

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

SAT 1/24/98

Todd - Here's a quick review of the latest version of the 11-Lab Study.

As you can see from the quick comments I assembled, this report can be quite unhelpful to our Kyoto position.

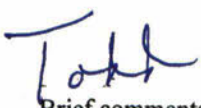
When it last appeared on the horizon, TJ called DOE & said the 11-Lab Study would have to go through interagency OMB review just like the 5-LAB study did so all WH agencies could review assumptions & conclusions. I think you should continue to insist on this! That requires at least 2 weeks.

This report has been widely thought to be a justification for all 11 Labs to stay in business indefinitely -- it is a "Christmas tree" of options & technologies ... (over)

Rosina

P.S.

Several months ago (November, I think) Jack spoke to Peña & told him this report would only confuse policy discussions & Peña seemed to agree that it need not come out. You & I had an e-mail exchange around that time too. Why can't it remain an internal planning document & not be published (no one ever asked for it - Peña just decided to do it). And, remember DOE is producing a National Energy Strategy, which is unlikely to be very similar to this!

MEMO: 
TO:
RE: Brief comments on Draft 11-lab study
DATE: January 24, 1998

p. xiv, middle: There is no discussion of the improved technologies that are available now and that could be put into place in the near term, nor the potential carbon reductions that could be achieved. By considering only new technologies that the labs could help bring on-line (and a discussion is needed of the role and interaction with industry as a partner) over the next decade or two, the presentation throughout the report significantly understates the potential carbon reductions, overstates how long it will take to put the technologies into place from a technology development perspective (although perhaps not from the perspective of the capital stock turnover times for the economy), and largely ignores the huge amount of institutional learning and policy tool development that is needed to realize carbon reductions. The report does explicitly state repeatedly that it only considers technology development and technology push strategies, but by indicating the carbon reduction from that alone, it is easy to take out of context that the Administration goals are not achievable.

p. xiv bottom: "by 2030, a vigorous RD&D program could deliver a wide range of cost-effective technologies that together could reduce the nation's carbon emissions by 400-800 million metric tonnes of carbon per year"

Note that the EIA Annual Energy Outlook puts 2010 carbon emissions at about 1800 MMTcE, above the roughly 1340 MMTcE in 1990. Thus, just to get to 1990 levels for carbon emissions requires a reduction by 2010 of 460 MMTcE. *Again, implies Kyoto impossible for U.S.*

p.1-2 first bullet: I believe that this statement, "advances in sci and tech are necessary to reduce GHG..." is probably true, but the report does not prove it and the analysis by Repetto and others would suggest that the linkage is not as strong as suggested here.

p.1-6, bottom right: "one survey of a number of energy economic models shows that the cost of stabilizing US emissions at 1990 levels by the year 2010 ranges between 0.2% and .75% of GDP, or roughly \$20B to \$75B (Gaskins and Weyant, 1993)" Problems with this statement include: (1) the Repetto work shows that these costs are not correct; the cost is a function of the policies put into place; (2) there is a huge literature beyond this that is much more recent that should be referred to; this statement seems to be unaware of that; (3) the work only appears to consider carbon taxes and ignores other policies and mechanisms; (4) etc. etc. etc..

p.2-5: Projections are substantially different than EIA Annual Energy Outlook 1998

p.2-8 and following: Tables could be used to construct the same figure that caused so much consternation the last time and could be misconstrued to attack the Administration position on the possibility of achieving the Kyoto targets

Throughout this report, there is little or no discussion of methodology and how the carbon savings projections were arrived at.

p.2-32: This is the ongoing push by some to move the nuclear agenda forward without acknowledging the problems of radioactive waste, safety, the poor economics – electricity from nuclear plants currently costs more than twice as much as for natural gas combined cycle systems—and proliferation problems. This discussion is not at all balanced.

p.2-36: The projections of potential savings by renewables are substantial underestimates compared to the PCAST report of what is possible—e.g, offsetting coal use with wind/storage systems by 2030.

TECHNOLOGY OPPORTUNITIES TO REDUCE U.S. GREENHOUSE GAS EMISSIONS

December 1997

Prepared by

**U.S. Department of Energy
National Laboratory Directors**

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.

CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	ix
ACRONYMS, ABBREVIATIONS, AND INITIALISMS	xi
EXECUTIVE SUMMARY	xiii
1. INTRODUCTION	1-1
1.1 GREENHOUSE GAS EMISSIONS AND ENERGY	1-3
1.2 THE ROLE OF TECHNOLOGY	1-5
1.3 STUDIES OF CLIMATE CHANGE AND TECHNOLOGY	1-6
1.4 ABOUT THIS STUDY	1-8
1.5 REFERENCES	1-10
2. TECHNOLOGY PATHWAYS	2-1
2.1 CARBON LEVELS: PRESENT AND FUTURE	2-3
2.1.1 Technology Approaches	2-3
2.1.2 Assumptions	2-5
2.2 ENERGY EFFICIENCY	2-7
2.2.1 Buildings	2-8
2.2.2 Industry	2-11
2.2.3 Transportation	2-16
2.2.4 Agriculture and Forestry	2-20
2.3 CLEAN ENERGY	2-23
2.3.1 Fossil Resource Development	2-23
2.3.2 Fossil Power Generation	2-28
2.3.3 Nuclear Energy	2-32
2.3.4 Renewable Energy	2-35
2.4 CARBON SEQUESTRATION AND MANAGEMENT	2-40
2.5 REFERENCES	2-44
3. BASIC AND APPLIED RESEARCH AND CROSSCUTTING TECHNOLOGIES	3-1
3.1 RESEARCH TO ADVANCE UNDERSTANDING OF THE GLOBAL CARBON CYCLE	3-3
3.1.1 Global Carbon Cycle Modeling and Measurement	3-3
3.2 BASIC RESEARCH RELATED TO GREENHOUSE GAS EMISSIONS	3-4
3.2.1 Materials Science	3-5
3.2.2 Chemical Sciences	3-6
3.2.3 Biotechnology	3-7
3.2.4 Geosciences	3-8

3.2.5 Environmental and Ecological Sciences	3-8
3.2.6 Nuclear Sciences	3-8
3.2.7 Computational Sciences	3-9
3.3 CROSSCUTTING TECHNOLOGIES SUPPORTING GREENHOUSE GAS REDUCTIONS	3-10
3.3.1 Hydrogen and Fuel Cells	3-10
3.3.2 Electrical Transmission, Distribution, and Components	3-11
3.3.3 Sensors and Controls	3-12
3.3.4 Energy Storage	3-13
3.4 REFERENCES	3-14
4. TECHNOLOGY INNOVATION APPROACHES	4-1
4.1 INTRODUCTION	4-1
4.2 APPROACHES	4-1
4.2.1 Government Led and Financed Approach	4-2
4.2.2 Industry Led and Financed Approach	4-3
4.2.3 Public-Private Strategic Alliances	4-3
4.3 STRATEGIC ALLIANCE ROLES	4-5
4.4 CONCLUSION	4-6
4.5 REFERENCES	4-7
5. SYNTHESIS AND MOVING FORWARD	5-1
5.1 SYNTHESIS	5-1
5.1.1 The RD&D Path to Carbon Stabilization	5-1
5.1.2 Factors Influencing GHG Reduction Potential	5-4
5.1.3 The Time-Line of Technology Products	5-8
5.1.4 Performance Goals	5-11
5.1.5 Basic and Applied Research Are Needed	5-12
5.1.6 Collateral Benefits and Costs	5-13
5.1.7 Research, Development, and Demonstration Resources	5-14
5.2 MOVING FORWARD	5-15
5.3 CONCLUSION	5-16
5.4 REFERENCES	5-17
Appendix A. Contributors	A-1

Appendix B. Climate Change Technology Pathways
(Forthcoming)

FIGURES

Figure	Page
1.1 Technology and policy components for a climate change strategy	1-3
1.2 The burning of fossil fuel and changing land use have resulted in human-induced alterations of the global carbon cycle	1-4
1.3 Overview of the sources of carbon emissions in the United States in 1995	1-5
2.1 Alternative technological opportunities for reducing greenhouse gas emissions	2-1
2.2 Sources of greenhouse gas emissions in the United States in 1995	2-3
2.3 Projected U.S. carbon dioxide emissions	2-6
2.4 Four technology pathways to increased industrial efficiency	2-13
2.5 Technology pathways for industry with associated benefits in carbon emission reductions	2-14
2.6 Long-term R&D in major oil companies continues to decline	2-27
2.7 Operable refineries in the United States	2-28
2.8 Relationship between CO ₂ release and electricity production in France, 1973-1996	2-32
2.9 Carbon emissions avoided under various scenarios of nuclear electricity generation	2-33
2.10 Renewables have the potential for significant reductions of U.S. carbon emissions	2-36
2.11 Renewable energy technologies are well along a path of decreasing costs	2-37
3.1 Ceramic composite hot gas candle filters can be used to remove particulates from gas streams in combined cycle fossil and biomass power facilities	3-5

3.2	This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur	3-9
3.3	Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate	3-10
4.1	Interactive model of innovation	4-5
4.2	Linear model of innovation	4-5
5.1	Illustrative time-line of anticipated technology products: 2000-2010	5-9
5.2	Illustrative time-line of anticipated technology products: 2015-2030	5-10

TABLES

Table	Page
2.1 Technology pathways	2-2
2.2 U.S. carbon dioxide emissions by end-use sector	2-5
3.1 Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2	3-2
4.1 Approaches to technological innovation	4-2
5.1 Potential reduction of U.S. carbon dioxide emissions from nine technology areas	5-3
5.2 Potential reduction of U.S. carbon dioxide emissions from selected sectors and technology pathways	5-6

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	gigatonnes of carbon (10 ³ million tonnes)*
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

*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 tonnes 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 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 the world's largest source 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, nearly 50 technology pathways are described that have significant potential to reduce greenhouse gas emissions. These technology pathways (which are described in greater detail in Appendix B, Climate Change 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 estimate 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 tonnes 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.

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. 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. 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 the United States will take 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 been convened. At the third conference in Kyoto, the parties to the FCCC will consider measures to strengthen it.

The United States faces a significant challenge in Kyoto and can play an important role in moving negotiations forward. If global atmospheric CO₂ 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 move onto a path that prevents the increase of their emissions while preserving their legitimate aspirations for economic growth.

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

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

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

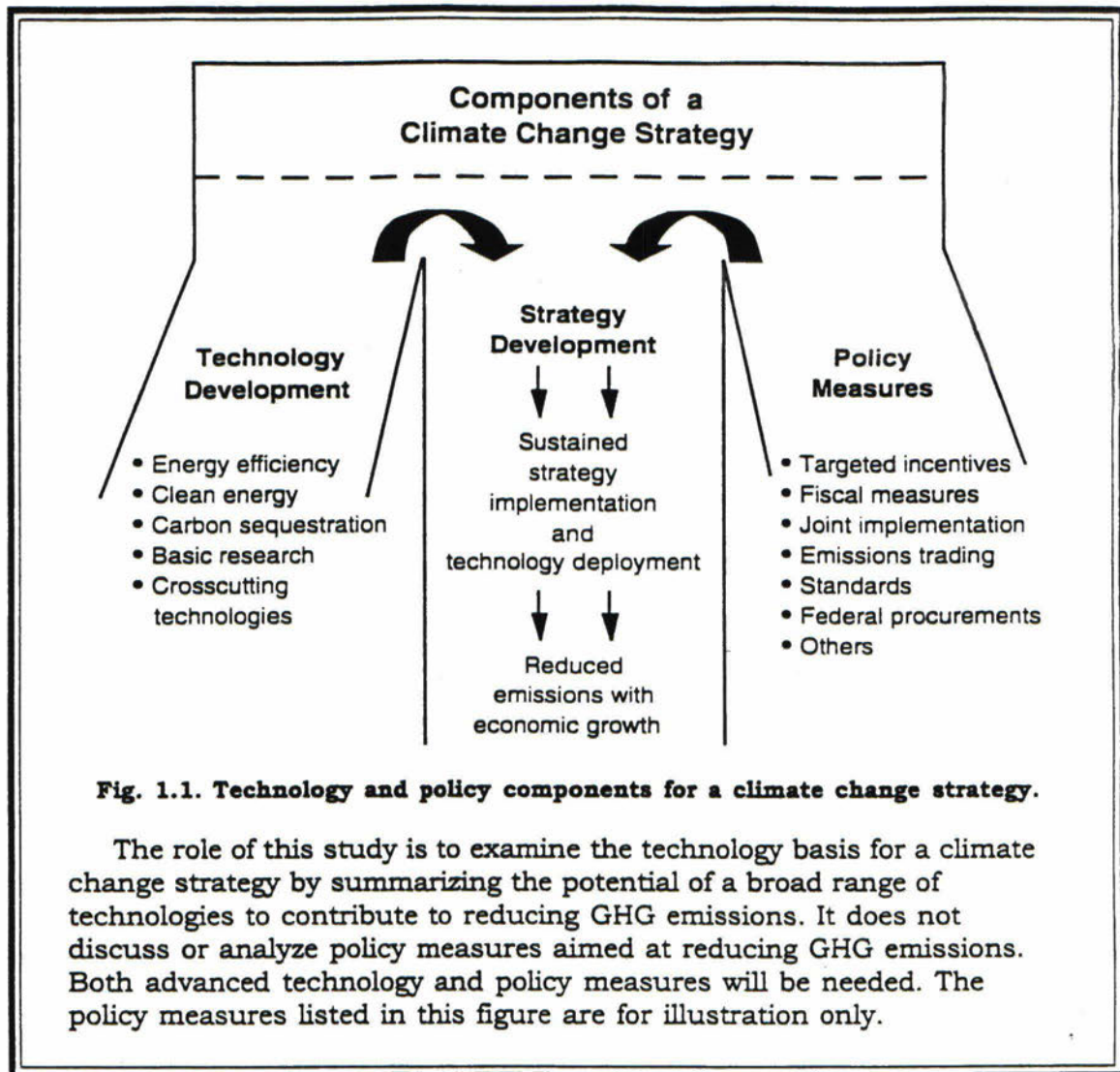
This document describes technology development efforts that need to extend through the first third of the next century. The impact of these efforts would in fact last much longer.

Energy-generating resources have lifetimes of many decades: the Grand Coulee Dam created in the 1930s continues to produce energy 60 years later. The new technologies introduced through the 30-year planning period of this report would have impacts that would extend throughout the next century.

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

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

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



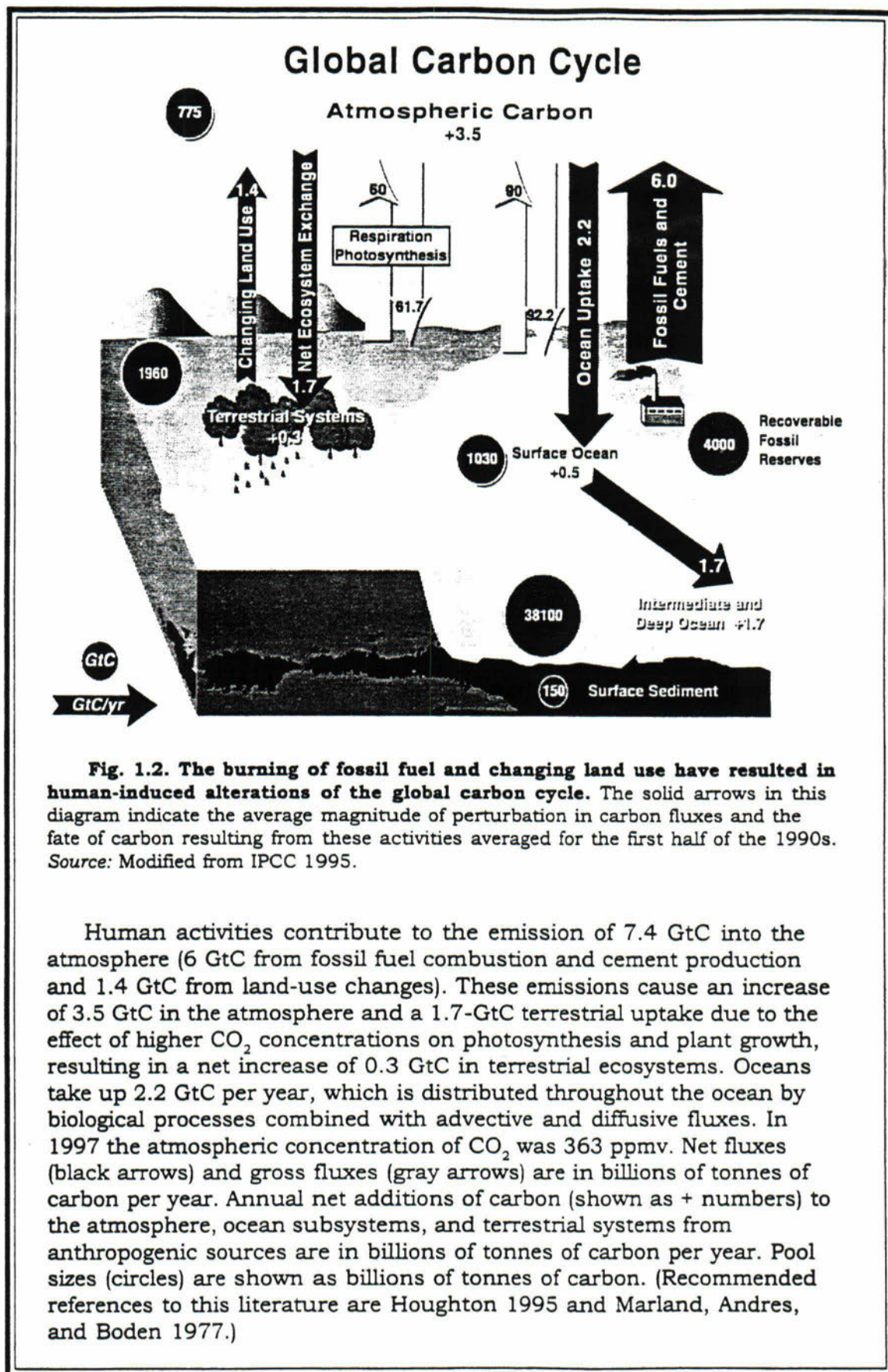
To ensure cost-effective, credible results, a climate change technology strategy also needs to be anchored in science. Much of this science base can be developed by leveraging and expanding existing efforts in the U.S. science and technology complex.

