The Honorable Federico Peña
Secretary of Energy
Forrestal Building
1000 Independence Ave., SW
Washington, D.C. 20585

Dear Mr. Secretary:

Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions

The national laboratory directors are delivering our report responding to your request that we identify cost-effective technological means to reduce greenhouse gas emissions. This study reinforces our belief that science and technology are key elements in any climate change strategy.

The technology opportunities outlined in this report are intended to serve as input to broader efforts to develop an integrated national climate change strategy. The climate change issue is highly complex and multidimensional. Considerable work remains to be done in determining which technologies are most promising and what the requirements are to further evaluate and undertake the development and deployment of these technologies.

We greatly appreciate the hard work by our friends and colleagues in developing the necessary information and preparing this report on a compressed schedule. We believe that this multi-lab effort represents a mode of cooperation and collaboration that will set a pattern for future efforts by industry, government, universities, and the Department's national laboratories.

Thank you for the privilege of allowing us to lead this effort.

Sincerely,

Al Trivelpiece
Alvin W. Trivelpiece, Co-chair
Oak Ridge National Laboratory

Richard H. Truly, Co-chair
National Renewable Energy Laboratory

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William J. Madia
Pacific Northwest National Laboratory

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The Secretary of Energy
Washington, D.C.

April 22, 1998

Dr. Alvin Trivelpiece
Director, Oak Ridge National Laboratory
P.O. Box 2008, Mail Stop 6255
Oak Ridge, Tennessee 37830

Admiral Richard H. Truly
Director, National Renewable Energy Laboratory
U.S. Department of Energy
1617 Cole Boulevard
Golden, Colorado 80401

Dear Dr. Trivelpiece and Admiral Truly:

Thank you for responding to my request for evaluating technology pathways to reduce greenhouse gas emissions with sustained economic growth. President Clinton framed this issue in his June 1997 United Nations speech, when he said

> 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, and universities, business and labor must work together. All these efforts must be sustained over years, indeed over decades.

I am pleased to receive your report, *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions,* and ask that you convey my gratitude to all your colleagues who contributed to it.

Your report, together with that of the President's Committee of Advisors on Science and Technology, will help significantly as we shape the Department's R&D portfolio in response to evolving environmental, economic, and security concerns. It is particularly valuable to have the detailed information that you provide on each of the technologies, including the current status, specific actions being taken now, and the long-term potential for energy savings and emissions reductions.

As your report indicates, substantial further analysis is needed. First, we need to prioritize our increased R&D investments to lay the foundation for future breakthroughs, to accelerate introduction of new technologies, and to complement and stimulate private sector research, development, and deployment. Also, as stated in the report, it is fortuitous that many of these technologies have already been supported by the Administration and Congress in recent years for their broader environmental and economic benefits. For the most promising pathways, the Department, under the auspices of the R&D Council, will work with stakeholders to produce technology road maps. Your report provides an excellent foundation for this activity, and your assistance will be sought together with that of academia and the private sector. The road maps will themselves evolve over time in the face of new challenges and opportunities. In addition, all proposals for increased R&D will be evaluated in the context of the complete portfolio of programs designed to spur innovation and meet environmental, economic, and national security goals.

Second, I recognize that your efforts focused solely on the technology pathways, as requested, and that due to the timing of your work, the funding views included in the report were developed in the absence of information about the tax and other policy aspects of the Administration's program. The synergies between such incentive approaches and increased research and development will help shape the optimal technology development investments. Nevertheless, many of the research priorities your group identified are reflected in the President's Fiscal Year 1999 Budget, and as we move forward, we will fold your work into the broader policy context in order to achieve long-term greenhouse emission reductions in the most cost effective manner.

I am optimistic that the Department of Energy Laboratories, together with our partners in the private sector and in academia, will make significant contributions to clean and affordable energy sources that meet America's environmental goals for the twenty-first century. I look forward to working with you toward that end.

Sincerely,

Federico Peña

cc: Dr. Dean E. Eastman
Director, Argonne National Laboratory

Dr. Peter D. Bond
Director, Brookhaven National Laboratory

Dr. Rita A. Bajura
Director, Federal Energy Technology Center

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TECHNOLOGY OPPORTUNITIES TO REDUCE U.S. GREENHOUSE GAS EMISSIONS

October 1997

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Prepared by

National Laboratory Directors
for the
U.S. Department of Energy

MASTER

On the World Wide Web:
http://www.ornl.gov/climate_change

PREFACE

President Clinton directed his cabinet to respond to the challenge of reducing greenhouse gas emissions in the United States. In turn, Secretary of Energy Peña asked the directors of 11 of the Department of Energy's national laboratories to identify technologies that could be used to meet this challenge. In response to this request, scientists and engineers from the Department's national laboratories built upon existing collaborations with technical leaders from industry, government, and universities in doing the work that led to the findings and conclusions reported here. In pursuing the goal of identifying cost-effective means to reduce greenhouse gas emissions, the following questions were used as guidelines:

> What technologies can be improved through research and development (R&D), which are not now deployed or utilized extensively?
>
> What are those new technologies that could be developed in the future, with reasonable effort and cost?
>
> What is the program of research and development which is needed to bring about these results?

In our efforts to answer these questions, we have taken the position that the development of a science-based, cost-effective technological means to reduce greenhouse gas emissions is a prudent step to take independent of the outcome of the continuing scientific debate on the subject of global climate change.

We believe that this report serves as the technology basis of a needed national climate change technology strategy, with the confidence that a strong technology R&D program will deliver a portfolio of technologies with the potential to provide very substantial greenhouse gas emission reductions along with continued economic growth. Much more is needed to define such a strategy, including identification of complementary deployment policies and analysis to support the scoping and prioritization of R&D programs. A national strategy must be based upon governmental, industrial, and academic partnerships.

In the final analysis, a combination of well-conceived national policy and the concurrent development of advanced technologies will be needed to achieve the nation's dual strategic goals of reducing greenhouse gas emissions and maintaining a robust economy. While our task was to focus on technology, and not on government policy, we recognize this important link.

We are honored to have been asked to lead this effort. We want to thank all of those who participated in the work upon which this report is based.

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Appendix B. Technology Pathways Characterization

FIGURES

TABLES

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

ATS	advanced turbine system
C	carbon
C/E	carbon intensity
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
CRADA	cooperative research and development agreement
DOE	U.S. Department of Energy
E/GDP	energy per unit of economic output
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EV	electric drive vehicles
FCCC	Framework Convention on Climate Change
FTTA	Federal Technology Transfer Act
GDP	gross domestic product
GHG	greenhouse gas
GRI	Gas Research Institute
GtC	gigatons of carbon (10^3 million tons)*
GW	gigawatt (10^3 MW)
GWe	gigawatt electric
HCFC	hydrochlorofluorocarbon
HEV	hybrid electric vehicles
HHV	high heat value
HVAC	heating, ventilation, and air conditioning
HVDC	high voltage direct current
IGCC	integrated gasification combined cycle
I/O	input/output
IOF	Industries of the Future
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hour

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*A tonne, or metric ton, is 1000 kilograms or about 2200 lb.

LEGO	lifetime extension and generation optimization
LIDAR	light detection and ranging
low-E	low emissivity
mpg	miles per gallon
mph	miles per hour
MSW	municipal solid waste
MtC	million metric tons of carbon
MWe	megawatt = 10^6 watt, electric
MWt	megawatt thermal
NA	not applicable
NASA	National Aeronautics and Space Administration
NCRA	National Cooperative Research Act
NFRC	National Fenestration Rating Council
NGO	nongovernmental organization
NO_x	nitrogen oxides
NRC	Nuclear Regulatory Commission
OBTS	U.S. DOE Office of Building Technology, State and Community Programs
OI	other industrial
OIT	U.S. DOE Office of Industrial Technologies
ORTA	Office of Research and Technology Application
PEM	proton exchange membrane
PNGV	Partnership for a New Generation of Vehicles
ppmv	parts per million by volume
PV	photovoltaic
PVMat	Photovoltaic Manufacturing Initiative
quad	quadrillion (10^{15}) Btus
R&D	research and development
RD&D	research, development, and demonstration
SBIR	Small Business Innovation Research
scf	standard cubic feet
SEMATECH	Semiconductor Manufacturing Technology
SMES	superconducting magnetic energy storage
SOM	soil organic matter
Tcf	trillion cubic feet
TRP	Technology Reinvestment Project
TWh	terawatt hour (terawatt = 10^6 MW)
USCAR	United States Council for Automotive Research
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program

EXECUTIVE SUMMARY

The rise in greenhouse gas emissions from fossil fuel combustion and industrial and agricultural activities has aroused international concern about the possible impacts of these emissions on climate. Greenhouse gases—mostly carbon dioxide, some methane, nitrous oxide and other trace gases—are emitted to the atmosphere, enhancing an effect in which heat reflected from the earth's surface is kept from escaping into space, as in a greenhouse. Thus, there is concern that the earth's surface temperature may rise enough to cause global climate change.

Approximately 90% of U.S. greenhouse gas emissions from anthropogenic sources come from energy production and use, most of which are a byproduct of the combustion of fossil fuels. On a per capita basis, the United States is one of the world's largest sources of greenhouse gas emissions, comprising 4% of the world's population, yet emitting 23% of the world's greenhouse gases. Emissions in the United States are increasing at around 1.2% annually, and the Energy Information Administration forecasts that emissions levels will continue to increase at this rate in the years ahead if we proceed down the business-as-usual path.

President Clinton has presented a two-part challenge for the United States: reduce greenhouse gas emissions and grow the economy. Meeting the challenge will mean that in doing tomorrow's work, we must use energy more efficiently and emit less carbon for the energy expended than we do today. To accomplish these goals, President Clinton proposed on June 26, 1997, that the United States "invest more in the technologies of the future."

In this report to Secretary of Energy Peña, 47 technology pathways are described that have significant potential to reduce carbon dioxide emissions. The present study was completed before the December 1997 United Nations Framework Convention on Climate Change and is intended to provide a basis to evaluate technology feasibility and options to reduce greenhouse gas emissions. These technology pathways (which are described in greater detail in Appendix B, Technology Pathways) address three areas: energy efficiency, clean energy, and carbon sequestration (removing carbon from emissions and enhancing carbon storage). Based on an assessment of each of these technology pathways over a 30-year planning horizon, the directors of the Department of Energy's (DOE's) national laboratories conclude that success will require pursuit of multiple technology pathways to provide choices and flexibility for reducing greenhouse gas emissions. Advances in science and technology are necessary to reduce greenhouse gas emissions from the United States while sustaining economic growth and providing collateral benefits to the nation.

Fortunately, many of these technologies are already the subject of some federally sponsored and private-sector research, development, and demonstration (RD&D) driven by the collateral benefits they offer. It is worth noting that DOE's applied energy technology programs are already supporting the development of many of the requisite technologies or elements of these technologies (see Appendix B). Similarly, DOE's Office of Energy Research funds basic research in areas that underpin the applied energy technology programs. If developed and widely used, these technologies would also improve air quality, reduce U.S. dependence on imported oil, and increase exports of U.S. technologies to help other nations reduce their greenhouse gas emissions while growing their economies, all of which will sustain national economic growth.

We believe that developing technology solutions sooner rather than later will be more effective in reducing greenhouse gas emissions. Postponing action could close technology options or increase future costs and risks. The laboratory directors and DOE recognize that supportive programs and policies will also be critical to bringing new technologies into the marketplace. New policies and programs to deal with emissions may be needed, such as subsidies or tax incentives or permit trading programs to encourage accelerated adoption of energy efficiency or clean energy technologies. However, these programs and policies are not specified in this study. In addition, the technology pathways are not prioritized in this report in terms of potential for commercialization or research and development (R&D) funding. Further analysis is required to accomplish that.

Our findings suggest that each decade is distinct in terms of the range of greenhouse gas reduction technologies that could be available.

- In the first decade, significant advances in energy efficiency technologies would deliver substantial near-term carbon-reducing impacts by decreasing the energy intensity (amount of energy used to do work) of the U.S. economy. Clean energy technologies would continue to grow, and carbon sequestration technologies could begin to emerge.
- Along with continued improvements in energy efficiency, research-based advances in clean energy technologies would reduce significantly the carbon intensity (amount of carbon emitted for the energy used) of the U.S. energy economy during the second decade. A wide range of improved renewable, fossil, and nuclear technologies could be introduced and widely deployed in this period. These clean energy options could begin to exceed the carbon reduction impact of increased end-use efficiencies by the year 2025.
- Complementing ongoing advances in clean energy and efficiency technologies well into the third decade, carbon sequestration technologies would add a third important dimension to the package of solutions. Success in this technology area could enable the nation to continue its extensive use of fossil fuels without harming the global climate. We assume that these technologies would not be widely available until the 2030 time frame; however, successful introduction earlier could result in significantly greater reductions in net carbon emissions.

We believe that by 2030, a vigorous RD&D program could deliver a wide array of cost-effective technologies that together could reduce the nation's carbon emissions by 400–800 million metric tons of carbon (MtC) per year. This decrease represents a significant portion of the carbon emission reductions that may be targeted by the United States for 2030. Additional reductions would result from the implementation of new policies and deployment programs, particularly in early years when the market penetration of existing and near-term technologies could be accelerated.

