing fossil $CO_2$ emissions comes from use of solid biomass in cofiring or stand-alone power plants.

***Cofiring biomass with coal and other fossil fuels.*** This option, which utilizes biofuel in a higher efficiency fossil fuel power plant, has been studied for many years (McGowin and Hughes, 1992). Earlier work emphasized cofiring of “refuse-derived fuels” (RDF), while more recent emphasis has shifted to wood-based fuels which are cleaner and more uniform than RDF. Cofiring of coal with wood wastes at low levels (about 1% by heat rate) is already in commercial practice at several utility sites. Recently several utilities (Hunt *et al.*, 1997; Benjamin, 1997) have been testing cofiring of biomass fuels with coal at higher levels. Preliminary indications are that some types of existing boilers are suitable for burning biomass up to at least 10% of the heating rate and 20% of the weight of the feed. The biomass component reduces sulfur emissions and burner improvements may also lead to lower $NO_x$ emissions; however, efficiency is reduced by the energy needed to pulverize the biomass and for vaporizing associated moisture. Active drying of biomass has a large energy penalty. Some thought is being given to burning biomass from selected dry waste streams, such as the sawdust from a sawmill.

Despite uncertainties, results from these studies suggest that for cyclone burners and for small-size biomass fuel, capital costs for the fuel preparation and feeding systems are only $100-200 per $kW_e$. Even for pulverized coal boilers, requiring more feed preparation and potential boiler modifications, costs appear substantially lower than any other end-of-pipe $CO_2$ mitigation option. However, a number of technical uncertainties remain to be resolved in cofiring: fly ash quality, maximum percentage of biomass that can be handled, and effects of resource variability in quality, cost and moisture content on overall plant performance. In September 1996, the DOE and the Electric Power Research Institute (EPRI) signed a $5 million, three-year cooperative agreement to co-fund cofiring and other $CO_2$ mitigation projects in collaboration with the electric utility industry (see Box 8).

Although a more detailed resource and economic analysis is required, preliminary estimates suggest that up to 5% of US coal-fired power plant emissions could be mitigated through co-firing, at a cost of less that $10 per tonne of $CO_2$ avoided (Hughes and Benneman, 1997). In the future, biomass suitable for cofiring could be greatly expanded by the use of specifically and intensively produced local wood fuels and energy crops.

***Artificial photosynthesis.*** There has been on-going basic research to develop photochemical processes that mimic biological photosynthesis -- converting solar energy into fixed chemical energy, using chlorophyll as a catalyst. Most of these studies have focused on a photolysis process, producing hydrogen from water using sunlight. Although some ruthenium complexes were able to catalyze such a reaction, the low efficiencies and instability of the reaction are discouraging. This remains an interesting area for basic research, but possible success appears to lie far in the future (Lewis, 1995).

***Hydrogen production by biophotolysis.*** Some very early studies (Miura *et al.,* 1997; Ohtaguchi *et al.*, 1997) are exploring bacterial systems that absorb $CO_2$ by light induced photosynthesis and then are subjected to a subsequent anaerobic fermentation step without light to generate $H_2$. An additional bioreactor can be used to convert the residual organic compounds to various biofuels. These novel systems create interesting possibilities, although they will be subject to the same types of scale-up constraints and costs that limit single-step bioconversion to fuels.

Another possibility is the use of certain algal strains which can split water to hydrogen and oxygen with a single light reaction. These algae can be grown with $CO_2$ as the sole carbon source

(Greenbaum, 1996). These types of reactions are very interesting, but will require much additional research and refinement for future usefulness.

***Ocean fertilization to induce $CO_2$ fixation.*** Martin (1990) suggested that the scarcity of phytoplankton productivity in the Southern Ocean was due to limited concentrations of iron. Kumar *et al.* (1995) confirmed this hypothesis by showing that during glacial periods where iron-bearing dust fertilized the oceans, productivity was greatly enhanced. An experiment with iron dusting in the equatorial Pacific yielded a large increase in productivity that exceeded expectations and seemed to be sustained over a period of days (Dopyera, 1996). While the short-term uptake of $CO_2$ was evident, the experiment was too short to study the needs for continuing fertilization or of the net $CO_2$ sequestration over the life cycle of the phytoplankton. Uncertainties exist about where the phytoplankton release their carbonaceous material. Little net sequestration occurs if this is in the upper layers of the ocean rather than in the deep ocean. Other research in Japan (Horiuchi *et al.*, 1997) is exploring general ocean fertilization with nitrogen and phosphorus using activated sludge. Again, this appears to produce a net short-term assimilation of $CO_2$ by phytoplankton.

The next phase for this research will involve shipboard experiments in the Southern Ocean. The Southern Ocean is protected by a set of international laws designed specifically to keep the environment uncontaminated. More impact data will be needed to demonstrate that a future, larger scale Southern Ocean experiment is acceptable. However, until more is learned about the possible ecological impacts of iron fertilization, it should be considered a highly speculative longer-term $CO_2$ abatement option.

***Offsetting the greenhouse effect.*** There are some more unlikely options that focus on inducing cooling to offset any global warming. It is known that sulfur emissions can produce aerosols that induce cooling in the atmosphere; this is usually not considered a responsible mitigation strategy (Messner, 1996). Proposals to “dust” the atmosphere (as is done naturally through major volcanic eruptions) also are a potential way of producing some cooling, as are proposals to orbit giant sunshades and the like. These geoengineering options seem extreme enough that they might only be seriously considered in the event of an impending global catastrophe.

***Summary.*** In the short-term, afforestation/reforestation and co-firing of biomass and suitable waste products seem to offer considerable potential for $CO_2$ reduction. In the longer term, larger-scale biomass farming and dedicated biomass power plants may be feasible if efficiencies and residue handling problems can be solved. A continued research activity on the fundamental chemistry and biochemistry of $CO_2$ reactions may lead to still other possibilities that are promising, including direct bioproduction of hydrogen from $CO_2$.