1.1 GREENHOUSE GAS EMISSIONS AND ENERGY

In 1995, human activities in the United States resulted in CO₂ 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



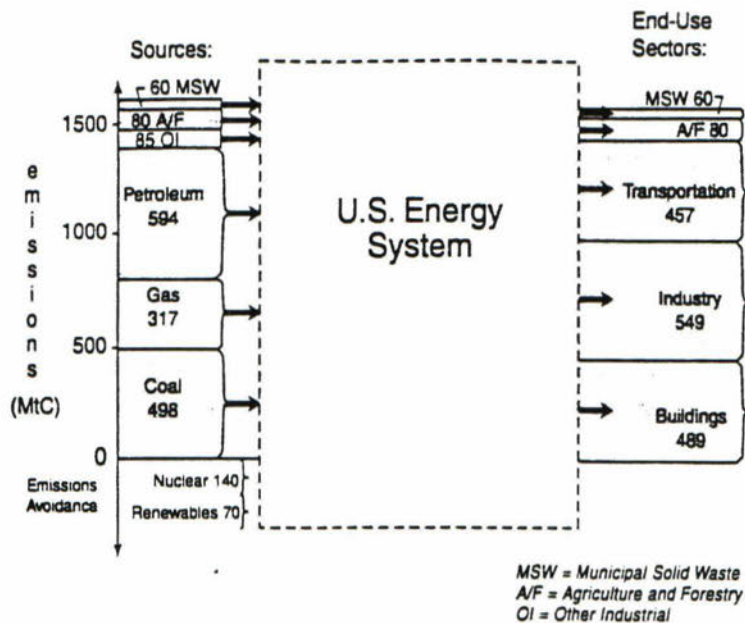


Fig. 1.3. Overview of the sources of carbon emissions in the United States in 1995 (in million tonnes equivalent and including CH_4 from MSW, A/F, and OI). Source: Based on EIA 1996a.

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:

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

where

- $\text{Net } C$ = 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ absorption through increased carbon sequestration—may be needed. They will definitely provide valuable choices and therefore should be pursued.

1.3 STUDIES OF CLIMATE CHANGE AND TECHNOLOGY

The role that technology can play in reducing GHG emissions has significant economic implications. For example, one survey of a number of energy economic models shows that the cost of stabilizing U.S. emissions at 1990 levels by the year 2010 ranges between 0.2% and 0.75% of GDP, or roughly \$20 billion to \$75 billion per

The lab saying all technology is not ready

year in 1995 dollars. (Gaskins and Weyant 1993.) To achieve these reductions would require a carbon tax of between \$10 and \$130 per tonne, or an equivalent policy, perhaps in the form of allowance trading.¹ The cost of reducing U.S. emissions to 80% of 1990 levels by 2010 ranges between 0.9% and 1.7% of GDP (\$90 billion to \$170 billion per year). Thus controlling carbon emissions could be quite costly, and the possibility that new technologies might reduce the costs of carbon control could be very valuable to the nation and the world.

The critical role that technology can play is evident in the research literature that considers U.S. climate change strategies. One recent study (Interlaboratory Working Group 1997) documents in detail how four key sectors of the economy—buildings, transportation, industry, and electric utilities—could respond to alternative scenarios that involve directed policies to expand adoption of energy-efficient and low-carbon technologies, increase the relative price of carbon-based fuels, and launch an aggressive program of targeted research and development (R&D). The “efficiency case,” which assumes aggressive R&D and accelerated adoption of cost-effective efficiency technologies, reduces carbon emissions by 120 MtC in 2010 compared with a “business as usual” forecast. In the “high-efficiency/low-carbon case,” which assumes even more aggressive R&D and carbon valued at \$50 per tonne, carbon emissions are projected to decrease by 380 MtC relative to the business-as-usual forecast. In all cases (with reductions varying between 120 and 380 MtC/year by 2010), the projected savings from reduced energy

expenditures exceed the projected direct costs of the required technology investments. Thus this study suggests the strong role that advanced technologies can play in reducing GHG emissions without harming the economy.

The idea that the United States must marshal a wide range of technological advances to meet climate change goals is presented in a second study (Kline et al. 1997). It shows that energy efficiency measures alone will not be able to meet a target of reducing U.S. carbon emissions to 1990 levels. Low-carbon supply measures will become necessary soon after the year 2000.

The cost impact of technology is assessed directly in a third study (Edmonds, Dooley, and Wise 1997). This study examines the cost of carbon emission reduction strategies under three hypothetical technology regimes:

- a “frozen technology” case, in which technology remains at its current cost and performance level
- an intermediate case that follows the technology path in the Intergovernmental Panel on Climate Change IS92a scenario (IPCC 1992)
- an “advanced” case in which technologies progress more rapidly

The projected cost of stabilizing atmospheric CO₂ at 450 ppmv in these three cases is \$21.5 trillion, \$12.6 trillion, and \$9.4 trillion, respectively. In the advanced technology case, targets above 500 ppmv can be achieved at no net cost. Thus this study suggests that advanced technology can have a dramatic impact on the cost of reducing carbon emissions.

¹ A charge of \$50 per tonne of carbon is equivalent to \$24 per tonne of coal or \$0.12 per gallon of gasoline.

A fourth recent paper expands upon the Edmonds et al. study to relate the cost of atmospheric CO₂ stabilization to R&D expenditures (Schock et al. 1997). Assuming there is only a 1 in 4 probability that the CO₂ level in the atmosphere needs to be stabilized at or below 550 ppmv and that the effectiveness of energy R&D in developing new technologies to substantively lower emissions is only 50%, Schock et al. calculate the value of energy R&D to the United States at \$2 billion per year over the next 15 years, or a total of \$30 billion (the U.S. share of world carbon emissions is 23%). Raising the probability of the need for action to 50% and increasing the effectiveness of R&D to 80% increases the value to society by a factor of over 3, to more than \$6 billion per year, or \$90 billion over 15 years. Their examination of the DOE portfolio indicates that approximately \$1 billion of the current energy R&D budget (~\$1.3 billion) is directed at research relevant to atmospheric stabilization of CO₂.

Self serving

In summary, these studies clearly support our tenets that advanced energy technologies are required to reduce GHG emissions and sustain economic growth, and that the development and use of such technologies would enable GHG reductions at relatively low net cost to the economy. The fourth study also indicates that a substantially larger R&D budget is warranted.

New technologies have frequently played key roles in resolving major issues facing the nation. Two recent examples include the catalytic converter—which has greatly reduced automobile emissions of carbon monoxide, hydrocarbons, and nitrogen oxides—and the development of alternatives to chlorofluorocarbons (CFCs) for coolants, thereby reducing

their threat to the protective stratospheric ozone layer. More broadly, the United States has realized significant environmental improvements with continued economic growth during the past 25 years by adopting environmental policies that emphasize the adoption of “best available technology economically achievable... [to] result in reasonable further progress toward [national environmental goals]” [Public Law 92-500, Federal Water Pollution Control Act Amendments of 1972; also see the Clean Air Act Amendments of 1970, Section 165 (a) (4)].

Advanced energy technologies will also provide important collateral benefits. Examples include the economic benefits that will result from exports of these technologies, enhanced environmental quality, and decreased reliance on oil imports due to the development of alternative fuels and more efficient transportation technologies.

As this report indicates, there is a solid basis for believing that pursuit of a technology strategy is an effective approach to reducing GHG emissions and stimulating economic growth.

1.4 ABOUT THIS STUDY

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 R&D and what those achievements imply for reducing GHG emissions. Fortunately, many of the advanced technologies

addressed in this report are already the subject of, at least, limited federally sponsored research, development, and demonstration (RD&D) driven by the collateral benefits they offer. In particular, DOE's applied energy technology programs, which are already supporting development of most of these technologies, should serve as the base for the expanded RD&D efforts recommended in this report.

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. The analysis of such policies and programs is the subject of a companion effort being led by DOE.

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 Council of Advisors on Science and Technology (PCAST 1997).

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.

1.5 REFERENCES

- Edmonds, J., J. Dooley, and M. Wise 1997. "Atmospheric Stabilization and the Role of Energy Technology," *Climate Change Policy, Risk Prioritization and U.S. Economic Growth*, American Council for Capital Formation, Washington, D.C.
- 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.
- Gaskins, D. W. and J. P. Weyant 1993. "Model Comparisons of the Costs of Reducing CO₂ Emissions," *American Economic Review* (AEA Papers and Proceedings), **83**(2), 318-323.
- 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.
- IPCC (Intergovernmental Panel on Climate Change) 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, ed. J. T. Houghton, B. A. Callandar, and S. K. Varney, Cambridge University Press, Cambridge, U.K.
- IPCC (Intergovernmental Panel on Climate Change) 1995. *Climate Change 1995: The Science of Climate Change*, ed. J. T. Houghton, L. G. Meira Filho, B. A. Callandar, N. Harris, A. Kattenberg, and K. Maskell, Cambridge University Press, Cambridge, U.K.
- Kline, D. et al. 1997. "The Role of Renewable Energy in U.S. Climate Change Strategies," to be published in *Proceedings of the 8th Annual North American Conference: International Markets, Competition, and Policy*, U.S. Association of Energy Economics/International Association for Energy Economics, San Francisco, September.
- Marland, G., R. J. Andres, and T. A. Boden 1977. *Global, Regional, and National CO₂ 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.

Schock, R., W. Fulkerson, M. Brown,
and R. San Martin 1997. "How Much
is Energy R&D Worth?" in
*Proceedings of the 32nd Intersociety
Energy Conversion Conference*,
Honolulu, Hawaii, July 27–August 1,
1997, Am. Inst. Chem. Engr., New
York.

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.

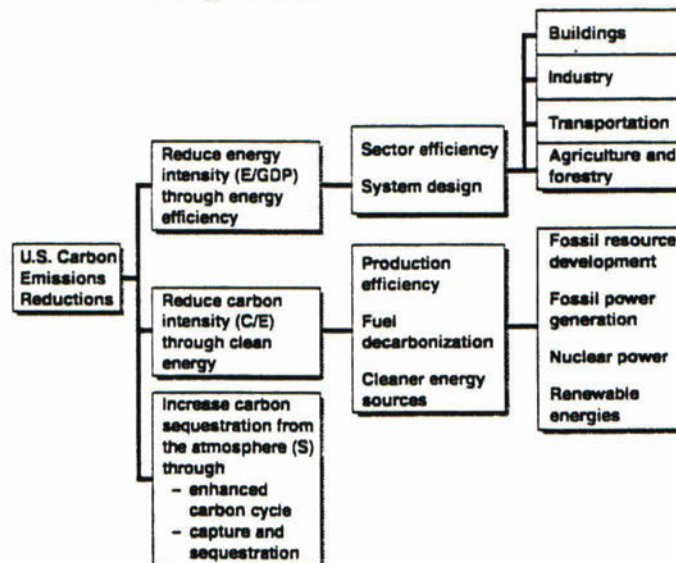


Fig. 2.1. Alternative technological opportunities for reducing greenhouse gas emissions. Electric utility technologies are covered in the fossil power generation, nuclear energy, and renewable energy areas.

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 Vehicles
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
9.2	Advanced Chemical and Biological Sequestration
9.3	Terrestrial Storage of CO ₂
9.4	Carbon Sequestration in Soils
9.5	Elemental Carbon Sequestration
9.6	Ocean Storage

^aThis 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

2.1.1 Technology Approaches

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) CO₂ 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

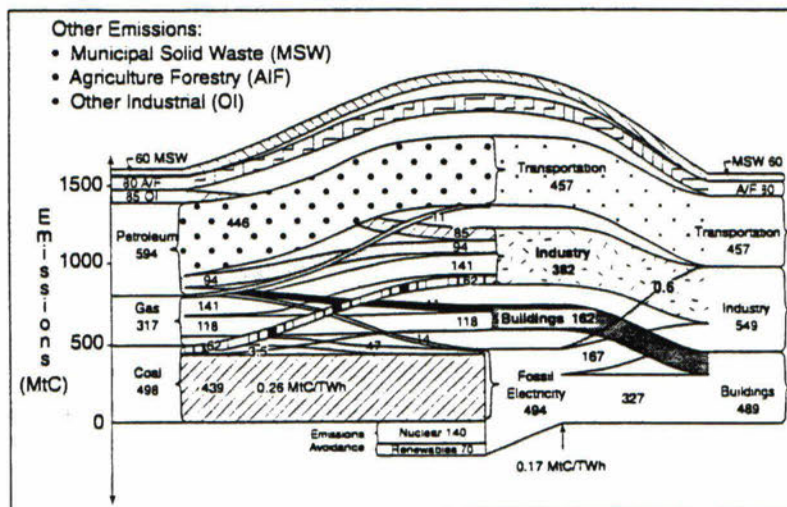


Fig. 2.2. Sources of greenhouse gas emissions in the United States in 1995 (in million metric tonnes equivalent). Note that if nuclear and renewables had not been used to generate electricity in 1995, carbon emissions would have been 210 MtC higher on each side of the chart. Source: Based on EIA 1996b.

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 CO₂ emissions captured during fossil fuel conversion processes, thus preventing their release into the atmosphere. A second approach is to increase the absorption of CO₂ 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 Chapter 5, Synthesis and Moving Forward.

2.1.2 Assumptions

Reference Case. U.S. CO₂ emissions are projected by DOE's Energy Information Administration (EIA) to increase at a rate of 1.2% per year under a "business-as-usual" scenario. This scenario assumes that some efficiency and process improvements will offset what would otherwise be a larger rate of CO₂ 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, CO₂ 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 Table 2.2 and Fig. 2.3 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.

Restructuring. The data in Table 2.2 and Fig. 2.3 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.

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

^aThe 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 CO₂ are not included.

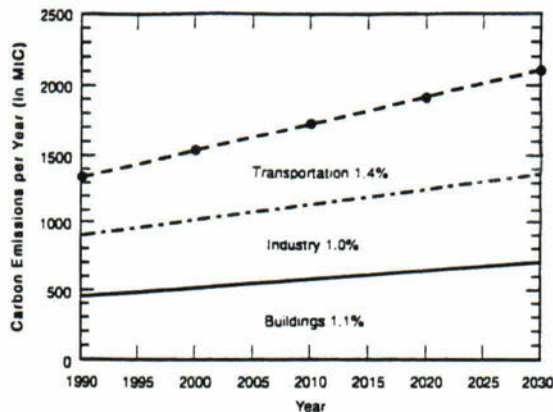


Fig. 2.3. Projected U.S. carbon dioxide emissions (in MtC per year). Source: Based on EIA 1996b.

It is also possible that deregulation will increase electrical power generation by gas turbines, making power generation by nuclear reactors and renewable energy sources less economically attractive; the result could be increases in 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 RD&D of 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. On the other hand, implementation of a renewable portfolio standard and public benefits programs might significantly promote clean power.

Federal RD&D Efforts. 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. Examples are energy efficiency improvements, development of new renewable energy technologies, coal power plant improvements, and nuclear capacity additions.

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. These additional federal resources include approximately \$1.8 billion spent in FY 1997 for the U.S. Global Change Research Program.

These existing RD&D programs form the basis of an expanded and accelerated RD&D effort to more fully address the issue of GHG emissions, including new technology pathways such as carbon sequestration. With rapidly evolving markets and technologies, it is difficult to estimate the impact of federal RD&D efforts on carbon reduction. Nonetheless, such estimates are needed to distinguish between technologies in developing a strategy. This report includes preliminary estimates of the impact of an enhanced federal RD&D program on the carbon reduction potential of technologies in the years 2010, 2020, and 2030. These estimates are the judgment of teams from the 11 participating national laboratories (in some cases in collaboration with experts from other organizations across the country). The RD&D support needed to achieve these estimates is

discussed further in Chapter 5, Synthesis and Moving Forward.

Federal RD&D is certainly not the only effort that will be needed to develop and demonstrate these technologies. Private-sector collaboration is a major element of current federal RD&D programs and will need to continue and expand along with the federal commitment to be able to achieve the advances described in this report. Supportive federal (and state and local) policies could also make a large difference.

Federal Policies. This report's estimated reductions in carbon are relative to the *Annual Energy Outlook 1997* reference (business-as-usual) case. They assume a continuation of today's existing federal programs and policies. The estimates do not presume the creation of any new incentives such as investment tax credits, a carbon charge, or a domestic or international CO₂ trading system. The carbon reduction impacts of the individual technology pathways discussed in this report could be even greater if more vigorous deployment programs and policies were implemented.

Market and Risk Factors. The effects of the market success of one technology pathway on the market success of another technology pathway were generally considered within one particular technology area, such as within nuclear energy or within buildings efficiency. Effects of competition among technology areas were not considered, however. Therefore, carbon reduction estimates from different technology areas (such as nuclear and buildings) cannot simply be summed.

The estimated carbon reductions do take into account many of the factors that can affect the performance and

market penetration of a new technology, such as

- 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
- environmental and health risks associated with the technology
- public perception and acceptance risks
- characteristics of competing technologies

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

2.2 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 subsections, by end-use sector:

- buildings
- industry
- transportation
- agriculture and forestry

2.2.1 Buildings

The Potential for Reduced Emissions

refer to 5 lab study

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.

2.2.2 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 (14.5 MtC) 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.

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

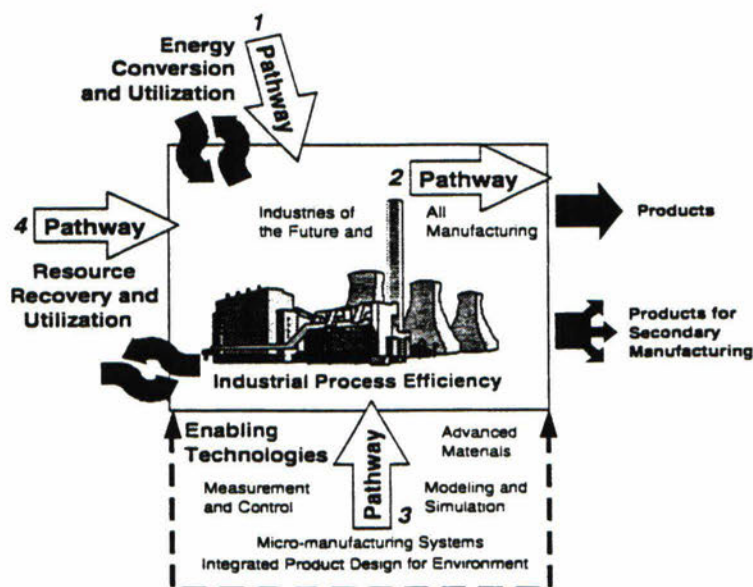


Fig. 2.4. Four technology pathways to increased industrial efficiency.

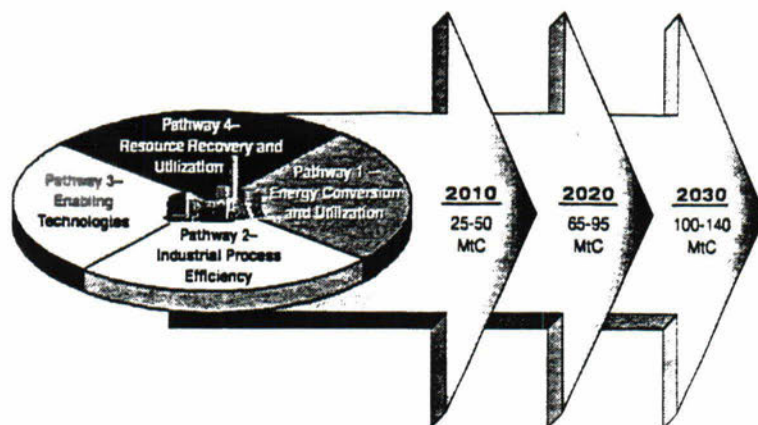


Fig. 2.5. Technology pathways for industry with associated benefits in carbon emission reductions.

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 CO₂ 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.

2.2.3 Transportation

The Potential for Reduced Emissions

Accounting for 32% of U.S. CO₂ 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. 2.3.4.)