Possible goals for an RD&D program are presented below, along with some of the technologies that could contribute to achieving them.

Energy Efficiency

- Use electricity more efficiently through the deployment of advanced technologies (e.g., intelligent building control systems, cost-effective refrigerators that use half as much electricity as today's models, and fuel cells for heat and power in commercial buildings).
- Reduce use of gas and oil for space and water heating through building efficiency measures (e.g., super insulation, gas-fired heat pumps that provide highly efficient space heating and cooling, and building envelopes that capture and store solar energy for later use).
- Improve industrial resource recovery and use (e.g., develop an integrated gasification combined cycle power technology, which can convert coal, biomass, and municipal wastes into power and products) and industrial processes to save energy (e.g., advanced catalysis and separations technologies).
- Increase transportation efficiency through new technologies (e.g., a hybrid electric vehicle that is three times more fuel-efficient than today's standard model).

Clean Energy

- Change the energy mix to increase use of sources with higher generating efficiencies and lower emissions—increased use of natural gas, safer and more efficient nuclear power plants, renewable energy (e.g., solar and wind power; electricity and fuels from agricultural biomass), and hydrogen (to produce electricity through fuel cells).
- Develop "energyplexes" that would use carbon efficiently without emitting greenhouse gases for the integrated production of power, heat, fuels, and chemicals from coal, biomass, or municipal wastes.
- Distribute electricity more efficiently to reduce emissions (e.g., distributed generation using superconducting transformers, cables, and wires).
- Switch transportation to energy sources with lower emissions (e.g., trucks that run on biodiesel fuel; ethanol from cellulosic feedstocks).
- Remove carbon from fuels before combustion.

Carbon Sequestration

- Efficiently remove carbon dioxide from combustion emissions before they reach the atmosphere.
- Increase the rate at which oceans, forests, and soils naturally absorb atmospheric carbon dioxide.
- Develop technologies for long-term carbon storage in geological deposits, aquifers, or other reservoirs.

Basic and Applied Research Are Needed

Meeting the goals described above also depends upon incremental improvements and breakthroughs in the basic sciences. For example, basic research is needed to

- understand the global carbon cycle (i.e., computational modeling and measurements to understand the ocean–atmosphere–terrestrial biosphere interactions) and judge the benefits and risks of sequestration options
- support greenhouse gas reduction technologies (i.e., materials, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, nuclear sciences, and computational sciences)

To support multiple technology pathways, enabling technologies also must be improved, especially transmission/distribution systems that deliver energy faster and more efficiently. Relevant enabling technologies include

- hydrogen production, storage, and distribution
- fuel cells
- electricity transmission, distribution, and components
- sensors and controls
- energy storage systems

Strategic Alliances Are Essential

Strategic public–private alliances provide the best approach for developing and deploying most greenhouse gas reduction technologies. Although many of these technologies will be able to compete cost-effectively in the marketplace in the future, industry is unlikely to lead and fully finance the innovation process because of the high risk associated with developing technologies that will not be deployed for decades, and because the market currently does not place a high value on carbon mitigation. Using public–private strategic alliances will help maximize the efficiency of the innovation process by bringing together stakeholders who are capable of overcoming the relevant scientific, technical, and commercial challenges.

Research, Development, and Demonstration Resources

This report describes the carbon emission reductions that could result from an accelerated RD&D program. It does not consider collateral benefits from initiating complementary deployment programs or policies aimed at stimulating markets for greenhouse gas reduction technologies. It is believed that an integrated approach (i.e., science and technology in combination with deployment programs and supporting policies) is the most cost-effective one.

To achieve the annual emission reductions of 400 to 800 MtC by 2030 described in this report, federal RD&D budget increments would be necessary in three areas:

- the development of advanced energy technologies
- the development of carbon sequestration technologies, including supporting research on carbon cycle modeling and ecosystems

- the basic research areas that are the wellspring of future technological breakthroughs.

Moving Forward

The laboratory directors recommend that the United States develop and pursue a detailed and comprehensive technology strategy for reducing greenhouse gas emissions. By summarizing the status, potential, and fundamental research needs of a broad range of technologies relevant to reducing greenhouse gas emissions, this report provides one key element, namely, the technology basis, for developing a climate change technology strategy. However, full definition of such a strategy requires several additional steps, especially an assessment of alternative programs and policies to promote deployment and an analysis of the costs and benefits of alternative technology and policy options to develop priorities. Further, we propose that DOE lead the development of this strategy because of its energy technology mission, its proven record in developing major national initiatives, and the attendant strategic alliances that are needed to solve complex national problems where science makes a difference. When implemented through focused public–private strategic alliances, this strategy should lead to technological advances that have broad market appeal. We believe that such a technology strategy could significantly reduce U.S. greenhouse gas emissions. Achieving this challenging goal while sustaining economic growth would require a vigorous RD&D program sustained by strong partnerships among government, universities, and the private sector.

In summary, this report concludes that a national investment in a technology RD&D program over the next three decades would provide a portfolio of technologies that *could* significantly reduce greenhouse gas emissions over the next three decades and beyond. To make effective progress against realistic goals and expectations, an outlay of approximately $1B/year above those presently dedicated to these efforts would be a prudent investment of resources. We believe that many technological opportunities exist that could *significantly contribute to* this goal without harming the nation's economy. A strategic plan that includes deployment policies to complement technology RD&D will be necessary for success. Plans will need to be formulated that reflect both the economic and technological implications of deploying these technologies. Hence, development of a climate change technology strategy is the recommended next step. The development process should include review of technology policy options to complement technology development options, and a detailed plan for supporting implementation which addresses technology goals, RD&D program plans, policies that support deployment, and fiscal resources. Development of this RD&D agenda should be a collaborative effort between government, industry, business, and the scientific communities. The implementation of a technology strategy to reduce greenhouse gas emissions will serve as an investment insurance policy. It should reduce the threat of climate change from fossil fuel use and provide acceptable technologies that produce savings and revenues that would far exceed the cost of an accelerated research program. The DOE's national laboratories stand ready to champion this enterprise.

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.)

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[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.

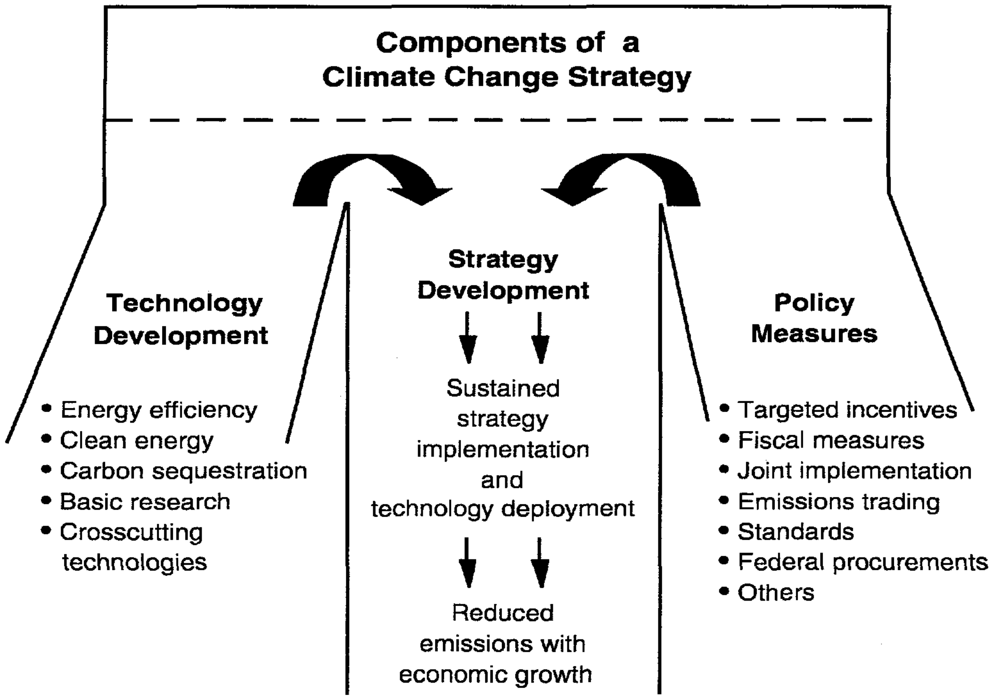

Fig. 1.1. Technology and policy components for a climate change strategy.

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

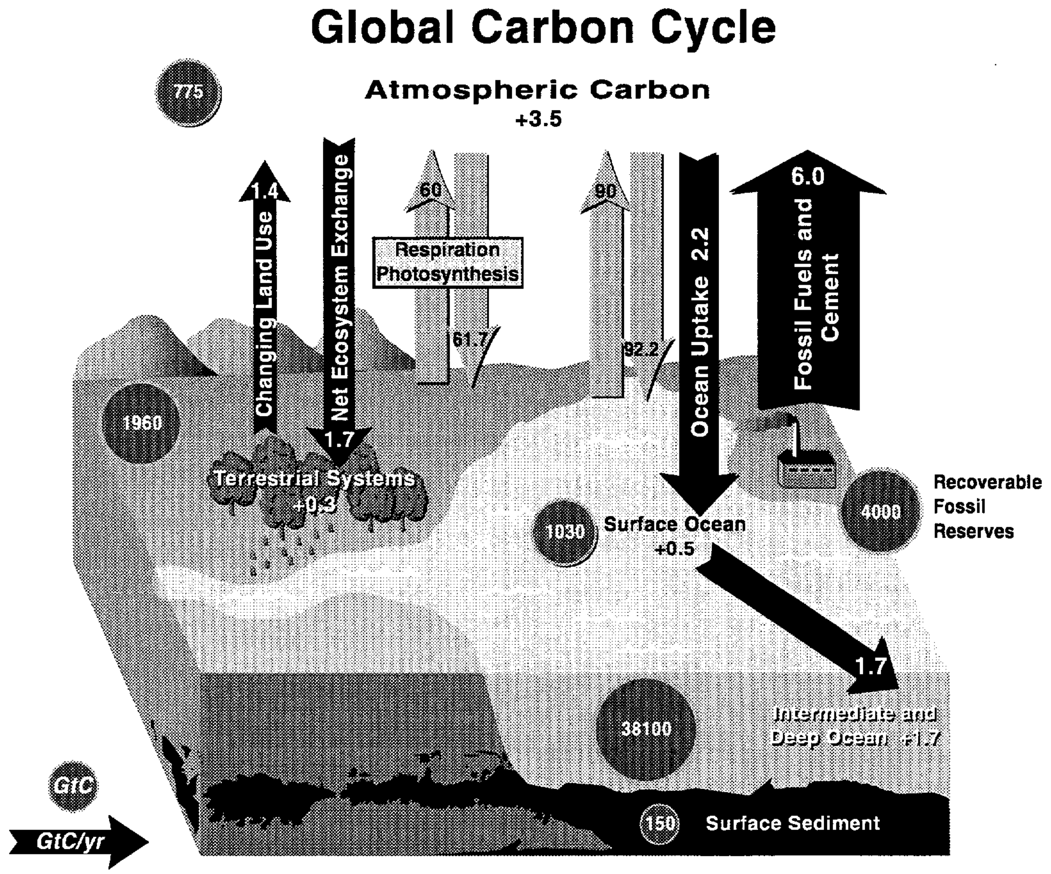

Fig. 1.2. The burning of fossil fuel and changing land use have resulted in human-induced alterations of the global carbon cycle. The solid arrows in this diagram indicate the average magnitude of perturbation in carbon fluxes and the fate of carbon resulting from these activities averaged for the first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

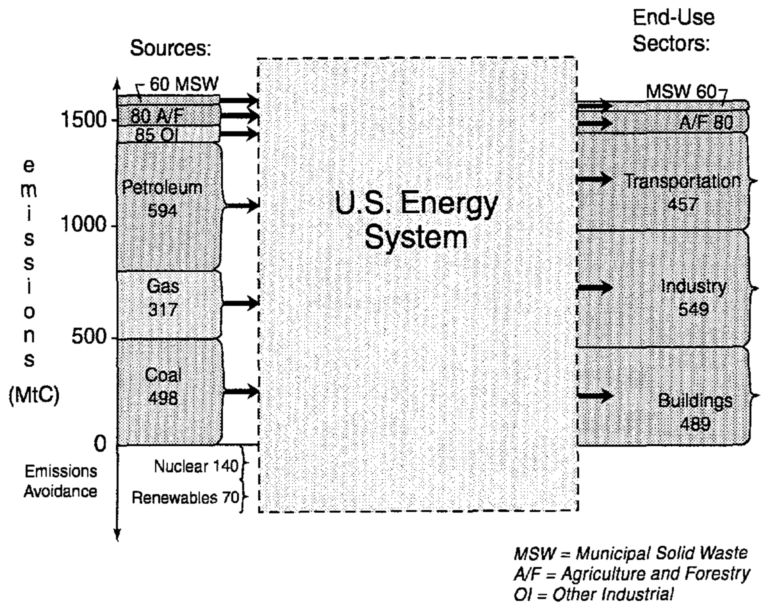

Fig. 1.3. Overview of the sources of carbon emissions in the United States in 1995 (in million tonnes equivalent and including CH_4 from MSW, A/F, and OI). *Source:* Based on EIA 1996a.