### Box 8. The DOE-PETC/EPRI Cooperative RD&D Agreement Planned Biomass Cofiring Projects (September 1996)

| | |
|---|---|
| **TVA** | The Tennessee Valley Authority will continue precommercial extended test runs, leading to full-scale tests at TVA power plants with low and moderate levels of cofiring. Both 200 $MW_e$ cyclone and wall-fired pulverized coal units are being investigated. |
| **NYSEG** | New York State Electric and Gas Company is conducting tests on the preparation of wood fuel for cofiring in a tangentially-fired pulverized coal unit, using a separate feed for the wood. Mid-level (10% of the thermal input) feeding rates will be used in a 100 $MW_e$ boiler. Cofiring of short-rotation willow biomass crops is planned for early 1997. |
| **GPU** | General Public Utilities and EPRI will co-fund a mid-level cofiring test in a wall-fired 30 $MW_e$ pulverized coal unit with a separate wood feed. Earlier work fed the wood through the pulverizers along with the coal, but this led to plant derating. |
| **Southern Company** | Southern Company has carried out short-term tests in a tangentially-fired pulverized coal boiler in Savannah GA, which indicates that separate wood feeding of up to 40% of the heating rate is possible. Longer term testing, possibly with some natural gas overfire, will allow exploration of the upper limits of cofiring. |
| **Madison Gas and Electric** | Madison Gas and Electric are conducting tests at a plant which had been previously retrofitted to burn refuse-derived fuel and shredded paper waste in a wall-fired 50 $MW_e$ pulverized coal unit. The unit will be used to conduct the first US tests of cofiring switch grass (a proposed energy crop) with coal in a full-size utility boiler. |
| **NIPSCO** | Northern Indiana Public Service Company is completing a study evaluating fuel supply and power plant operation for cofiring wood in a full-size 500 $MW_e$ cyclone burner at 5% of the thermal input. |
| **University of Pittsburgh** | The University of Pittsburgh is planning test burns in one or more of a series of chain grate stoker boilers (15 $MW_e$ total), cofiring wood waste at up to 10% of the thermal input to the boilers. Urban wood residues will be used in these tests. |

Projects on aquifer storage of $CO_2$ and the use of microalgae for wastewater treatment are also contained in this agreement.

## 10. Proposed Plans and Actions

The evidence is accumulating that $CO_2$ emissions abatement will eventually be needed, but there is much uncertainty as to the timing and magnitude. A broad based research program is required to explore a diverse spectrum of options valid for multiple time frames. Therefore, we propose an initial five year research program into the capture and sequestration of $CO_2$ with the following strategic goals:

- ***Encourage/accelerate near-term opportunities.*** There are some opportunities for commercial scale $CO_2$ capture that may be able to be developed and implemented now, similar to the Sleipner West project in Norway. Early emission reductions may receive credit for these activities in the event of a mandatory emission reduction program.

- ***Assess the feasibility of $CO_2$ capture and sequestration technologies.*** Before one can add $CO_2$ capture and sequestration to the active list of mitigation options, two key questions concerning its feasibility must be answered. First, can we make the technologies cost-effective enough to compete economically? We need much more research to better understand the future mitigation supply curves in terms of both cost and mitigation potential. Secondly, do large-scale storage options exist that are technically feasible and publicly acceptable? While the studies to date suggest cause for optimism, large-scale feasibility has not yet been proven.

- ***Position the US to become a technology leader.*** On the current trajectory, Japan is becoming a research and technology leader for $CO_2$ capture and sequestration. The research program presented below will provide the US with the option to become a technology leader in this field.

- ***Leverage on-going international research.*** With the current level of funding, it is impossible for the US to monitor and participate in the extensive on-going research activities worldwide. At an expanded level of funding, we can seek international collaboration to leverage our research dollars. One mechanism already in place is the IEA Greenhouse Gas R&D Programme. International collaboration is also inherent in the US-signed Climate Technology Initiative (CTI), which calls for the international research community to "assess the feasibility of developing longer-term technologies to capture, remove or dispose of greenhouse gases and strengthen relevant basic and applied research."

- ***Assess compatibility with on-going advanced combustion and efficiency programs.*** Fossil Energy has a major research program investigating advanced combustion systems. By taking into account the possibility of $CO_2$ capture and sequestration technologies, these technologies may be more widely adopted when modified for a greenhouse world. The time to make this assessment is now, so the possibility of $CO_2$ capture and sequestration can be built into their design.

- ***Stimulate private sector R&D.*** Energy related R&D in both the public and private sectors has been declining. This trend has been accelerated in the utility industry due to deregulation. However, programs can be set up to both stimulate private sector R&D and leverage scarce DOE research dollars. One example is the $5 million, 3 year DOE-PETC/EPRI Cooperative RD&D Agreement.

To date, the cumulative research funding for $CO_2$ capture and sequestration technologies in the US has been less than $10 million, limiting the research effort to theoretical or laboratory studies. In addition to these types of studies, pilot-scale research in the field is required as part of a proposed five year program to achieve the strategic goals outlined above. However, it is still premature to conduct costly demonstration projects. Decisions on demonstration projects can be made near the end of the proposed research program, when more information will be available concerning the feasibility of $CO_2$ capture and sequestration technologies, as well as the status of international agreements aimed at limiting greenhouse gas emissions.

We recommend the following specific program components, with their relative share of available funds indicated:

- ***Promotion of near-term opportunities (15%).*** Potential areas include cofiring of biomass, industrial capture (e.g., from oil and gas operations), enhanced oil recovery, and utilization opportunities. This program component can coordinate with on-going DOE industrial initiatives, such as those in the Office of Industrial Technologies. This component should focus on applications that are economically feasible today and that will yield a positive return on investment when implemented.

- ***Assessment and development of capture technology (25%).*** This element needs to focus on three strategies: improving solvents and processes for $CO_2$ scrubbing from flue gases, developing new power plants based on an oxygen feed, and integrating capture technology into advanced combustion systems including gasifiers and fuel cells. Research on $CO_2$ solvents should include the private sector which has commercial processes available for related problems.