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. 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.

2.2.4 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 CO₂ 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-bioprocess 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 CO₂ 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.

2.3 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

2.3.1 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. 2.5) 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.

Because of the desire to reduce CO₂ 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 CO₂ 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 CO₂.

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 H₂ with only a CO₂ 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.

CO₂ 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 CO₂ and minimizing fugitive gas emissions from pipelines and other remote sites. CO₂ is pumped into oil reservoirs to enhance the recovery of petroleum. Instead of present practice, CO₂ that would otherwise be emitted to the atmosphere (from fossil fuel combustors) could be captured and used to enhance energy recovery. In the future, CO₂ 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 CO₂ 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 CO₂ from nitrogen in very large-scale flows. Development of these high-throughput gas separation technologies would allow recycled CO₂ from fossil fuel combustors to replace CO₂ that is produced from dedicated production wells.

Collateral Benefits

Improved crude oil refining processes would eliminate GHGs that are considerably more damaging than CO₂. Converting coal-based synthesis gas to transportation fuels would reduce several pollutants compared with conventional fuels, as would using CO₂ 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 CO₂ 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. 2.6), which does not bode well for the implementation of new high-technology programs.

Efficiency improvements in crude oil refining and processing pose a high level of commercial risk. As shown in Fig. 2.7, 46% of domestic refineries have closed since 1981, many because of perceived environmental problems. Reconfiguring a new domestic refinery

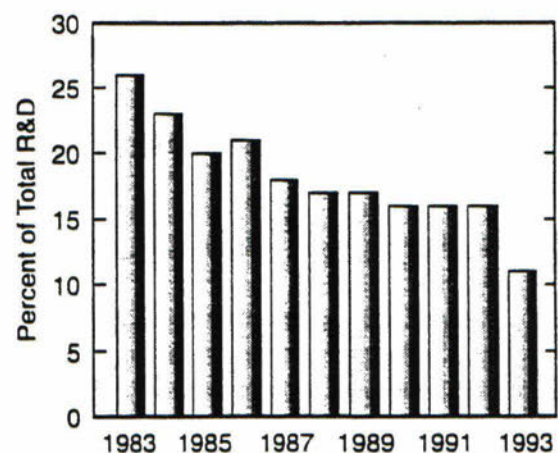


Fig. 2.6. Long-term R&D in major oil companies continues to decline.

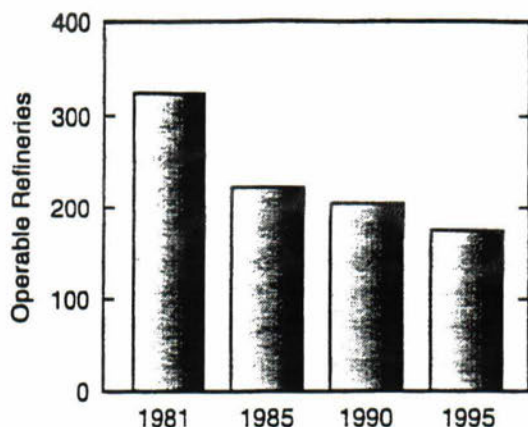


Fig. 2.7. Operable refineries in the United States.

industry will entail very significant commercial risks.

2.3.2 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 CO₂.

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 CO₂ 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 CO₂. 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 CO₂ capture methods for this pathway, including similar methods in the technologies from the first two pathways could lead to additional reductions. Typically, CO₂ may be captured by chemical, biological, or physical means. CO₂ 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 CO₂ 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 CO₂, but these are only cost effective if the CO₂ exists at a high concentration in the effluent stream.

Research needs that have been identified in CO₂ capture include (1) means to concentrate the CO₂ 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 CO₂ could include use of a blend of pure oxygen and recycled CO₂ 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 CO₂ and hydrogen. Improved separation techniques for the hydrogen would then leave a concentrated CO₂ stream, which would be available for further processing.

Currently, CO₂ 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-term carbon reduction and capture international market share arising from the 50-year service life of power plants. The low-carbon fuels pathway

faces moderate risks both technologically and commercially, although ATSS for stand-alone systems are probably low risk. The energyplex pathway faces low to moderate technical risk related to the challenges for system integration, and moderate to high risk related to the breakthroughs in capture, including those related to novel combustion configurations. The health and ecological risks are considered low to moderate.

Supporting science and crosscutting technologies needed to achieve these pathways include combustion; materials for high-temperature and corrosion-resistant performance; industrial ecology; hydrogen separation or production, transportation, and storage; improved processes for low-cost separation of oxygen; advances in fuel cells; and identification of alternative working fluids and determination of their thermodynamic properties.

Collateral Benefits

These pathways not only will reduce GHG emissions but also will provide a clean, secure energy future and help the nation respond to its international commitments. An accelerated RD&D program will enable the United States to capture a larger share of the \$1.4 trillion export market for coal technologies between now and 2010 and help the U.S. economy grow by creating an energy technology export business. An accelerated R&D program would also allow U.S. industry to take advantage of the domestic markets for ATSS and fuel cells, which are estimated to be worth tens of billions of dollars between now and 2010.

Strategy and Recommendations

For the high-efficiency coal-based pathway, about \$70 million per year is currently being spent on DOE

programs. For the low-carbon fuel pathway (fuel cells and advanced turbines), about \$90 million per year is currently being spent on DOE programs. As part of this initiative, accelerating and completing the development of these technologies is recommended. For the energyplexes pathway, relevant technical ideas (such as fuel cells and coal liquefaction) are currently being funded at various levels. Pursuing the grand challenges envisioned both for this pathway and for additional options is recommended for the next two decades.

In summary, the technology pathways described provide a range of options for using coal, natural gas, and other solid fuels—such as biomass, synthesis gas, and hydrogen—to generate power at competitive power costs, to reduce emissions of criteria pollutants and CO_2 to the atmosphere, and to develop strong positions in crucial technologies important to economic growth in the next century. Not all of these will necessarily enjoy widespread commercialization; however, they represent a family of options that spread technology risks, address fuel flexibility, and hedge against upsets in fuel prices. They include both improvements on familiar technologies, which should pose reduced commercialization risks, and bold new concepts that may pose as yet unrecognized commercialization risks.

2.3.3 Nuclear Energy

Nuclear power is deployed worldwide to produce 20% of world electrical generating capacity (in some countries, as much as 80%). Electricity generation using nuclear power results in very small emissions of GHGs, so nuclear power is an important tool in reducing global CO_2 .

In the period when France converted 70% of its electricity generation to nuclear, all related emissions were reduced dramatically. CO_2 was reduced by 80%, SO_2 by 90%, NO_x by 60%, and particulates by 97% (Fig. 2.8). Today, in the United States, 109 nuclear power plants generate nearly 22% of U.S. electrical capacity (100 GWe). This nuclear generating capacity avoids the emission of about 140 MtC/year compared with generating this electrical capacity by burning fossil fuels.

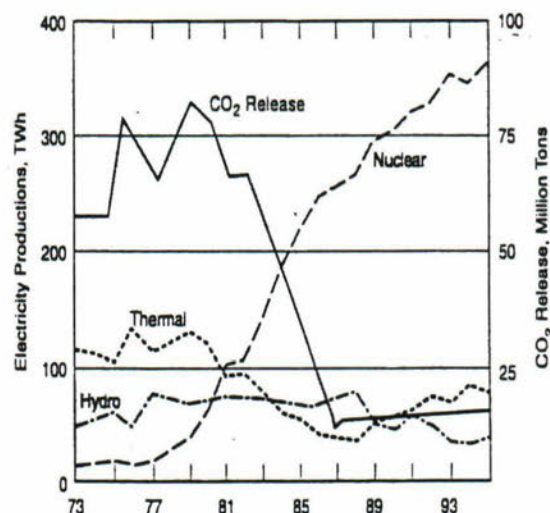


Fig. 2.8. Relationship between CO_2 release and electricity production in France, 1973-1996.

The Potential for Reduced Emissions

In the near term, the development and use of technologies for lifetime extension and for generation optimization (LEGO) of existing nuclear power plants could reduce carbon emissions by increasing nuclear electricity contributions from existing plants over the next several decades. A modest carbon reduction is also assumed for new nuclear plants in 2020 and 2030. Total potential reductions are shown in the following table.

Estimated carbon emissions reductions (MtC/year)			
	2010	2020	2030
Total nuclear	0-15	30-70	70-150

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

If the current 100 GWe of nuclear electrical generating capacity were eventually replaced by next-generation nuclear plants, the United States would continue to avoid emissions of more than 100 MtC/year. If, in addition, electrical demand in the United States continued to grow at 1.5% per year and the installed nuclear generating capacity grew along with it to maintain its current share of the U.S. market (22%), then this new nuclear capacity could result in the avoidance of about 160 MtC/year by 2030. If the market for nuclear generated electricity expanded to 30%, then the result would be an avoidance of about 250 MtC/year by 2030 (see Fig. 2.9).

In the long term, by 2030, the development and use of evolutionary

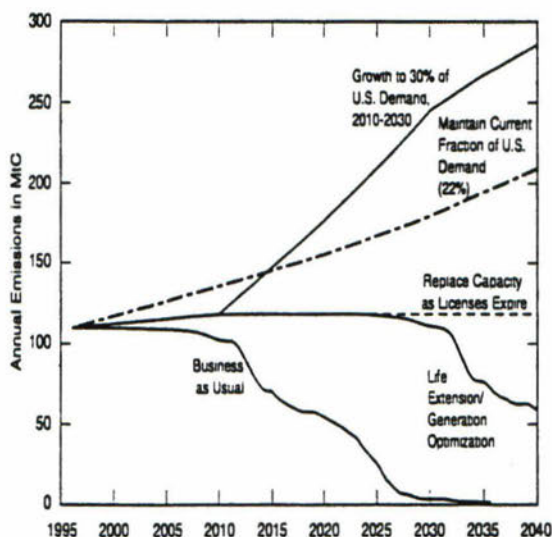


Fig. 2.9. Carbon emissions avoided under various scenarios of nuclear electricity generation.

and advanced fission reactors are projected to reduce carbon emissions by about an additional 100 MtC/year. In the longer term, the second half of the twenty-first century, fusion energy systems may become a significant economic power generation source, free of GHG emissions. The actual amount of nuclear-generated electricity will depend on the future financial viability of the nuclear option.

Technology Pathways and Opportunities

Lifetime Extension and Generation Optimization. The near-term approach to the use of nuclear energy should be to provide technologies to increase electricity generation and extend lifetimes of the existing set of 108 nuclear power plants. The initial 40-year license period for these reactors will expire roughly from 2005 to 2030. If the United States is faced with replacing this capacity with fossil-fueled generating plants, CO₂ emissions will **increase** more than 100 MtC/year. Both the renewal of plant licenses and increases in plant capacity factors can be enabled by new nuclear and nonnuclear technologies. With targeted R&D investments in monitoring, diagnostic, and materials technologies, these nuclear plant lifetimes could be extended for an additional 20 years, and the efficiency and output of the plants could be incrementally increased, thus avoiding the GHG emissions that would result from replacing this nuclear capacity with other power generation systems.

Examples of generation optimization technologies include advanced technologies for on-line monitoring of cables and conventional equipment (pumps, valves, etc.) to minimize losses of production because of unplanned

outages. In addition, improved materials measurement and diagnostic technologies could reduce scheduled downtime for diagnostics and repairs. Plants could be operated at higher net power output to the grid by using sensors and controls that more accurately measure operational parameters, thereby reducing in-plant power demands, improving the thermal-to-electric conversion efficiency, and increasing the core power.

Nuclear power plant life extension hinges on the resolution of issues related to the aging of key components, including reactor pressure vessel embrittlement, stress corrosion cracking of reactor internals, degradation of instrumentation and power cables, and steam generator tube cracking. The effort to resolve these issues could also benefit from improved instrumentation and materials characterization technologies. In addition, R&D on in situ component annealing and on materials cladding processes could provide effective and economical repair technologies. Specific examples of approaches that offer the promise of resolving these issues include gas-fired thermal annealing, water chemistry control to avoid stress corrosion cracking, and various approaches to the deposition of lining materials.

Next-Generation Fission Reactors. The mid-term approach to the use of nuclear energy is to develop and install next-generation fission reactors. Even if LEGO technologies were fully utilized, a major increase in carbon emissions could only be avoided through new nuclear capacity after 2015, which would replace existing reactors that reach the end of their lives.

Evolutionary designs for next-generation fission reactors have received Nuclear Regulatory Commission licensing certification and are available for construction today without significant research; several have been built in Japan. These designs are simple and rugged, and they incorporate passive safety features intended to provide safer, more trouble-free operation over 60-year design lifetimes. Advanced fission reactors, which use fuel cycles that are proliferation resistant, are also designed for higher efficiencies coupled with improved safety compared with currently operating plants.

The long-term (beyond 2030) approach to the use of nuclear energy would likely use nuclear reactor concepts, such as the liquid-metal cooled fast-spectrum reactor, that extract far more of the energy available in the uranium fuel than the 1% currently used and that produce less waste per GWe, thus extending the resource. In addition, efforts are under way to develop accelerator-driven systems using high-energy protons to produce nuclear energy from subcritical targets.

Finally, one can conceive of a new set of technologies that could be implemented in the next century. The concept of a hybrid nuclear-hydrogen cycle in which nuclear heat is used for production of hydrogen, with subsequent use of hydrogen as an energy source, has considerable potential. R&D on fission heat-to-hydrogen conversion technologies and on hydrogen distribution technologies has the longer-term potential to produce fundamental changes in the world's energy supply approach and make it consistent with our ecological goals.

Fusion Power. Fusion power, when developed and deployed, would be a carbon-free energy source. The U.S.

domestic fusion energy sciences program is concentrating on science and innovation supporting the development of attractive fusion systems based on toroidal magnetic configurations. It also supports a small R&D effort on driver systems for inertial fusion energy. Most of the research effort for the inertial approach to fusion energy is supported for its defense applications. The development of technologies required for fusion, and the pursuit of ignited or burning plasmas, are being pursued through international collaboration.

Collateral Benefits

One collateral benefit of the continued pursuit of nuclear power would be the economic benefit of serving as a domestic and international supplier for this major electric power technology. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. As of today, the United States has invested \$200 billion in nuclear power plants and has 400,000 nuclear-related jobs. In addition, a benefit of pursuing LEGO technologies would be enhanced safety and reduced worker radiation dose at existing plants.

Furthermore, if the United States did not pursue research into next-generation reactors, there would be several negative impacts. The first would be the loss of the technical infrastructure to support the nuclear enterprise, which also supports nuclear medicine, isotope production, and neutron science. This loss could also lead to increasing safety concerns for existing reactors. The second would be the decreased ability to design and construct fission, and eventually fusion, plants to export or to replace the existing ones in the United States at the end of their lives. Finally, with the loss of U.S. infrastructure, the

ability to influence the nuclear policy of other countries would disappear.

Technical Risks and Other Issues

Nuclear power faces environmental risks and issues, including the disposal of nuclear wastes. But most of all, the risk is economic. Nuclear power shares the same economic attributes of many renewable technologies—a high fixed cost and a low variable cost—that make market penetration difficult today in the United States. Technology R&D along the technology pathways outlined here could have a major impact on alleviating all of these risks.

Strategy and Recommendations

Nuclear technology is currently offsetting approximately 140 MtC emissions per year. Pursuit of technologies for both LEGO and next-generation nuclear power would allow this offset to continue, as well as provide additional GHG emission reductions in the future. Successful development and use of improved nuclear power technologies could also have a major impact on global GHG emissions.

This study recommends pursuit of nuclear energy R&D to provide the United States and the world with an improved nuclear technology option to help address the very challenging climate change issue. Continued support of a broad base of concepts in fusion R&D is required, and, as these concepts mature, investment will be necessary and appropriate.

2.3.4 Renewable Energy

The Potential for Reduced Emissions

Renewable energy pathways—using energy from sunlight, wind, rivers and

oceans, the hot interior of the earth (geothermal energy), and biomass (agricultural and industrial wastes, municipal solid waste, energy crops) to produce electricity, fuels, and heat—hold significant potential for reducing GHG emissions in the next century by displacing fossil-fuel-generated electricity or petroleum transportation fuels. This potential is shown in the table below and is compared with the business-as-usual carbon projections in Fig. 2.10.

Estimated carbon emissions reductions (MtC/year)			
	2010	2020	2030
Total renewable energy	30–60	75–130	135–260

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

All regions of the United States have renewable resources of one type or another. Renewable resources currently account for about 8 to 10% of the energy consumed in the United States; most of this is from hydropower and traditional biomass sources. Solar, wind, and geothermal technologies are cost-effective today in small and niche markets, which are important steps to full commercialization.

- In the electricity sector, renewable power avoids about 70 MtC emissions per year at the present emissions rate of 0.17 MtC/TWh for electricity.
- Renewable energy technologies are well along a path of decreasing cost (Fig. 2.11), making their expanded commercialization prospects very realistic for early in the next century.
- A level of 20% use in 2025 and 50% use in 2050 is foreseen for the world in a number of projected energy scenarios from, for example, Shell Petroleum Limited (1996), the World Energy Council, and the International Panel on Climate Change (1995). A group of U.S. environmental organizations has also projected the future uses of renewables in the United States in a just-released report, *Energy Innovations* (1997).

Each of the renewable energy technologies is in a different stage of research, development, and commercialization; and all have differences in current and future expected costs, current industrial base, resource availability, and potential impact on GHG emissions. Appendix B describes each of these aspects of the various technologies.

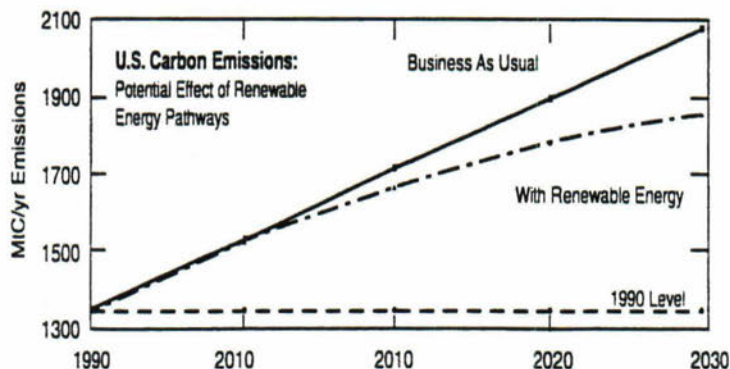


Fig. 2.10. Renewables have the potential for significant reductions of U.S. carbon emissions.