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.

2. TECHNOLOGY PATHWAYS

Many technological opportunities exist to reduce U.S. GHG emissions. Some involve incremental improvements to existing equipment and processes; others can be realized only through breakthroughs in the fundamental sciences and subsequent technological developments. Some technologies can be translated into market-ready products during the next decade; others may be available as one-of-a-kind prototypes by 2025. Some can be inserted into our current energy economy with relative ease; others require major transformations of infrastructure.

This section contains an inventory of climate change technologies. The authors concluded that about 50 technological pathways warrant serious consideration (see Table 2.1 and Appendix B). The pathways are divided into nine technological areas that can be addressed by three major approaches: improving energy efficiency, using more clean energy, and sequestering carbon (Fig. 2.1). Coverage of electric utility technologies is included in the fossil power generation, nuclear energy, and renewable energy areas.

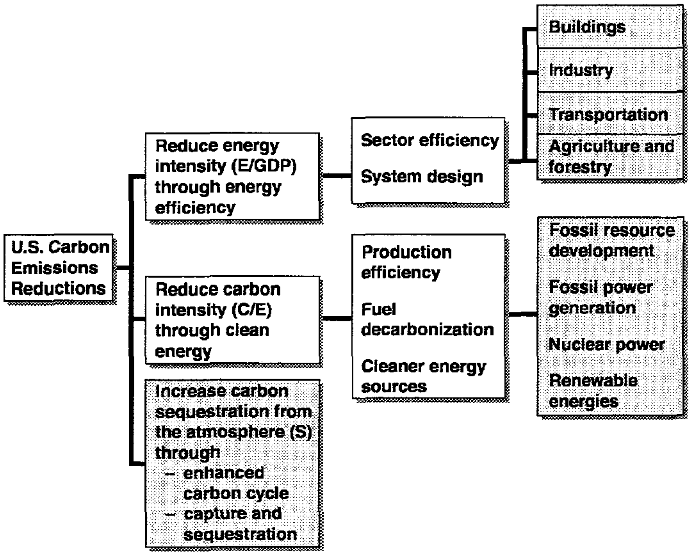

Fig. 2.1. Alternative technological opportunities for reducing greenhouse gas emissions. Electric utility technologies are covered in the fossil power generation, nuclear energy, and renewable energy areas.

Table 2.1. Technology pathways[a]

1. Buildings
    1.1 Equipment and Appliances
    1.2 Building Envelope
    1.3 Intelligent Building Systems
2. Industry
    2.1 Energy Conversion and Utilization
    2.2 Resource Recovery and Utilization
    2.3 Industrial Process Efficiency
    2.4 Enabling Technologies
3. Transportation
    3.1 Advanced Conventional Vehicle
    3.2 Freight Vehicles
    3.3 Hybrid, Electric, and Fuel Cell Vehicles
    3.4 Alternative Fuel Vehicles
    3.5 Air and High-speed Ground Transport
4. Agriculture and Forestry
    4.1 Conversion of Biomass to Bioproducts
    4.2 Advanced Agricultural Systems
    4.3 Plant/Crop Engineering
5. Fossil Resource Development
    5.1 Energy Efficiency for Crude Oil Refining
    5.2 Natural Gas to Liquids
    5.3 Increased Natural Gas Production
    5.4 Co-production with Integrated Gasification Combined Cycle
    5.5 CO_2 for Improved Oil and Gas Recovery
6. Fossil Power Generation
    6.1 Accelerated Development of High-Efficiency Coal-Based Power Generation Technologies
    6.2 Low-Carbon Fuels and High-Efficiency Power Generation
    6.3 Ultra-High Efficiency, Zero-Carbon Emission Energyplexes
7. Nuclear
    7.1 Lifetime Extension and Generation Optimization
    7.2 Next-Generation Fission Reactors
    7.3 Fusion Power
8. Renewable Energy
    8.1 Biomass Electric
    8.2 Wind Energy
    8.3 Advanced Hydropower
    8.4 Solar Photovoltaics
    8.5 Geothermal Energy
    8.6 Solar Thermal Electric and Buildings
    8.7 Biomass Transportation Fuels
    8.8 Solar Advanced Photoconversion
9. Carbon Sequestration and Management
    9.1 Augmented Ocean Fertilization to Promote Additional CO_2 Sequestration
    9.2 Advanced Chemical and Biological Conversion and Sequestration
    9.3 Terrestrial Storage of CO_2
    9.4 Carbon Sequestration in Soils
    9.5 Elemental Carbon Sequestration
    9.6 Ocean Storage

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[a] This table does not include basic research needs (i.e., global carbon cycle modeling and measurement, materials science, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, and nuclear sciences) and enabling technologies (hydrogen and fuel cells, electrical transmission, distribution, and components, sensors and controls, and energy storage) needed to support the technology pathways (see Chap. 3).

2.1 CARBON LEVELS: PRESENT AND FUTURE

The sources of carbon emissions in the United States must be understood before characterizing the potential benefits of technologies to reduce GHG emissions. For example, in 1995, most anthropogenic (human activity–related) CO_2 emissions in the United States were caused by the combustion of coal, natural gas, and petroleum. A fraction (less than 2%) came from other sources, including the manufacture of cement and lime. Figure 2.2 shows how these primary fuels are transformed to provide energy and products that are ultimately consumed in homes, office buildings, factories, cars, trucks, and farms.

Energy Efficiency. In 1995, the three major end-use sectors (buildings, industry, and transportation) emitted approximately equivalent levels of carbon. However, the sources of this carbon vary widely. For instance, 80% of the carbon emissions attributable to the energy used in buildings comes from electricity, whereas 99% of the energy used for transportation comes directly from consumption of petroleum products. Energy consumption in each of the end-use sectors has grown during the past decade at about the same rate as the nation's GDP, causing significant increases in carbon emissions. The increases illustrate the importance of reducing the amount of energy consumed per unit of economic output, or "energy intensity," of our economy (see Chap. 1). Technology that increases energy efficiency is the key to achieving this goal. It can reduce the energy used per square foot of home or office space, the energy required per unit of industrial output, and the energy consumed per vehicle-mile traveled. Through advances in technology, these energy intensities can be decreased without sacrificing any of the services that energy provides.

Clean Energy. "Clean energy" technologies can decrease the amount of carbon produced per unit of energy, or "carbon intensity," of the nation's energy economy. In 1995, coal, natural gas, and a small amount of petroleum were responsible for 494 MtC of emissions in the electricity industry (Fig. 2.2). Nuclear power and renewable sources can be credited with displacing what would have been an additional 140 and 70 MtC of carbon emissions, respectively, if fossil

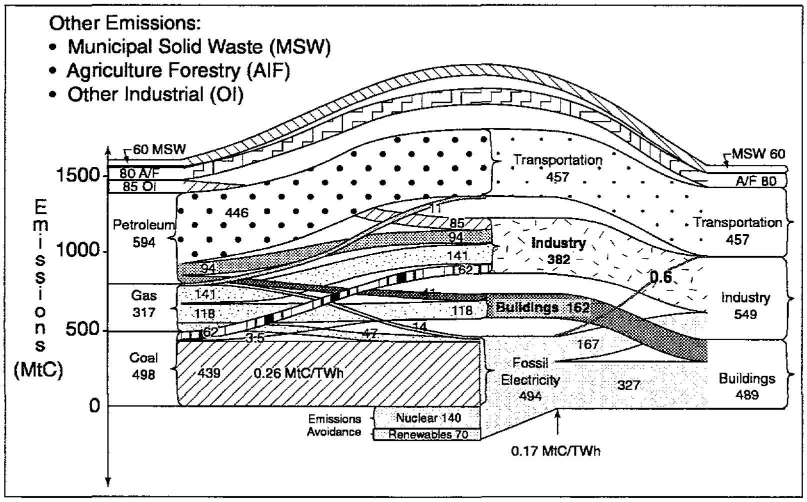

Fig. 2.2. Sources of greenhouse gas emissions in the United States in 1995 (in million metric tons equivalent). Note that if nuclear and renewables had not been used to generate electricity in 1995, carbon emissions would have been 210 MtC higher on each side of the chart. *Source:* Based on EIA 1996b.

fuels had been used. As a result, the electricity sector produced only 0.17 MtC per terawatt hour (TWh), instead of 0.26 MtC/TWh. Switching to low-carbon fuels for transportation is an important means of reducing carbon emissions; for instance, biofuels can replace petroleum-based liquid fuels. Another option for reducing carbon intensity involves fuel decarbonization, in which carbon is removed from fuel and sequestered before the fuel is used. Improving the efficiency of producing energy from fossil fuels is also important.

Carbon Sequestration. Carbon sequestration is another technological route to reducing the magnitude and impacts of U.S. carbon emissions. One approach is to sequester CO_2 emissions captured during fossil fuel conversion processes, thus preventing their release into the atmosphere. A second approach is to increase the absorption of CO_2 by either the oceans or the terrestrial biosphere.

Synergies and Integrations. While these three approaches of energy efficiency, clean energy, and carbon sequestration are convenient for discussion, the synergies and interdependencies among them and among sectors must be considered as well in further development of a technology strategy. For example, the carbon reductions that result from energy efficient technologies depend on the carbon content of the energy that is being displaced, and reductions from the use of electric vehicles depend on the carbon content of the electricity generated. If electricity continues to be generated largely by inefficient coal plants, end-use efficiency improvements will produce sizeable carbon reductions. Greater reliance on electricity from renewables or nuclear reactors will reduce the carbon benefits resulting from energy efficiency.

Some interactions are potentially positive. Fuel cells using methane require that carbon and hydrogen be separated anyway, so there would be no separation cost in sequestering the carbon. Some interactions are potentially negative, such as the possibility that the heavy use of natural gas for low-carbon electricity production and cogeneration could increase prices for natural gas, if not paired with more efficient natural gas consumption in buildings and industry. Also, increases in energy efficiency can cause lower prices, which can increase demand and potential carbon emissions. Some interactions make it possible for certain technologies to be more effectively adopted, such as integrating intermittent renewables such as solar thermal electric with IGCC using natural gas.

A potentially dramatic synergy is expected between non-carbon electricity generation (e.g., solar, wind, biomass, and nuclear) and vehicles using electricity or hydrogen produced from electricity. The large but flexible electricity demand these technologies could represent (25–50% of the electricity market) would enable large reductions in energy storage needed for intermittent renewables to become widely adopted.

This report does not examine these types of synergies in depth, but some examples include the pathways for energyplexes (Fossil Power Generation), resource recovery and utilization (Industry), and hydrogen (Crosscutting). Other integrated systems are mentioned in Chap. 5, Synthesis and Moving Forward.

2.2 STUDY METHODOLOGY AND ASSUMPTIONS

Participants. Compiling detailed information on the potential of a wide range of energy-related technologies to reduce CO_2 emissions required the expertise and judgment of a large number of individuals. The laboratory directors first identified representatives from each of the 11 labs involved in this study. These representatives defined the 11 technology areas that formed the structure of the study (9 categories of technology pathways plus cross-cutting enabling technologies and related areas of basic research). Each representative then assumed responsibility for a working group corresponding to one of the 11 areas. Each working group, consisting of relevant experts from the various laboratories, identified the individual technology pathways appropriate to its technology area as listed in Table 2.1 and prepared the pathway drafts.

Overall direction for the study was provided by the laboratory directors through a coordinating committee and the group of lab representatives. The coordinating committee and lab representatives provided guidance and assumptions to the working groups for developing the desired information and took on the task of summarizing the information into the main report. Participants in these groups are listed in Appendix A.

In addition, a small focus group served an important role in the overall study methodology by carefully reviewing all of the technology pathways for consistency and credibility and then interviewing their authors to ensure that the material presented had a firm technical basis and had been developed in a reasonable way. This process included ensuring that the guidelines for developing the carbon emission reduction estimates and the risk factor scores had been followed.

The assumptions for the study are given in detail in the introduction to Appendix B and summarized here. In general, the working groups relied upon Delphi method principles to reach their conclusions about the technology pathways. Conditions and assumptions not defined herein were based on a consensus of the working group members.

Information Considered. The technology pathways provide detailed information describing the technology: its developmental status and outlook for technological progress through RD&D, recent successes, commercialization and deployment prospects, potential benefits and costs, various types and levels of risks the technology faces, and recommendations for federal actions. The potential benefits and costs were quantified, under common assumptions, in terms of the estimated carbon emissions reductions in each of the next three decades and a general estimate of what levels of federal RD&D support might be needed to fully develop the individual technology pathways over the next three decades.

It is important to note that the descriptive text and the numerical estimates presented in these pathways are based on the judgment of teams from the 11 participating national laboratories (in some cases in collaboration with experts from other organizations across the country). Some of the numerical estimates were supported by analysis; others were simply the best estimates of experts based on available information. The estimates for each technology area were developed independent of the other technology areas; competition and interactions among the technology areas were not considered. Therefore, summing carbon reduction estimates from different technology areas would lead to "double counting."

