1. INTRODUCTION

In an address to the United Nations on June 26, 1997, President Clinton stated

> *The science is compelling and clear: we humans are changing the global climate. Concentrations of greenhouse gases in the atmosphere are at their highest levels in more than 200,000 years and climbing sharply.*
>
> *....Here in the United States, we must do better. With 4 percent of the world's population, we already produce more than 20 percent of its greenhouse gases.*
>
> *....In order to reduce greenhouse gases and grow the economy, we must invest more in the technologies of the future. I am directing my cabinet to work to develop them. Government, universities, business, and labor must work together. All these efforts must be sustained over years, indeed over decades.*

The President's remarks were made on the occasion of the fifth anniversary of the Rio Conference on the Environment. It was also the beginning stage of the public presentation of the position of the United States at the third conference of the parties to the Framework Convention on Climate Change (FCCC), which will be held in December 1997 in Kyoto, Japan.

The goal of the FCCC is "to stabilize the concentration of greenhouse gases in the atmosphere at a level which would prevent dangerous anthropogenic interference with the climate system." The United States was among more than 150 nations of the world that signed the Convention. While the FCCC established an important goal, it provided only minimal tools with which to achieve that goal. The principal tool is a provision for future meetings of the parties to the Convention. Numerous meetings and negotiations have taken place. The upcoming conference of the parties in Kyoto will be a key event because of its focus on developing an international protocol for reducing greenhouse gas emissions.

The United States faces a significant challenge and can play an important role in moving negotiations forward. If global atmospheric CO_2 concentrations are to be stabilized in the next century, the United States and other developed nations must reduce their emissions significantly. In addition, the developing nations must limit the increase of their emissions while preserving their legitimate aspirations for economic growth.

In response to the President's direction, this report of the national laboratories of the U.S. Department of Energy (DOE) outlines a broad range of technologies with the potential for reducing greenhouse gas (GHG) emissions and recommends their development as an essential component of a climate change technology strategy.

The focus of this report is reduction of U.S. GHG emissions through the development and application of new technologies.[1] The report delivers two key messages:

- advances in science and technology are necessary to reduce GHG emissions from the United States while sustaining economic growth and providing collateral benefits to the nation
- success will require the pursuit of multiple technology pathways, providing choices and flexibility for reducing GHG emissions

This document describes technology development efforts that need to extend through the first third of the next century. The impact of these efforts would in fact last much longer. Energy-generating resources have lifetimes of many decades: the Grand Coulee Dam created in the 1930s continues to produce energy 60 years later. The new technologies introduced through the 30-year planning period of this report would have impacts that would extend throughout the next century.

The success of a technology strategy depends on the successful commercialization of new technologies as well as their development. Commercialization may well require programs and policies to encourage the use of new technologies in the marketplace. For example, with the electric utility sector evolving toward competitive markets, technologies with low emissions and high capital costs may need assistance in competing with technologies with low capital costs but higher emissions. Also, carbon sequestration technologies will not be adopted per se unless that sequestration has an economic value. While this report does not discuss alternative policies, it does recognize that they need to be examined and that a climate change technology strategy needs to consider both technology development and its commercialization (Fig. 1.1).

Both technology development and policy decisions also depend on developing a better understanding of the carbon cycle. Modeling and monitoring of the global carbon cycle are essential to understanding emission reduction requirements and the potential contributions of different technologies and policies. (See Fig. 1.2 in sidebar on page 1-4.)

[1] This report does not address the relationship between climate and atmospheric concentrations of GHG, nor does it discuss the reduced GHG emission levels required for achieving specified levels of atmospheric concentrations.

