A Low-Cost Sequestration Approach: A Critical Need in an Energy Hungry World

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This conference begins with the assumption that concern over climate change is an important public policy issue. The issue is increasing concentrations of greenhouse gases in the atmosphere, particularly CO_2. Figures 1a and 1b show CO_2 concentrations in the earth's atmosphere for the past 150,000 years [1,2]. Historic data for CO_2 concentrations were derived from ice core measurements, while the most recent CO_2 levels were measured in the atmosphere at Mauna Loa, Hawaii. The trend has been a significant increase in atmospheric CO_2 concentrations since pre-industrial times (1860). Over the past 150 years, CO_2 levels have increased 30 percent — from 280 ppm to 365 ppm.

In 1995, the Intergovernmental Panel on Climate Change (IPCC) issued its Second Assessment Report. The IPCC reviewed the current scientific knowledge-base available at that time on climate change. The panel included 2,500 scientists and experts from 80 countries. Their three-volume report concluded that the about 1 degree Fahrenheit increase in global average temperature over the past century ". . .is unlikely to be entirely natural in origin." The IPCC acknowledged that solar activity, changing tilts in the earth's axis, and aerosols in the atmosphere all influence climate, but they said ". . .the balance of evidence suggests a discernable human influence on global climate."

The IPCC attributed the change in climate to the buildup of greenhouse gases in the atmosphere, particularly CO_2. About 80 percent of the world's anthropogenic CO_2 emissions are associated with energy use. Figure 2 shows the history of the world's energy use [3].

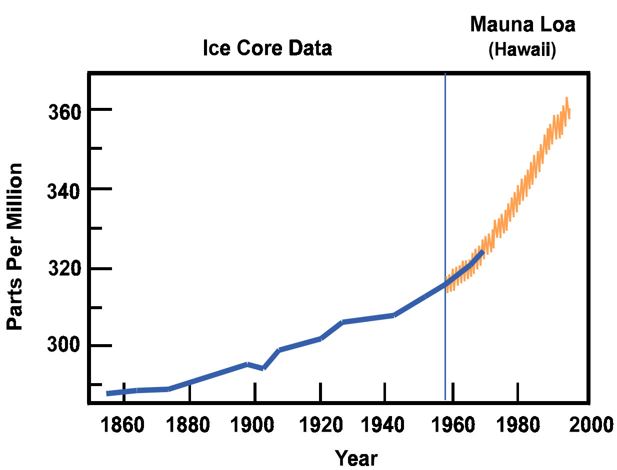


Figure 1a. Atmospheric carbon dioxide concentrations

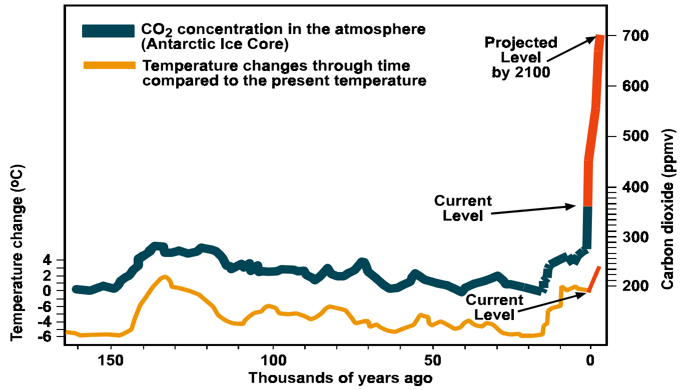


Figure 1b. Atmospheric carbon dioxide concentration and temperature

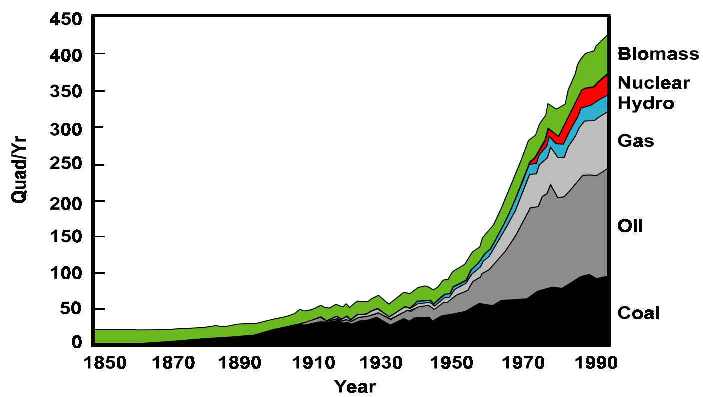
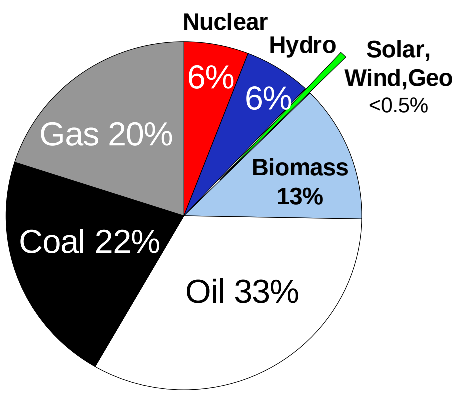