While today's renewables are usually more expensive than the conventional competition on a first-cost basis, they are cost-effective in certain niche markets, especially on a life-cycle-cost basis. Several technologies produce electricity from renewable sources; those nearing

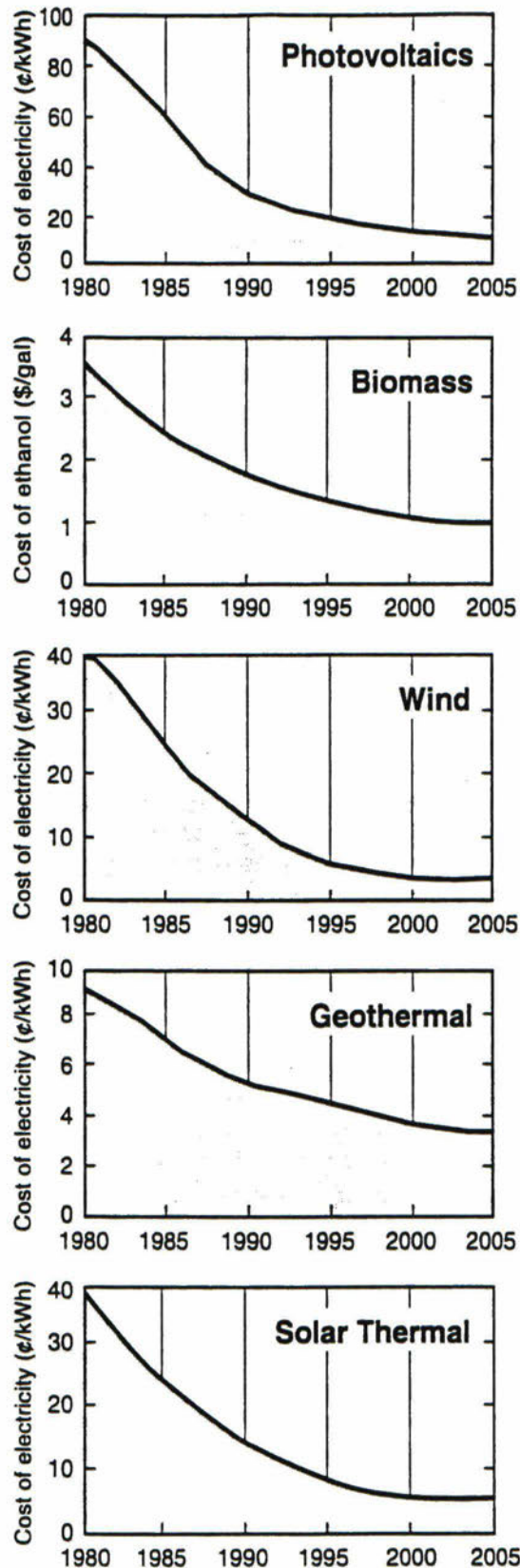


Fig. 2.11. Renewable energy technologies are well along a path of decreasing costs.

commercialization face common problems such as difficulty in obtaining capital, uncertainties related to future electric utility restructuring, and current competition from natural gas. Those technologies further from commercialization need more emphasis on R&D, from fundamental research to resolution of process scale-up issues.

Technology Pathways and Opportunities

Biomass Electric refers to technologies that generate electric power from such biomass resources as cofiring biomass with coal, using biomass as the sole fuel in new power plants, or gasifying biomass to replace natural gas. From now through 2010, new biomass electric technologies (including landfill gas) are likely to be commercialized and should have a strong impact on CO₂ emissions. Biomass cofired with coal could also replace a significant portion of coal in electricity production in the near term. Biomass gasification could have a major impact in the forest products industry during the next 10 to 15 years, when many existing boilers will be replaced. RD&D challenges include resolving issues around ash chemistry and NO_x reduction, demonstrating long-term operation of gas turbines on synthesis gas, improving materials, developing sufficient energy crops for feedstocks, and demonstrating advanced technologies.

Wind Energy systems today are very close to being cost-competitive, on a levelized cost basis, with projects at \$0.04 to \$0.07 per kWh; nearly 1800 MW are installed in the United States, and another 6000 MW in other nations. High-quality wind resources are available in 34 of the 50 states and could provide major carbon offsets

before 2010. Technology challenges to achieve lower cost and increased reliability include further advances in the understanding of wind flow, aerodynamics, structural dynamics, advanced power conversion devices, and development of durable and lightweight structural components. In the near term, up to 10 to 20% of a region's electrical capacity could be from wind power without any adverse operating or economic effects. Larger market penetrations in the mid to long term would require addressing the impact of the variation of wind through modification of systems operation, hybrids with other technologies, energy storage, transmission and infrastructure, and improved wind forecasting.

Hydropower currently generates 10% of the nation's electricity, but generation is declining. Current technology often has adverse effects on fish and downstream water quality and quantity; the goal is to generate electricity without these adverse effects. R&D challenges include quantifying the biological response of fish affected by hydropower projects, modeling the forces inside turbines to predict stress levels on fish, and demonstrating the cost-effectiveness of retrofits.

Solar Photovoltaic (PV) technology uses semiconductor-based cells and modules to directly convert the energy of sunlight to electricity. PV can be used to produce electricity on almost any scale, depending only on how many PV modules are connected together. About 100 MW of PV modules were sold in 1997; annual growth has been 15 to 20%. Hundreds of U.S. applications are currently cost-effective for off-grid electric power needs, such as powering remote telecommunications installations and utility sectionalizing switches.

International interest is also very high. PV costs are currently too high for bulk power generation, but costs are decreasing rapidly. Goals are to compete for peak power shaving by 2010, then daytime utility electricity by 2020. RD&D challenges including improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes.

Geothermal Energy technologies use energy from within the earth to produce electricity or provide heat for industrial processes. Geothermal heat pumps use the thermal mass of the earth as a heat sink for air-conditioning and heating. Hydrothermal reservoirs produce about 2100 MWe in the United States and about 6000 MWe worldwide. In the United States, direct-use applications produce about 400 MWt; heat pumps produce 4000 MWt and are increasing by 25% per year. Only a small fraction of the huge geothermal resource can be used economically today. With research and policy support, electricity production could be doubled, and thermal production (including heat pumps) could be tripled or more. Geothermal RD&D challenges include improved methods for predicting reservoir performance and lifetime, innovative low-cost drilling technologies, new concepts to expand the use of the resource, improved energy conversion through thermal and fluids science and modeling, and lowering costs through thermal science and process chemistry.

Solar Thermal Electric and Buildings includes technologies that concentrate the heat of the sun to generate

electricity or use the heat directly. Solar thermal electric technologies have been successfully demonstrated in nine commercial plants (354 MW) operating in California. Using existing, relatively conventional technology, including unique cost-effective storage, hundreds of additional megawatts of peaking power could be on-line by 2005; and evolutionary R&D improvements will allow bulk power market penetration by 2020. Solar hot water systems are commercially available, and ventilation preheat systems using unglazed transpired collectors have made significant progress in commercial/industrial markets. RD&D challenges include improving performance and lifetime and reducing manufacturing costs with improved designs and manufacturing technologies, and addressing commercialization challenges similar to those facing wind energy.

Biomass Transportation Fuels include methanol, ethanol, and hydrogen, which can displace petroleum in internal combustion engines. Biomass sources, including agricultural and other wastes, energy crops, and microalgae, are converted to fuels through biotechnology methods (using microbes) or through thermochemical processes. R&D goals are to demonstrate a biomass waste-to-fuels process with an industrial partner by 2000 and larger-scale production and conversion technologies by 2005. By 2010, energy crops should begin to be available, allowing biofuels to compete with petroleum for direct fuel replacement. R&D challenges include low-cost production of enzymes, development of microorganisms for consolidated processes, improved performance of thermochemical processing, and advances in energy crop productivity, cultivation, and harvesting. Biomass transportation

fuels are also discussed in Transportation Sect.. 2.2.3.

Solar Advanced Photoconversion technologies use the energy of sunlight to directly produce fuels, materials, chemicals, and electricity from renewable sources such as water, CO₂, and nitrogen. Most of these technologies—involving photobiological, photochemical, and photoelectrochemical approaches—are in the fundamental research stage where technical feasibility must be demonstrated. Examples of these natural and artificial photosynthesis processes include producing hydrogen from water or biomass and producing biodiesel, methane, and methanol from water, waste, and CO₂.

Collateral Benefits

A significant increase in the use of renewable energy pathways would provide benefits beyond reducing GHGs, such as lessening the reliance on foreign oil (especially biomass for transportation fuels), contributing little to waste storage or safety problems, and reducing pollutants. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies.

Technical Risks and Other Issues

The technical risks vary among the pathways, but there are clear R&D paths to address these risks. Overall, ecological and human health risks are low. Commercial, regulatory, and economic risks are generally moderate to high. In many cases, first costs are higher than for conventional energy choices, while the benefits of renewables do not currently motivate and reward private investment. Mechanisms are required that

acknowledge the public value of renewables and help to attract private capital to develop these technologies. Small renewable energy companies in the United States face very strong international competition. Finally, decisions made under utility restructuring will have a major impact on market penetration for renewable electricity technologies.

Supporting R&D is needing in a variety of basic science and crosscutting areas, such as photosensitive materials, innovative semiconductors, corrosion-resistant and higher-temperature materials, biotechnology, catalysts and separations systems, sustainable agriculture, sensors and controls, electrical components, and computational modeling. A wide range of energy storage and transmission systems—along with the production of hydrogen as transportation fuel—would broaden the opportunities for the deployment of intermittent renewable energies, such as wind, solar photovoltaic, and solar thermal electric.

Strategy and Recommendations

Eventually, the private sector is likely to complete the development and commercialization of renewable energy technologies. But well-considered and sustained government investments, both in the underlying R&D and in actions that will remove deployment barriers, are critical. This is the most important step in realizing the full potential that renewable energy pathways can contribute to reducing carbon emissions early in the next century.

Significant investment would be required from both the private and the public sectors. Currently, the annual federal investment is about \$250 million for these pathways. Increased federal investments to

reduce carbon emissions would also return additional environmental benefits and the opportunity for U.S. companies involved in the area to be key players in the \$1 trillion global energy market and the \$400 billion market for environmental technologies.

2.4 CARBON SEQUESTRATION AND MANAGEMENT

This subsection discusses the reduction of net carbon emissions by capturing and sequestering CO₂ after combustion, decarbonizing fuel before combustion, or increasing the absorption of CO₂ from the atmosphere. These approaches are required for the continued use of fossil fuels as energy sources with reduced impacts on concentrations of atmospheric CO₂. For both approaches, there are a number of technological options, ranging from storage of CO₂ in the ocean or in geologic formations to chemical or biological stimulation of the absorption of CO₂ from the atmosphere.

The eventual path to stabilization of atmospheric CO₂ concentrations would require portfolios of GHG reduction technologies, portfolios that would vary from nation to nation and require systems-level analysis. Risks associated with any one pathway suggest that developing an effective approach to large-scale carbon sequestration would require evaluation of a number of alternatives as described in this report. These ideas and technologies should have a sound basis in science, both for understanding each technology and for evaluating the effectiveness of the technologies in actually ameliorating the atmospheric carbon loading. Thus it is imperative that we have a science-based model of the carbon cycle (atmospheric, oceanic, and terrestrial ecosystems) and that we verify the

actual effectiveness of our model through measurements. One set of essential elements are models of each part of the carbon cycle, anchored with georeferenced measurements and verified by checking performance predictions against data gathered using remote sensing technologies on local, regional, and global scales. The resulting science-based program would permit us to direct our investments with greater confidence and with improved cost-effectiveness.

The Potential for Reduced Emissions

The developmental status of the carbon sequestration technologies discussed in this report varies widely. For example, the injection of CO₂ into oil wells or coal seams to enhance oil or methane production is a commercial practice today, whereas the understanding of soil biochemistry is not yet adequate to identify the most promising means for increasing soil uptake of atmospheric CO₂. Therefore, estimating the potential impacts of these carbon sequestration technologies on net carbon emissions is difficult. It is generally believed that net carbon emission reduction from carbon sequestration could be very high in the time frame of the late 2030s and beyond. In the nearer term, carbon sequestration potentials are uncertain, but they may range from low to medium. All of these estimates should be considered possible targets and should only be considered within an order of magnitude indication of what might be likely to result from R&D on these technologies.

Technology Pathways and Opportunities

CO₂ and Carbon Storage Technologies.

Promising concepts for reducing CO₂ emissions are the storage of CO₂ in the ocean or in geologic formations. The technical feasibility of both of these

storage concepts has been established, and it is believed that the CO₂ escape rates in both cases could be low enough to consider the carbon as permanently sequestered. However, the ecological impacts of various specific approaches—which are likely to depend on the location and type of storage media—are not known, nor are the economics of different oceanic or terrestrial CO₂ injection technologies.

For ocean storage, the most critical R&D questions include the stability of CO₂ clathrates and hydrates at various temperatures and ocean depths, as well as the diffusivity of CO₂ in the ocean, again as a function of temperature, depth, and concentration. In addition, the biological impacts of oceanic injection need to be studied.

Terrestrial storage of CO₂ in depleted oil or gas wells, coal seams, or underground aquifers deserves analysis. For the injection of CO₂ into oil or gas wells or coal seams, which has enhanced oil and gas production (as well as, perhaps, mine safety), to be commercially motivated, the critical research questions center on understanding the total potential storage capacity and the economics of different specific candidate sites. Answers to these questions will depend on proximity to CO₂ sources, as well as on the size and other characteristics of the site.

For storage in underground aquifers, the critical research questions include fluid, thermal, geological, and chemical properties of aquifers and the implications of that environment for injected CO₂. For example, would the formation of complex carbonates result from CO₂ injection, and at what rate? The economics of such CO₂ storage also needs to be analyzed.

A third approach to reducing net emissions through storage is the

terrestrial storage of elemental carbon. This concept basically entails removing some or all of the carbon from a fossil fuel and then storing the carbon as a solid. For this approach, the challenge is primarily economic, because the carbon component of the starting fossil resource represents a major part of the energy value of that resource. Not using the carbon fraction in effect increases the energy cost of the remaining hydrogen-rich energy fraction. The advantage of this approach is that it should be less expensive to store carbon than to store CO_2 . It may also be possible to market the carbon as a materials commodity to offset the increased energy cost. If carbon is placed in retrievable storage, the carbon energy may be used at a later date under less severe CO_2 emission control conditions.

Currently, storage is believed to be relatively less expensive than capture technologies, but neither is being employed on a large scale. This, however, will change with time as combustion processes are reengineered to facilitate capture. As the cost of capture comes down, storage becomes a greater part of the cost equation. Managing this cost suggests that storage near the point of combustion is advantageous because it reduces the transportation cost of the waste carbon.

Which of the storage pathways is best matched to any single combustion or conversion location will vary, so parallel development is required. As discussion of the individual technology pathways highlights, it is important to emphasize that very clear technological and environmental risks are associated with these technologies. The R&D agenda must therefore be very aggressive if cost-effective technologies are to be in place in time.

Advanced Chemical and Biological Sequestration. There are also several advanced chemical and biological concepts for CO_2 sequestration, including

- chemical sequestration as a mineral carbonate
- direct solar conversion of CO_2 to methanol or other benign products
- reducing the carbon/hydrogen ratio of fossil fuels and capturing the excess carbon
- microalgae sequestration

Advanced chemical and biological sequestration is aimed at permanent stable sequestration and at recycle of carbon to new fuels and chemical feedstocks. Reduction of emissions is accomplished through converting CO_2 into an environmentally benign product, reducing atmospheric CO_2 while generating liquid fuels, generating hydrogen as a fuel from coal without CO_2 emissions, and converting CO_2 into organic compounds. The major advantage of these technologies is that they eliminate the hazards to humans and to the environment that are intrinsic in the disposal of gaseous CO_2 . Carbonate disposal accomplishes this by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products. All of these are at a research stage, with conceptual engineering design currently being completed. A better understanding of the basic processes is needed before practical achievable technology performance or cost levels can be estimated. However, because of the inherent attractiveness of these sustainable solutions, further work is merited.

Technologies for Removing CO_2 from the Atmosphere. The annual exchange of CO_2 between the

atmosphere and the combination of the ocean and terrestrial biosphere is very large (IPCC 1995):

- gross annual atmosphere-ocean exchange—approximately 92 GtC
- gross annual atmosphere-terrestrial exchange—approximately 63 GtC (IPCC 1995)
- oceans currently hold 44,000 GtC

By comparison, the total annual anthropogenic emissions of CO₂ are only around 7 GtC. This suggests that small increases in the absorption of CO₂ as a manipulation of the global carbon cycle could have a very significant effect on net GHG emissions.

Dissolved CO₂ in the oceans is removed by the growth of phytoplankton. When carbon is thus removed, it is ultimately replaced by CO₂ drawn from the atmosphere. Two concepts have been proposed for enhancing oceanic uptake of atmospheric CO₂. These are iron enrichment or nitrogen enrichment, both targeted at stimulating the growth of phytoplankton. The general understanding of these approaches is in its infancy. While some experiments on iron fertilization have been conducted, no such studies of nitrogen fertilization exist. Key questions include what rates of CO₂ uptake can be achieved, what the biological impacts are, and to what extent the gains would be offset by carbon or methane emissions resulting from increasing harvests or decay of higher levels of the food chain. The economics of these approaches, which depend directly on the costs and efficacy of different fertilization approaches and rates, also need to be studied. An important risk factor is that of anoxia, or oxygen depletion, which needs to be understood as a function of site characteristics and fertilization rates.

An important component of terrestrial uptake of CO₂ is plant growth, which is treated in the Agriculture and Forestry technology pathway. However, carbon sequestration in soils is also a key of the carbon cycle. The fundamental concept here is the level of "soil organic matter" (SOM). Many agricultural practices, such as breaking of grasslands for crop farming or draining of wetlands, tend to decrease SOM. Technologies that can increase SOM include minimum tillage agriculture, increased return of crop residues to the soil, use of irrigation and fertilizers at levels that maximize crop and root biomass, and return of lands to forests or perennial plants. The most critical R&D needs include research on soil productivity (including the interactions of fertilization levels), tillage practices, water management practices, different plant species, regional soil biochemistry and climate, and the implications of these for affecting SOM. A better understanding of these factors and their interactions can then enable the analysis of the economics of specific technological approaches to increasing SOM.

Collateral Benefits

The most important benefit of successes with these carbon sequestration technologies would be that they could help to enable the continued extensive use of fossil fuels without harm to the climate. Thus they could indirectly have a major impact on global economics, given that economic growth is highly dependent on energy use, about 75% of which is derived from fossil fuels.

Technical Risks and Other Issues

The most important risks for these carbon sequestration technologies are environmental and economic. Each

has the potential for environmental damage, and developing means to prevent that is a primary research need in each case. The economics for all of these technologies should be analyzed to determine their actual carbon sequestration potential and their associated costs.

The risks that are difficult to quantify today, however, are those associated with scaling up limited but promising field experiments to full-scale practice. The global infrastructure requirements for realizing large net carbon sequestration rates from carbon sequestration technologies would require a system of technologies that match or exceed the infrastructure requirements of the fossil fuel combustion enterprise of the next century. It will only be through an aggressive R&D program that we can develop a fundamental understanding of these risks.

2.5 REFERENCES

- Cramer-Kresselt Research 1996. *Facilities and Real Estate Strategies*, prepared for the National Summit on Building Performance, November.
- EIA (Energy Information Administration) 1996a. *Annual Energy Outlook 1997: with Projections to 2105*, DOE/EIA-0383 (97), U.S. Department of Energy, Washington, D.C., December.
- EIA (Energy Information Administration) 1996b. *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573 (95), U.S. Department of Energy, Washington, D.C.
- Energy Innovations 1997. *Energy Innovations: A Prosperous Path to a Clean Environment*, Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, and Union of Concerned Scientists, Washington, D.C.
- Interlaboratory Working Group 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, September.
- IPCC (Intergovernmental Panel on Climate Change) 1995. *Climate Change 1995: The Science of Climate Change*, ed. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge University Press, Cambridge, U.K.
- Shell Petroleum Limited 1996. *World's Energy Systems*, Group Internal Affairs, Shell Centre, London.
- The National Corn Growers Association and Inverizon International, Inc. 1997. *Plant/Crop Biobased Renewable Resources 2020*.