- ***Assessment and development of storage technology (35%).*** Since the US has the potential to take advantage of all of the major storage options suggested (oil and gas wells, coal beds, aquifers, and the ocean), all should be investigated. Cooperation with the oil and gas industry will be a key component in realistic assessments of geologic storage potential. Major opportunities exist for international collaboration in this research with Japan (oceans), Norway (aquifers), and the Netherlands (oil and gas wells).

- ***System analysis (10%).*** To help guide and focus the research on practical solutions, we need to undertake some general system studies. Questions to be addressed include: What existing sites in the US can take advantage of this technology and at what costs? Since plants built today will last for 50 years or longer, how can we address global change concerns in their design given the uncertainties that exist today? What opportunities exist worldwide for $CO_2$ capture and sequestration as part of a joint implementation (JI) strategy?

- ***Generation and assessment of longer-term technologies (15%).*** Since $CO_2$ mitigation is projected to become more difficult in the long-term, we need to start examining some longer-term technologies today. Part of this research will attempt to generate new and creative ideas and to identify the ones with real potential. Perhaps a contest-type program (similar to Golden Carrot[3]) can be used to achieve this goal.

Based on the program outlined above, we recommend a budget that averages $50 million per year for 5 years as detailed below:

| | |
|---|---|
| FY98 | $20 million |
| FY99 | $40 million |
| FY00 | $60 million |
| FY01 | $70 million |
| FY02 | $60 million |

We envision a leveraging of this budget through collaboration, both domestically and internationally. Approximately half the research dollars should go to collaborative projects. Domestically, agreements can be modeled on the DOE-PETC/EPRI Cooperative R&D Agreement. Internationally, in addition to the IEA Greenhouse Gas R&D Programme, preliminary negotiations are underway with the Japanese and Norwegians (to collaborate on research into $CO_2$ storage, both geological and ocean) and the Canadians (to collaborate on $CO_2$ capture using an oxygen feed).

To put this budget request in perspective, we can make the following comparisons:

- The alternative longer-term mitigation strategies of increased nuclear and renewable energy have had billions of DOE research dollars expended on their development, while research into $CO_2$ capture and disposal is still in its infancy (less than $10 million spent on research

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[3] In 1989, the US EPA, 24 electric utility companies, and the NRDC developed the Super Efficient Refrigerator Program (aka the Golden Carrot program). The program provided a $30 million prize to the winning manufacturer to develop a refrigerator that used no CFCs and boosted appliance efficiency by at least 25% over current standards. This public/private collaborative effort represented a novel “market pull” approach to innovation. The $30 million was distributed as rebates for each refrigerator sold in the utilities service area. Whirlpool was proclaimed the winner and, if the projected sales are met, the new efficient refrigerators will save $75 million in reduced electric bills over their lifetimes.

by DOE). The limited funding to date for $CO_2$ capture and sequestration has not allowed significant program development, making it difficult to fairly assess the potential of these technologies.

- According to the Energy Information Administration, the total US energy expenditures are approximately $500 billion annually. The existing capital stock of the utility industry worldwide is estimated in excess of $2 trillion. It seems wise to investigate whether $CO_2$ capture and sequestration technologies can allow fossil fuels to remain a cost-effective energy source, while concurrently contributing to a significant reduction in greenhouse gas emissions.

- On the surface, it seems the magnitude of the proposed program is similar to the Japanese government's effort of the past several years (see Chapter 3). However, when one considers that the Japanese figures presented are only direct costs (no overhead) and the program proposed here is more broadly based, this research program is modest in comparison to the Japanese government expenditures (by at least a factor of 2). In addition to the government programs, Japanese industry funds significant research in this area.

- The US now spends about $1.6 billion annually investigating various aspects of the climate change problem. Spending at that level indicates that global climate change is being taken seriously. It seems prudent to spend at just 3% of that level to investigate one of the few possible longer-term mitigation solutions.

As a next step, a detailed list of prioritized research needs based on the above program components has to be developed. This effort is currently underway at the MIT Energy Laboratory, which has received a grant from DOE to update its 1993 research needs assessment. The report will be completed in September, 1997. After the report is issued, a workshop should be held to design a specific plan of action. In prioritizing the research, the following points will be considered:

- What are the US needs and how do proposed options fit in with US policies? We need to focus on solutions that reflect the US situation. For example, the large role coal plays in generating our electricity (vs. natural gas for Japan). However, because taking advantage of potential JI opportunities may be part of future US policies, we also need to keep a world view.

- Where does the greatest potential lie? While there are no single solutions, we still need to focus on solutions that can have a real impact.

- How risky is the technology? We need practical solutions, so we need to focus on strategies using proven methods for the near- and mid-term. For the longer-term, we can investigate some of the more novel technologies.

- To what extent can the private sector be involved? Where possible, we need to engage the private sector, since this is where these technologies will ultimately be applied.

- Can we leverage existing programs? Where possible, the research should build on existing national and international programs. Nationally, we already mentioned advanced combustion technology development as well as some of DOE's industrial initiatives. Internationally, opportunities exist through the IEA Greenhouse Gas R&D Programme and the CTI, as well as direct bilateral and multilateral collaboration.

## 11. References

Adams E, D Golomb, X Zhang and H Herzog, "Confined Release of $CO_2$ into Shallow Seawater", in *Direct Ocean Disposal of Carbon Dioxide* (Handa and Ohsumi, ed.) pp. 153-164 (1995).

Albanese AS and M Steinberg, *Environmental Control Technology for Atmospheric Carbon Dioxide*, DOE/EV-0079, Brookhaven National Laboratory, Brookhaven, NY (1980).

Arashi N, N Oda, M Yamada, H Ota, S Umeda and M Tajika, "Evaluation of Test Results of 1000 $m^3$N/h Pilot Plant for $CO_2$ Absorption using an Amine-based Solution", *Energy Convers. Mgmt.*, in press (1997).

Aresta M and I Tommasi, "Carbon Dioxide Utilisation in the Chemical Industry", *Energy Convers. Mgmt.*, in press (1997).