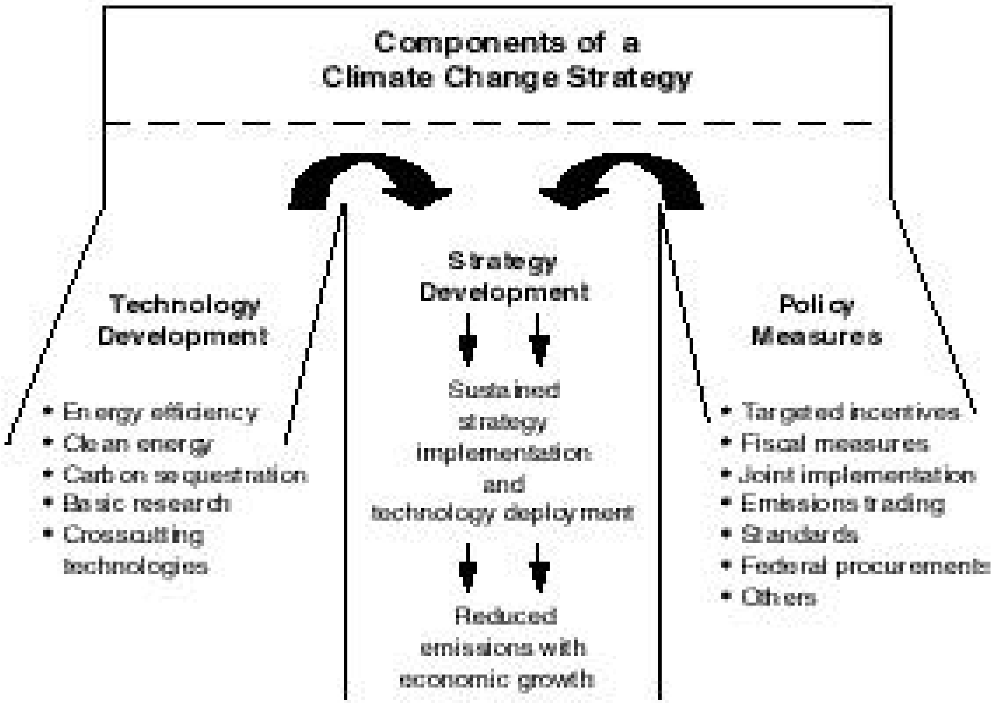

Fig. 1.1. Technology and policy components for a climate change strategy.

The role of this study is to examine the technology basis for a climate change strategy by summarizing the potential of a broad range of technologies to contribute to reducing GHG emissions. It does not discuss or analyze policy measures aimed at reducing GHG emissions. Both advanced technology and policy measures will be needed. The policy measures listed in this figure are for illustration only.

To ensure cost-effective, credible results, a climate change technology strategy also needs to be anchored in science. Much of this science base can be developed by leveraging and expanding existing efforts in the U.S. science and technology complex.

1.1 GREENHOUSE GAS EMISSIONS AND ENERGY

In 1995, human activities in the United States resulted in CO_2 emissions totaling about 1440 million tonnes of carbon (MtC). Human activity–related (anthropogenic) emissions of other GHGs, such as methane and nitrous oxide, represented the equivalent of another 220 MtC. Nearly all of the anthropogenic GHG emissions, about 1500 MtC, resulted from energy production and use, primarily the combustion of fossil fuels. Thus the energy sector represents about 90% of U.S. GHG emissions (EIA 1996a). The GHG emissions related to the sources and uses of this energy are displayed in Fig. 1.3.

These data make it clear that significant reductions in GHG emissions can be accomplished only