3. BASIC AND APPLIED RESEARCH AND CROSSCUTTING TECHNOLOGIES

Scientific research and the technological advances associated with it have been the basis for a multitude of new technologies that have appeared in the last 20 years. Many of the most successful and globally competitive industries in the United States (e.g., semiconductors, pharmaceuticals, aeronautics, biotechnologies) have strong ties to the products of U.S. R&D. The future security of our energy resources, the quality of our lives and health, and the competitiveness of our industries increasingly depend on further scientific and technological advances (*R&D Magazine* 1997). To create the innovative technologies required for energy systems with reduced carbon emissions requires (1) a broad interdisciplinary and visionary research program that develops the scientific understanding of the problem and (2) a strong industrial base.

Are there critical paths forward that require technological advances? If so, what types of research will enable those advances? At a workshop on R&D integration, Dr. Mary Good, until recently an undersecretary for technology for the U.S. Department of Commerce, concluded that basic research is the major factor that will determine the long-term outcomes of the technologies used to control carbon emissions. But reducing the levels of carbon emissions in the United States will require a commitment to both basic and application-driven research. In addition, disparate technologies for emissions control often will require work in the same critical basic research areas. Advances in both crosscutting basic research and enabling technologies are required to provide technological options like those outlined in Chap. 2 to reduce GHG emissions (Table 3.1).

This chapter addresses basic research needs and identifies a set of enabling technologies that will support the development of a wide range of technology pathways. Basic research needs and crosscutting technology developments are aggregated in the following list.

Table 3.1. Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2. Shaded boxes indicate a strong need for specific basic science or enabling technologies to advance a specific technology pathway. White boxes indicate that work in that basic research or technology area could be useful to develop a technology pathway

	Energy efficiency				Clean energy				CS
	Bld	Ind	Trn	A&F	FRD	FPG	Nuc	Ren	
Modeling and measurements									
Materials									
Chemical sciences									
Biotechnology									
Geosciences									
Environmental and ecological sciences									
Nuclear sciences									
Computational sciences									
Hydrogen and fuel cells									
Electrical transmission distribution, and components									
Sensors and controls									
Energy storage and retrieval									

Bld = buildings, Ind = industry, Trn = transportation, A&F = agricultural and forestry, FRD = fossil resource development, FPG = fossil power generation, Ren = renewables, CS = carbon sequestration.

- basic research to understand the global carbon cycle (i.e., computational modeling and measurements to understand the ocean-atmosphere-terrestrial-biosphere interactions)
- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, nuclear sciences, and computational sciences)
- enabling technologies supporting GHG reduction technologies (i.e., hydrogen and fuel cells; electrical transmission, distribution and components; sensors and controls; and energy storage)

The sections of this chapter of the report draw heavily upon the draft white paper, *Carbon Management: Fundamental Research Needs Assessment* (August 6, DOE-OER) and the report of the Secretary of Energy Advisory Board (SEAB 1995).

3.1 RESEARCH TO ADVANCE UNDERSTANDING OF THE GLOBAL CARBON CYCLE

CO₂ emissions from fossil fuels are divided among the atmosphere, ocean, and terrestrial biosphere. Measurements indicate that the atmosphere is storing carbon at a rate roughly equivalent to 60% of the emissions being produced by fossil-fuel consumption. Additional quantities of the excess carbon emissions are being stored in the ocean, where they do not affect the earth's radiation balance. Carbon storage changes in the terrestrial biosphere are difficult to measure and/or model; but there is reason to suspect that, while some areas are losing their ability to store carbon as a result of land-use changes, carbon storage is

increasing in other areas. Therefore, a satisfactory balance of the contemporary global carbon budget has not yet been reached. In order to plan, assess, and verify the performance of CO₂ sequestration strategies, the fate of emitted CO₂ must be understood and quantified on a global scale.

Verification of the fate of anthropogenic CO₂ via direct measurement programs is now technically feasible in both the atmosphere and the oceans. It is becoming possible to infer changes in terrestrial carbon storage using tracer methodologies, remote sensing, and modeling.

In general, CO₂ sequestration strategies and scenarios must be based on the assumption that the natural carbon cycle will function largely as it has over the past several thousand years. However, in the context of elevated CO₂ levels and perhaps of altered climates in the future, this assumption is not necessarily valid. Basic research is therefore required to identify and evaluate possible feedback on future atmospheric levels of CO₂. This feedback could arise from either direct effects (e.g., CO₂ fertilization of terrestrial plant growth, ocean ecosystem changes due to CO₂-related pH changes) or indirect effects (e.g., climate-related changes in deep-ocean circulation that might alter the sequestration of fossil-fuel CO₂).

3.1.1 Global Carbon Cycle Modeling and Measurement

Coupled atmospheric, terrestrial, and oceanic models are required for basic understanding of the integrated response of the global environmental system and for predicting changes in the global carbon cycle (see Fig. 1.1). This level of complex systems modeling demands high-performance computing (e.g., Accelerated Strategic Computing

Initiative) and fundamental research in the earth and ecological sciences. High-performance computing is critical to increase spatial and temporal resolution, to implement coupling between subsystems, and include important processes in the global systems model needed to assess carbon mitigation strategies. Research is necessary to quantify feedback among the terrestrial, atmospheric, and oceanic subsystems—including the implications of global changes for local and regional environments and economies and, conversely, local and regional inputs to the global systems. These models can be used to evaluate the effectiveness of carbon mitigation technologies and, through integrated assessments, to determine the cost-effectiveness and ecological impacts of carbon mitigation strategies.

In conjunction with the modeling activities, observations of the global environment are critical to document changes in the carbon cycle and to provide the basis for how and why changes are occurring. The strategy for systematic monitoring of CO₂ storage is now based on direct measurements of changes in atmospheric CO₂, oceanic storage of CO₂, and the inferred terrestrial carbon storage. The atmospheric and oceanic measurements should be continued, and measurement systems that directly estimate terrestrial storage must be developed. These measurements must then be used to verify the predictions and to suggest continuous improvement of the models.

The U.S. Global Change Research Program (USGCRP) is implementing a global observing and monitoring system for certain key physical measurements. This should be augmented with global and regional measurements that are especially pertinent to the global carbon cycle. These efforts should be coordinated

and should take advantage of all available technologies and measurement systems in addition to those of the USGCRP.

3.2 BASIC RESEARCH RELATED TO GREENHOUSE GAS EMISSIONS

Scientific discovery is difficult to mandate or even predict. It can, however, be stimulated by the nature of basic R&D. The returns on investments in basic research have been immense. Who could have anticipated the profound impacts on society of the revolutionary technologies enabled through the development of, for example, antibiotics, gene therapy, transistors, structural polymers, nuclear fission, and superconductivity. Areas of visionary research that could be profitably explored to reduce GHG emissions might include developing a hydrogen-based economy, producing electric power from nuclear energy without any radioactive by-products, developing global electrical transmission using high-temperature superconductors, and significantly increasing photosynthesis processes via genetic engineering.

Scientific understanding from basic research efforts will provide the United States with a sound basis to advance technological options. Creating a strong science base makes it likely that the United States will be capable of developing a portfolio of technological options to meet GHG reduction targets. Discoveries resulting from basic research will almost certainly provide the United States with technologies that today might seem highly uncertain and unrealistic but that tomorrow might be essential problem-solving tools. Our long history of scientific progress has shown that basic scientific research alters the technological options available for

responding to threats to our environment, security, and quality of life.

The following examples of progress in the areas of materials science, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences could offer vastly improved or completely new technologies for reducing GHG emissions. We have already seen the pull of technology in Chap. 2; here is the push of basic science and its promise for the future.

3.2.1 Materials Science

Improvements in materials can significantly impact the production of GHGs and wastes. Materials found in systems that produce energy (e.g., combustors and turbines), store energy (e.g., batteries and fuel cells), and use energy (e.g., vehicles and industrial/chemical processing) can improve system efficiencies, extend component lifetimes, and increase performance or capacity (Fig. 3.1). Furthermore, the production and processing of materials consumes the largest fraction of the energy used by U.S. industry. Reducing the energy required to supply materials is essential to reducing GHG production.

Basic research into materials synthesis and processing is needed to provide new ways to produce the materials currently used and enable the creation of new materials for energy systems. Areas in which breakthroughs are needed include nonequilibrium thermodynamics, microstructure-properties characterization, interface science, optical and electronic property optimization, and computational modeling of materials processes. Examples of potential near-

term improvements include high-temperature-tolerant materials that allow improvements in the efficiency of combustion processes, heterogeneous catalysts that increase yields and selectivity, high-temperature superconductors to reduce energy losses in electrical systems, lightweight materials to decrease vehicle weight, improved magnets for sensors and motors, improved coatings and surface treatments to reduce wear and surface degradation, improved insulation to reduce heat loss, and miniaturization of equipment to improve efficiency and reduce cost.

Interdisciplinary theoretical and experimental research in condensed matter physics, metallurgy, bioscience, and materials chemistry are key components of a long-term research strategy. For example, cross-disciplinary efforts are needed to develop bio-inorganic composite



Fig. 3.1. Ceramic composite hot gas candle filters can be used to remove particulates from gas streams in combined cycle fossil and biomass power facilities. The filter is made up of an oxide fiber structure into which silicon carbide is deposited by a chemical vapor infiltration process.

materials systems or “smart” materials that are self-constructing or self-adapting. Interdisciplinary biological and materials research is needed to create biomimetic materials—materials patterned after nature. The development of materials engineered at the nano-scale requires the merger of materials science and condensed matter physics; the result will be optoelectronic, organic-electronic, thin film, and semiconductor materials for use in energy generation and distribution (e.g., solar cells, sensors in power plants, and power grid control circuits) and in energy-efficiency applications (e.g., engine sensors and processors, solid-state lighting and displays, advanced windows).

3.2.2 Chemical Sciences

Chemistry is central to the design and synthesis of a wide range of useful materials, as well as to the conversion of energy into heat, work, and light. Advances in the chemical sciences in key areas of separations, catalysis, and combustion are necessary for significant GHG reductions.

Separation processes are used to purify raw materials, separate by-products, and remove contaminants. The membrane materials market alone is currently \$1 billion. Improved separation techniques using membranes, novel separating agents, or hybrid processes could make many industrial processes more efficient while enhancing productivity and reducing environmental impacts. For example, distillation, which consumes more than 40% of the energy used in chemicals and petroleum manufacturing, seldom exceeds a thermodynamic efficiency of 10%. It would benefit greatly from improved separations technology. Other industries, such as microelectronics,

require new standards in separation performance to improve the purity of the components and materials used. Adsorption and ion exchange processes are attractive for removing and recovering materials from dilute systems. Pharmaceuticals, biotechnology, food processing, and pulp and paper processing use separation technologies for product preparation or waste recovery and reuse. Waste treatment and recovery constitute another potentially large market for membrane and adsorption or ion exchange systems.

Catalysts and catalytic processes account for nearly 20% of the U.S. gross domestic product and nearly 20% of consumer products. Improved catalysts could increase efficiency to shrink energy requirements, while increasing product selectivity and thereby decreasing wastes and emissions. New catalytic processes could also reduce GHG emissions in alternative fuel resources, electricity production, transportation, and carbon sequestration. Several studies (e.g., the Council on Chemical Research’s Vision 2020 document) have cited critical areas for innovation in catalysis including

- the development of theoretical and experimental tools to improve understanding of catalytic processes at the molecular level, and to enhance predictive capabilities and the ability to design catalysts and develop industrial catalytic processes to increase yield, selectivity, and reliability
- methods to improve the speed of catalyst discovery
- novel reactors and reaction engineering including reactive separation concepts
- low-temperature selective oxidation of fuel-value feedstocks to high-value chemicals

- conversion of gases (e.g., methane) to liquid fuels and chemical feedstocks
- novel methods for producing recyclable polymers and other materials with specific designed properties
- new catalyst systems for achieving high regio- and/or stereo-selectivity, including supported catalysts
- biomimetic synthesis of chemicals and materials,
- fuel cells for cogeneration of chemicals and energy
- new, more economical abatement technologies
- on-line monitoring and in situ catalyst characterization technologies

Combustion is employed in the conversion of 90% of primary energy to end uses in the United States. It powers practically all electric power and provides most heating and process heating (either directly or indirectly, by electricity). Key R&D needs include improved basic understanding and advanced analysis of combustion processes; nonintrusive (e.g., laser and microwave) diagnostics to improve understanding of the chemical, heat transfer, and fluid mechanics relationships that characterize combustion processes; understanding of processes that control flame shape and stability under different conditions; and flame chemistry to control emissions.

3.2.3 Biotechnology

Biotechnology as a crosscutting technology affects four of the nine major technology impact areas shown in Table 3.1: industry, agriculture/forestry, renewables, and carbon sequestration. However, under the broad realm of biotechnology as it applies to reducing carbon emissions,

the status of research and technology-development efforts varies greatly.

The range of technological areas where biotechnology could have an impact on GHG/global carbon cycle issues is broad and includes crop improvement (including energy crops), alternative fuels other than biomass (noncellulosic), carbon cycle manipulation/sequestration, bioprocessing for fuels and chemicals, and biological/biochemical hydrogen production. Energy crop production and efficiencies in the agriculture and forest products sectors will result from advances in genetics and cropping systems. In addition to biomass energy crops, biotechnological approaches offer promise for production of other alternative fuels, including oils/lipids from algae and certain higher plants, and hydrogen from photosynthesis or enzymatic conversion of cellulosic biomass. The recent discovery of a one-photon photosynthesis system and protein engineering of the carboxylase/decarboxylase pathway offers the promise of increases in the efficiencies of carbon fixation by plants.

Fundamental studies of global carbon cycles and the importance of the biosphere as a major sink could lead to major breakthroughs in deploying biological phenomena in strategies to sequester CO₂. Bioprocessing of cellulosic biomass into alternative fuels is necessary in order to realize the full value of biomass-based energy. In addition, cells and enzymes are capable of synthesizing many organic chemicals of industrial interest. Because of mild reaction conditions, unique specificity, and selectivity, biocatalytic conversions are now being considered for many industrial uses. Organic-phase bioprocessing, a particularly promising application,

employs microorganisms and enzymes in nonaqueous media such as organic liquids, gases, or supercritical fluids. This technique could provide alternatives for processing fossil fuels, synthesizing organic chemicals, and converting alternative feedstocks to fuels and chemicals.

3.2.4 Geosciences

The geosciences play a central role in understanding and mitigating the impacts of carbon emissions. A better understanding of the terrestrial, atmospheric, and ocean carbon cycles—and the interactions among them—will lead to new ideas for managing excess carbon and provide the foundation for comparing alternative technologies that could contribute to carbon emissions reductions. Moreover, evaluating the feasibility of most of the mitigation technologies under consideration today will require new knowledge in such disciplines as geophysics, flow and transport, geomechanics and geochemistry. For example, the geosciences are critical for developing or enhancing technologies to inject CO₂ into oil reservoirs, aquifers, and the deep oceans; increasing production of clean fuels such as natural gas; tapping into the huge natural gas supplies found in methane hydrates; and enhancing the natural carbon cycle to capture and sequester more carbon. In addition, closing the nuclear fuel cycle through geologic disposal of nuclear waste is critical to the widespread future use of nuclear power generation.

A fundamental research program in the geosciences would include studies of transport phenomena and the movement of fluids, the kinetics of geochemical systems, and the modeling of complex interactive systems.

3.2.5 Environmental and Ecological Sciences

Ecological and environmental sciences provide the fundamental knowledge of the structure and function of ecosystems (carbon and nutrient cycling) and, therefore, understanding of the responses of ecosystems to the effects of increased GHG emissions. Ecological science is fundamental to quantify the role of the world's ecosystems as net carbon sources or sinks, and to predict ecosystem response to future climate change events and/or carbon mitigation strategies.

Key research goals in ecological and environmental science include

- quantifying current carbon sequestration potential in both managed and unmanaged ecosystems, including soils
- understanding the response of ecosystems to increased atmospheric concentrations of CO₂
- understanding how future changes in climate variables will affect ecosystems and their role in carbon cycling
- developing carbon cycle models to predict future carbon sequestration
- understanding how land use changes and land management options affect carbon storage and exchange
- developing biological productivity potentials to offset fossil fuel usage with biomass energy

3.2.6 Nuclear Sciences

From the birth of nuclear power to the present, the United States has been the technological and policy leader. U.S. technology has been exported and adapted for use throughout the world. U.S. nuclear plant technology is among

the safest and most reliable of nuclear technologies available worldwide.

Nuclear science and engineering is a discipline that is rapidly disappearing in the United States. If the United States is to maintain nuclear fission as an option for its future energy generation and is committed to avoiding additional carbon emissions, then a vital nuclear science basic research program is essential. It is likely that nuclear power will continue to be developed globally, with or without U.S. technology.

Research on nucleonics, new fission reactor concepts, proliferation-resistant technologies, fusion and fission-fusion hybrids, hybrid accelerator-driven subcritical systems, advanced fuel cycle technologies, advanced component design, waste transmutation (both accelerator and reactor based) and fast neutron burning, and systems safety are all vital to a successful industry in the future and to U.S. viability in this important area. In addition, research reactors form a vital component in this system and in our national research and educational infrastructure. They are essential and critical to many national priorities in addition to reducing carbon emissions, such as health care, environmental science and education, and technology transfer. Perhaps the most important goal of nuclear science is to improve the acceptance—by the public and by industry—of nuclear energy as a safe, reliable, and cost-effective resource for a sustainable future.

3.2.7 Computational Sciences

Advanced energy technologies with low carbon emissions can benefit greatly from modern simulation technology, particularly in the areas of combustion modeling, airborne

particulates, and global carbon cycle modeling. High-fidelity simulations of manufacturing and power generation operations and the distribution of gases resulting from internal combustion engines (Fig. 3.2) can be used to predict the behavior of pollutants in the atmosphere at scales ranging from a few rooms in a building all the way to global simulation of the buildup of GHGs. Process design and optimization using simulations including social and economic components can result in improved processes and reduced environmental impact, without the expense of trial-and-error experimental designs. These tools can aid development of advanced energy technologies by allowing advanced modeling and visualization where direct experimentation or prototyping is very expensive, inaccessible, or otherwise unfeasible.