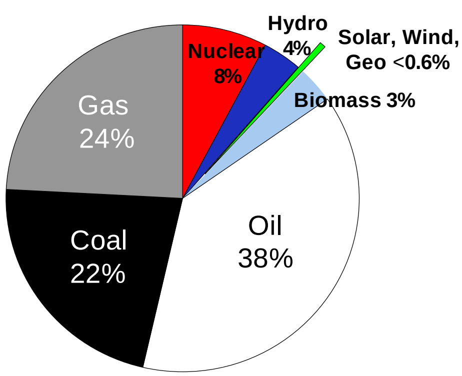
Figure 2. History of the world energy mix

Between 1850 and 1990, world energy consumption increased by a factor of 20, with the sharpest increases occurring over the last 50 years. The energy mix has also changed. In 1850, biomass, primarily wood, was the predominant energy source. Today, we use a diverse mix of fossil fuels, nuclear and renewables. However, fossil fuels — coal, oil, and natural gas — are the dominant energy sources. Figures 3a and 3b show the fuel mix for the world and the U.S. [4,5].



World: 420 Quad/yr; 5.9 Billion People; 75% fossil energy

Figure 3a. Energy consumption by fuel type for the world



US: 94 Quad/yr; 0.27 Billion People; 85% fossil energy

Figure 3b. Energy consumption by fuel type for the U.S.

The 5.9 billion people in the world currently use 420 quads of energy per year, and fossil fuels provide 75 percent of that energy. On the other hand, emerging renewable technologies (solar, wind, and geothermal) provide less than 0.5 percent of the world's energy.

Figure 3b shows the same type of information for the U.S. Our 270 million people use 94 quads of energy per year. Fossil fuels supply 85 percent of our energy; emerging renewables provide less than 0.6 percent.

Figure 4 shows the relationship between the growth of world energy use and population [6]. Forecasters maintain that world energy use will continue to increase during the next century. However, as history has repeatedly proven, predicting the future of energy use is difficult. Growth rates depend on assumed changes in population, economic growth, and per-capita energy use.

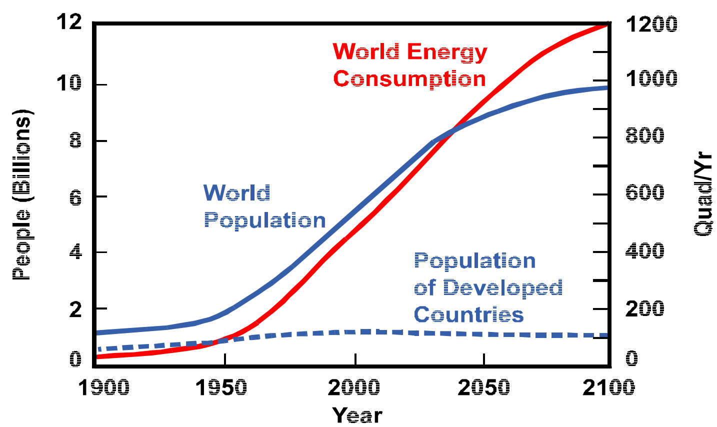
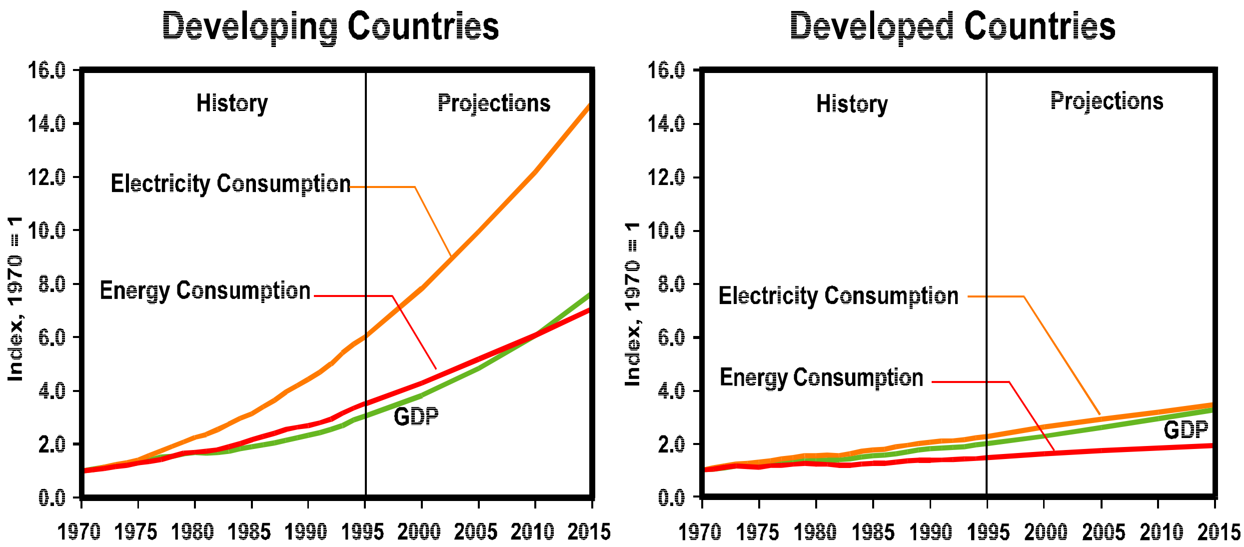