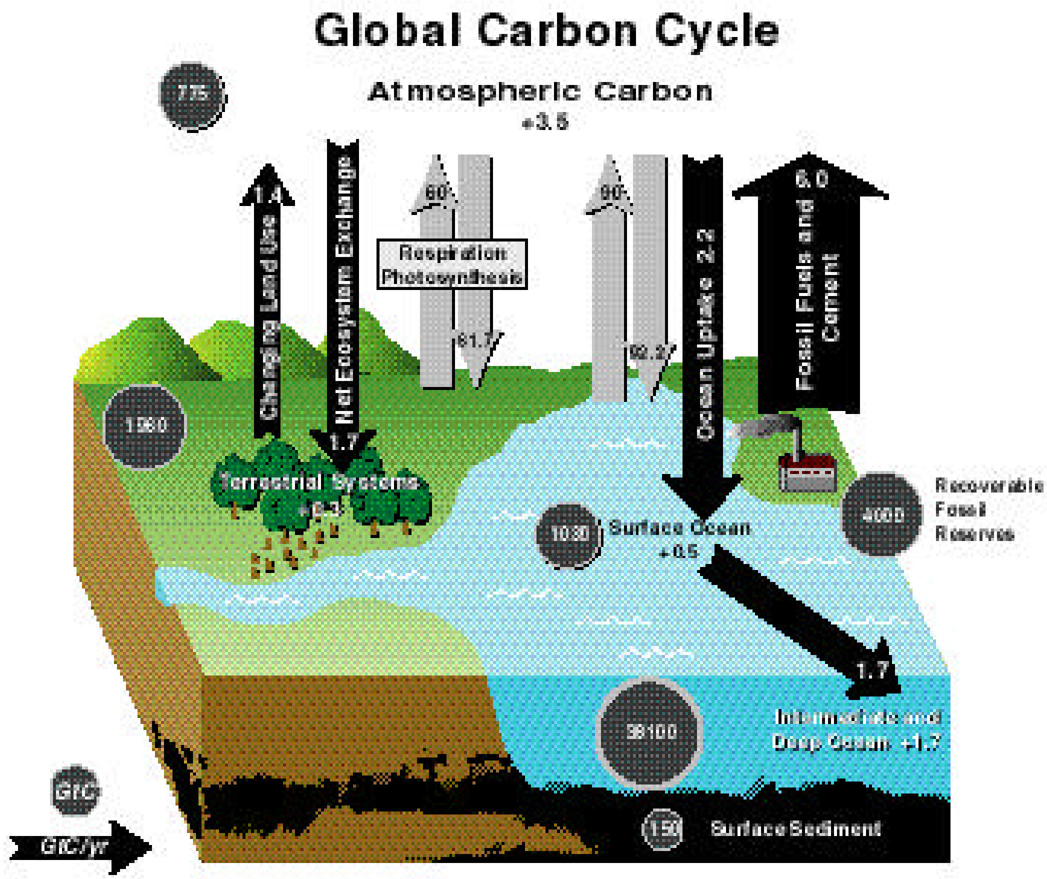

Fig. 1.2. The burning of fossil fuel and changing land use have resulted in human-induced alterations of the global carbon cycle. The solid arrows in this diagram indicate the average magnitude of perturbation in carbon fluxes and the fate of carbon resulting from these activities averaged for the first half of the 1990s. *Source:* Modified from IPCC 1995.

Human activities contribute to the emission of 7.4 GtC into the atmosphere (6 GtC from fossil fuel combustion and cement production and 1.4 GtC from land-use changes). These emissions cause an increase of 3.5 GtC in the atmosphere and a 1.7-GtC terrestrial uptake due to the effect of higher CO_2 concentrations on photosynthesis and plant growth, resulting in a net increase of 0.3 GtC in terrestrial ecosystems. Oceans take up 2.2 GtC per year, which is distributed throughout the ocean by biological processes combined with advective and diffusive fluxes. In 1997 the atmospheric concentration of CO_2 was 363 ppmv. Net fluxes (black arrows) and gross fluxes (gray arrows) are in billions of tonnes of carbon per year. Annual net additions of carbon (shown as + numbers) to the atmosphere, ocean subsystems, and terrestrial systems from anthropogenic sources are in billions of tonnes of carbon per year. Pool sizes (circles) are shown as billions of tonnes of carbon. (Recommended references to this literature are Houghton 1995 and Marland, Andres, and Boden 1977.)

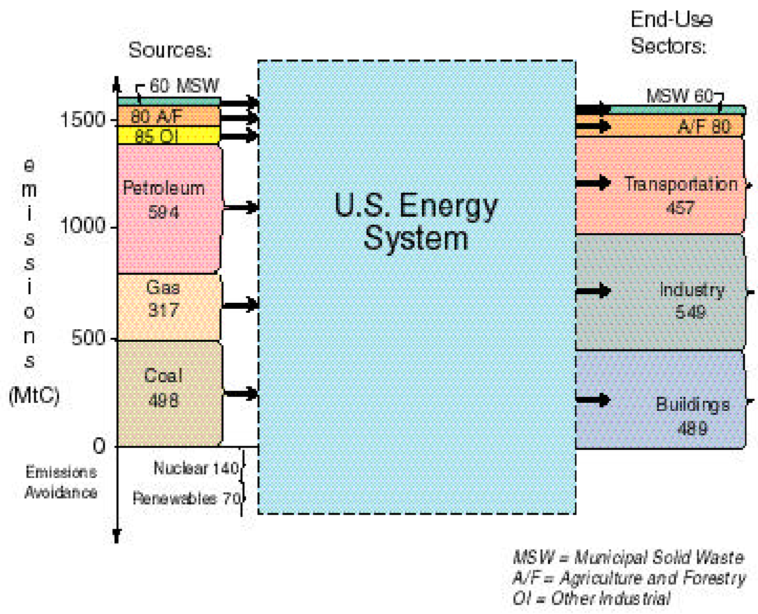

Fig. 1.3. Overview of the sources of carbon emissions in the United States in 1995 (in million tonnes equivalent and including CH_4 from MSW, A/F, and OI). *Source:* Based on EIA 1996a.

through changes in our energy economy (more effective production, distribution, and use of energy).

1.2 THE ROLE OF TECHNOLOGY

A simple equation that expresses carbon emissions in terms of four other parameters provides a good context within which to discuss approaches to reducing carbon emissions:

$$Net\ C = [GDP \times (E / GDP) \times (C_a / E)] - S\ ,$$

where

Net C	=	net carbon emissions
C_a	=	anthropogenic carbon emissions
GDP	=	gross domestic product
E	=	total energy use
S	=	natural and induced sequestration of carbon

Continued economic growth implies that *GDP*, the first factor, continues to rise. Therefore, for the economy to grow while carbon emissions decrease, one or more of the remaining three terms in the equation must change.