Predictive modeling and simulation involves the use of the most advanced parallel computers—in speed, memory capacity, and I/O capability. By the

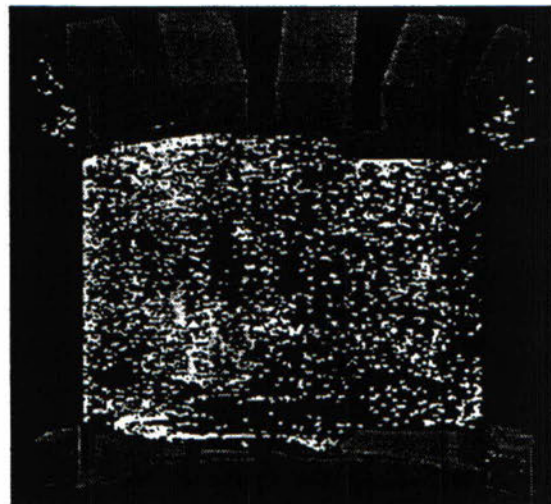


Fig. 3.2. This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur. The simulation includes the flow of gases, heat transfer, combustion, and creation of pollutants.

year 2000, U.S. vendor systems will be capable of 10 thousand billion floating point operations per second. Advanced visualization and analysis techniques, including virtual reality, will be necessary for scientists and decision makers to understand the huge amounts of data generated by these simulations and to compare these simulations with observational and experimental data. Advanced network communications will allow the establishment of national and international collaborations, as well as enabling the remote operation of unique experimental facilities.

Effective use of this immense capability will require development of new mathematical models of relevant physical, biological, social, and economic processes; stable programming paradigms that support—over a decade or more—changing hardware capabilities; algorithms and computational techniques that can efficiently make use of parallel, distributed computing resources; software frameworks that allow rapid prototyping of new capabilities; and, perhaps most important, a verification and validation methodology that provides both qualitative and quantitative assurance of what can and cannot be predicted.

3.3 CROSSCUTTING TECHNOLOGIES SUPPORTING GREENHOUSE GAS REDUCTIONS

In addition to the broad portfolio of technological opportunities for reducing GHG emissions presented in Chap. 2, a number of technologies crosscut a wide range of applications, including those which impact U.S. carbon emissions. Advancing these enabling technologies integrates the pull of technology with the push of basic science.

This subsection presents four crosscutting technology areas: hydrogen and fuel cells; electrical transmission, distribution, and components; sensors and controls; and energy storage.

3.3.1 Hydrogen and Fuel Cells

Hydrogen is a carbon-free energy carrier that can be used to fuel every aspect of society. For example, it can fuel transportation vehicles (air and ground), provide process heat for industrial processes, supply domestic heating needs through cogeneration or heat recovery systems, and fuel power plants for centralized or distributed electrical generation (Fig. 3.3). Hydrogen is an energy carrier that must be produced efficiently from a primary energy source. Depending on the source, its production may or may not involve CO₂ emissions. Hydrogen also burns cleanly and efficiently, an advantage that lowers the operating

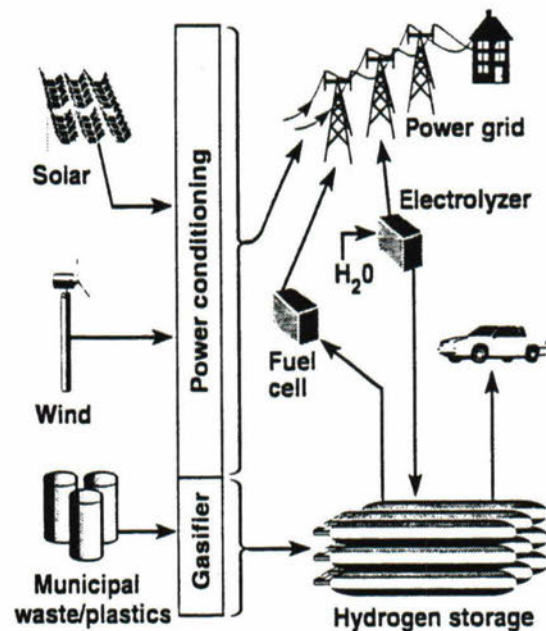


Fig. 3.3. Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate.

cost. Expanded production-related R&D is needed on biological, thermochemical, and electrochemical processes. Goals of the RD&D for production include a 10 ton/day process demonstration using municipal solid waste by 2000 and the development of advanced steam electrolysis, photobiological, and photoelectrochemical processes by 2010.

Hydrogen can be used in modified conventional combustion energy conversion devices (e.g., engines) to ease the transition to a completely new energy infrastructure where hydrogen will be used in fuel cells for energy conversion. Fuel cells promise potentially higher system efficiency and solid-state operation with water as the only effluent.

Lack of suitable hydrogen storage technologies is the greatest obstacle to its use as a transportation fuel. For 2000, the RD&D goals are to develop an automotive on-board hydrogen storage system capable of a 300 to 400 mile range and to demonstrate a fuel cell or hydrogen-powered internal combustion engine hybrid vehicle fleet with associated infrastructure. For 2010, the goals are to develop (1) advanced solid-state storage systems based upon such innovative materials as carbon fibers and structures and metal hydrides and (2) a conversion system for waste and biomass capable of producing hydrogen at a cost of \$10/GJ (lower heat value of hydrogen).

Fuel cells convert chemical energy directly into electrical energy; no combustion is involved. They are significantly more efficient than other power-generation technologies or internal combustion engines operating on conventional fuels. Individual cells produce less than 1 V and are stacked

in electrical series to produce higher voltages for utility, industrial, transportation, and residential use. Fuel cells span all important energy use sectors. Molten carbonate and phosphoric acid fuel cells target power generation, both large-scale and distributed power production. Solid-oxide fuel cells, which in stacks have recently reached the 100-kW size, are mostly considered for stationary application. Proton exchange membrane fuel cells target transportation as well as distributed power applications.

Key targets for R&D are materials and fabrication issues concerning the catalyst/electrode/membrane designs, as well as the cell stacking design. Future improvements in manufacturability will strive to reduce the currently high cost of fuel-cell fabrication to levels competitive with combustion devices.

3.3.2 Electrical Transmission, Distribution, and Components

Many proposed GHG reduction technologies involve alternative ways of producing electricity. In most cases, the U.S. electric transmission and distribution system is the means by which these alternative approaches will be made available to energy users. Almost 40% of the capital investment currently required to produce and deliver electricity goes to construct transmission and distribution facilities, and the availability of reasonably priced transmission capacity will be crucial in determining the commercial success of alternative generation strategies. This is particularly a concern for large-scale development of such remote resources as renewable generation, which could require significant investments in new transmission capacity because of the

distances between the best resource areas and load centers. At the same time, public opposition to the construction of conventional transmission lines for environmental reasons has focused attention on opportunities for increasing the capacity of existing corridors, as well as on development of transmission technologies that are compatible with public concerns and therefore present a minimum of permitting risk. In addition, the importance of other collateral benefits of these technologies cannot be overlooked, especially their contribution to improving power quality.

R&D is needed on automated system control technologies that better use the capacity of existing systems, as well as advanced composite-reinforced high-strength overhead line conductors to increase the capacity of individual lines. Developments in power electronics—including wide-bandgap semiconductors for high-power switching devices and advanced converter designs—are needed to improve power management on existing systems and to enable high-voltage DC transmission for long-distance power transfers.

Improvements in superconducting materials and associated refrigeration technologies will lead to development of superconducting cables and power transformers that offer half the energy losses and many times the capacity of conventional devices while taking up less space and reducing environmental impact.

While electrical transmission and distribution system improvements are essential to enable deployment of alternative electrical generating strategies, power system component development also offers significant opportunities to reduce GHG production. Energy losses in U.S. transmission and distribution systems

were 7.2% in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC of carbon emissions. Roughly 70% of these losses are due to the resistance of the conductors used on transmission and distribution lines, while 20% are in the distribution transformers used by utilities and commercial building owners to provide the last step of voltage reduction for customer equipment. In addition, the bulk of U.S. electricity production goes to drive motors—most commonly the ubiquitous polyphase induction motor, whose limited speed control reduces associated process efficiency by as much as 30%.

Research needed to improve the efficiency of power system components includes the development of superconducting generators, motors, and transmission cables, as well as low-cost methods for manufacturing amorphous metal materials for high-efficiency distribution transformers. R&D on advanced power electronic converters and controls for variable-speed motor drives, integrated with high-efficiency motors, could substantially improve industrial process efficiency and product quality.

3.3.3 Sensors and Controls

Sensors and controls will play a significant role in any technological advances for reducing CO₂ emissions and in CO₂ sequestration processes. Each primary area of clean energy production, energy efficiency, and carbon-cycle/carbon sequestration, will require sensors and controls technology for ensuring maximum efficiency at minimal cost.

R&D is needed to develop sensors that can improve the efficiency of primary energy production. For example, chemical sensors capable of operation in boreholes can improve fossil fuel

recovery. Both refining processes and fossil fuel reforming for CO₂ sequestration require substantial chemical processing that can be enhanced through real-time process sensors and controls. Sensors and controls that more accurately measure operational parameters can be used to increase the output of nuclear power plants.

In the area of energy efficiency, transportation remains a major factor in energy consumption. Novel sensors are needed to enable the use of more efficient engine technologies. Almost all industrial processes depend on sensors and controls to ensure the quality of goods produced, and advanced sensors can help to reduce wasted energy and thus CO₂ emissions. In carbon cycle/carbon sequestration, innovative sensors for analyzing photochemical processes and carbon fixation are needed. They may also be required for efficient biomass energy production.

Often a single fundamental sensor technology will meet the needs of different applications, so sensors are a true crosscutting technology. The best example is the solid-state oxygen sensor developed for the space program in the 1960s. This sensor is now universally used in gasoline engine control and is common in industrial combustion control, touching virtually every major energy-consuming industry.

A large variety of novel sensor technologies that are robust, sensitive, cost-effective, and capable of supporting real-time control will be required in a successful climate change technology development program, as will commensurate methods of data analysis and fusion for control. Across the industrial arena, sensors are needed that can be used in harsh environments and that will

measure such on-line process parameters as viscosity, moisture, chemical composition, density, flow, temperature, and pressure. Research is also needed in the development of multi-analyte sensors and in the integration of sensors and microtechnologies, such as microflow devices. Further RD&D is necessary in the development of "smart controllers" that couple a multitude of sensors and/or sensor arrays to sophisticated data analysis systems that can provide real-time on-line process control and improve process efficiencies.

3.3.4 Energy Storage

Stationary energy storage is now primarily in the form of bulk storage of fossil fuels (piles of coal, oil in tanks, gas in pipelines) and water in reservoirs. Reversible energy storage technologies in use today include pumped hydropower, compressed air, and chemical batteries for small uninterruptible power. Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), and purely electrical (ultracapacitors, superconducting magnetic storage). The major hurdle for all storage technologies is cost reduction.

In transportation, hybrid powertrains that use batteries, flywheels, or ultracapacitors in conjunction with engines allow the reduction of engine size. A hybrid powertrain can increase overall efficiency by up to 100% without a loss in vehicle performance (acceleration, range, and passenger capacity). When combined with other vehicle improvements, such as weight reductions, aerodynamic improvements, and rolling-friction, this efficiency increase results in up to three times the equivalent mileage of

current direct-drive automobiles, which is the current goal of the PNGV.

Key R&D needs for energy storage include developing

- new electrocatalysts, electrode materials, and structural materials for electrochemical systems
- higher specific-energy composite rotors, magnetic bearings, fail-safe designs, and lightweight containment for flywheels
- better corrosion-resistant materials for higher power-density batteries
- commercial high-temperature superconductors (operating at liquid nitrogen temperatures) for superconducting magnetic energy systems
- higher energy-density ultracapacitors for light-duty vehicles
- improved power conditioning systems.

The greatest value of advanced energy storage for electric utilities is that it can enable better use of intermittent renewable energy sources, such as solar PVs and wind, that produce no direct CO₂.

3.4 REFERENCES

Carbon Management: Fundamental Research Needs Assessment 1997. (Draft), DOE-Office of Energy Research, August 6.

R&D Magazine 1997. "Basic Research White Paper: Defining Our Path to the Future," *R&D Magazine*, A. Cahnners Publication, Des Plaines, Ill.

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.

4. TECHNOLOGY INNOVATION APPROACHES

4.1 INTRODUCTION

Previous chapters of this report identified a set of technology pathways that we believe offer the United States affordable options to reduce GHG emissions to sustainable levels. We have emphasized that R&D, both fundamental and applied, needs to be continued and/or initiated to advance the technologies identified within the pathways, thereby moving them closer to the goal of deployment in the marketplace. This section discusses three technology innovation approaches and presents several factors for consideration in deciding which approach to use to develop a particular technology. While each of the approaches provides a viable option; we believe that in most cases public-private strategic alliances are the best approach for developing and deploying these technologies.

4.2 APPROACHES

In this section, we evaluate the pros and cons of three approaches for advancing the RD&D of GHG reduction technologies. These approaches can be characterized as

- government led and financed
- industry led and financed
- public-private strategic alliances

Although we recommend public-private strategic alliances as the best approach for developing and deploying most of the technologies discussed in the technology pathways section, in some cases one of the other approaches may be more appropriate.

When selecting an approach to pursue the RD&D of a technology, we recommend the following factors be considered:

- national strategic value of the technology
- target market of the technology
- return on private-sector investment

A technology has *strategic value to the nation* when it provides a significant benefit to national security, economic well-being, environmental quality, and/or public health. National defense is the casebook example of high strategic value to the nation.

Historically, the strategic value criterion has also been a justification for government support of technologies in the areas of space, health, energy, and agriculture.

The *target market* factor refers to the expected end-user or consumer of the technology. In some cases, a technology is developed for a specific target market or end-user (e.g., the federal government), and the technology has little application beyond that market. For example, technologies to process uranium have had little application beyond the nuclear industry. In other cases, a technology, such as the transistor, has applications in multiple markets and industries. Technologies that are applicable to a variety of markets and industry are sometimes referred to as "generic technologies" (Bloch 1991).

The third criterion refers to whether the private sector believes it can attain a large enough *return on its RD&D investment* within a reasonable time frame and at acceptable levels of risk to warrant supporting the innovation process. The complexity and the length of time needed to develop and deploy a technology are key variables considered by private industry when it

is deciding whether to invest in a technology, because both factors can increase the risk of not receiving the expected return on investment. Of the three factors presented, expected return on investment is the key factor companies consider when deciding whether to invest in the development of a technology. Although this factor is of primary importance to the private sector, it is not necessarily mutually exclusive from the national strategic value criterion. In many cases, companies have led and financed the development of technologies that have underpinned the formation of industries with a high strategic value to the nation (e.g., computer software, drug, and automobile industries).

The following sections discuss the characteristics and relationship among the three approaches to technology innovation in an effort to provide selection criteria for determining the optimum approach to achieving the RD&D goals for individual technologies (Table 4.1).

4.2.1 Government Led and Financed Approach

The government typically leads and finances projects throughout the RD&D process when a technological innovation has a high strategic value to the nation, the public sector is the intended end-user of the technology, and the expected return on investment is too low to warrant the private sector's

Table 4.1. Approaches to technological innovation

	National strategic value	Target market	Return on private sector investment
Government led and financed	High	Public sector	Low
Industry led and financed	Low-medium	Specific market	High
Public-private alliance	Medium-high	Multiple markets	Low-medium

bearing the RD&D costs (Table 4.1). Examples of projects led and financed primarily by the federal government include the Manhattan Project, which developed the atomic bomb in World War II, and the Apollo Project, which put a man on the moon in 1969. Government led and financed projects have been very successful in meeting their goals when the conditions warrant government leadership and it has been able to focus the best resources of the nation on solving a problem with clearly defined technological goals and large public benefits and support.

The government led and financed approach could be applied to reducing GHGs, but it contains some inherent barriers to full effectiveness. In contrast to the examples given earlier, the government is not the primary target market for GHG reduction technologies, and there is no single technological solution to stabilizing atmospheric concentrations of CO₂. Therefore, significant GHG reductions will be achieved only if a number of technologies penetrate a broad spectrum of commercial target markets. In addition, some of the GHG technologies will have economic benefits in reduced fuel use, higher productivity, and reduced waste generation. Therefore, we expect the private-sector return on investment in the innovation process to be at a sufficiently high level for some of the technologies to warrant private-sector RD&D cost sharing.

4.2.2 Industry Led and Financed Approach

The private sector typically leads and finances projects throughout the RD&D process when a technological innovation has a high potential return on investment from specific commercial markets, regardless of its

national strategic value. Historically, technological innovation leading to products for the commercial market has been primarily the responsibility of the private sector. Numerous examples exist of technology innovation led and financed primarily by industry, including plastics, pharmaceuticals, scientific instrumentation, information systems, and robotics. These technologies were driven by the demands of consumers in target markets, not by the federal government. Market-driven technology development is critical to continued economic growth because it enables companies, through the deployment of technological innovations, to profit by meeting the demands of consumers.

The strong relationship between technological development and quality of life in America in the twentieth century is a testament to the value of the industry led and financed approach to innovation. However, for this to be the primary approach for developing and deploying GHG reduction technologies, carbon mitigation would have to be highly valued in the marketplace to enable private companies to profit from their RD&D investments. Some technologies that result in GHG reduction may attract sufficient private-sector investment because they offer additional benefits that consumers are willing to pay for to amortize the RD&D costs and to provide adequate profits. However, short of policies that create a large economic incentive for reducing carbon emissions, industry is not likely to lead and finance RD&D on a broad spectrum of GHG reduction technologies.

4.2.3 Public-Private Strategic Alliances

Public-private alliances are typically established to share the costs of RD&D and deployment of technologies that

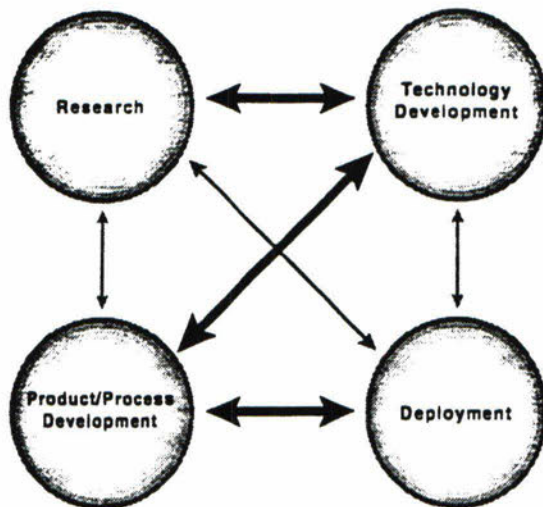
have a strategic value to the nation and have value for multiple markets and industries, but do not promise sufficient return on investment to motivate the private sector to bear all the RD&D costs. Many of the technology pathways for reducing GHGs have these characteristics, making public-private strategic alliances the optimum approach for promoting their development and deployment.

Numerous examples of public-private alliances exist, such as SEMATECH, PNGV, IOF, the International Energy Agency Greenhouse Gas R&D Programme, the Clean Coal Technology program, the Advanced Light Water Reactor program, and PVMaT. In the case of PNGV, technologies to increase the fuel efficiency of automobiles have a *high strategic value to the nation* because they reduce our consumption of oil, thereby increasing our economic and national security, and mitigate GHG emissions, thereby reducing global warming and improving the quality of the air we breathe. In addition to being deployed in the automobile industry, many of the technologies being developed by the PNGV consortia are likely to be deployed in *multiple markets*. For example, one of the goals of PNGV is to increase fuel economy threefold. In order to meet this goal the vehicle weight must be reduced 40%; therefore, a significant portion of the steel and cast iron components in these vehicles must be replaced with aluminum and polymer composites. These new lightweight, high-strength materials will be deployed in other transportation markets (e.g., aircraft and rail), as well as multiple segments of our infrastructure (e.g., bridges, buildings, energy). Finally, although the technologies being developed by PNGV have a high strategic value, the *market return* on fuel efficiency investments is currently very small

because the cost of gasoline in the United States has been decreasing at an average annual percentage rate of 1.8% (in constant dollars) since 1978.