Figure 4. Growth of world energy use and population

In this figure, the population is forecasted to grow from 6 billion to about 10 billion by 2100. Ninety percent of this population growth is expected to occur in the less developed countries of Asia, Africa, and Latin America, some of which are also undergoing rapid economic development. World energy consumption will triple to sustain this population and economic growth.



Figures 5a and 5b. Trends in energy, electricity, and GDP for developed and developing countries

Energy use, electricity consumption, and economic development are related. Traditionally, a nation's economic growth rate, its growth in Gross Domestic Product (GDP), correlates directly to its growth in energy use. Figure 5a shows this is still true in developing countries [7]. Since 1970, energy consumption grew at nearly the same rate as GDP; however, electric consumption much grew faster than GDP.

Figure 5b illustrates that in developed countries, overall growth has stabilized at a much lower rate than that of developing countries [7]. Since 1970, growth in GDP in developed countries exceeded growth in energy consumption and electric consumption tracked GDP.

The higher growth rate for electricity consumption in both developing and developed countries reflects the increased importance of electricity in the energy mix — perhaps because we are moving away from industrialized economies and toward service and knowledge-based economies. A reliable supply of electricity has become a necessary condition for prosperity. With this significant need for electricity, it is hard to imagine that one-third of the world's population still does not have access to electricity.

The policy implications of this increased need for electricity are significant! There are security implications. We recognize that for the first time in history, the poor of the world know they are poor. Reruns of U.S. television shows are aired worldwide; people can see what they are missing, and this may set the stage for civil unrest. And the search for a better life also has tremendous environmental implications. It has contributed, in part, to the largest migration in history. In developing countries, rural residents are moving to urban areas in search of a better life, and the resulting "megacities" have horrendous environmental problems. Governments of developing nations focus on meeting basic human needs for food, housing, medical care, and education — overcoming poverty is the dominant social concern. In these societies, the key environmental issues are local — the necessity of providing drinkable water and breathable air. Except for some island nations, a global issue, like climate change, is a lower priority.

These trends set the stage for a collision course — the collision of economic growth, population growth, and environmental degradation. The challenge for the scientific community is to identify ways to reduce the environmental impact per unit of economic growth. Clearly, developed countries are not immune to the environmental or security implications of activities in developing countries. The challenge to the scientific community becomes more complex if we try to take actions that do not simply replace an environmental threat with an economic threat.

Consider the issue of rising CO_2 emissions. There are only three technical options for mitigation. The first is decarbonization — reducing the carbon intensity of fuels. The second is efficiency improvement — both on the demand side and on the supply side. The third is CO_2 sequestration.

Figure 6 illustrates the first option for CO_2 mitigation — decarbonization. We can accelerate our transition to less carbon intensive fuels. This trend has been underway for the past 100 years. Wood is the most carbon intensive fuel. As technology has progressed, society moved to coal, then oil, and eventually natural gas. (At the same time, we were dramatically increasing energy use.) Today, the average H/C ratio for the fuels we use is about 2.0. This figure, reproduced from the *EPRI Journal* [8], suggests that we will evolve toward a methane-based economy in 2050. After that, we will transition to non-carbon-based energy sources, such as hydrogen, nuclear,