E/GDP refers to the "energy intensity" of our economy. It historically has risen as standards of living have improved in the United States. However, between 1973 and 1986, rising energy prices caused the nation's consumption of primary energy to freeze at about 74 quads—while the GDP grew by 35% (a quad is 1 quadrillion or 10^{15} Btus). As a result of this decrease in energy intensity, nearly 450 MtC in emissions was avoided in 1986. The trend since 1986 has been toward flat or slightly rising energy intensities.

C/E refers to the "carbon intensity" of our energy economy. This ratio has remained fairly constant since 1973, reflecting the transportation sector's continued reliance on petroleum fuels and the slow pace of technological change and capital stock turnover in the electricity sector.

The amount of atmospheric carbon that is removed through natural and induced sequestration, *S*, is the last term in the equation. It represents a third lever that can be used to reduce CO_2 levels while at the same time enabling the U.S. economy to grow. These three terms embody distinct technology routes to reducing GHG emissions.

How can energy intensity be decreased? Through more efficient use of fossil fuels and electricity from fossil fuel plants, less CO_2 is emitted to the atmosphere. Energy-efficient products, such as more efficient transportation vehicles and household appliances, provide the same energy services using less fuel or electrical power. Energy requirements can also be reduced through system designs, such as co-locating facilities that produce both electrical power and heat (cogeneration systems) with facilities that need them. Such approaches can reduce our national energy intensity without lowering GDP.

How can carbon intensity be decreased? Carbon emissions from energy production and use can be curbed by increasing the efficiency of energy production or by using fuels that emit less carbon or technologies that use no carbon-emitting fuels, such as nuclear power plants; hydroelectric, wind, and solar power plants; and other renewable energy sources. For example, natural gas emits 14 MtC per quad of energy used compared with 26 MtC per quad for coal. Biomass feedstocks offer an array of low-carbon options, including liquid transportation fuels, chemicals, materials, and electricity. The carbon emissions from biomass combustion are largely offset by CO_2 absorption in biomass production (plant growth). Another strategy is to remove carbon from fuels before combustion (decarbonization).

How can carbon sequestration be increased? One approach involves capturing CO_2 after combustion but before it enters the atmosphere and storing it in terrestrial or oceanic repositories that will sequester it over geological time scales. A second approach is to increase the rate at which oceans, forests, and soils naturally absorb CO_2 from the atmosphere. Worldwide, human activities have hindered the natural sequestration process through deforestation, soil destruction, and desertification. This trend can be reversed through the development and deployment of advanced technologies.

Of course, there are important relationships among these three approaches. As specific examples, reducing the energy consumed in lighting and building appliances generally also reduces cooling loads; reducing overall electric demand reduces the capital required to meet a fraction of that load with renewables; precombustion removal of carbon from fossil fuels complements both hydrogen production and carbon sequestration; and the science and technologies necessary for sequestration of CO_2 in ocean hydrates may also hold the key for economical production of natural gas from the very large gas hydrate deposits that are currently untapped.

To reduce carbon emissions significantly while sustaining economic growth, all three of these technology approaches—decreased energy intensity through energy efficiency technologies, reduced carbon intensity through clean energy technologies, and increased CO_2 absorption through increased carbon sequestration—may be needed. They will definitely provide valuable choices and therefore should be pursued.

1.3 ABOUT THIS STUDY

This study is focused on the potential role of advanced technologies to reduce CO_2 emissions. It presents a survey of a broad range of technology pathways; describes their potential for advances and energy economy contributions that would result from enhanced research, development, and demonstration (RD&D); and estimates their potential contributions to CO_2 emission reductions.

Note that there are several closely related subjects that this study does not address. First, in estimating carbon emission reductions that advanced technologies might provide, it does not address the role of policy measures to support their adoption. Thus, as examples, it does not discuss such policy approaches as carbon taxes or domestic or international carbon emissions trading programs.

This study also does not discuss the fact that a number of energy efficiency and clean energy technologies are already developed that could make significant contributions to GHG emission reductions through wider adoption. This topic is addressed in the "5-Lab Study," which was also conducted in 1997 (Interlaboratory Working Group 1997). Finally, this study is focused only on potential reductions of CO_2, the principal GHG; it does not address reductions in emissions of the other GHGs.