The combination of high strategic value, multiple target markets, and expected low return on investment makes public-private strategic alliances the optimal approach for developing and deploying GHG reduction technologies. This approach will allow sharing of costs and pooling of resources, thereby motivating private companies to invest in the technology even though the return on investment is likely to be low in the short term, and encouraging government agencies to support the RD&D process even though the public sector may not be the targeted end-user of the technology.

The interactive nature of the innovation process is another reason to use public-private alliances to develop and deploy GHG reduction technologies. It is now widely recognized (Kline 1991; OTA 1995; Branscomb et al. 1997; *R&D Magazine* 1997) that most complex technological innovations advance through a nonlinear, interactive innovation process (Fig. 4.1), in which there is synergy between scientific research, technology development, and deployment activities. The interactive process is a more effective model for developing and deploying technology than the linear model that depicts the innovation process as starting with basic scientific research and then advancing sequentially through the technology development and deployment phases (Fig. 4.2). This linear approach can take longer and can result in potential innovations being delayed or never making it to the marketplace. The interactive process has several advantages in that it provides the following:



The thicker lines indicate high degrees of interaction.

Fig. 4.1. Interactive model of innovation.

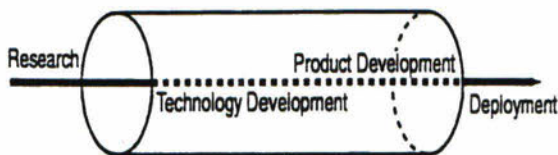


Fig. 4.2. Linear model of innovation.

- a continuous feedback loop for development and use of new scientific capabilities and facilities that can expedite the innovation cycle
- effective dialog between the research and user communities on innovation needs
- an effective basis for focusing research in the highest priority areas and evaluating progress along the technology pathways

4.3 STRATEGIC ALLIANCE ROLES

One of the major benefits of strategic alliances is that they help maximize the efficiency of the innovation process by bringing together an interdisciplinary team of scientists, engineers, and analysts (e.g., market, social, and financial) from industry, government laboratories, universities,

and nongovernment organizations who can ensure that the scientific, technical, and commercial challenges that arise throughout the innovation process are successfully resolved. We recognize that there will be many stakeholders in a climate change technology strategy and that over the course of time, some of the technology pathways will dramatically restructure the nation's energy, buildings, industrial, and transportation sectors. International customers and suppliers will be concerned about their costs and their markets. The financial community, insurance industry, and standards organizations all have a stake in the process; the list is long. Their input will be important for formulating effective public-private alliances, monitoring progress toward GHG reductions, and sustaining interest in the climate change technology strategy over the decades that will be required to implement it.

In many respects, the whole is greater than the sum of its parts in strategic alliances, for while private companies, universities, federal laboratories, government organizations, and nongovernment organizations each have unique capabilities, a synergy results when their resources are applied strategically toward a common goal, such as developing technologies to reduce GHG emissions. For example,

- Private companies and industrial consortia, such as the Electric Power Research Institute and the Gas Research Institute, play a key role in the innovation process by identifying requirements for technologies that help ensure their commercial viability, by performing R&D in collaboration with federal laboratories and universities, and eventually by demonstrating and deploying the technologies.

- Government laboratories and nongovernment research organizations provide scientific staff who have conducted and managed research for more than 50 years. These laboratories have conducted much of the research that provides the scientific underpinning for many technological breakthroughs. This scientific resource can provide new approaches to reducing emissions in the future. The national laboratories also provide unique facilities for use by researchers from industry and academia, as well as by their own researchers, in the development of these technologies.
- Universities provide a wealth of scientific talent to undertake the scientific research required to understand the role of GHGs in global climate change and to understand the basic mechanisms of biological and chemical processes that might be used to reduce GHG emissions. The linking of science and technology in the interactive process of innovation makes the scientific resources of universities and laboratories critical throughout the innovation process. In addition to providing scientific resources, universities are the training ground for future scientists and engineers needed for a sustained national effort to minimize the effect of GHGs on climate change.

Along with private companies, federal laboratories, and universities, it is important that government agencies, international organizations, and other nongovernmental organizations that are stakeholders in global climate change have a role in strategic alliances.

- Government agencies at the federal, state, and local levels contribute financial resources that are critical

for advances in scientific research and basic technologies, as well as legislative mechanisms that can play an important role in removing barriers to the deployment of climate change technologies. In addition, government institutions can help educate the American public about climate change and can provide a forum for stakeholders to express their views on this subject.

- Climate change is a global issue, and international collaborative RD&D efforts will be needed. Japan has recently announced a national program to support international R&D on technologies to mitigate global climate change and pollution. Other efforts involving the U.S. federal government and U.S. companies are under way (e.g., the International Energy Agency Greenhouse Gas R&D Programme).
- Nongovernment organizations, including end-users, environmental organizations, financial institutions, and other interest groups, possess expertise that can be valuable to scientists, engineers, and market analysts as they work to better understand climate change and market issues.

4.4 CONCLUSION

Three specific approaches for implementing RD&D and deployment activities on GHG technologies are considered: (1) government led and financed, (2) industry led and financed, and (3) public-private strategic alliances. In selecting an implementation approach, we encourage the consideration of three factors: strategic value to the nation, target market, and expected return on private-sector investment. A systematic assessment of the relationship between the technology being developed and the three implementation approaches

will allow selection of the optimum approach.

For most of the GHG emission reduction technologies discussed in this report, we believe that the public-private strategic alliance approach is the best choice. Although many of these technologies will be able to compete cost-effectively in the marketplace in the future, industry may not be willing to lead and finance the innovation process for many of these technologies 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. Additional factors favoring public-private strategic alliances include the *interactive nature* of the innovation process and the need to develop and deploy a variety of technologies in a number of target markets to reduce GHG emissions significantly. A public-private alliance will enhance the efficiency of the innovation process by bringing together stakeholders who can meet the scientific, technical, and commercial challenges involved in developing and deploying the required technologies. In this context, institutional efforts, such as collaborative RD&D enterprises, that help bring together industries, government laboratories, universities, government agencies, and nongovernment organizations to focus on common technological issues will be of great value in fostering the development of public-private alliances.

While public-private strategic alliances are only one part of the nation's climate change technology strategy, we feel they are a vital element if we hope to efficiently and effectively develop and deploy the GHG reduction technologies discussed in this report.

4.5 REFERENCES

- Bloch, Erich 1991. "Science and Technology: The False Dichotomy," *Powernomics: Economic and Strategy After the Cold War*, ed. Clyde Prestowitz Jr., Ronald Morse, and Alan Tonelson, Economic Strategy Institute, Washington, D.C.
- Branscomb, Lewis et al. 1997. *Investing in Innovation: Creating a Research and Innovation Policy That Works*, MIT Press, Cambridge, Mass., in press.
- Kline, Stephen 1991. "Styles of Innovation and Their Cultural Basis," *Chemtech*, 473-480, August.
- OTA (Office of Technology Assessment) 1995. *Innovation and Commercialization of Emerging Technologies*, U.S. Government Printing Office, OTA-BP-ITC-165, Washington, D.C., September.
- R&D Magazine 1997. "Basic Research White Paper: Defining Our Path to the Future," *R&D Magazine*, A. Cahn's Publication, Des Plaines, Ill.

5. SYNTHESIS AND MOVING FORWARD

5.1 SYNTHESIS

In this report to Secretary of Energy Peña, the directors of 11 DOE national laboratories conclude that

1. 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.
2. Success will require the pursuit of multiple technology pathways, providing choices and flexibility for reducing GHG emissions.

One cost-effective strategy for reducing long-term GHG emissions while continuing economic growth is to develop and deploy a portfolio of new and improved technologies (as described in Chapter 2). Successful development of these technologies would require advances in many fields of basic science (as described in Chapter 3) along with strong public-private strategic alliances (as described in Chapter 4). Rapid and widespread deployment may also require the development and implementation of supportive programs and policies. The features of such programs and policies are not specified in this report.

5.1.1 The RD&D Path to Carbon Stabilization

Chapter 2 described the broad menu of technology pathways that could significantly reduce U.S. carbon emissions over the next three decades. If a vigorous, accelerated RD&D program were pursued, these pathways would enable the transformation of our nation's energy system. Given the breadth of technology options, this transformation could take place in an orderly fashion. Industry and consumers would be able to recover their investments in the nation's current energy infrastructure, while new energy and carbon sequestration technologies were gradually absorbed, as they became profitable, through the normal process of capital stock turnover.

By offering a technology-based, evolutionary—not revolutionary—path to a sustainable energy future, this report outlines the possibility of a transition that could be profitable to a wide array of potential constituents.

Over a 30-year planning horizon, implementing a climate change technology strategy could quickly expand the portfolio of options available for reducing U.S. GHG emissions. The three decades of this planning horizon appear to be distinct in terms of the dominant climate change technology opportunities.

- In the first decade, significant advances in energy efficiency technologies would reduce carbon emissions substantially by reducing the energy intensity (E/GDP) of the U.S. economy. Based on the five-laboratory study, the increased use of these technologies could offer energy-savings benefits that exceed their implementation costs (Interlaboratory Working Group 1997). Clean energy technologies would continue to gain market share, and carbon sequestration technologies could begin to emerge.
- Along with continued improvements in energy efficiency, research-based advances in clean energy technologies would begin to reduce the carbon intensity (C/E) of the U.S. energy economy significantly during the second decade. A wide range of renewable, fossil, and nuclear technologies could be introduced and widely deployed in this period. These clean energy options could begin to overshadow the impact of increased end-use efficiencies by the year 2030.
- 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. We assume that these would not be widely available until the 2020 to 2030 time frame; however, successful introduction earlier could result in significantly greater reductions in carbon emissions. Success in this technology area could enable the nation to continue its extensive use of fossil fuels without changing the climate.

This technological progression can be seen in Table 5.1, which summarizes the carbon reduction estimates of each of the nine technology areas described in Chapter 2. Estimates of carbon-saving potential are difficult because of the many factors that can affect the performance and market penetration of a new technology. Consistent with these uncertainties, the values shown in Table 5.1 are provided in five ranges from low to high.

These estimates of carbon reduction potential were made relative to the *Annual Energy Outlook 1998* reference (business-as-usual) case (EIA 1997). They assume an accelerated federal RD&D program and a continuation of current federal programs and policies. The estimates do not presume the creation of any new incentives. The carbon reduction estimates were made individually for each technology area; competition between technologies and other effects of one technology on the success of another were not fully considered.

Because of the uncertainties associated with the carbon impacts of each pathway and the complexities associated with aggregation across pathways, our estimate of the combined potential effects of all of the pathways has a wide range. In total, it is estimated that an accelerated RD&D effort could provide advanced

**Table 5.1. Potential reduction of U.S. carbon dioxide emissions
from nine technology areas
(in MtC)**

	2010	2020	2030
Energy efficiency			
Buildings	L/M	M/H	H
Industry	L/M	M/H	H
Transportation	M	H	H
Agriculture and forestry	L	L	L/M
Clean energy			
Fossil resource development	L	M/H	H
Fossil power generation	L	M	H
Nuclear energy ^a	L	M	H
Renewables	L/M	H	H
Carbon sequestration	NA	NA	NA

L = 0–25 MtC, L/M = 25–50 MtC, M = 50–75 MtC, M/H = 75–100 MtC, and H = 100+ MtC. Shaded areas show significant additions to the technology routes to reducing greenhouse gases. NA = Not applicable because the carbon reductions require policy changes.

^aThe 2020 and 2030 estimates for nuclear energy (M and H, respectively) are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010. By extending the operation of one-third to one-half of these plants, significant carbon emissions can be avoided.

technologies with the potential to reduce U.S. carbon emissions by 400 to 800 MtC/year in the year 2030. This represents a significant portion of the carbon emission reductions that may be targeted by the United States for 2030.

Table 5.1 and the discussions of each pathway in Chapter 2 also indicate that no single area or pathway can deliver sufficient GHG emission reductions; success will require pursuit of multiple technology pathways. The lower range of the estimated impact (400 MtC per year) could result from major technological advances and market success in several of the pathways. Achieving the upper range (800 MtC per year) would require technological breakthroughs and market success in a wider spectrum of pathways. This higher, more optimistic range is viewed as unlikely without also strengthening the policies and deployment programs that exist today. We did not attempt to quantify the potential reductions from a combination of accelerated RD&D

and more vigorous deployment programs, policies, and financial incentives. However, it is believed that such a combination could drive U.S. carbon emissions down much further than the 400 to 800 MtC range described in this report.

This report's estimates of carbon reduction potential are quite modest compared with the estimates produced by many other studies. The smaller overall impacts estimated by this report are due primarily to our focus on the potential of accelerated RD&D within the context of today's policies and programs.

The 1991 report by the Office of Technology Assessment titled *Changing by Degrees* (OTA 1991) analyzed the potential for energy efficiency to reduce carbon emissions by the year 2015, starting with the base year of 1987. Its "moderate" scenario results in a 15% rise in carbon emissions, from 1300 MtC/year of carbon in 1987 to 1500 MtC/year of

carbon in 2015 (compared with a business-as-usual forecast of 1900 MtC/year). Its "tough" scenario results in a 20% to 35% reduction in emissions relative to 1987 levels, or emissions levels of 850 to 1000 MtC/year of carbon in 2015.

Scenarios of U.S. Carbon Reductions by the Interlaboratory Working Group (1997) modeled three scenarios of carbon emissions in the year 2010 based on an array of assumptions about increased RD&D efforts, supporting policies, and deployment programs (see Chapter 1 for further details). The results were carbon reduction estimates of 120, 230, and 390 MtC in the year 2010. The most aggressive scenario reduces carbon emissions in 2010 to their levels in 1990 and reduces energy consumption in 2010 to 1997 levels.

Energy Innovations (1997) provides a third point of comparison. It estimates the levels of carbon emissions that are possible in 2010 and 2030 as the result of vigorous RD&D, deployment, and policies. It estimates that by 2010, carbon emissions could drop to a level that is 10% below emissions in 1990. By 2030, it suggests, carbon emissions could possibly be reduced to 728 MtC per year, which is almost half of the 1990 benchmark and well below the estimates provided in this report.

A fourth study by the National Academy of Sciences (NAS), *Policy Implications of Greenhouse Warming* (1992), identified a set of energy conservation technologies that would have either a positive economic return or a cost of less than \$2.50 per tonne of carbon. Altogether, NAS concluded that these technologies offer the potential to reduce carbon emissions by 463 million tonnes, with more than half of the reductions arising from cost-effective investments in building

energy efficiency. The NAS study characterized the current technological potential available at the time; thus it did not take into account stock turnover rates and other factors that prevent the instantaneous, full market penetration of technologies. Nor did it describe the role of RD&D in expanding future technology opportunities.

5.1.2 Factors Influencing GHG Reduction Potential

Many factors influence the ability of technology development efforts to reduce future U.S. GHG emissions. These include the magnitude of available R&D resources, technological risk, market size, stock turnover rates, and public acceptance issues. While this study has not attempted to analyze the effects of all of these various factors, it has compiled a considerable amount of information on them in its review of nearly 50 technology pathways. That information can be found in Appendix B, which includes a two-page description of each pathway that explains many of the factors.

Table 5.2 summarizes some of this information for technology areas grouped as energy efficiency, transportation fuels, electricity, and carbon sequestration. The table expands on the information in Table 5.1 in two ways. First, it includes information for those specific sectors and technologies that at this time appear to represent the largest potential carbon emission reductions over the 30-year planning period. For example, in the transportation sector, light-duty vehicles represent 58% of the CO₂ emissions in the transportation sector. Therefore, one entry in Table 5.2 summarizes information for the two technology pathways that address light-duty vehicles:

(1) advanced conventional technologies for light-duty vehicles and (2) hybrid, battery-electric, and fuel cell vehicles.

Second, Table 5.2 provides information on several of the key factors that will influence future carbon emission reductions. This includes a column listing some of the significant issues or opportunities that will impede or enable the realization of potential carbon reductions. These issues and opportunities are selected from a more comprehensive accounting in Appendix B.

Altogether, Table 5.2 provides the reader with an indication of the most important results of this study in the form of the sectors and technologies that can play the largest role, as well as the factors and considerations that will determine their future contributions to GHG emission reductions.

The key factors that are used in Table 5.2 are defined as follows:

- Total market size: current total market in terms of carbon emissions (MtC/year) that is relevant to the technology
- Turnover rate: rate of retirement of the current stock of energy equipment or systems displaceable by this technology, with
 - “Fast” corresponding to less than 10 years average lifetime
 - “Moderate” corresponding to 11 to 20 years average lifetime
 - “Slow” corresponding to greater than 20 years average lifetime
- Estimates of carbon emissions reductions: best estimate of the carbon emissions reductions (in MtC/year) that are likely to be achieved given this accelerated RD&D effort and continuing

government deployment programs and policies. The estimates are based on the overall market size, the stock turnover rate, some consideration of the expected competitive position of the technology, and so on. For energy efficiency and clean energy technologies, the estimates assume no new fiscal incentives such as a carbon charge. See Sect. 2.1.2 for a more complete description of the study’s assumptions. The entries are defined as follows:

“High” corresponding to
>100 MtC/year

“Medium” corresponding to
50 to 100 MtC/year

“Low” corresponding to
0 to 50 MtC/year

- Technological risk: subjective estimate of the risk that the technology will not be developed to the point that it can compete in its market as expected with

“High” reflecting research that is still at the basic sciences level or involves complex systems integration

“Moderate” reflecting research that is currently at both the basic research and technology prototype level

“Low” reflecting development activities for technologies at the prototype or more advanced stage

- Significant issues or opportunities: illustrative major factors particularly noteworthy for this technology

The estimates of potential GHG reductions shown in Table 5.2 are consistent with the conclusions that were offered in conjunction with Table 5.1; that is, substantial reductions are available by 2030, and many technology areas can be

Table 5.2. Potential reduction of U.S. carbon dioxide emissions from selected sectors and technology pathways

Sector/area ^a	Technologies	Market size (MtC in 1995) ^b	Turnover rate	Estimated carbon emission reductions ^c			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Efficiency— Buildings (1)		489	Mod	L/M	M/H	H	Lo	• minimal private sector R&D
	Building Equipment and Appliances (1.1)	489	Mod to Fast	L/M	L/M	L/M	Lo	• slow adoption of innovations • CFC ban accelerates chiller turnover
Efficiency— Industry (2)		463	Mod	L/M	M/H	H	Med	• short payback periods required
	Industrial Energy Conversion (2.1)	463	Mod	L	L/M	L/M	Med	• pollution prevention often saves energy
Efficiency— Transportation (3)		457	Mod	M	H	H	Med	• cost of lightweight materials
	Light-Duty Vehicles (includes trucks through class 6) (3.1 and 3.3)	265	Mod	L/M	M/H	H	Med to High	• consumer preference for power and size over high mpg
Transportation fuels (5.2 and 8.7)		457	Fast	L	L/M	L/M	Med	• distribution infrastructure barriers
	Biomass Fuels (8.7)	457	Fast	L	L/M	L/M	Med	• limited stocks at competitive prices
Electricity— Fossil (6)		494	Slow	L	M	H	Med	• large domestic coal resources
	Accelerated Development of High-Efficiency Power Generation (6.1)	494	Mod	L	L/M	M/H	Lo	
Electricity— Nuclear ^d (7)		494	Slow	L	M	H	Med	• public acceptance
	Lifetime Extension and Generation Optimization (7.1)	113	Mod	L	L/M	M/H	Lo	• nuclear waste storage • competition with natural gas

Table 5.2. (continued)

Sector/area ^a	Technologies	Market size (MtC in 1995) ^b	Turnover rate	Estimated carbon emission reductions ^c			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Electricity— Renewables (8)		494	Slow	L/M	H	H	Med	• competition with natural gas • large domestic resources • biomass resource limitations at competitive prices
	Biomass Electric (8.1)	494	Mod	L	L	L/M	Lo	
	Wind and Photovoltaics (8.2, 8.4)	247	Slow	L	L/M	M	Med	• price penalty for intermittent power
Carbon Sequestration (9)		>6200	NA	NA	NA	NA	High	• small potential impact without regulations, incentives, or growth in markets for CO₂ • extends fossil fuel use • ecological risk
	Enhanced Carbon Cycle (4.3, 9.1, 9.4)	>6200	NA	NA	NA	NA	High	
	Capture and Sequestration (9.2, 9.3, 9.4, 9.5, 9.6)	1400	NA	NA	NA	NA	High	• stability of clathrates and hydrates • diffusivity of CO₂ in the ocean • permanency

NA=not applicable because the carbon reductions require policy changes. The carbon sequestration pathways could enable the nation to continue its extensive use of fossil fuels without changing the climate.