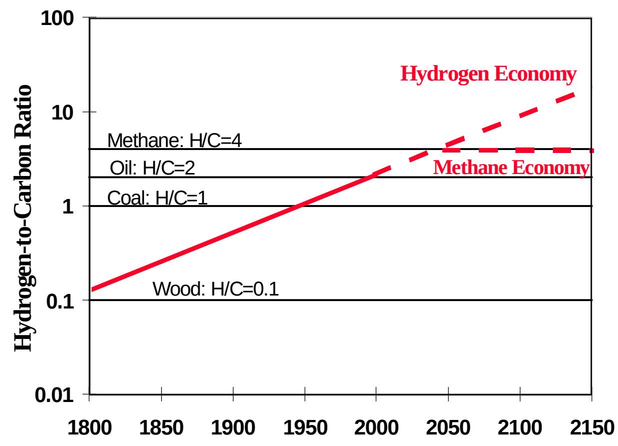


Figure 6. Trend in fuel H/C ratio for global energy use

or other yet-to-be-developed energy sources. This trend is consistent with our present understanding that the fossil resource base is finite. While nuclear is an obvious choice, it is also definitely a controversial choice. We must solve the waste disposal issue before nuclear will be an acceptable option in the U.S. Nevertheless, advanced design reactors are currently being built in Taiwan and Japan, and China has 20 nuclear plants in development.

Our present energy system works — it is relatively low-cost and represents a huge capital investment in an infrastructure. Ultimately we will need to transition to less carbon intensive fuels, but a crash program to replace traditional fuels is neither realistic nor economically feasible. Natural gas may be the fuel that bridges us to a less carbon intensive future. The technologies and resources are available. Under a Business-as-Usual scenario, DOE/EIA projects that gas use will increase by 50 percent — from 21 Tcf in 1995 to 32 Tcf in 2020. Gas prices are expected to remain constant until 2010 and then rise modestly. However, if we double or triple gas consumption to reduce greenhouse gas emissions, we need to consider two other issues: How big is our natural gas reserve base? And what price will consumers have to pay to have that gas produced, transmitted, and delivered?

Unfortunately, there are no definitive answers. Recently, the Department of Energy has asked the National Petroleum Council to revisit its 1992 study on gas availability. Worldwide, gas reserves are estimated to be 5,000 Tcf, equal to a 65-year supply at our current production rate — a very finite resource.

The wildcard in gas reserve estimates may be methane hydrates! These are methane molecules encased in an ice latticework, found principally in arctic regions and under the ocean floor. If estimates are accurate, hydrates could potentially provide a several-hundred-year gas supply. However, we currently do not have the technology to produce this gas. When we do learn how to produce it, the gas is likely to be difficult and expensive.

Renewable energy is an obvious option for reducing greenhouse gas emissions. The traditional renewables, hydro and biomass, already provide almost 20 percent of the world's energy (although much of the biomass is used by primative means in developing countries). Commercial developers are now showing tremendous interest in the emerging renewables: solar, wind and geothermal. However, each of these energy sources has its own set of environmental and cost issues that need to be addressed before they will see widespread commercialization without a substantial increase in electric cost or a government subsidy.

Internationally, most biomass is wood, a depleting resource. In the U.S., most biomass consists of lumber industry residues or municipal solid waste. If dedicated crops are used to produce biomass fuels, large amounts of land near a power plant are needed to grow the crops — a difficult proposition for densely populated countries. In addition, producing dedicated crops is currently more expensive than using fossil fuels. Research is needed into development high growth-rate biomass crops. Co-firing biomass and coal is a promising near-term option.

In the U.S., we have already developed most of the likely hydropower sites and there have been calls by some in the environmental community to demolish some existing dams. Globally, many potential sites exist. However, hydropower development has been plagued with issues related to interference with fish migration and spawning, habitat destruction, and displacement of people.

Geothermal is another site-specific energy source. Sometimes, the use of that resource has led to supply degradation and therefore it cannot always be considered a renewable resource. In developing countries, geothermal energy is often associated with local religious beliefs, making project development difficult.

Cost-wise, wind power is the most competitive, but issues such as bird kill, visual impact, and noise continue to be problematic. Wind requires a windy site, a large land area, and a backup power source. Wind turbines effective under light wind conditions are a developmental goal.

Finally, solar energy is an attractive option, but is only suitable for locations with considerable sunshine. It is expensive since the conversion efficiency of solar cells still requires improvements. It will remain a niche market until low-cost storage options are developed and deployed. Photovoltaics are showing real promise in non-grid connected applications such as providing village power in developing countries.

The bottom line with renewable energy is that there are no "silver bullets!" However, technology improvements underway will help move renewable energy technologies toward more widespread use in the U.S. and in developing nations.

Improving the efficiency of energy use is a "no regrets" way to reduce greenhouse gas emissions. Figure 7 shows productivity per unit of energy consumed for seven of the G8 countries, the highly developed countries of the world [9]. Japan, Italy, France, Germany, and England are noticeably more energy efficient than the U.S. This may be caused by different societal expectations in the U.S. compared with other countries. A four-bedroom house and a sport utility vehicle are becoming the norm. Or it may be caused by real situational differences in the U.S. compared with most other industrialized nations. Our population density is lower in the U.S.; our winter and summer temperatures are more extreme. Or it may be that the U.S. needs to be more diligent and conscientious about energy efficiency and conservation. With less than 5 percent of the world population, the U.S. emits more than one-fourth of the world's greenhouse gas emissions. Over our lifetimes, Americans use 500 times as much energy as residents of undeveloped countries.