Chapter 2 of this report provides the technological basis for recommending a broad technology development strategy. It provides a credible vision of the technologies that President Clinton is requesting. It discusses the current status of energy conversion and use technologies and their relationship to carbon emissions and then describes, in considerable detail, what can be achieved through technology research and development (R&D) and what those achievements imply for reducing GHG emissions.

Chapter 3 of this report discusses basic research areas of most relevance to the pursuit of a climate change technology strategy. It also discusses crosscutting technologies that support a number of the technological pathways, and it describes appropriate R&D for their development.

Chapter 4 recommends establishing strategic public–private R&D alliances to pursue the RD&D of GHG reduction technologies. Chapter 5 synthesizes the report's findings and provides recommendations and directions for moving forward.

A technology strategy should be designed to provide a portfolio of technologies that will allow the nation to meet its future emission reduction targets at the least cost to our economy. Both incremental and breakthrough technologies are needed, and basic scientific research is required to provide a foundation for these technological solutions.

New policies and programs will also be needed to ensure the rapid adoption of these technologies in our energy economy.

In developing such a technology strategy, every effort should be made to build on existing information, such as the report by the Task Force on Strategic Energy Research and Development (SEAB 1995) and to coordinate these efforts with closely related activities such as DOE's development of a comprehensive national energy strategy and the national energy strategy review recently completed by the President's Committee of Advisors on Science and Technology (PCAST 1997).

The federal government has a substantial program in energy RD&D, designed to support the broad national goals of energy security and environmental quality (DOE Strategic Plan draft 1997). Although the existing energy RD&D programs were not designed specifically to reduce carbon emissions, they will have some benefits for mitigating climate change. The current DOE budget for the development of low-carbon energy technologies is approximately $1 billion per year. This budget includes the RD&D portions of DOE's Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy programs. Federal RD&D resources, including DOE's Energy Research Programs, are also spent on the basic sciences and crosscutting technologies that undergird the energy technology programs. Additional federal resources of approximately $1.8 billion were appropriated in FY 1997 for the U.S. Global Change Research Program. These existing RD&D programs form the basis for the expanded and accelerated RD&D efforts outlined here; the financial support needed is discussed further in Chapter 5.

Many other agencies and institutions, national and international, are engaged in related activities. To name just a few, the National Aeronautics and Space Administration has pioneered in global measurements of atmospheric constituents; the National Science Foundation has supported university scientists investigating complex interactions between the sea, atmosphere, and land; the National Oceanic and Atmospheric Administration has collected essential data; the Environmental Protection Agency has concerned itself with issues of environmental protection and regulation; the Federal Emergency Management Agency is concerned with consequences of climatic variability; and industry and industrial organizations such as the Gas Research Institute and the Electrical Power Research Institute have contributed expertise.

Collaboration of all these contributors, and the many not mentioned, will facilitate a U.S. strategy based on technology. For success, this mission-focused effort must catalyze the scientific and technological expertise of industry, universities, government agencies, and the national laboratories. Therefore, contacts are being made with a broad array of governmental, academic, and industrial institutions, and discussions with them are continuing.

In all, this report provides a solid "technology basis" for a climate change technology strategy. With it, the United States can begin to develop that strategy with the confidence that a strong technology R&D program will deliver a portfolio of technologies with the potential to provide very substantial GHG emission reductions along with continued economic growth. Clearly, more collaborative planning and analysis are needed to develop and implement the strategy. However, it is vital that the nation carefully plan the role of technology in addressing the climate change issue. We offer this technology report as a key information source to help guide those national policy decisions.

1.4 REFERENCES

EIA (Energy Information Administration) 1996a. *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573(95), U.S. Department of Energy, Washington, D.C.

EIA (Energy Information Administration) 1996b. *International Energy Outlook 1996*, DOE/EIA-0483(96), U.S. Department of Energy, Washington, D.C.

Houghton, R. A. 1995. "Land-Use Change and the Carbon Cycle." *Global Change Biology* 1, 275–287.

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

Marland, G., R. J. Andres, and T. A. Boden 1977. *Global, Regional, and National CO_2 Emission Estimates from Fossil Fuel Burning, Cement Production, and Gas Flaring: 1950–1994* (revised February 1997).

PCAST (President's Committee of Advisors on Science and Technology) 1997. *Federal Energy Research and Development for the Challenges of the Twenty-First Century*, U.S. Department of Energy, Washington, D.C., November.

SEAB (Secretary of Energy Advisory Board), (D. Yergin, Chairman) 1995. *Energy R&D: Shaping Our Nation's Future in a Competitive World*, U.S. Department of Energy, Washington, D.C.