The time frame of this study did not allow analysis of all of the various factors that could affect the performance and market penetration of a new technology. However, the study has compiled a considerable amount of information on a wide range of factors and has taken this information into account in estimating carbon reductions and in drawing conclusions. The working groups and other teams considered the following factors:

- Size of domestic and international markets for the technology
- Turnover rate of capital stock
- Technical risks associated with the RD&D
- Size of the federal RD&D resources required
- Magnitude of the technology's capital and operating costs
- Extent of changes in infrastructure required for commercialization
- Size of the resource base available to support the technology
- Technical, commercial, ecological, human health, economic and regulatory risks associated with the development and use of the technology
- Characteristics of competing technologies

The timeframe of the study also did not allow for the important process of prioritizing the technology areas and pathways; thus the study recommends that some type of prioritization be included in the development of a detailed and comprehensive technology strategy for reducing greenhouse gas emissions.

Reference Case. All carbon emission reductions are relative to the "business as usual" scenario outlined by the DOE EIA (Fig. 2.3 and Table 2.2). This scenario assumes that some efficiency and process improvements will offset what would otherwise be a larger rate of CO_2 increases. The rise in emissions is driven by a forecasted GDP growth rate of 1.9%. (Underlying this growth rate is the assumption of sustained economic growth and an increasing population.) Without a major intervention, CO_2 emissions will increase by almost 50% from the current annual level of approximately 1.4 billion MtC to about 2.1 billion MtC in 2030.

The data shown in Fig. 2.3 and Table 2.2 for the period 2015 to 2030 are based on extrapolations of the EIA reference case for 2015. Thus they do not take into account the significant reduction in nuclear power that could occur after 2015 if nuclear power plants are retired according to their current license expiration dates.

Federal Policies. One of the key features of these carbon emission reduction estimates is that they assume no significant changes in existing market policies that would

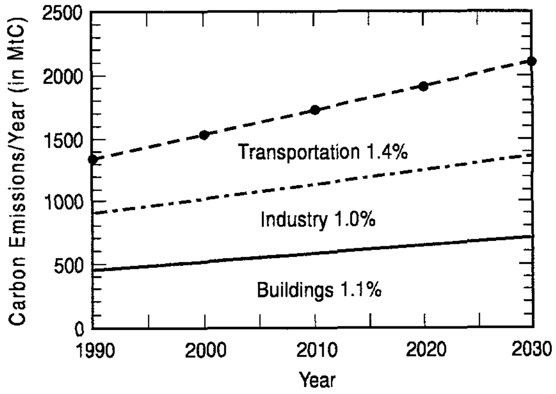

Fig. 2.3. Projected U.S. carbon dioxide emissions (in MtC per year). *Source:* Based on EIA 1996b.

Table 2.2. U.S. carbon dioxide emissions by end-use sector
(in MtC per year)

	Emissions				Change from 1990		
	1995	2010	2020	2030	2010	2020	2030
Buildings							
Fossil	159	170	178	185	22	30	37
Electricity	335	406	463	515	94	151	203
Subtotal	494	576	641	700	116	181	240
Industry							
Fossil	293	335	357	380	49	71	94
Electricity	171	213	241	269	47	75	103
Subtotal	464	548	598	649	96	146	197
Transportation							
Fossil	464	591	655	727	160	224	296
Electricity	1	7	10	14	6	9	13
Subtotal	465	598	665	741	166	233	309
Total							
Fossil	918	1096	1189	1291	231	324	426
Electricity[a]	506	626	714	798	147	235	319
Total	1424	1722	1904	2089	378	560	745

[a] The extrapolation beyond 2015 does not take into account the significant reduction in nuclear power that could occur as nuclear power plants are retired according to their current license expirations. Recent results of a new forecast by the Energy Information Administration suggest that carbon emissions will grow at a slightly faster pace through the year 2015. This new forecast is not yet published and is therefore not used in this report. In any event, using the new forecast would not substantially change the results of this report.

Sources: The carbon estimates for 1995 and the forecast for 2010 are taken directly from the Reference Case of EIA 1996a. Carbon emissions for 2020 and 2030 are forecasted using the same growth rates as for 2010. Electric utility emissions are distributed across sectors. GHGs other than CO_2 are not included.

affect adoption of advanced technologies. For example, policies such as tax incentives or rebate measures that encourage energy efficiency or clean energy technologies, or carbon charges or carbon emissions trading programs, could provide both additional and earlier reductions in carbon emissions.

Restructuring. The data in Fig. 2.3 and Table 2.2 also do not take into account any long-term impacts that might be precipitated by restructuring of the electric utility industry. If restructuring produces lower electricity rates, energy use will increase and investments in conservation technologies might decrease, with a concomitant rise in GHG emissions.

On the other hand, future utility restructuring legislation calling for renewable portfolio standards and public benefits programs could significantly promote clean power, thereby reducing GHG production. The deregulation issue underscores the uncertainties faced by developers and consumers of advanced energy technologies. Such uncertainties tend to dampen private-sector investments in research on advanced technologies, making the role of government-funded RD&D that much more critical. In general, the competitive market forces that accompany utility restructuring are significantly reducing utility sector investment in R&D, and the focus of that R&D is shifting to near-term results and becoming less strategic.

The introduction to Appendix B further discusses the methodology and assumptions relevant to the study. The remaining sections of this chapter describe the nine technological areas that constitute the menu of technological opportunities identified in this report (Fig. 2.1). We note the following for each area:

- the magnitude of carbon-emission reductions that could be realized as a result of successful development and subsequent market adoption of the technologies, without any significant policy changes
- the specific pathways and related scientific and technological challenges that must be met
- the technical, market, and other risks associated with pursuing the technological area
- anticipated collateral benefits
- recommended strategies for moving forward

2.3 ENERGY EFFICIENCY

Improving the efficiency of energy use in the United States by developing advanced technologies can offer immediate, significant carbon reductions. Incremental and breakthrough technologies hold the promise of buildings that consume half the energy of current new construction, industries (such as forest products) that can meet all of their energy needs internally, cars that offer three times the fuel economy of current vehicles, and farms that are more productive and enable greater carbon fixation while using less energy.

Many technological opportunities exist for improving the efficiency of the U.S. economy. These are described in the following sections, by end-use sector:

- buildings
- industry
- transportation
- agriculture and forestry

2.3.1 Buildings

The Potential for Reduced Emissions

The buildings sector in the United States accounts for 36% of the nation's use of primary energy. Buildings are responsible for 66% of electricity use and 37% of natural gas use. In 1995, the energy consumed in the buildings sector accounted for emissions of 489 MtC, and this is forecasted to increase to 576 MtC in 2010 and to 700 MtC in 2030. Thus the buildings sector is key to constraining or reducing the nation's use of energy—whether the concern is GHG emissions and global climate change, urban and regional air quality, energy security, sustainable development, or any number of other concerns associated with energy use. Also, the "human dimensions" must be kept in mind—buildings exist to house the myriad needs and activities of our civilization: shelter, community involvement, relaxation, office work, industrial processes, and the like. Energy only serves to help meet these needs. Within this broad context, the following are technological approaches for reducing GHG emissions associated with buildings:

- reducing electricity use through energy efficiency measures and thereby reducing GHG emissions from fossil fuel power plants
- reducing natural gas and oil use for space and water heating and other

domestic uses through energy efficiency measures and thereby reducing on-site GHG emissions
- generating electricity on site and/or providing space and water heating using measures that are inherently more efficient than conventional ones (e.g., advanced cogeneration concepts) or that do not emit GHGs (e.g., building-integrated photovoltaic systems and solar hot water systems).

The status of various building energy technologies and their potential to reduce GHG emissions by the year 2010 are covered in the report *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies*, by a group representing five national laboratories (Interlaboratory Working Group 1997). Most of the technological opportunities presented in the following table would have an actual impact on emissions by the year 2020, although in some cases the impacts would not occur until 2030.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total buildings	25–50	50–100	75–150

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Equipment and Appliances. By definition, all primary energy used in buildings is consumed by equipment that transforms fuel or electricity into end-uses, such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, information management, or entertainment. The overall efficiency of this transformation depends largely on the efficiency of the equipment itself.

Numerous opportunities exist to develop equipment that is much more efficient than that currently available. Just a few examples of exciting new prospects include gas heat pumps with twice the efficiency of today's residential furnaces, distribution systems that deliver 50% more conditioned air, highly efficient lamps with long lifetimes, full-size refrigerator-freezers that use as little power as a 40-W light bulb, fuel cells in the garage, photovoltaics systems integrated into the building envelope, and flat panel displays to replace cathode ray tubes.

Efficient components, by themselves, are not enough, however. It is equally important to ensure that the equipment is properly sized to meet the load, that its operation conforms to varying demands (i.e., controls that vary output as load varies and that minimize standby losses), and that individual pieces of equipment are intelligently integrated into a multifunction unit or into a total building system (to exchange and reuse heat, balance electrical demand, or combine functions to share the use of burners or compressors).

The Building Envelope. The building envelope provides fundamental thermal load control for a building. Walls, roofs, and floors block or delay the flow of heat between a building's interior and exterior. Windows can also block heat flow, provide daylight, transmit solar energy, and provide a view of the outside. High-capacitance internal walls, ceilings, and floors can provide thermal storage that reduces energy use by storing solar energy and reduces peak loads by balancing energy use over a 24-hour period. Improvements in the energy performance of these building elements reduce energy use in buildings and thereby reduce GHG emissions.

Decreasing the building thermal load reduces the need for heating and cooling energy. These emerging building envelope technologies will significantly reduce building energy use:

- super insulation, based on vacuum principles
- new-formula high-efficiency foam insulation that uses no CFCs or hydrochlorofluorocarbons
- advanced gas-filled, multiple-glazing, low-emittance windows and electrochromic glazing
- self-drying roofs
- passive solar components
- durable high-reflectance coatings
- advanced thermal storage materials

Intelligent Building Systems. The process of designing, constructing, starting up, controlling, and maintaining building systems is very complex. If it is done properly, the final product delivers comfort, safety, and a healthy environment and operates efficiently at reasonable cost. If any part of this process breaks down, the product fails to deliver these benefits. The lost health and productivity in office environments alone costs U.S. businesses over $400 billion per year (Cramer-Krasselt Research 1996). In addition, operating these "broken" systems is estimated to cost at least 30% of commercial building energy use (more than $45 billion). The key to designing and operating buildings efficiently is the ability to manage information, deliver it in a timely manner to the proper audience, and use it effectively for building design and operation. More intelligently designed and operated buildings use energy more efficiently and thus reduce GHG emissions.

In the intelligent building systems concept, data from the design of the building, together with sensed data, will be used to automatically configure controls and commission (i.e., start up and check out) and operate buildings. Control systems will use advanced, robust techniques based on smaller, cheaper, and more abundant sensors than are in use today. Intelligent devices will use this wealth of data to ensure optimal building performance by continuously controlling and recommissioning building systems using automated tools that detect and diagnose performance anomalies and degradation. Such systems will optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, and report building performance while ensuring that occupant needs for comfort, health, and safety are met at the lowest possible cost.

Such human factors as productivity, health, comfort, safety, and aesthetic acceptance can serve as barriers to advanced technologies that adversely affect (or are perceived to adversely affect) these factors. Conversely, technology options that take these factors into account in a positive way (e.g., cause productivity to increase in an office) will be accepted quickly in the market. Most buildings are in an urban or suburban environment; they affect their local community and are affected by it. Thus research on human factors and community systems is a necessary complement to application of energy-efficient technologies if their full potential for reducing GHG emissions is to be realized. The research on intelligent building systems will also require considerable investment in whole-building demonstrations.

Collateral Benefits

DOE has a remarkable record of "success stories"—cases of federally supported R&D leading to products in the marketplace that have resulted in substantial energy and cost savings. Electronic ballasts for fluorescent lighting, low-emissivity windows, design tools, and advanced HVAC equipment are examples of products resulting from R&D for which the reduction in life-cycle costs from reduced energy use more than compensates for the increase (if any) in first costs. These products have reduced energy costs to consumers by an estimated $28 billion through 1996, many times the cost of all federal R&D on buildings. Additional benefits typically result from energy-efficiency improvements in buildings, including improved indoor air quality, public health and safety, and worker productivity.

Technical Risks and Other Issues

The risks associated with a broadly based research program (technical, economic, commercial, ecological, human health, and regulatory) tend to be low, or can be kept low if proper regard is given to these topics in the research program. A building consists of many components and systems that affect energy use. Therefore, a research line that leads to a technical or economic success is likely to more than compensate for a line that is not successful. The historical experience of federal building energy R&D indicates substantial successes leading to important commercial products that have enabled large reductions in energy use and GHG emissions. There is every indication that continued R&D will lead to continued commercial success.

The ecological impact of buildings energy use is associated with (1) direct emissions of air pollutants from combustion devices and (2) resource extraction, conversion, transport, and the waste streams of conventional energy sources. Energy efficiency and renewable energy measures that reduce GHG emissions will also reduce the ecological impacts. Regulations can either impede or accelerate the introduction of advanced energy technologies in buildings. For example, energy-efficient appliance and building standards are credited with substantial energy savings.