Technology can help to improve end-use efficiency. For example, Figure 8 shows potential fuel efficiency improvements for light duty vehicles. The boxes show, in ascending order, the potential efficiency improvements for four technologies identified in DOE's "Five-lab Study" [10]. These technologies are being developed by the Partnership to Develop a New Generation of Vehicles.

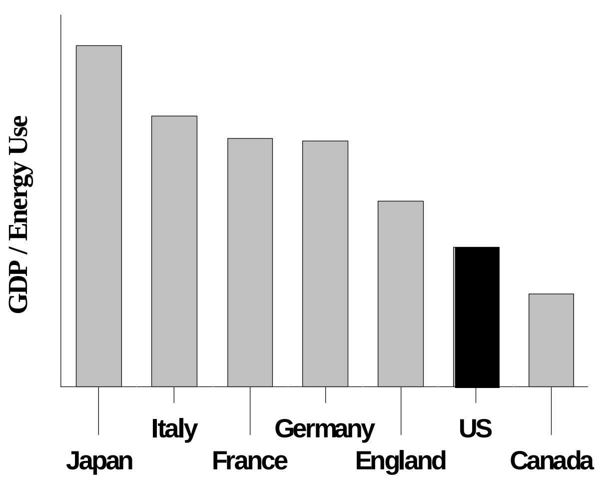


Figure 7. Productivity and energy use in G7 countries

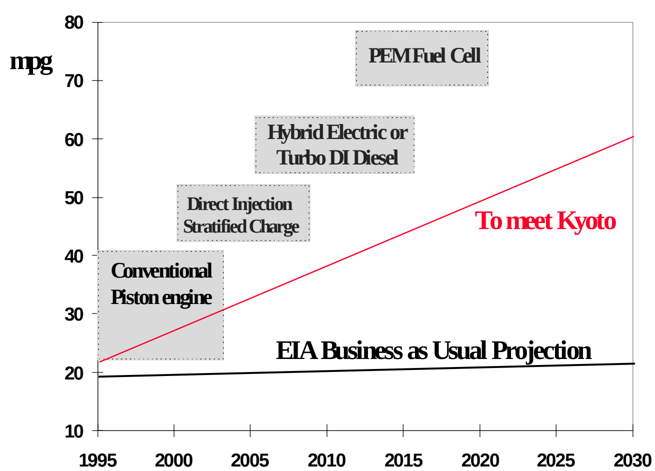


Figure 8. Future light vehicle efficiencies

On the supply side, efficiency improvements to coal-fired power system involve the use of hybrid power cycles that operate at higher temperatures and pressures. Figure 9 illustrates three cycles that show this efficiency progression.

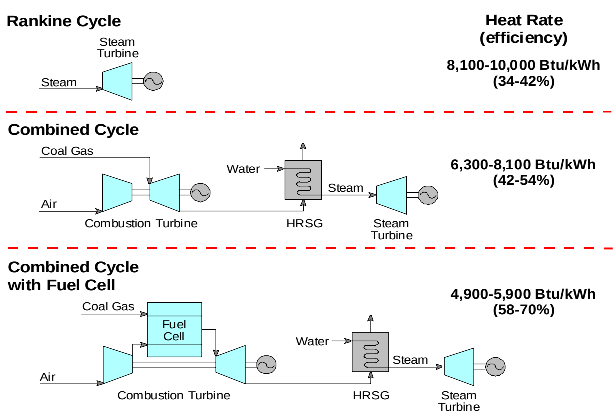


Figure 9. Efficiency improvements in coal-fired power systems.

Conventional coal-fired power plants raise superheated steam by burning pulverized coal in large, atmospheric-pressure boilers. Electricity is generated through the Rankine cycle by expanding high-pressure steam through a steam turbine. Efficiencies range from 34 to 42 percent. We have approached the practical efficiency limits of a simple Rankine cycle. But its efficiency can be improved by combining it with a Brayton gas-combustion cycle. In one example of a Brayton cycle, coal is gasified and then burned in a combustion turbine. Heat is recovered from the combustion turbine exhaust to raise steam for the Rankine cycle. Efficiencies range from 42 to 54 percent.

Integrating a fuel cell with a combined cycle can further improve efficiency. In this arrangement, coal gas is first fed to the fuel cell, where most of it is electrochemically oxidized to produce electric power directly. The depleted fuel gas exiting the fuel cell is burned in a combustion turbine. A steam turbine bottoming cycle completes the system. Efficiencies range from 58 to 70 percent. This is a dramatic improvement in efficiency!