Arnold DS, A Barrett and RH Isom, "$CO_2$ Can Be Produced from Flue Gas", *Oil & Gas Journal* **80**(47), pp. 130-136 (1982).

Aroonwilas A and P Tontiwachwuthikul, "Mass Transfer Studies of High Performance Structured Packing for $CO_2$ Separation Processes", *Energy Convers. Mgmt.*, in press (1997).

Auerbach D, "Global Warming Mitigation via Ocean Disposal of Power Plant-Generated $CO_2$: an Environmental and Political Analysis", MS Thesis, Dept. of Civil and Environ. Engrg., MIT, Cambridge, MA (1996).

Audus H, "IEA Greenhouse Gas R&D Programme: Full Fuel Cycle Studies", *Energy Conv. Mgmt.* **37**(6-8), pp. 837-842 (1996).

Audus H and L Saroff, "Full Fuel Cycle Evaluation of $CO_2$ Mitigation Options for Fossil Fuel Fired Power Plant", *Energy Convers. Mgmt.* **36**(6-9), pp. 831-834 (1995).

Audus H and H Oonk, "An Assessment Procedure for Chemical Utilisation Schemes Intended to Reduce $CO_2$ Emissions to the Atmosphere", *Energy Convers. Mgmt.*, in press (1997).

Bacastow RB and RK Dewey, "Effectiveness of $CO_2$ Sequestration in the Post Industrial Ocean", *Energy Convers. Mgmt.* **37**(6-8), pp. 1079-1086 (1996).

Baes CF Jr., SE Beall, DW Lee and G Marland, "Options for the Collection and Disposal of Carbon Dioxide" ORNL-5657, Oak Ridge National Laboratory, Oak Ridge, TN (1980).

Barchas R and R Davis, "The Kerr-McGee/ABB Lummus Crest Technology for the Recovery of $CO_2$ from Stack Gases", *Energy Convers. Mgmt*. **33**(5-8), pp. 333-40 (1992).

Benemann JR, “$CO_2$ Mitigation with Microalgae Systems”, *Energy Convers. Mgmt.*, in press (1997).

Benneman JR and WJ Oswald, *Systems and Economic Analysis of Microalgae Ponds for Conversion of $CO_2$ to Biomass*, report to DOE/PETC (1996).

Benjamin W, “Biomass Development and Waste Wood Co-Firing”, *Energy Convers. Mgmt.*, in press (1997).

Bergman PD and EM Winter, “Disposal of Carbon Dioxide in Deep Saline Aquifers in the US”, *US/Japan Joint Technical Workshop,* US Dept. Of Energy, Sept. 30 - Oct. 2, State College, PA (1996).

Bergman PD, EM Winter and Z-Y Chen, "Evaluation of $CO_2$ Disposal in Oil and Gas Reservoirs in Texas", *Energy Convers. Mgmt.*, in press (1997).

Blok K, WC Turkenburg, CA Hendriks and M Steinberg, eds., *Proceedings of the First International Conference on Carbon Dioxide Removal*, Oxford: Pergamon Press, 544 pp. (1992).

Bruce J, H Lee and E Haites, eds., *Climate Change 1995 - Economic and Social Dimensions of Climate Change*, Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press (1996).

Caulfield J, "Environmental Impacts of Carbon Dioxide Ocean Disposal: Plume Predictions and Time Dependent Organism Experience”, MS Thesis, Dept. of Civil and Environ. Engrg., MIT, Cambridge, MA (1996)

Dawson FM, “Coal bed Methane: A Comparison Between Canada and the United States”, *Geological Survey of Canada Bulletin* **489**, 60 pp. (1995).

Doctor RD, JC Molburg, and PR Thimmapuram, *KRW Oxygen-Blown gasification Combined Cycle: Carbon Dioxide Recovery, Transport, and Disposal*, ANL/ESD-34, Argonne National Laboratory, Argonne, IL (1996).

Dopyera C, “The Iron Hypothesis”, *Earth*, October, 26-39 (1996).

Dunsmore HE, “A Geological Perspective on Global Warming and the Possibility of $CO_2$ Removal as Calcium Carbonate Mineral”, *Energy Convers. Mgmt.* **33**(5-8), pp. 565-572 (1992).

Farla J, C Hendriks and K Blok, *Carbon Dioxide Recovery from Industrial Processes,* Report No. 92076, Dept. of Science, Technology, and Society, Utrecht University, The Netherlands (1992).

Feron PHM and AE Jansen, “The Production of Carbon Dioxide from Flue Gas by Membrane Gas Absorption”, *Energy Convers. Mgmt*., in press (1997).

Freund P and WG Ormerod, "Progress Toward Storage of Carbon Dioxide", *Energy Convers. Mgmt*., in press (1997).

Golomb D, "Transport Systems for Ocean Disposal of $CO_2$ and Their Environmental Effects", *Energy Convers. Mgmt*., in press (1997).

Greenbaum E, “Renewable Hydrogen Production for Fossil Fuel Processing”, *US/Japan Joint Technical Workshop,* US Dept. Of Energy, Sept. 30 - Oct. 2, State College, PA (1996).

Gunter WD, EH Perkins and TJ McCann, “Aquifer Disposal of $CO_2$-rich Gases: Reaction Design for Added Capacity", *Energy Convers. Mgmt* **34**(9-11), pp. 941-948 (1993).

Gunter WD, T Gentzis, BA Rottenfusser and RJH Richardson, "Deep Coal bed Methane in Alberta, Canada: A Fuel Resource with the Potential of Zero Greenhouse Gas Emissions", *Energy Convers. Mgmt.*, in press (1997).

Haugan PM and H Drange, “Sequestration of $CO_2$ in the Deep Ocean by Shallow Injection”, *Nature*, **357**, pp. 318-20 (1992).

Haugan P and H Drange, "Effects of $CO_2$ on the Ocean Environment”, *Energy Convers. Mgmt* **37**(6-8), pp. 1019-1022 (1995).

Hendriks C, *Carbon Dioxide Removal from Coal-Fired Power Plants*, Kluwer Academic Press, Dordrecht, The Netherlands (1994).