Basic research is very important to buildings technology advances. Areas include "smart" materials for controlling energy flows; optical, thin film, and semiconductor materials for advanced windows, lighting, and flat-panel displays; and advanced techniques for heat transfer.

Strategy and Recommendations

The report *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies* indicates that by the year 2010 a high-energy-efficiency case in the building sector could reduce energy consumption in buildings from 33.7 quads in 1997 to 32 quads in 2010 (relative to the business-as-usual forecast of 36 quads), at a net economic benefit to consumers, if very vigorous efforts are made to bring energy-efficient technologies into widespread market acceptance. A vigorous R&D program is essential to achieve some of the efficiency gains by 2010 and to develop advanced technological options that are cost-effective in the longer term.

2.3.2 Industry

The Potential for Reduced Emissions

Industry's efficient use of energy is critical to the U.S. economy. Through efficient use of energy, the industrial sector also can be a direct contributor to reducing GHG emissions. Industry consumed 34.5 quads of primary energy in 1995—about 38% of all energy used in the United States. It was responsible for emitting the equivalent of 549 MtC during that same year (297 MtC from fossil energy consumption, 167 MtC from electricity consumption, and 85 MtC from other industrial emissions). About 83% of industrial energy is used in the manufacturing sector. Nonmanufacturing industries—including mining, oil and gas extraction, construction, and agriculture—account for about 17%. Within manufacturing, about 80% of the energy used is consumed by a total of just seven highly energy-intensive materials and process industries; the other 20% is consumed by industries primarily engaged in fabrication and assembly. EIA projects that industrial sector end-use energy consumption will remain roughly constant (between 29.1 and 34.4 quads) in the year 2015 even with economic growth. In the longer term, technological advances will play a key role in reducing industrial energy use and GHG emissions. Experts believe that it is possible for some industries (e.g., forest products) to meet all of their energy needs internally by 2010 without purchasing from outside sources.

EIA forecasts that industrial energy efficiency will improve in the future, contributing to the expected decline in energy intensity. The major factors are gradual restructuring of industry toward knowledge-intensive rather than materials-intensive products, higher-capacity use because of improved computer controls, gains in process efficiency, and just-in-time manufacturing methods. Increased on-site power generation using materials currently sent for disposal and noncombustion technologies, such as fuel cells and gasification, will also play a crucial role in reaching energy reduction targets in the industrial sector. Within manufacturing, materials and process industries account for about 80% of the hazardous and toxic wastes and about 95% of nonhazardous wastes. These wastes often impose high cleanup and disposal costs but offer the potential for recovering the "embedded" energy and materials value.

Energy remains an important driver of investment and operating decisions for materials and process industries because of their intensive energy use. Industry spent approximately $104 billion on energy in 1993 and approximately $29 billion for pollution abatement and control. Although this cost represents less than 5% of total costs of operation for all industry, the percentage of costs attributable to energy and waste ranges from about 7% to more than 30% for materials and process industries. It is clear that industry will deploy an energy-reducing technology or process only if it can see the economic benefits. Where such a combination of favorable economics, energy savings, and waste reductions is recognized, the chance of seeing the technology implemented and achieving GHG reductions increases markedly because of accelerated penetration of technologies into the market.

DOE has targeted for its collaborative R&D program the seven materials and process industries (forest products, chemicals, steel, aluminum, metal casting, glass, and petroleum refining).

To plan and direct its research effectively, DOE has initiated the Industries of the Future (IOF) program, which encourages industries to identify their collective high-risk, high-payoff technology needs. This analysis allows DOE and other federal R&D organizations (in particular the Department of Commerce–National Institute of Standards and Technology Advanced Technology Program) to align their resources to best meet those needs. Using this same process, technologies for reducing GHG emissions will be developed in collaboration and cost-shared by industry, thus ensuring accelerated implementation and deployment in industrial processes.

An analysis of the current programs indicates that when implemented, the technologies currently being researched with industrial participation could lead to the following annual reductions.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total industry	25–50	65–95	100–140

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technologies developed through the IOF process and crosscutting technologies under development are likely to be adopted by the seven energy-intensive industries, other nonmanufacturing industries, and, in some cases, all sectors of the U.S. economy. For example, advanced turbine systems (ATSs) are high-efficiency, next-generation gas turbines that produce less carbon per kilowatt hour than technologies used in conventional power markets. ATS deployment will reach an electric-generating capacity of an estimated 24 to 27 GW (4 to 6 MtC) by 2010. Through the National Industrial Competitiveness for Energy, Environment, and Economics program, which DOE is conducting with a more than 55% industry cost share, innovative technologies are introduced in industrial processes, leading to wider use of these technologies. Full deployment of these technologies (currently in their demonstration stage) is expected to result in energy savings of more than 1 quad by 2010.

Technology Pathways and Opportunities

The industrial sector is extraordinarily complex and heterogeneous. The needs are diverse: hundreds of different processes are used to produce millions of different products at many locations throughout the United States. In the U.S. chemicals industry alone, more than 70,000 products are produced at more than 12,000 plants. The primary opportunities to reduce GHG emissions exist in the technologies identified in the IOF program. In addition, redesign of whole facilities with a view toward environmental and energy performance can accelerate the objective of reducing GHGs by completely eliminating some of the production steps now deemed necessary. This new way of thinking may also involve designing for the environment in all steps along the way, from extraction of raw materials through the production stages to the consumption stage.

More than 90% of the carbon emissions from the industrial sector are associated with the conversion and use of energy. Reviewing the industrial needs and opportunities that lie ahead, four major technological pathways have been identified. Figures 2.4 and 2.5 illustrate the relationship among them for the industrial sector.

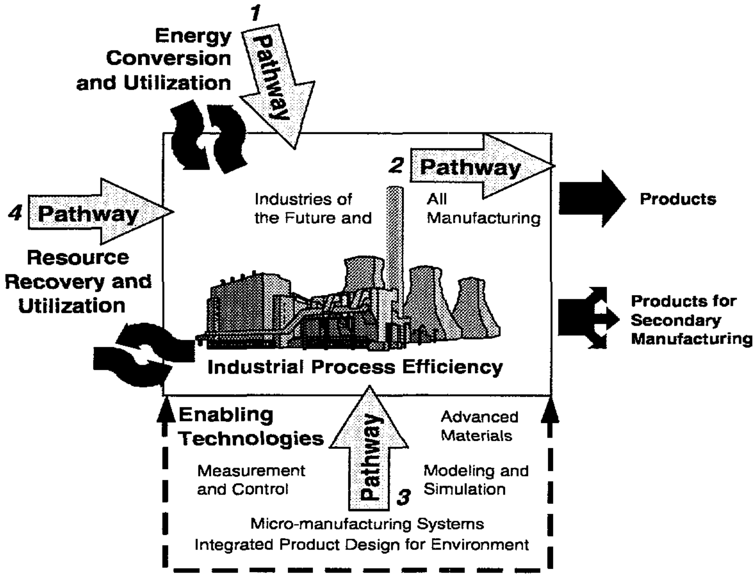

Fig. 2.4. Four technology pathways to increased industrial efficiency.

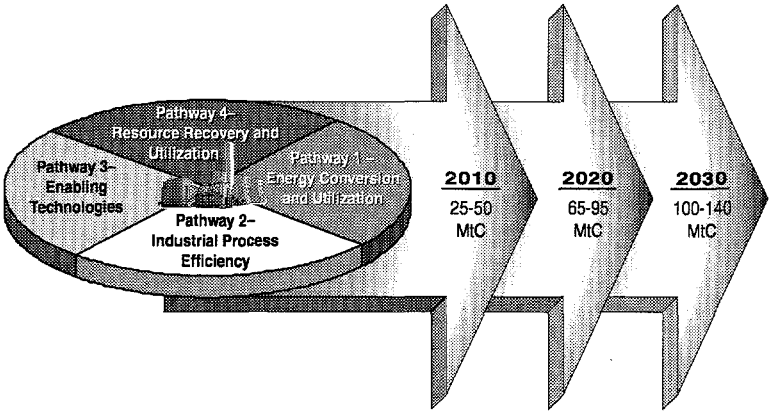

Fig. 2.5. Technology pathways for industry with associated benefits in carbon emission reductions.

Energy Conversion and Utilization. Energy efficiency could be improved through incorporating the best technologies in a systems approach. Technologies include ATSs, fuel cells, higher combustion efficiencies, and using thermal energy in a systems approach to mill/plant design. In the longer term, noncombustion technologies are likely to have a significant impact, such as fuel cells and gasification of biomass and in-plant residues (e.g., black liquor in the forest products industry).

Biobased materials are also discussed under Agriculture and Forestry (Conversion of Biomass to Bioproducts) and Renewable Energy (Solar Advanced Photoconversion). Carbon reduction estimates are included only under Conversion of Biomass to Bioproducts.

Industrial Process Efficiency. Emissions from energy use in industrial processes can be substantially reduced by developing new, more efficient processes as well as by the energy conversion processes mentioned earlier. These more efficient processes can encourage new, higher-quality products, while generating less waste and fewer undesirable by-products; they also offer the potential for increased economic growth. DOE is pursuing many opportunities for improving process efficiency via more selective catalysts, advanced separations, improved measurement and control systems, improved materials, and improved electric motor systems, such as large motors with superconductivity wires. A particularly attractive longer-term opportunity is the use of biotechnology and bioderived materials. DOE is already developing technologies to employ crop and forest materials in the production of chemicals and materials. Other agencies such as the U.S. Department of Agriculture are leaders in evaluating new uses for agricultural goods and conducting research on products from biomass. Large chemical companies, such as Eastman Chemicals, Monsanto Chemicals, and DuPont, have announced that they will pursue bioprocessing and plant-based processing as avenues to the production of chemicals and materials in the future.

Enabling Technologies. Increased fundamental understanding in chemistry, metallurgy, and biotechnology will allow the development of novel manufacturing processes. This knowledge, along with advanced modeling and simulation, improved industrial materials, and measurements (sensors) and intelligent control systems, will result in major incremental improvements and lead to fundamental breakthroughs. Likewise, developing and demonstrating micromanufacturing systems (i.e., mini-mills, micro-chemical reactors) for flexible process configuration and on-site/just-in-place (similar to just-in time) manufacturing can reduce GHG emissions in the long term. Decentralized manufacturing using locally distributed resources offers the advantage of reduced transport of raw materials and finished goods.

Resource Recovery and Utilization. This technology pathway is built upon the idea of an industrial ecology, wherein a community of producers and consumers perform in a closed system. Fossil energy is conserved and/or energy is obtained from non-GHG sources; materials are reused or recycled. Through technological advances, the raw materials and resources needed for manufacturing can be obtained by designing products for ease of disassembly and reuse, using more recycled materials in finished goods, and selecting raw materials to eliminate waste discharge or undesirable by-products. Some examples are developing new advanced polymers, composites, fibers, and ceramics engineering through advances in surface techniques and molecular structures. Another approach is to substitute materials such as biomass feedstocks for petroleum feedstocks in producing chemicals. Some longer-term technological approaches will seek to use CO_2 as a feedstock and non-GHG reductants as substitutes for carbon. Such fundamental changes in the way raw materials are obtained, the properties they exhibit, and the way they are used in the design process are likely to yield energy and GHG savings. Economic success will depend upon industry's using new design approaches and involving the entire supply chain in thinking about energy reduction in the materials life cycle.

Collateral Benefits

Numerous environmental benefits would result from improved industrial process efficiency and waste minimization. In addition to reduced carbon emissions, these collateral benefits include reduced ground-level ozone, less demand for landfill space, and decreased emissions from incinerators and hazardous waste sites. U.S. industries would also be better prepared to compete in the $400 billion international market for environmental technologies.

Technical Risks and Other Issues

Industry faces a number of risks (technical, regulatory, financial) in addition to the risk posed by international competitiveness. U.S. industry has met the challenges of higher productivity and increased profitability, as evidenced by the increase in market value of U.S. industries. Consolidation and integration in industry is an ongoing process that keeps the industrial sector focused on its costs. The technical risks in general are low, while the regulatory and financial risks are relatively high. International competition is moderate to high, leading U.S. industry to increase production capacity in other countries and increase market share. Environmental and economic pressures will continue to encourage industry in other countries to employ new technologies also, as the technical and economic risks are reduced through R&D.

Strategy and Recommendations

The IOF program provides an excellent foundation of strategic public–private R&D alliances for achieving GHG reduction goals in the energy-intensive industries. These alliances need to be extended to embrace climate change mitigation goals. Different types of public–private R&D partnerships are needed to reduce GHG emissions in the light manufacturing sector. Finally, utility restructuring may challenge industrial self-generation and power sales using advanced industrial turbines integrated with combined-cycle generation or with noncombustion generation techniques such as fuel cells.

2.3.3 Transportation

The Potential for Reduced Emissions

Accounting for 32% of U.S. CO_2 emissions and 26% of energy use, and almost totally dependent on petroleum fuels, the transportation sector presents significant opportunities and challenges for advanced technology. Opportunities lie in the continuous improvement of conventional vehicle technologies; in the promise of new, revolutionary propulsion systems and alternative fuels; and in the application of information technologies to manage and integrate intermodal transport systems in innovative and more efficient ways. Advances in information technology create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well-being and the overall quality of life.