Figure 10 shows CO_2 emissions from several power generation technologies. The units are pounds of CO_2 per kilowatt-hour. The top four bars represent coal-fired technologies: conventional coal plants, Clean Coal Technology (CCT) demonstration plants, improved CCT plants, and Vision 21 Plants. The Vision 21 plant is part of our research program to develop the ultimate energy facility. Every usable Btu in coal or other carbon-based fuels is used to produce electricity, process heat, liquid fuels, chemicals, or a combination of these. The bottom two bars represent natural gas-fired systems — currently available systems and advanced combined cycle systems. Advanced coal technologies do produce less CO_2 than conventional systems, but the figure also confirms that, because of the lower carbon content of natural gas, natural gas systems always produce less CO_2 than coal systems.

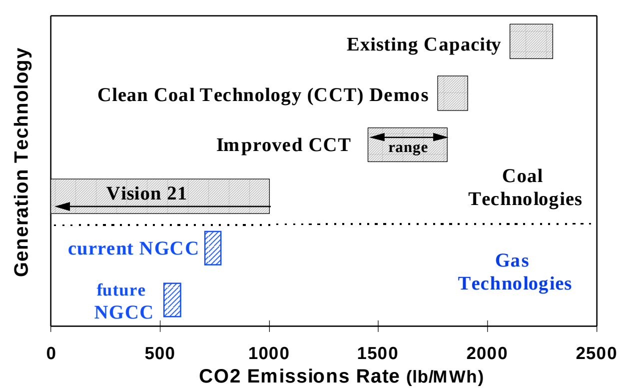


Figure 10. CO_2 emission rates of fossil fuel technologies

The ultimate Vision 21 plant will have zero emissions — no net discharges of waste-water, solid waste, SO_2, NO_X, or CO_2. It will use sequestration to achieve zero CO_2 emission. Sequestration means we can reduce CO_2 emissions from Vision 21 Plants, or any other fossil plant, to zero — a concept that could revolutionize the energy business. We could decouple fossil fuel use and CO_2 emissions!

But improving efficiency and fuel-switching to natural gas will not be enough to solve the greenhouse gas emission issue over the long term — particularly if the "science" determines that dramatic emission reductions are required. The goal of the 1992 Rio Framework Convention on Climate Change was to stabilize atmospheric CO_2 concentrations — not just reduce emission levels. Stabilizing CO_2 concentrations to whatever level that society finds acceptable will require deep reductions in greenhouse gas emissions. For example, to stabilize CO_2 concentrations in the atmosphere at double their current level (750 ppmv), we would need to slash world CO_2 emissions to only 30 percent of their 1990 levels. To stabilize CO_2 concentrations at current level of 370 ppmv, we would need to slash world CO_2 emissions to only 10 percent of the 1990 level. Given the unlikeliness of the world population deciding to reduce energy consumption more than 90 percent, the only realistic answer to achieve these dramatic emission reductions is sequestration.

The working definition of sequestration is the removal of greenhouse gases, usually CO_2, either directly from the exhaust gases of industrial or utility plants or from the atmosphere, and disposing of them either permanently or for geologically significant periods.

A challenge might be to identify a more appropriate name for sequestration. To non-researchers, the term "sequestration" does not always have positive connotations. Sequestration needs to be viewed as a positive and effective method of addressing the greenhouse gas issue. Figure 11 shows the three basic approaches to sequestration, the first of which is direct sequestration. Here, a concentrated CO_2 stream is captured inside a power plant and transported off-site for long term storage. The various storage options include: injecting CO_2 into depleted oil and gas wells or saline aquifers; injecting CO_2 into the ocean; and injecting the CO_2 into deep, unmineable coal seams. In the latter case, the coal seams retain the CO_2 and force out methane into a production well. This is convenient since coal-fired power plants are frequently near deep, unmineable coal seams.

But we must resolve several issues before any of these options can be considered vialbe candidates for CO_2 storage. These issues include the geologic integrity of storage sites; pipeline transportation costs; and potential accidental releases of large volumes of CO_2.

Theoretically, oceans and geologic sinks have more than enough storage capacity to handle the CO_2 emissions that could be produced by burning all our known reserves of fossil fuels.

The second option is indirect sequestration. In this option, CO_2 is removed from the atmosphere by enhancing the ability natural sinks, oceans or forests, to absorb CO_2.