Herzog H, E Drake, J Tester and R Rosenthal, *A Research Needs Assessment for the Capture, Utilization, and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants*, DOE/ER-30194, US Department of Energy, Washington, DC (1993).

Herzog HJ and EM Drake, *Long-Term Advanced* $CO_2$ *Capture Options*, IEA/93/0E6, IEA Greenhouse Gas R&D Programme, Cheltenham, UK (1993).

Herzog HJ, E Adams, D Auerbach and J Caulfield, *Technology Assessment of* $CO_2$ *Ocean Disposal*, Report 95-001, MIT Energy Laboratory, Cambridge, MA (1995).

Hitchon B, *Aquifer Disposal of Carbon Dioxide--hydrodynamics and Mineral Trapping: Proof of Concept*, Geoscience Publ. Ltd., Sherwood Park, Alberta, Canada (1996).

Hoffert MI, YC Wey, AJ Callegari and WS Broeker, "Atmospheric Response to Deep-Sea Injections of Fossil-Fuel Carbon Dioxide”, *Climatic Change* **2**(1), pp. 53-68 (1979) .

Holloway S, "Safety of the Underground Disposal of Carbon Dioxide", *Energy Convers. Mgmt.*, in press (1997).

Hopson S, "Amine Inhibitor Copes with Corrosion", *Oil & Gas Journal* **83**(26), pp. 44-47 (1985).

Horiuchi K, T Kojima and A Inaba, "Optimization of Fertilization of Nutrients to the Ocean Taking into Account Horizontal Diffusion and Fixation by Phytoplankton", *Energy Convers. Mgmt.*, in press (1997).

Hughes E and JR Benemann, "Biological Fossil $CO_2$ Mitigation", *Energy Convers. Mgmt.*, in press (1997).

Hunt E, DE Prinzing, JJ Battista and E Hughes, "A Coal/Power Industry Cooperative Test of Direct Fossil-Fuel $CO_2$ Mitigation", *Energy Convers. Mgmt.*, in press (1997).

Jarvis PG, "Atmospheric Carbon Dioxide and Forests", *Phil. Trans. R. Soc.*, London B **324**, pp. 369-392 (1989).

Kaarstad O and H Audus, "Hydrogen and Electricity from Decarbonised Fossil Fuels", *Energy Convers. Mgmt.*, in press (1997).

Kadam K, "Power Plant Flue Gas as a Source of $CO_2$ for Microalgae Cultivation: Economic Impact of Various Process Options", *Energy Convers. Mgmt.*, in press (1997).

Kajishima T, T Saito, R Nagaosa and H Hatano, "A Gas-Lift System for $CO_2$ Release into Shallow Seawater", *Energy Convers. Mgmt* **36**(6-9), pp. 467-470 (1995).

Kaplan LJ, "Cost-Saving Process Recovers $CO_2$ from Power-Plant Fluegas", *Chemical Engineering* **89**(24), pp. 30-31 (1982).

Kojima T, A Nagamine, N Ueno and S Uemiya, "Absorption and Fixation of Carbon Dioxide by Rock Weathering", *Energy Convers. Mgmt.*, in press (1997).

Kollek R, "Carbon Dioxide Disposal: Evaluation of a Scheme for Disposing of the $CO_2$ Product from a 2 $GW_e$ Coal-Fired Power Station in the Ocean at a Depth of 500 m", IEA Greenhouse Gas R&D Programme Report IEA/93/OE13, Cheltenham, UK (1993).

Kondo J, T Inui and K Wasa, eds, *Proceedings of the Second International Conference on Carbon Dioxide Removal*, Oxford: Pergamon Press, 570 pp. (1995).

Kongsjorden H, “Aquifer Storage of Carbon Dioxide in the Sleipner Project”, presented at the *International Symposium on Ocean Disposal of Carbon Dioxide*, NEDO and IEA GHG, Tokyo, Oct. 31 - Nov. 1 (1996).

Korbøl R and A Kaddour, “Sleipner Vest $CO_2$ Disposal - Injection of Removed $CO_2$ into the Utsira Formation”, *Energy Convers. Mgmt* **36**(6-9), pp. 509-512 (1995).

Kumar N, RF Anderson, RA Mortlock, PN Froelich, P Kubik, B Dittrich-Hannen and M Suter, “Increased Biological Productivity and Export Production in the Glacial Southern Ocean”, *Nature* **378**, pp. 675-80 (1995).

Lackner KS and DP Butt, “Carbon Dioxide Disposal as Mineral Carbonate”, *Energy Convers. Mgmt.,* in press (1997).

Lake LW, *Enhanced Oil Recovery*, Prentice-Hall, Englewood Cliffs, NJ (1989).

Leci CL, “Development Requirements Necessary for $CO_2$ Absorption Processes for Effective $CO_2$ Capture from Power Plants”, *Energy Convers. Mgmt*., in press (1997).

Lewis NS, “Artificial Photosynthesis”, *Amer. Scientist* **80**, pp. 534-541 (1995).

Lindeberg E, “Escape of $CO_2$ from Aquifers", *Energy Convers. Mgmt*., in press (1997).

Liro C, E Adams and H Herzog "Modeling the Release of $CO_2$ in the Deep Ocean", *Energy Convers. Mgmt* **33**(5-8), pp. 667-674 (1992).

Magnesen T and T Wahl, "Biological Impact of Deep Sea Disposal of Carbon Dioxide", The Nansen Environmental and Remote Sensing Center (NERSC) Technical Report No. 77A, Bergen, Norway (1993).

Marchetti C, "On Geoengineering and the $CO_2$ Problem”, *Climatic Change* **1**(1), pp. 59-68 (1977).

Martin J, *J. Paleoceanography* **5**, pp. 1-13 (1990).

Masutani SM, CM Kinoshita, GC Nihous, H Teng, LA Vega and SK Sharma, "Laboratory Experiments on $CO_2$ Injection into the Ocean", in: *Direct Ocean Disposal of Carbon Dioxide* (Handa and Ohsumi, ed.), pp. 239-252 (1995).