Improvements and new technologies in transportation can make substantial reductions in GHG emissions, as shown in this table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total transportation	40–70	100–180	200–300

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Advanced Conventional Vehicles. The modern internal combustion engine vehicle has made significant technological advances during the past three decades, yet the potential for technology to further reduce the environmental impacts of conventional vehicles is far from exhausted. The direct-injection stratified-charge gasoline engine and the turbocharged direct-injection diesel engine offer efficiency improvements of 15% to 30% over conventional gasoline engines; these technologies are already in commercial production outside the United States. Relatively high NO_x and particulate emissions and additional cost hinder their penetration into U.S. markets; improved NO_x catalysts must be developed and particulate emissions reduced. Replacing gasoline engines in light trucks, vans, and sport utility vehicles with more efficient diesel engines represents a significant opportunity to reduce carbon emissions from the transportation sector.

Lightweight materials, from aluminum to carbon fiber composites, have the potential to reduce vehicle weight but pose significant problems with respect to low-cost fabrication and recycling. Improved aerodynamic design, lightweight materials, and improved tires could help to double the efficiency of new passenger cars and light trucks during the next 10 to 15 years, cutting the transport sector's carbon emission by one-fourth. Many of these technologies are currently under development by the Partnership for a New Generation of Vehicles (PNGV) program and by foreign competitors, but considering that the expected life of a passenger car is nearly 14 years, implementing such changes would require more than a decade.

Hybrid, Electric, and Fuel Cell Vehicles. Developing commercially viable, mass-market electric-drive vehicles (EVs) would free the automobile from dependence on carbon-based liquid fuels while simultaneously reducing vehicular emissions. Hybrid vehicles (HEVs), the PNGV design of choice to achieve triple the miles per gallon of the conventional passenger car, combine electric drive with an auxiliary power unit and energy storage device (e.g., battery). A heat engine could be used as the auxiliary power source, but if fuel cell technology could be sufficiently advanced and the infrastructure for supplying hydrogen fuel developed, a potentially pollution-free propulsion system would be available.

HEVs, EVs, and fuel cell vehicles all face formidable technical hurdles, many of which they share. Developing low-cost, rapidly rechargeable batteries is a critical factor in the success of HEVs and EVs. Fuel cells will also require cost reductions (on the order of 95%) as well as improvements in energy density and reliability. Recent, dramatic progress in batteries and fuel cells (much of it attributable to the PNGV effort) suggests that commercially competitive EVs can eventually be developed. A U.S. manufacturer has introduced an improved battery-electric vehicle that has been leased to 215 customers; a Japanese manufacturer has introduced a first-generation HEV. Although still prohibitively expensive at U.S. fuel prices, the Japanese HEV showcases the hybrid's potential for very low emissions and high efficiency. Proton-exchange-membrane fuel cells are currently being demonstrated in buses and have shown dramatic improvements during the past few years.

Carbon savings from battery-electric vehicles depend directly on the primary energy sources used to generate electricity. Potential advances in electricity generation technology could make EVs very-low-carbon vehicles. The power plants for HEVs may be fossil-fuel-burning *internal combustion engines* that could run on alternative fuels or could someday be replaced by fuel cells. In any case, an HEV that is three times more efficient would cut carbon emissions by at least two-thirds. Fuel cells may initially run on gasoline or alcohol fuels (reformed to produce hydrogen) and ultimately would use hydrogen stored on board the vehicle.

Which fuels are used and how they are produced will determine whether carbon emissions are reduced by 50 or 100% over those of conventional vehicles.

Freight Vehicles. Freight vehicles—heavy trucks, railroad locomotives, and ships—are the second largest energy consumers in the transport sector after light-duty vehicles. Heavy trucks and locomotives are universally powered by highly efficient (40–45%) diesel power plants. The efficiency of diesel engines could be further improved to 55% by use of such technologies as advanced thermal barrier coatings, high-pressure fuel injection, turbocharging, and reduced-friction and lightweight, high-strength materials. Fuel cells are an especially promising technology for locomotives, where problems of size and fuel storage and reforming are greatly reduced. Emissions of NO_x and particulates remain the greatest barriers to ultrahigh-efficiency diesels, while for fuel cells, cost and the state of development of mobile fuel cell systems present the biggest challenges.

Improvements to heavy truck fuel economy could reduce carbon emissions by 20 to 33%, or by up to 100% for hydrogen-powered fuel cells, depending on how the hydrogen is produced. Because freight vehicles and their power plants have useful lives measured in decades, the transition to low-carbon technologies would require decades.

Alternative Fuel Vehicles. Alternative transportation fuels are those that require substantial changes in conventional infrastructure, whether in fuel production, distribution, and retailing or in vehicles. Most alternative fuels currently under consideration are being explored for their ability to reduce pollutant emissions or displace petroleum and would have modest GHG reduction potential. Fuels such as compressed natural gas and propane can reduce carbon emissions by 10 to 20%, on a full fuel-cycle basis, over conventional gasoline or diesel fuel.

Far more promising from a GHG reduction perspective are biofuels, such as biodiesel produced from soy or rapeseed oils or ethanol or methanol produced from cellulosic feedstocks. Ethanol from cellulosic feedstocks using conversion processes under development by DOE has been independently estimated to produce essentially zero carbon emissions over the full fuel cycle. Vehicle technology for using ethanol and biodiesel is at a relatively advanced stage of development. The chief barriers to widespread use of these fuels are cost and limitations on feedstock production. Recent estimates by DOE indicate that by 2010, 5 to 10 billion gal of cellulosic ethanol could be produced in the United States per year at prices that would make it economical for refiners to use it as an octane-enhancing, oxygenating blend stock, although ethanol still would not be competitive with gasoline as a neat fuel. This 5 to 10 billion gal would produce zero net carbon emissions and displace imported petroleum. (Biomass fuels are also discussed in Renewables Sect. 2.4.4.)

Air And High-speed Ground Transport. Commercial air travel is the second largest and fastest growing energy-using mode of transport. It is also the mode that has achieved the greatest improvements in energy efficiency during the past three decades. Yet commercial air transport is also the most petroleum-dependent mode. Opportunities to replace kerosene jet fuel appear to be many decades away. In the meantime, petroleum displacement in high-speed intercity transport may be achievable by integrating high-speed rail systems with the commercial air network. Operating at 180 to 300 mph, magnetically levitated or steel wheel rail cars could substitute electricity for kerosene in short-distance intercity travel, at the same time relieving both air traffic and highway congestion.

Although air transport has already more than doubled its energy efficiency over the past quarter century, opportunities remain for at least another 50% improvement during the next 25 years. Propfan technology, improved thermodynamic efficiency of turbine engines, hybrid laminar flow control and other aerodynamic improvements, and greater use of lightweight materials could accomplish this 50% improvement, and they are currently under development by NASA and aircraft and engine manufacturers. A potentially important issue for civil aviation will be the advent of a new generation of far more energy-intensive supersonic high-speed civil transports. The unique requirements of supersonic and hypersonic aircraft could eventually drive the development of alternative fuels for commercial transport.

Having the best and most efficient commercial aircraft technology not only would reduce carbon emissions and petroleum use, but also will be critical to keeping the U.S. aircraft industry competitive. The principal impediment to continued efficiency improvement and lower carbon emissions is likely to be the relatively low cost of jet fuel, providing an inadequate incentive to adopt new, more complex, and possibly more costly aircraft technology.

Technical Risks and Other Issues

There are technical challenges to be met in certain areas, including reducing pollutants and improving performance, but there are clear ways to address these challenges. Also, while smaller and lighter vehicles may result from advanced vehicle development, R&D program goals generally specify equal or improved performance, comfort, and safety. Therefore, ecological and human health risks are expected to be low for these advanced technologies. Commercial risks are moderate, led by the success of existing transportation systems and determined global competitors that are investing heavily in the race to develop sustainable transportation technology for the expanding global economy. The ability of U.S. industry to develop clean, efficient, environmentally sustainable technologies for global transport markets will be critical to the competitiveness of the U.S. transportation industry, an industry that accounts for more than one-tenth of U.S. GDP and directly or indirectly employs one U.S. worker in ten. Social risks are moderate in some areas—such as high-speed ground transportation, which may require public subsidy to be economical—and demand reduction—which to date has achieved only modest success.

The revolution in information technology is creating expanding opportunities for efficient transportation alternatives to improve the efficiency of transportation systems and reduce the vehicle miles traveled. Already, railroads, trucking firms, and shipping and air freight companies are using advanced information technology to more efficiently plan and manage their operations. Development of more comprehensive frameworks for intermodal integration could produce still greater efficiency benefits, leading to improved service with less energy use. Telecommuting and electronic marketing are well known examples of virtual travel.

Advances in information technology create new opportunities to increase system-wide efficiency and substitute communication for transportation to enhance economic well-being and the overall quality of life. R&D activities in these areas include continued development of the concept of transportation as an integrated network of physical and electronic services that can be coordinated by systems engineering approaches, by development of such analysis tools as the National Transportation System initiative, and by research that encourages the infusion of information and network technology into transportation operations.

Collateral Benefits

In addition to reducing emissions, the development of these transportation options would reduce pollutant emissions, improve human health, and reduce the nation's dependence on imported petroleum.

Strategy and Recommendations

Advanced technologies offer enormous potential to reduce U.S. and world carbon emissions from transport. Efficiency improvements of 50 to 200% across all modes appear to be possible for new equipment over the next two to three decades. Beyond that point, use of electricity and hydrogen that are not derived from fossil fuels could virtually eliminate carbon emissions from the transport system during the next century, if the necessary technological advances could be made in other sectors. Significant cost and technical barriers remain; however, a technological pathway from the present fossil fuel-dependent transport system to a future globally sustainable system is in sight.

The comprehensive R&D programs described in the transportation pathways would produce substantial economic benefits in the form of avoided costs of GHG mitigation. The concept of efficient transportation alternatives may also have the potential to develop as a significant technology pathway. There would also be important benefits in the form of cleaner air and reduced national dependence on petroleum. To achieve these goals, a significantly greater investment in federal transportation energy R&D budgets would be necessary. Because of the importance of the endeavor and the magnitude of its cost, estimates should be made not in haste, but after carefully and thoroughly planning the full range of R&D efforts required.

2.3.4 Agriculture and Forestry

The Potential for Reduced Emissions

Sustained economic growth depends on having a secure supply of raw materials. Agriculture and forestry can supply additional and renewable resources for industrial production and energy needs. Currently, managed forest and agricultural lands in the United States fix 3.6 billion tonnes of carbon annually from the atmosphere. Most of this carbon is rereleased in short-lived products, and little is used to substitute for fossil-based products.

The primary opportunities to reduce GHG emissions in the agriculture and forestry sector lie in technologies that remove GHG from the atmosphere (carbon sequestration in durable biobased products, soils, and standing crops) and substitution of biomass-based products for fossil-based products. The carbon sequestration and renewable energy sections of this report cover carbon sequestration and biomass-based energy. The focus of this section is on development of biomass to bioproducts technologies (other than fuel) that can further reduce GHG emissions through both biomass substitution and reduced energy and fertilizer consumption.

Technology pathways that offer the best opportunities to realize these GHG emission reductions are conversion of biomass to bioproducts, advanced agricultural systems, and plant/crop engineering, as shown below.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total agriculture and forestry	3–7	15–25	30–45

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Conversion of Biomass to Bioproducts. Annual crops, perennials, and short-rotation woody species represent plant/crop-based resources that are renewable source materials in the food, feed, and fiber industries (National Corn Growers Association 1997). The use of such biomass-based processes to produce materials and products provides a modest but significant reduction in GHGs because biomass-based feedstocks are synthesized from the CO_2 in the atmosphere and petroleum-based feedstocks are not.

Historically, plant/crop resources have seen limited use as industrial feedstocks in fossil material processing systems. However, in the future, biomass-based products are likely to become functional replacements for fossil-derived products with the same level of performance. The technology needs involve the following challenges:

- to use plant/crop-based inputs in modified processing systems
- to develop modified plant/crop production systems to provide desirable feedstocks
- to integrate these approaches to create optimized systems that generate a new economic platform based on the use of plant/crop-derived inputs

The use of plant/crop-based resources requires the development of concepts around “alternative processing” rather than just “alternative sources” for existing processes. New advances in biotechnology and plant genetics, new discoveries in organic synthesis using carbohydrates, and novel materials and micromanufacturing technologies should drive development of these new “alternative processing” options.

Substitution of biomass-based products for fossil-based products has significant potential to reduce U.S. GHG emissions. Additional emissions reductions could come from new markets, chemical production, process improvements, and energy savings. The forest products industry is 63% energy self-sufficient, and the cogeneration techniques it uses could be adapted to other bioindustries.