The third option to sequestration is through the use of novel concepts. This includes revolutionary approaches, such as the

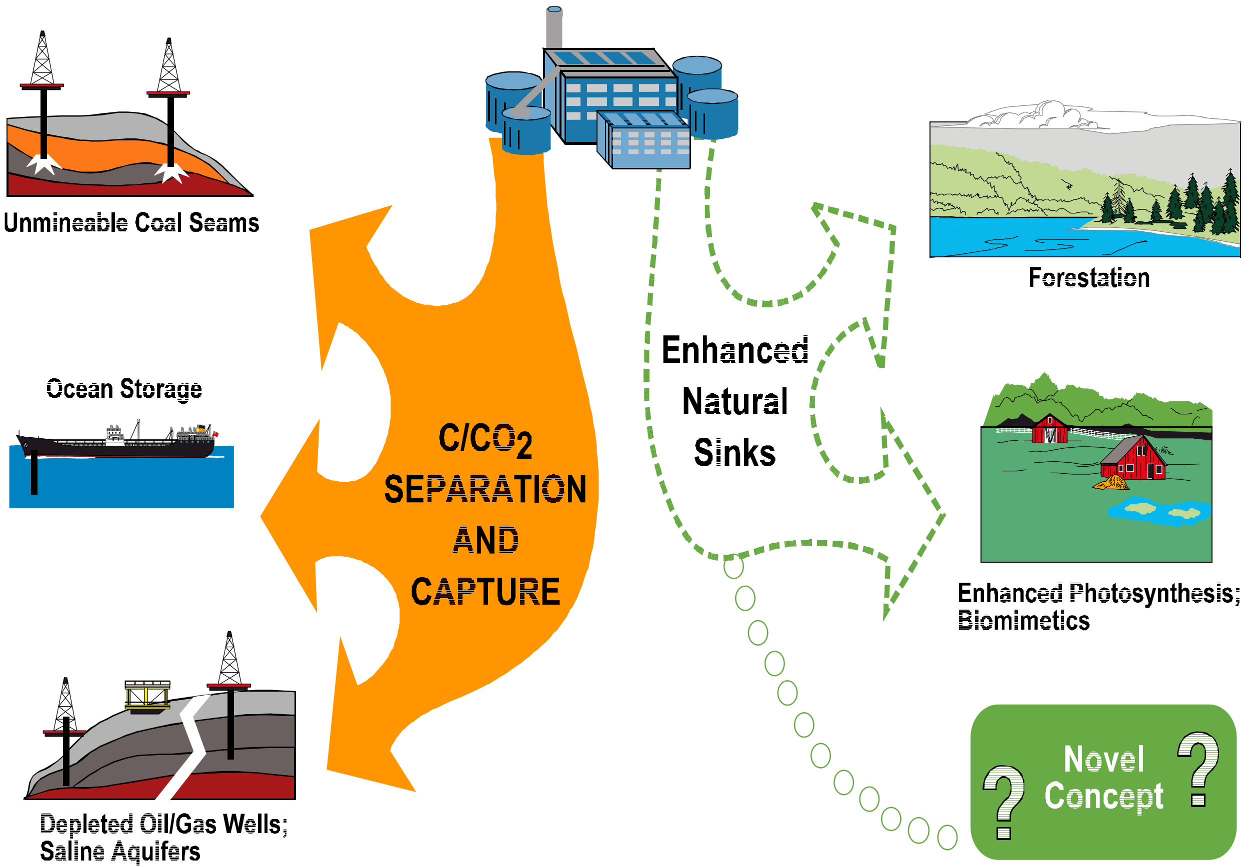


Figure 11. Three basic approaches to sequestration

development of chemical or biological processes that mimic photosynthesis.

These technologies are feasible, as shown in Figure 12. In 1996, Statoil, a Norwegian oil company, began storing CO_2 from a gas field in an aquifer beneath the North Sea. The amount of CO_2 sequestered is equivalent to that produced by a 140-MW coal-fired power plant. In addition, during the 1970s and 1980s, several commercial power plants separated CO_2 from flue gas using amine solutions, and used the CO_2 for enhanced oil recovery projects. Today, the Alberta Research Council is injecting CO_2 into a deep coal seam to produce methane from a nearby production well. This small-scale test involves six other government participants (including the Department of Energy's Office of Fossil Energy) and ten industrial organizations. Worldwide, forests are being replanted in several locations. (However, reforestation as an emission control strategy is tempered by the fact that we deplete more than 1 percent of our remaining old growth forests each year.)

DOE's Office of Fossil Energy initiated sequestration research in the early 1990s. At FETC, we are conducting lab-scale research

Figure 12. Statoil's Sleipner natural gas platform, with CO_2 injection

to better understand clathrate hydrate formation in oceans. We are also researching geologic sequestration of CO_2 in coal seams to learn why CO_2 is more stable than methane, and the influence of flue gas containing SO_2 and NO_X on microbial organisms in coal seams.