McGowin CR and EE Hughes, “Clean Energy from Waste and Coal”, in *Amer. Chem. Soc. Symp. Series No. 515*, p. 14 (1992).

Messner S, “Synergies and Conflicts of Sulfur and Carbon Mitigation Strategies”, *Energy Convers. Mgmt.*, in press (1997).

Mimura T, H Simayoshi, T Suda, M Iijima and S Mituoka, “Development of Energy Saving Technology for Flue Gas Carbon Dioxide Recovery by Chemical Absorption Method and Steam System in Power Plant”, *Energy Convers. Mgmt.*, in press (1997).

Miura Y, T Akano, K Fukatsu, H Miyasaka, T Mizoguchi, K Yagi, I Maeda, Y Ikuta and H Matsumoto, “Stably Sustained Hydrogen Production by Biophotolysis in Natural Day/Night Cycle”, *Energy Convers. Mgmt.*, in press (1997).

Myers FS, "Japan Bids for Global Leadership in Clean Industry”, *Science*, **256**, pp. 1144-1145 (1992).

Nakashiki N, T Ohsumi and K Shitashima, "Sequestering of $CO_2$ in a Deep Ocean -- Fall Velocity and Dissolution Rate of Solid $CO_2$ in the Ocean", CRIEPI Report (EU 91003), Japan (1991).

National Academy of Sciences (NAS), *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, National Academy Press, Washington, DC (1992).

Oak Ridge National Laboratory (ORNL), *Estimating Fuel Cycle Externalities: Analytical Methods and Issues*, Vol 2, prepared by ORNL an Resources for the Future for DOE under contract DEAC0584OR21400 (1994).

Ohsumi T, "$CO_2$ Disposal Options in the Deep Sea", *Marine Technology Society Journal*, **29**(3), pp. 58-66 (1995).

Ohtaguchi K, S Kajiwara, D Mustaqim and N Takahashi, “Cyanobacterial Bioconversion of Carbon Dioxide for Fuel Production”, *Energy Convers. Mgmt.*, in press (1997).

Ormerod W, *The Disposal of Carbon Dioxide from Fossil Fuel Fired Power Stations*, IEAGHG/SR3, IEA Greenhouse Gas R&D Programme, Cheltenham, UK (1994).

OTA, *Enhanced Oil Recovery Potential in the United States*, Office of Technology Assessment, Washington D.C. (1978).

Ozaki M, K Sonoda, Y Fujioka, O Tsukamoto, and M Komatsu, “Sending $CO_2$ into Deep Ocean with a Hanging Pipe from Floating Platform”, *Energy Convers. Mgmt.* **36**(6-9), pp. 475-78 (1995).

Ozaki M, “Vertical Pipelines from Platforms and Moving Ships”, in *Ocean Storage of $CO_2$ - Workshop 4 Practical and Experimental Approaches*, IEA Greenhouse Gas R&D Programme, Cheltenham, UK, in press (1997).

Palmer A, “Deep Water Pipelines”, , in *Ocean Storage of $CO_2$ - Workshop 4 Practical and Experimental Approaches*, IEA Greenhouse Gas R&D Programme, Cheltenham, UK, in press (1997).

Pauley CP, PL Simiskey and S Haigh, "N-ReN Recovers $CO_2$ from Flue Gas Economically”, *Oil & Gas Journal* **82**(20), pp 87-92 (1984).

Richels R and J Edmonds, “The Economics of Stabilizing Atmospheric $CO_2$ Concentrations”, *Energy Policy* **23**(4-5), pp. 373-377 (1995).

Riemer PWF, ed., *Proceedings of the International Energy Agency Carbon Dioxide Disposal Symposium*, Oxford: Pergamon Press, 517 pp. (1993).

Riemer PWF and AY Smith, eds., *Proceedings of the International Energy Agency Greenhouse Gas: Mitigation Options Conference*, Oxford: Pergamon Press, 728 pp. (1996).

Robertson T and H Shapouri, *Proc. First Biomass Conf. of the Americas,* NREL/CP-200-5768 DE 93010050, National Renewable Energy Laboratory, Golden, CO (1993).

Rosen MA and DS Scott, “Analysis of the Efficiencies of Several Hydrogen Production Processes”, *Hydrogen Energy Progress XI*, Proc. of the 11th World Hydrogen Energy Conf., Stuttgart, **1**, pp. 479-488 (1996).

Sampson RN, GA Moll and JJ Kelbaso, “Opportunities to Increase Urban Forests and Potential Impacts of Carbon Storage and Conservation”, in *Forests and Global Change*, Vol. 1 (RN Sampson, ed.), American Forests, Washington DC, pp. 51-72 (1992).

Sander MT and CL Mariz, "The Fluor Daniel Econamine FG Process: Past Experience and Present Day Focus”, *Energy Convers. Mgmt*. **33**(5-8), pp. 341-48 (1992).

Sarmiento JL, “Ocean Carbon Cycle”, *C&EN*, pp. 30-43, May 31 (1993).

Saroff L, “Coal Fuel Cycle Externalities Estimates”, *Energy Conv. Mgmt.* **37**(6-8), pp. 1241-1246 (1996).

Steinberg M, *An Analysis of Concepts for Controlling Atmospheric Carbon Dioxide*, DOE/CH/00016-1, Brookhaven National Laboratory, Brookhaven, NY (1984).

Steinberg M, “Production of Hydrogen and Methanol from Natural Gas with Reduced $CO_2$ Emission”, *Hydrogen Energy Progress XI,* Proc. of the 11th World Hydrogen Energy Conf., Stuttgart, **1**, pp. 499-510 (1996).

Tek MR, ed., *Underground Storage of Natural Gas: Theory and Practice*, NATOASI Series E: Applied Sciences Vol. 171, Kluwer, Boston (1989).

Usui N and M Ikenouchi, “The Biological $CO_2$ Fixation and Utilization Project by RITE (1) -- Highly-effective Photobioreactor System”, *Energy Convers. Mgmt*., in press (1997).

Watson RT, MC Zinyowera and RH Moss, eds., *Climate Change 1995 - Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press (1996).