The barriers to use of biomass-based processes arise from the history of our country’s use of its indigenous resources. While biomass-based feedstocks are employed at competitive costs by the paper- and grain-processing industries, chemical manufacturing systems are optimized for petroleum and natural gas and are not designed to process alternative feedstocks. A successful scenario for using biomass-based processes involves the development of viable manufacturing platforms based on renewable forestry/crop feedstocks. These industries would produce materials and chemicals, such as cosmetics, textiles, and pharmaceuticals, that either would fill their own particular niche or would be integrated into the mainstream fossil-based chemical-processing industry.

Conversion of biomass to bioproducts is also discussed under Industry (Resource Recovery and Utilization) and Renewable Energy (Solar Advanced Photoconversion). Carbon reduction estimates are included only in Resource Recovery and Utilization.

Advanced Agricultural Systems. Agriculture and forest management practices have achieved significant increases in productivity and carbon fixation with decreased energy use. However, intensive agriculture and forestry production continue to add to the emissions of GHG and significantly affect nitrogen, soil carbon, and water biogeochemical cycles. Research should focus both on technologies that continue to increase productivity without increasing GHG emissions and on those which offer the possibility of significantly reducing GHG emissions. Advanced agricultural systems involve ways to deliver adequate quantities of nutrients that are efficiently assimilated by plants and water to maintain photosynthesis and support plant growth. Advanced agricultural systems include sensors, controls and monitoring, improved fertilizers and pesticides, improved delivery systems, genetic design of pest-resistant crops, and control of microbial processes. These technologies will result in increased biomass production for a given area of land with reduced nutrient, water, and energy inputs.

Advanced agricultural systems will lead to small but significant reductions in GHG emissions along with reduced energy consumption and fertilizer use. Currently, 3% of U.S. fossil fuel emissions result from agricultural crop production and only 27% of U.S. agriculture uses low- or no-till systems. Advanced agricultural systems technologies have the potential to significantly increase the use of no- or low-till systems. In addition, technologies that lead to improved fertilizer efficiency could result in significant carbon savings.

Some components of advanced agricultural systems, such as the use of global positioning systems to map yields, are in or close to commercial use. Others, such as real-time monitoring of water and nutrient status, are not. Although fertilizer delivery and chemistry have significantly improved during the last 10 years, advancements in biologically released fertilizers and control of microbial processes still require significant efforts. Detailed real-time and small-area geographic matching of fertilizers and other agricultural chemicals to plant requirements are in the early stages of development. Technologies involving biocontrol of pests are evolving; some are to the point of commercial development.

Plant/Crop Engineering. Plant/crop engineering is expected to contribute to reductions in GHG emissions through improvements in biomass production, carbon sequestration, and biomass conversion to bioproducts. Technologies include

- engineering plants with improved carbon-use efficiency, and therefore increased yield and carbon fixation
- control of physiological processes that determine a plant's ability to grow on low nitrogen and to recycle nitrogen
- manipulation of cell wall structure and assembly to create crops and to produce high-strength structural wood and composites for use in construction
- genetic transformation of desirable genes into target biomass plant species for specific biomass-to-bioproduct conversions

To successfully develop these technologies, basic research is necessary for better understanding of the metabolic pathways that control how plant productivity responds to changes in nutrients, water, and CO_2 concentrations. Research on gene insertion efficiency is also needed across the wide range of species relevant to bioproducts. In addition, gene identification to improve biomass quality is needed and will result from functional genomics research (sequencing and characterization of gene function).

Successful deployment of these technologies will occur only through integration with the development of bioproducts technologies and advanced agricultural technologies. Transgenic varieties and common crops are being introduced that are resistant to specific diseases and pests and that require smaller amounts of nutrients and water. They constitute a significant advancement in this field. Ecosystem assessments are needed as these new varieties are introduced. Because of the strong interdependency among advanced agricultural systems, the production of bioproducts, and plant/crop engineering, the carbon savings that can be realized with plant engineering are incorporated into the carbon savings reported in this section.

Strategy and Recommendations

Integrated research, both basic and applied, needs to be pursued in cooperation with commercial agricultural and forest sectors as well as with manufacturing industries. Key objectives should include integrated systems management and improvement of agriculture and forestry sustainability and cost-competitiveness.

Technical Risks and Other Issues

The rate of fundamental plant engineering research is limiting; it is inherently slow because of the life cycles of plants (especially trees). Ecological, commercial, and economic risks include the availability of and competition for land among agriculture, forestry, cities, and recreational areas. Trade-offs between food-feed-fiber and chemicals production have not been fully evaluated, and the environmental impacts of increased land cultivation will have to be carefully considered.

2.4 CLEAN ENERGY

The development and use of advanced energy production technologies has a large potential for reducing GHG emissions without increasing energy costs. Technological approaches include using fuels with lower or zero carbon content; increasing the useful energy output per unit of carbon emitted; and capturing carbon emissions to prevent their entry into the atmosphere. With successful development, these advanced technologies generally have the potential to reduce carbon emissions by 25 to 50% or more in the time frame beyond 2020. Their potential for carbon emission reductions by 2010 is considerably more limited because of stock turnover rates in energy production.

These advanced energy production technologies are described in four technology areas:

- fossil resource development
- fossil power generation
- nuclear energy
- renewables

2.4.1 Fossil Resource Development

The Potential for Reduced Emissions

Fossil energy dominates the nation's and the world's energy supplies and is likely to do so for the foreseeable future. It provides more than 87% of the nation's energy (40% oil, 25% natural gas, and 22% coal; Fig. 2.6) and about 90% of the world's energy (40% oil, 23% natural gas, and 27% coal). Because the nation's economy is so heavily reliant on each of these three fuels, altering this fuel mix will require at least two decades of dedicated technical and infrastructure development.

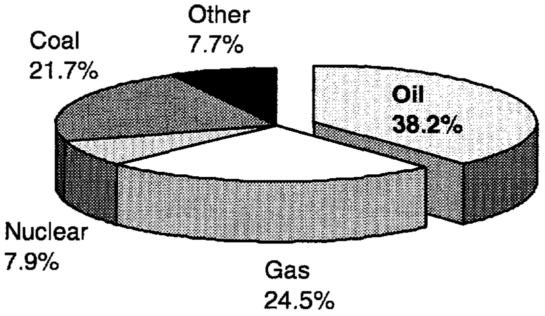

Fig. 2.6. Fossil fuels account for most of the energy used in the United States.

Because of the desire to reduce CO_2 emissions per unit of energy expended, fossil fuels containing a lower carbon:hydrogen ratio need to be developed. Therefore, any major clean fossil-fuel-based alternative energy plan must center on enhanced production of natural gas and the efficient conversion of abundant fossil feedstocks into electricity, clean liquid transportation fuels, and chemical feedstocks whose impact would be to reduce net CO_2 emissions compared with current sources for these commodities. Coal reserves are expected to last for many hundreds of years, and increasing amounts of natural gas are being discovered. Estimates of the impact of new technologies on carbon emissions are shown in this table.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total fossil resource development	15–30	80–115	115–225

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

Energy Efficiency for Crude Oil Refining. Developing technology to increase the efficiency of converting crude oil to transportation fuels, and separating and using valuable components of refinery off-gases (light hydrocarbons) would have a significant impact on increasing liquid hydrocarbon utilization efficiency. Because the United States produces significant quantities of heavy oil, an improved refining process could add $1 to $2 per barrel to the value of this oil. Capturing off-gases produced during refining adds value to the process and eliminates GHGs that are more damaging per molecular weight than CO_2.

Natural Gas to Liquids. The cost-effective conversion of natural gas to clean liquid transportation fuels and commodity chemicals offers a significant potential for GHG emissions reduction while allowing greater use of domestic natural gas supplies. Breakthrough technologies under development include deriving diesel fuel from natural gas (far exceeds conventional diesel fuels in emission reductions), converting natural gas or synthesis gas to methanol or gasoline, and converting gas to liquefied natural gas in remote areas at commercial efficiencies using thermoacoustic refrigeration technology.

Increased Natural Gas Production. The nation (and North America) has abundant natural gas resources that help to fuel the industrial and electric power sectors. It needs only the development of new technology to make natural gas available as a substitute for some oil consumption in transportation fuel markets and for coal use in electricity generation. Current U.S. natural gas supplies can be augmented in the near term through secondary gas recovery (230 tcf); in the mid-term through low-permeability formation development (500 tcf), offshore supplies (100 tcf), and coalbed methane (400 tcf); and in the long term by exploiting currently untapped methane hydrates (2700 tcf) and deep-source gas (3000 tcf). Only a moderate success rate would be needed to effectively meet the expected demand of 28 tcf in 2010.

Co-Production with Integrated Gasification Combined Cycle. To make full use of abundant supplies of low-cost solid fuels, the integrated gasification combined cycle (IGCC) process represents a unique combination of technologies that offers industry low-cost, highly efficient options for meeting a variety of market requirements. Compared with today's commercial and advanced technologies, IGCC is one of the most efficient and environmentally friendly technologies for the production of low-cost electricity and is capable of processing a number of feedstocks including coal, petroleum coke, biomass, and municipal wastes. The IGCC system, operated in conjunction with steam reforming, is capable of producing a stream rich in H_2 with only a CO_2 byproduct (which is ready for sequestration). In combination with synthesis gas conversion technologies, it is the only advanced power generation technology that is capable of coproducing a wide variety of commodity and premium products in addition to power to meet future market requirements.

Through coproduction, other products can be obtained either by processing the feedstock before gasification to extract valuable components or by converting the synthesis gas to products. With feedstocks such as coal, valuable precursors can be extracted for the production of high-strength, lightweight carbon fibers and of anode coke for manufacturing industries. Clean synthesis gas can be catalytically converted into environmentally superior transportation fuels, high-value chemicals, or hydrogen.

Numerous IGCC gasification demonstration projects using coal, petroleum coke, or other petroleum refinery wastes are currently in operation or under construction both in the United States and worldwide. Many of these facilities have been designed for operation in the coproduction mode, whereby improved thermal efficiencies can be gained.

The conversion of coal-based synthesis gas to transportation fuels has been the subject of investigation for several decades; however, significant recent advances in catalysis and reactor design are generating considerable interest from industry. The environmental superiority of the resulting transportation fuels—which have substantially reduced emissions of hydrocarbons, carbon monoxide, and particulates—has been demonstrated; and they are recognized as a key ingredient for meeting future environmental regulations in the transportation sector.

CO_2 for Improved Oil and Gas Recovery. From a carbon management perspective, improvements in reducing GHG emissions could be attributed to flooding petroleum reservoirs with recycled CO_2 and minimizing fugitive gas emissions from pipelines and other remote sites. CO_2 is pumped into oil reservoirs to enhance the recovery of petroleum. Instead of present practice, CO_2 that would otherwise be emitted to the atmosphere (from fossil fuel combustors) could be captured and used to enhance energy recovery. In the future, CO_2 contained within power plant stack gases could also be pumped into coal seams to recover methane economically or to replace base gas in storage wells. Estimates have placed the sequestration potential of this approach at 50 MtC/year.

Tracers can be developed to identify fugitive emissions of methane from refineries and pipelines. Backscatter absorption gas imaging and light detection and ranging (LIDAR) technologies have recently proved effective in imaging methane plumes at remote distances and concentrations in the part-per-million range. Recent improvements in LIDAR systems for national security missions should be applicable to fugitive gases as well. The GHG reduction potential of eliminating leaks has been estimated at 12 MtC/year in the United States.

Crosscutting Technologies. Technologies that affect the conversion of abundant fossil fuels to liquids are very important for reducing GHG emissions. Some of the most significant challenges are the identification of new catalyst compositions to promote the efficient synthesis of diesel fuel and the production of chemical feedstocks from natural gas or coal. Additionally, the use of predictive simulation and concurrent process development of various schemes to determine the most economical configuration merit further attention.

The following areas should also be investigated:

- optimizing an integrated process using ion-transport membranes for conversion of natural gas to synthesis gas, followed by the conversion of synthesis gas to transportation fuels
- addressing the broad range of technical issues related to commercial scale-up in remote locations
- demonstrating high daily production of liquefied natural gas from sources previously vented to the atmosphere, using improved thermoacoustic refrigeration

Increased natural gas production in the short term will result from incremental improvements in drilling, completion, and stimulation technology; improved seismic imaging of natural fracture systems; fracture access to low-permeability formations; and enhanced methane drainage from coalbeds (perhaps stimulated by CO_2 or flue gas injection). In the intermediate time frame, conversion of natural gas from the North Slope of Alaska or other remote sites into a high-quality liquid fuel that is moved by pipeline to a distribution infrastructure would have the greatest impact on increasing natural gas production. (This technique will be keyed to the success of the gas-to-liquids effort.)

In the long term, entirely new technology will be required to map and produce undersea methane hydrates and perhaps even deep-source gas. Gas hydrates are physical combinations of hydrocarbon gas (predominantly methane) and water that are classified as clathrates. They represent a potential energy source greater in volume than all known oil, gas, and coal deposits combined. No technology exists to extract methane from these undersea deposits, but there recently has been some resurgence of interest in this resource in the United States and internationally.