In 1992, DOE initiated a collaboration with the International Energy Administration on greenhouse gas emissions. In addition, Japan Norway, and the U.S. are collaborating on a $3.8 million project to address the technical feasibility and environmental impacts of pumping liquefied CO_2 3,000 feet into the ocean. This effort is relevant to the 30 percent of U.S. power plants that are within 150 miles of an ocean and therefore could potentially use deep-water sequestration. The U.S. and Canada have also initiated a project to explore CO_2 sequestration in geological formations. Finally, in April of this year, Secretary Peña announced that DOE would award grants to 12 research teams to explore practical, affordable ways to sequester CO_2. Each project will receive up to $50,000 in the initial phase. Projects that continue into later stages could receive up to $1.5 million each. (A Fossil Energy Techline is available that describes these projects.)

In 1997, the President's Committee on Science and Technology (PCAST) recommended that DOE budget several million dollars for a major sequestration program. PCAST recommended that DOE's Office of Fossil Energy (FE) manage the program in collaboration with DOE's Office of Energy Research (ER) and the U.S. Geological Survey. They further recommended that DOE collaborate with ongoing international sequestration projects in Japan and Europe.

The FY99 budget request for FE includes $12 million for sequestration research. DOE's program preliminary allocation of the $12 million budget request is $3 million for direct sequestration, $4 million for enhanced natural sinks, and $5 million for novel concepts. A purpose of this conference is to solicit opinions from industry on all aspects of the future direction of the sequestration program, including this preliminary budget allocation.

DOE's Office of Energy Research (ER) is also beginning a carbon management research program. ER's FY99 budget included $27 million for carbon management. The ER program will address the material, chemical, energy, and biological science of carbon management — essentially, the fundamental science to support the FE sequestration program. We are coordinating with ER on its programs.

Let me list some characteristics DOE envisions for the Office of Fossil Energy's sequestration R&D program. The program will focus on applied research with industry, university, and national laboratory involvement. It will have significant international collaboration and be applicable to all carbon-based fuels. It will target the longer term — provide options for the post 2015 period. It will develop many parallel approaches to sequestration to accelerate progress.

The sequestration R&D program will also have a bold goal for the cost of sequestration. Recently, a group called the Costa Rica/Environmental Financial Partners announced its intention to sell CO_2 credits from rainforest preservation and reforestation. The announced price is $20 per metric ton of carbon. This may be the preliminary cost goal, but your ideas on the appropriate cost targets for the sequestration R&D program are needed.

Globally, we rely on fossil fuels for more than 75 percent of our energy. Thus a greenhouse gas control option that is compatible with our current energy infrastructure is important. Sequestration is that option. It could expand our options for dealing with greenhouse gases beyond efficiency improvement and decarbonization. The eventual economic benefits of a sequestration option could be in the billions of dollars. We will never know if the concept is valid, or if the economic benefits can be realized, however, unless we begin the necessary R&D. At a minimum, we need reliable information on cost, performance, and environmental implications of CO_2 sequestration — which, I believe, is a critical option for an energy-hungry world.

We seek your ideas on how to structure a rational R&D program. We will take your ideas seriously. And we will reflect them in our R&D program plans.

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References

1. Climate Change: The Science of Climate Change, Intergovernmental Panel on Climate Change, 1996.

2. Climate Change — Modelling and Measurement, IEA Coal Research, Figure 1, 1997.

3. Federal Energy Research and Development for the Challenges of the Twenty-First Century, Figure 1.1, The President's Committee of Advisors on Science and Technology, November, 1997. Data source is *Global Energy Perspectives to 2050 and Beyond*, World Energy Council and the International Institute for Applied Systems Analysis, 1995.

4. Data sources are *Federal Energy Research and Development for the Challenges of the Twenty-First Century*, The President's Committee of Advisors on Science and Technology, November, 1997; *BP Statistical Review of World Energy*, 1996; *International Energy Outlook 1997*, USDOE Energy Information Administration; and *Renewable Energy: Sources for Fuels and Electricity*, Johannson, et al., 1992.

5. Renewable Energy Annual, Table 2 and Annual Energy Outlook 97, Table A2, USDOE Energy Information Administration.

6. Population data from World Resources: 1996-97, Figure 8.1 and Long-Range World Population Projections: 1950-2150, 1992. Energy data from EPRI.

7. International Energy Outlook 97, Figures 11 and 13, USDOE Energy Information Administration.

8. *EPRI Journal*, 2/98.

9. International Energy Outlook 97, Table A1, and The International Energy Database, http://www.eia.doe.gov/emeu/international/contents.html, USDOE Energy Information Administration.

10. Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond, Interlaboratory Working Group on Energy-Efficient and Low Carbon Technologies, 1997.