Webster IC, "IEA Greenhouse Gas Programme: Continued International Collaboration”, *Energy Convers. Mgmt*. **36**(6-9), pp. 865-68 (1995).

Williams RH, *Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated* $CO_2$*,* PU/CEES report No. 295, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ (1996).

Wilson TRS, “The Deep Ocean Disposal of Carbon Dioxide”, *Energy Convers. Mgmt.*, **33**(5-8), pp. 627-33 (1992).

Wiltsee GA Jr., CR McGowin and EE Hughes, “Biomass Conversion Technologies for Power generation”, *Proc. First Biomass Conf. Of the Americas*, National Renewable Energy Laboratory, Golden, CO, NREL/CP-200-5768 DE 93010050, pp. 347-367, 1993.

Winter EM and PD Bergman PD, “Potential for Terrestrial Disposal of Carbon Dioxide in the US”, *US/Japan Joint Technical Workshop,* US Dept. Of Energy, Sept. 30 - Oct. 2, State College, PA (1996).

Yokoyama S, “Potential Land Area for Reforestation and Carbon Dioxide Mitigation Effect through Biomass Energy Conversion”, *Energy Convers. Mgmt*., in press (1997).

## Appendices

### A. Current DOE Initiatives Which Address Greenhouse Gas Emissions

***Clean Coal Technology.*** The growing concern of global climate change is being addressed in part through the demonstration of high-efficiency advanced electric power generating technologies. Under the Clean Coal Technology (CCT) Demonstration Program nearly 900 $MW_e$ of new capacity and more than 900 $MW_e$ of repowered capacity are represented by 12 projects valued at nearly $3.4 billion. These projects include five fluidized-bed combustion systems, four integrated gasification combined-cycle (IGCC) systems, and three advanced combustion/heat engine systems. These projects will not only provide environmentally sound electric power generation in the mid- to late 1990's, but will also provide the demonstrated technology base necessary to meet new capacity requirements in the 21st century. One system, the integrated gasification fuel cell (IGFC), promises to cut greenhouse gas emissions by over 50% in comparison to conventional operating plants. Advanced turbines under development by DOE in another large program will contribute to the overall 70% efficiency expected of the IGFC system.

Under another program, development control devices and pilot-scale, advanced power systems will be demonstrated at the Power Systems Development Facility in Wilsonville, AL, beginning in 1997 through the year 2002 at a cost of $231 million. Specifically there appears to be a gap between the years 2000 and 2015 which offers the opportunity to build second generation, integrated advanced power systems incorporating $CO_2$ control and lessons learned from the initial demonstration projects.

***The Climate Change Action Plan.*** In April 1993, President Clinton announced the US commitment to return GHG emissions in 2000 to their 1990 levels. President Clinton also instructed his Administration to prepare an action plan to achieve this goal and continue the trend of reduced emissions. The Climate Change Action Plan (CCAP), published in October, 1993, consists of about 50 distinct but interrelated federal initiatives. A majority of these initiatives seek to reduce or avoid GHG emissions via influencing patterns of energy demand and supply. In addition, special programs are also employed for methane emission reduction and recovery, reduction of minor GHGs (HFC, PFC, and $N_2O$), and enhancement of carbon sequestration via forestry actions.

The centerpiece of the utilities’ response to the climate change issue is the “Climate Challenge” program. Climate Challenge is a joint initiative between the US Department of Energy (DOE) and the electric utility industry to voluntarily reduce greenhouse gas emissions. The initiative, announced as a foundation action under the Climate Change Action Plan, consists of voluntary commitments by electric utilities to undertake actions to reduce, avoid, offset or sequester GHG emissions. As a partnership between DOE and the electric utilities, Climate Challenge utilities are moving to reduce their GHG emissions using a wide range of emission reduction options and innovative approaches.

Climate Challenge commitments are formalized in individual Participation Accords with the utilities. These Participation Accords contain specific commitments describing the actions that the utility and DOE have each committed to undertake under the Climate Challenge Program. The types of commitments are broad enough that any utility can participate, whether large or small, with or without generation facilities, and having all kinds of resource mixes and load growth. “Flexibility” is a key word in all of these efforts. The participants agree to periodically report their individual progress and the obstacles that they have encountered, and they can modify the accords as needed.

As of November 1996, about 600 electric utilities had signed 114 Participation Accords with DOE, specifying the actions they would be taking. These utilities represent over 60% of 1990 US electric utility generation and utility carbon emissions. As additional utilities enter into Participation Accords with DOE, the share of the industry’s generation and carbon emissions covered by Climate Challenge utilities will continue to rise.

In the Participation Accords so far signed, the Climate Challenges utilities are pledging a wide range of GHG reduction activities, in aggregate about 44 million metric tons of carbon equivalent. About half of the pledged GHG reductions stem from supply-side activities, coming as the result of improvements in nuclear plant availability, improved fossil generation efficiency, renewable energy sources, transmission and distribution modifications, fuel switches to natural gas from coal and oil, and others. Substantial GHG reductions are also pledged from demand-side management programs, landfill and coal bed methane capture, forest carbon programs, international programs, and others.

Climate Challenge is still in its infancy, not quite three years old. Yet in that brief time, it has garnered the support of most of the electric utility industry, demonstrated the value of voluntary and flexible approaches, and is making a substantial contribution to the Administration’s Climate Change Action Plan.

## B. Calculating the Cost of Mitigation

As further documentation of the numbers presented in the cost discussion of Chapter 3, attached are two tables documenting our sources and calculations. Table B1 shows how we calculated costs for $CO_2$ capture and sequestration options. The calculational procedure is explained further in Chapter 4, Box 3. Table B2 shows our sources for costs of nuclear and renewable energy technologies and some notes on the calculational assumptions. Some further observations on the data follow:

- The negative values for the cost of end-use energy efficiency are controversial. While they are measured against a relatively higher delivered cost of electricity, they do not include the costs in overcoming potential market imperfections, which make it unlikely that the stated cost and emission reduction potential will be realized.