Efficiency improvements in crude oil refining and processing will be keyed to new catalysts with improved efficiencies and selectivities, advanced membrane separation methods with high throughputs and high separation factors, and the development of pretreatment conversion technologies that would allow more heavy oil to be converted to higher-value, efficient transportation fuels. Advanced inorganic membranes that could be used to separate and utilize refinery off-gases would be particularly valuable.

An extension of this work would be improved gas-gas separations, particularly the separation of air into oxygen and nitrogen and the separation of CO_2 from nitrogen in very large-scale flows. Development of these high-throughput gas separation technologies would allow recycled CO_2 from fossil fuel combustors to replace CO_2 that is produced from dedicated production wells.

Collateral Benefits

Improved crude oil refining processes would eliminate GHGs that are considerably more damaging than CO_2. Converting coal-based synthesis gas to transportation fuels would reduce several pollutants compared with conventional fuels, as would using CO_2 for improved oil and gas recovery. Increased natural gas production would enhance energy security, as would IGCC systems. IGCC would also coproduce a variety of products in addition to power, creating new jobs.

Technical Risks and Other Issues

Technical and commercial risk ranges from low to challenging, depending on the pathway. For example, natural gas-to-liquids conversion and crude oil efficiency improvements face scale-up problems; increased natural gas production may require demonstrations; and IGCC requires advanced materials and technologies for membranes and filters. Ecological risk is generally low to moderate, and human health risks would be lower than for current technology.

Strategy and Recommendations

While natural gas is expected to capture an increasing share of the new market for fossil fuels during the next decade, the 2010–2020 time frame should usher in a significantly larger potential for natural gas and for more highly efficient coal-based IGCC technologies. If research efforts were well funded and successful, breakthrough developments in catalysts, simulations, membrane separations, and overall gas-to-liquids conversion (including IGCC-based) technology would be pilot-scale tested by 2010. Allowing for further improvements and scale-up to commercial size plants, a major impact could be expected by 2020.

Increased natural gas production to satisfy these needs can be seen as taking place over three time periods. Near term improvements would be seen through incremental improvement of extractive technologies, such as drilling, completion, and reservoir stimulation technology; seismic imaging of fracture systems; access to low-permeability formations; and enhanced methane drainage from coalbeds (via CO_2 injection).

Intermediate term improvements in production would occur through increased use of Alaskan natural gas, or natural gas from other remote resources, via the transport of a liquefied product. Finally, long-term contributions can be expected from the use of vast undersea methane hydrates. Currently, no known technology exists to extract methane from these undersea deposits.

Liquid fuels from Alaskan natural gas may even be ahead of this schedule. The commercial success of the gas-to-liquids industry would spur even greater increases in natural gas production beyond 2020, including the first contributions from undersea methane hydrates.

Development of a large-scale, oil-competitive, commercial gas-to-liquids industry (natural gas and coal-based) offers the highest technical risk. Research on this topic has been ongoing for decades, and although some commercial plants are in operation, much remains to be accomplished. In addition, long-term R&D in major oil companies continues to decrease (Fig. 2.7), which does not bode well for the implementation of new high-technology programs.

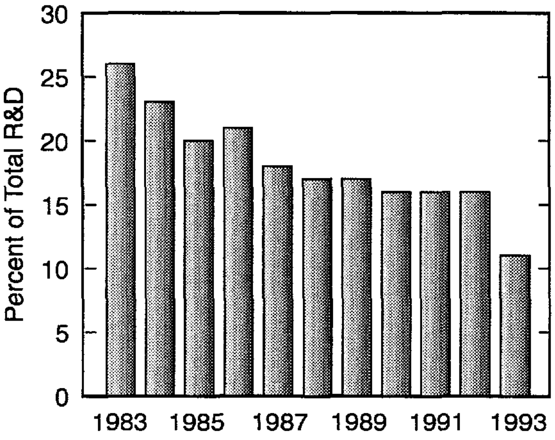

Fig. 2.7. Long-term R&D in major oil companies continues to decline.

Efficiency improvements in crude oil refining and processing pose a high level of commercial risk. As shown in Fig. 2.8, 46% of domestic refineries have closed since 1981, many because of perceived environmental problems. Reconfiguring a new domestic refinery industry will entail very significant commercial risks.

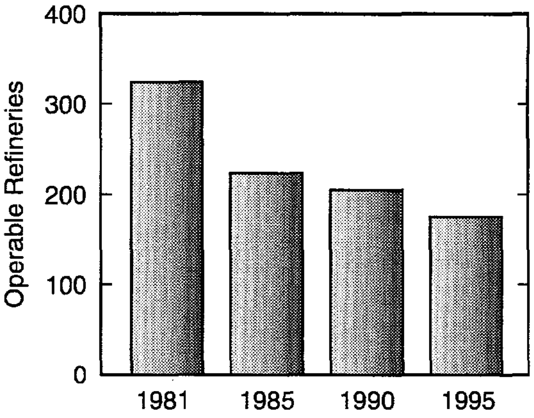

Fig. 2.8. Operable refineries in the United States.

2.4.2 Fossil Power Generation

Today, coal supplies 55% of electricity, while natural gas makes a small contribution to U.S. electricity needs. By 2015, EIA predicts that coal will still account for 50% of electricity, but that the contribution of natural gas will rise to 20%. EIA also predicts that, barring significant technology developments or policy changes, carbon emissions from coal will rise from 460 to 550 MtC between 1995 and 2015, while carbon emissions from natural gas for power generation will rise from 50 to 125 MtC during that period.

The Potential for Reduced Emissions

To reduce this projected increase in carbon emissions, several approaches are being studied. Low-cost approaches to reduce emissions from existing plants include cofiring with natural gas or biomass; reburning to reduce NO_x; and land-based capture of CO_2 to be used in aquaculture, pharmaceuticals, or waste encapsulation. However, for a major impact on emissions, more advanced technologies are being developed that have excellent potential to reduce carbon via more efficient power generation in the near, mid, and long terms, based on the success of ongoing research and development efforts. Estimates are shown in the table below.

Estimated carbon emissions reductions (MtC/year)

	2010	2020	2030
Total fossil power	0–20	40–90	110–185

Assumes successful technology development and subsequent marketplace adoption without significant policy changes.

Technology Pathways and Opportunities

The three fossil power generation pathways that are outlined in Appendix B represent a broad technology portfolio that could reduce GHG emissions in the near term and accelerate these reductions as new technologies are phased in at normal or near-normal replacement rates in the mid and long terms. All technologies within this portfolio are targeted for availability within the first third of the next century, but the success of these pathways depends on the success of ongoing R&D efforts.

High-Efficiency Coal-Based Technologies. It is unlikely that high-efficiency coal-based technologies would achieve significant market penetration before 2010. But by 2020, introduction of high-efficiency coal-based technologies could significantly reduce carbon emissions. By 2050, total carbon emissions could be below those produced from the electricity sector in 1990 (a reduction of about 210 MtC/year).

The high-efficiency coal-based pathway increases power generation cycle efficiency by combining two or more advanced energy conversion cycles. Ideas being developed include low-emission boiler systems, pressurized fluidized bed combustion, IGCC, and high-efficiency power systems. Goals are to increase conversion efficiencies from around 33% to 42% in 2000 to more than 55% in 2010, at a cost considerably lower ($0.03/kWh) than today's pulverized coal costs and with pollutant emissions at one-third to one-tenth of current new-source performance standards. These technologies may have additional potential for performance improvement of up to 60%, depending on the success of ongoing basic research. An area where primary technology development is needed is high-temperature materials that are stable and that resist corrosion, erosion, and decrepitation so that they can be used for heat exchangers, turbine components, particulate filters, and SO_x removal. Other challenges include the use of alternate working fluids for turbine and heat-exchange cycles, cycle optimization environmental control technologies with low energy penalties, and solids handling.

Low-Carbon Fuels. Low- or no-carbon fuels—such as natural gas, synthesis gas, or hydrogen—used in the technologies being proposed for accelerated development in this initiative could lead to a significant reduction of carbon emissions after 2020.

Fuel cells and gas turbines are currently in use, taking advantage of plentiful supplies of natural gas.

However, neither technology has reached its potential. For gas turbines, the R&D goals are to lower bus-bar energy costs to 10% less than costs for current state-of-the-art technology and to develop ATSs and gasification adaptation technology by 2010. Improvements in blade cooling and materials will be required to move these technologies beyond the current practice, and considerable development is required before they will be capable of high performance when firing hydrogen. Also, further improvements are needed to avoid increasing NO_x emissions as operating temperatures rise. For industrial applications, small and medium-sized turbines are being developed to achieve a 15% improvement in efficiency over vintage equipment. These may supply distributed generation of power to serve customers unable to obtain needed power from the transmission grid, or they may be employed in industry to contribute both power and heat. Advanced turbines and industrial cogeneration are important technologies for both industrial efficiency and fossil power and are counted for the purpose of emissions projections in industrial efficiency.

Fuel cells represent another gas-fueled technology. Recent successes have shown the potential to build larger stacks of fuel cells, leading to larger generating capacity, but costs need to be reduced to make them competitive. Performance targets include developing market-ready fuel cell systems with efficiencies higher than 50%; adapting them to operate on synthesis gases from coal and other solids; and validating the hybrid fuel cell/advanced gas turbine system that could have efficiencies approaching 70% by 2010. Demonstration of advanced turbines on hydrogen alone or in some hybrid cycle is expected to occur between 2020 and 2030. Additional effort would be required to address all the system integration issues identified in these two validation steps.

Energyplexes. These two pathways, high-efficiency coal and low-carbon fuels, converge in a third group of technologies that integrates production of power, fuels, and /or chemicals, maximizing use of available energy. It would create "energyplexes," a type of industrial ecosystem. An energyplex is a series of modular plants capable of coproducing power and chemicals or fuels that can be integrated to use local sources of carbon (coal, biomass, municipal solid waste) as fuel and feedstocks. Eventually, modules would be included for capture and sequestration of CO_2.

These energyplexes would feature high efficiencies of carbon use, essentially zero carbon emissions, and cost-competitive power. Unlike the first two pathways, which focus on electricity generation, this pathway strives to optimize the entire cycle of carbon utilization by incorporating coprocessing concepts and the tenets of industrial ecology. Energyplexes would have essentially zero carbon emissions and could result in 100% reduction of carbon after 2030.

Substantial benefits are possible when carbon sequestration strategies are coupled with advanced energy production systems. Fossil fuel production and conversion facilities that either integrate cost-effective sequestration into the facility design or incorporate an equivalent offset can achieve zero net CO_2 emissions. If this zero emission strategy were applied to all new fossil fuel energy production facilities after 2010, the cumulative reductions (carbon emissions avoided), in addition to those realized from advanced efficiency systems, would be about 4 GtC by 2030 in the United States alone. This estimate was derived by extrapolating the EIA *Annual Energy Outlook 1997* projection to 2050 as the baseline, or business-as-usual, scenario (EIA 1996a). Commensurate benefits could be realized if sequestration were implemented worldwide for fuels production as well.

This pathway challenges the R&D community to make significant technology breakthroughs—or "grand challenges"—such as novel industrial process configurations, novel power cycles, and coproduction of heat and power, with suitable energy-efficient reuse or disposal options for carbon and CO_2. A series of activities are envisioned that would develop a portfolio of breakthrough technologies by 2015, including coal liquefaction, development and validation of combinations of fuel cells and advanced gas turbines, and validation of fuel cell systems incorporating carbon capturing and/or reuse methods. Between 2015 and 2030, system integration issues and larger-scale testing would be needed to bring this approach to the point of commercialization.

Along with developing cost-effective CO_2 capture methods for this pathway, including similar methods in the technologies from the first two pathways could lead to additional reductions. Typically, CO_2 may be captured by chemical, biological, or physical means. CO_2 capture is a common practice in some process industries, where the process usually occurs in some type of chemical absorber. In addition, biological systems capture CO_2 by conventional means and use it as a nutrient for growth of algae or other simple organisms. Finally, cryogenic processes, membrane processes, and adsorption using molecular sieves are physical means to capture CO_2, but these are only cost effective if the CO_2 exists at a high concentration in the effluent stream.

Research needs that have been identified in CO_2 capture include (1) means to concentrate the CO_2 which will facilitate existing capture processes and (2) improvements in chemical absorption, including identification of improved solvents and advances in contacting methods to reduce the size and cost of process vessels. Means to concentrate CO_2 could include use of a blend of pure oxygen and recycled CO_2 as a replacement for air in the combustion processes under development. Furthermore, IGCC system concepts could be carried to the point where they produce a product stream of only CO_2 and hydrogen. Improved separation techniques for the hydrogen would then leave a concentrated CO_2 stream, which would be available for further processing.

Currently, CO_2 capture technologies would impose an energy penalty of approximately 30% on a coal-fired plant if one sought 90% capture. Improvements in existing approaches could reduce this penalty to 9%. This pathway would encompass research to blend high-efficiency power production with fuel and chemical production. This synergistic approach is based on analyses that indicate that a closed carbon system could be developed having a competitive levelized cost of electricity for the period after 2025.

Technical Risks and Other Issues

The highest risks associated with the high-efficiency coal-based pathway are commercial and economic because of formidable competition with domestic natural gas and international coal technologies. There is a near-term critical window of time to achieve long-