- The reduction potential of gas assumes that all existing coal plants will be replaced by natural gas combined cycle plants. While this is the maximum technical potential, the achievable potential will be much less. The same argument can be applied to most of the reduction potential numbers.

- The NAS study did not assign a mitigation potential for geothermal due to resource constraints. However, we disagree with this conclusion and have supplied our own geothermal data.

- Reviewers of this paper drew our attention to studies that show much higher prices for forestation and nuclear energy. This highlights the controversy associated in doing this type of analysis. It is not the purpose of this report to arbitrate these differences. Suffice it to say that we recognize that even though we reported a large range of costs, there are still outliers.

As mentioned in Chapter 3, the data presented is very dependent on the assumptions that go into the analysis, which leads to a high level of uncertainty. Therefore, we felt we could only credibly draw the following two conclusions from this data:

- The current and projected costs for $CO_2$ capture and sequestration are similar to those for nuclear and renewable energy.

- There are a set of “least-regrets” options that are relatively inexpensive, but also may be limited in terms the amount of $CO_2$ they can mitigate.

To use these numbers for any other purposes, we strongly recommend referencing the original sources.

# Table B1. Cost of $CO_2$ Capture and Sequestration

| Case ID | | Storage | Storage | Utilization | Utilization | EOR | EOR | Industrial | Industrial |
|---|---|---|---|---|---|---|---|---|---|
| High/Low | | High | Low | High | Low | High | Low | High | Low |
| Energy Penalty | | 35% | 15% | 35% | 15% | 35% | 15% | 35% | 15% |
| Disposal Costs ($/tonne captured) | | $15.00 | $5.00 | -$35.00 | -$35.00 | -$12.00 | -$12.00 | $15.00 | $5.00 |
| Electricity Costs in cents/kWh | | | | | | | | | |
| | No Capture | Capture | Capture | Capture | Capture | Capture | Capture | Capture | Capture |
| Base Generating Cost | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 |
| Capture Cost | 0 | 1.35 | 0.85 | 1.35 | 0.85 | 1.35 | 0.85 | 0.68 | 0.43 |
| Subtotal (per kWh gross) | 4.6 | 5.95 | 5.45 | 5.95 | 5.45 | 5.95 | 5.45 | 5.275 | 5.025 |
| Net Power (MW) | 500 | 325 | 425 | 325 | 425 | 325 | 425 | 325 | 425 |
| Subtotal (per kWh net) | 4.6 | 9.15 | 6.41 | 9.15 | 6.41 | 9.15 | 6.41 | 8.12 | 5.91 |
| T&D, etc. | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Total Delivered Cost | 6.6 | 11.15 | 8.41 | 11.15 | 8.41 | 11.15 | 8.41 | 10.12 | 7.91 |
| $CO_2$ emitted (kg/s) | 115 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 |
| $CO_2$ emitted (kg/kWh) | 0.828 | 0.127 | 0.097 | 0.127 | 0.097 | 0.127 | 0.097 | 0.127 | 0.097 |
| Cost of Capture ($/tonne avoided) | | $65 | $25 | $65 | $25 | $65 | $25 | $50 | $18 |
| Cost of Disposal ($/tonne avoided) | | $26 | $6 | -$60 | -$42 | -$20 | -$14 | $26 | $6 |
| Total ($/tonne avoided) | | $91 | $31 | $5 | -$17 | $45 | $10 | $76 | $24 |
| Impact (million tonnes) | 1700 | 1500 | 1500 | 20 | 20 | 50 | 50 | 80 | 80 |

See Box 3 for additional documentation.

## Table B2. Cost of $CO_2$ Mitigation from Nuclear and Renewable Energy

| Mitigation Option | Net Cost (NAS, 1992) **($/ton avoided)**[A] | **Net Cost Calculated ($/ton avoided)**[B] | **Future Cost Calculated ($/ton avoided)**[C] | **Low** | **High** |
|---|---|---|---|---|---|
| Nuclear | 13 - 61 | 17[1] | | 13 | 61 |
| Biomass | 16 - 30 | 8[2] - 42[3] | | 8 | 42 |
| Hydroelectric | 25 | 25[4] - 38[3] | | 25 | 38 |
| Wind | 19-125 | 26[5]-50[4] | (3.6)[4] - 23[2] | 0 | 125 |
| Solar Photovoltaic | 82 | 26[2] - 400[4] | 23[5] - 76[4] | 23 | 400 |
| Solar Thermal | 130 | 88[4] - 178[2] | 24[D,2]- 68[4] | 24 | 178 |
| Geothermal | | 0[6] - 144[6] | 15[2] | 0 | 144 |

Notes:

A. Net costs based on 1989 dollars and 1989 fuel and electricity use. Calculational method based on EPRI's Technical Assessment Guide (1989). The costs are based on 6% discount rate. High and low cost estimates are based on discount rates of 3% and 10% and uncertainty across different studies. Results normalized to an average generating cost of 3.5¢/$kWh_e$ and an average emission factor of .828 kg $CO_2$/$kWh_e$.

B. Calculated costs based on 1990 dollars, an average generating cost of 3.5¢/$kWh_e$, and an average emission factor of .828 kg $CO_2$/$kWh_e$. Sources of data for each calculation is referenced.

C. Projected for year 2010.

D. Central receiver technology only.

References:

[1] OECD/IEA, *Renewable Sources of Energy*, (1987).

[2] US DOE, *The Potential of Renewable Energy An Interlaboratory White Paper*, DE 90000322, (1990).

[3] Rubin ES, RN Cooper, RA Frosch, TH Lee, G Marland, AH Rosenfeld and DD Stine, "Realistic Mitigation Options for Global Warming", *Science* **257**, pp. 148-9, 261-6, July 10 (1992).

[4] Sokolinski A, *A review of the Cost Estimates for Selected Backstop Technologies*, MIT (1994).

[5] Alliance to Save Energy, *America's Energy Choices. Investing in a Strong Economy and a Clean Environment*, (1991).

[6] Pabich W, *Hydrothermally-Generated Electricity in the United States: An Industry Analysis*, MIT (1994).