^aTechnology pathways identified in () are cross-referenced to Table 2.1

^bThe technologies and sectors shown in this table overlap in terms of the carbon reductions they can deliver. For instance, decarbonization of the electricity sector through the introduction of clean energy technologies will reduce the potential carbon reductions from end-use sector efficiency technologies. As a result, it is not valid to simply add either the market size or the carbon reduction estimates.

^cL=0–25 MtC, L/M=25–50 MtC, M=50–75 MtC, M/H=75–100, and H=100+ MtC. These estimates assume an enhanced federal RD&D program aimed at developing GHG reduction technologies. They do not presume the creation of any new financial incentives for reducing carbon emissions. The technologies covered in this table could deliver even greater GHG reductions if incentives, such as a carbon emissions trading program, or more vigorous deployment programs and policies, were implemented.

^dEstimated carbon emission reductions are relative to the reference case in the *Annual Energy Outlook 1998* (EIA 1997), extended to 2020 and 2030 by extrapolating current carbon emission growth rates. The exceptions are the 2020 and 2030 estimates for nuclear energy (M and H, respectively). These are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010.

contributing to these savings at that point.

Table 5.2 also shows that technology areas face different challenges, opportunities, and issues. Many of the technology issues can be addressed by the technology RD&D outlined in this report.

Technical risks are low to moderate in each of the energy efficiency areas and especially in the buildings sector. Counterbalancing this advantage in terms of delivering carbon impacts is the low level of private-sector R&D, the slow pace of adoption of innovations by builders, and the moderate rate of stock turnover in the buildings sector. The transportation and industrial sectors face generally moderate levels of technical risk. In transportation, economic risk is increased by consumer preferences for power and size over efficiency; and in industry, economic risk results from high discount rates that impede investments in efficient equipment.

Many of the clean energy options for generating electricity are threatened by the uncertainty of utility industry restructuring and competition with inexpensive natural gas combined-cycle technology. Nuclear power also has the additional institutional risks of a long-term waste repository solution and concerns over proliferation.

Carbon sequestration technologies face high technical risks because of the exploratory stage of their development. In addition, environmental and economic issues need to be resolved. However, these technologies hold the potential to extend the continued use of fossil fuel.

In most cases, risk can be reduced by technology and basic research programs that include analysis of

economic and social consequences. Modeling tools and analyses are needed to complement the technology RD&D process to assess the potential acceptance of developmental technologies, identify likely concerns, and develop mechanisms to address those concerns. Such efforts to understand the social and economic risks are critical.

5.1.3 The Time-Line of Technology Products

Consistent with the notion of an orderly technology evolution, the products of a vigorous RD&D program to develop GHG reduction technologies could be adopted and implemented in time frames that mirror the typical pace of capital stock turnover. As a result, improvements in energy efficiency, clean energy, or carbon sequestration technologies would typically be available long before their impact on carbon emissions could be discerned. Thus, it is useful to forecast when different incremental improvements and breakthrough technologies will be available as cost-effective alternatives, recognizing that many years will typically be required before they are mature technologies.

Figures 5.1 and 5.2 present time lines of selected technology products. They illustrate the steady stream of important accomplishments that the vigorous RD&D program could produce. (Many more technology products are identified in Appendix B.) The technology products shown in these figures are consistent with the trend in carbon savings from energy efficiency gains in the first decade, to significant contributions by a variety of clean energy technologies in the second decade, followed by the emergence of carbon sequestration technologies in the third decade.

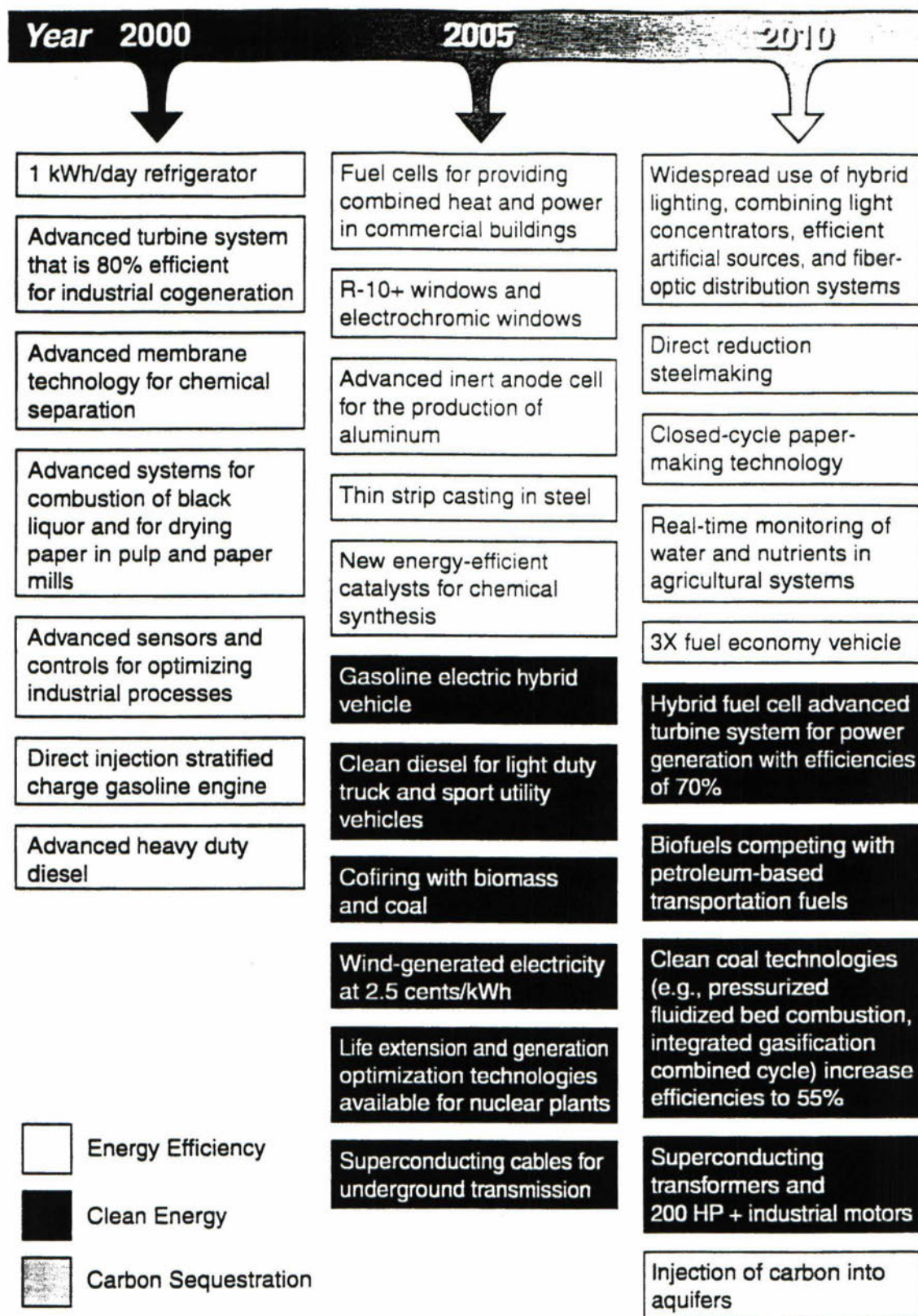


Fig. 5.1. Illustrative time-line of anticipated technology products: 2000–2010.

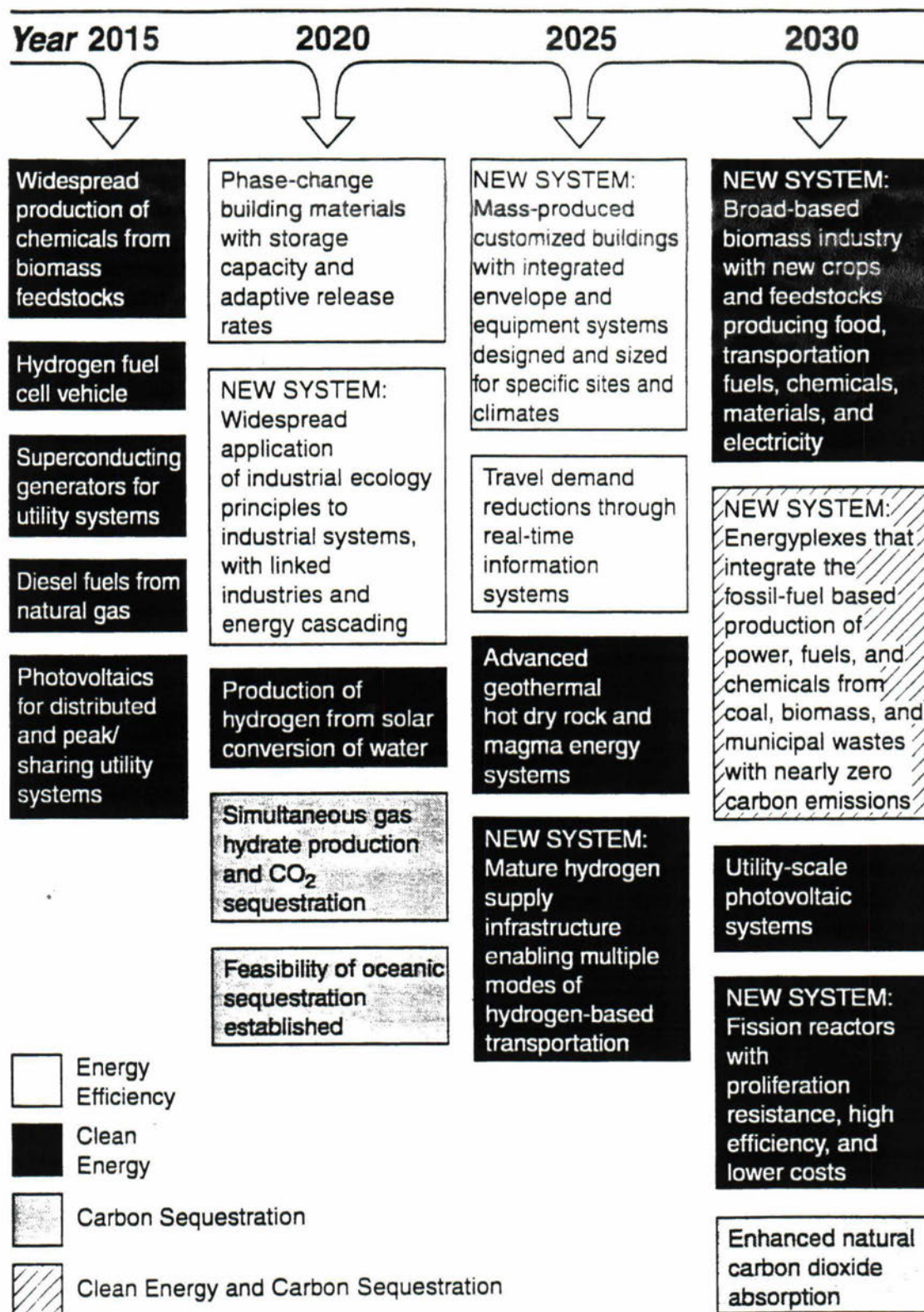


Fig. 5.2. Illustrative time-line of anticipated technology products: 2015–2030.

A second trend illustrated in these figures is the transition from the development of individual components to the emergence of novel, integrated systems. Over the next two decades, many components will be designed and engineered that can be woven into existing technology and capital infrastructures to improve their performance while reducing carbon emissions. Ultimately, these components will overhaul many of the systems that exist today. Such orderly sequencing of component development, with the ultimate goal of creating entirely new systems, can minimize the costs of capital displacement and economic disequilibrium. Two examples are provided below.

- The gasoline/electric hybrid vehicle (envisioned for development before 2005) is a precursor to the hydrogen fuel cell vehicle, which could be available by 2015. Following breakthroughs in hydrogen production, such as the manufacture of hydrogen from the solar conversion of water (perhaps by 2020), we envision a transformed transportation system by 2025 with a mature hydrogen supply infrastructure fueling multiple modes of transportation
- By 2010, we envision that biofuels could be cost-competitive with transportation fuels and that they could be distributed by the existing infrastructure of filling stations (worth hundreds of billions of dollars) with only modest modifications. By 2015, RD&D could enable the widespread production of chemicals from biomass feedstocks. Ultimately, 2030 could see a broad-based biomass industry with new crops, feedstocks, and distribution systems producing food, transportation fuels, chemicals,

materials, and electricity, and possibly an entirely new distribution system at the wholesale and retail levels

The two examples illustrate the need for pursuing multiple technology pathways in critical areas (e.g., for alternative transportation fuels), because the success of any single pathway cannot be guaranteed. In addition, no single pathway appears able to deliver the amount of GHG reductions that may be needed.

Figures 5.1 and 5.2 portray a possible time line for the commercial introduction of new technology. The technologies themselves will endure much longer than the 30-year horizon indicates. They will become the legacy of the technology strategy that eventually is followed. With many of these technologies is an infrastructure and a whole economic system. Just as the introduction of the mass-produced Model-T Ford and the interstate highway system transformed transportation, these technologies will have comparable enduring effects.

Of course, RD&D programs by their very nature cannot guarantee that anticipated outcomes will result. Many technical and market risks prevent laudable efforts from producing successful technologies. However, there will also be important technological successes not foreseen at this time. If we invest in a portfolio of RD&D activities, historic data indicate that the winners will more than compensate for the cost of the failures (Brown 1997).

5.1.4 Performance Goals

Another way of viewing the products of the proposed technology pathways is by specifying performance goals they

could achieve. These goals do not rely on particular technology developments; rather, they specify performance criteria that could be met by many alternative technologies. Recommended goals are presented, along with some of the technologies that could contribute to meeting 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 the 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 IGCC 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 the use of sources with higher generating efficiencies and lower emissions—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 GHGs 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

- Sequester CO₂ in large-capacity geological formations in deep oceans.
- Efficiently remove CO₂ from combustion emissions before they reach the atmosphere.
- Increase the rate at which oceans, forests, and soils naturally absorb atmospheric CO₂.
- Develop carbon storage technologies sufficient for geologic times.

5.1.5 Basic and Applied Research Are Needed

Meeting the goals described above also depends upon incremental improvements and breakthroughs in the basic sciences. These basic research needs include

- basic research 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

- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences)

To support multiple technology pathways, enabling technologies also must be improved, especially those that enhance the utilization of energy carriers and systems. Relevant enabling technologies include

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

5.1.6 Collateral Benefits and Costs

In addition to the benefits of GHG avoidance, the technology pathways described in this report could have significant secondary effects, as such pathways have in the past. For example, in the buildings area, there is a remarkable record of success in federally supported RD&D leading to products in the marketplace that have generated energy savings far exceeding their costs of development. In addition to reducing energy costs, the pathways would lead to improved environmental quality and public health, reduced U.S. dependence on imported oil, and increased exports of U.S. technologies to help other nations reduce GHG emissions, all of which will sustain economic growth.

The environmental and public health benefits of new and improved GHG reduction technologies could be very large. Clean energy options for generating electricity offer the prospect

of significantly reducing air pollution. The development of efficient low-carbon transportation fuels would reduce pollutant emissions and abate ground-level ozone. Pollution prevention and waste minimization are important hallmarks of improved industrial process efficiencies. These collateral benefits would lead directly to major improvements in public health (Romm and Ervin 1996).

These environmental and public health benefits would not be limited to the United States. Better technology options would help to control the GHG emissions of other countries for many decades to come. They could also position the United States as the provider of choice for these new energy and environmental systems, with major economic growth consequences. The global energy market is estimated at \$1 trillion, and the market for environmental technologies is estimated to be \$400 billion. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies. An important collateral benefit of continued pursuit of nuclear power is the economic benefit of serving as an international supplier. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. The international market for ATSS and fuel cells is also likely to grow rapidly. Thus, implementation of a technology strategy would help to grow the U.S. economy by creating an energy technology export business.

The reductions in petroleum use that would result from the technology pathways would cut U.S. oil import dependence and could lower oil prices to consumers (Interlaboratory Working Group 1997, p. 5.47). It is estimated

that efficiency improvements and alternative fuels in the transportation sector could result in reductions of one billion barrels per year by 2010.

Some of the pathways might also spawn significant collateral costs. For instance, increased nuclear waste might result in negative environmental repercussions, large-scale biomass production might cause soil and water contamination, and ocean fertilization might precipitate ecosystem damage. Regions that flourish in today's energy economy might be negatively impacted by shifts in the resource and labor requirements of new energy systems. The workplace requirements associated with advanced energy technologies might strain the nation's capacity to train and educate its labor force. History has shown that such challenges often can be managed. Further, if multiple pathways are pursued, those judged unacceptable can be set aside in favor of those that are preferred.

5.1.7 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 GHG 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. However, to be consistent with the technology RD&D focus on this study, we have estimated the magnitude of only the associated technology RD&D resources, excluding deployment program or policy costs.

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

- The annual federal RD&D budget for the development of advanced energy technologies would need to grow to produce a sufficient number of the technological solutions.
- Additional resources are needed to initiate research into carbon sequestration technologies, which would also require supporting research on carbon cycle modeling, monitoring, and ecosystems.
- Supplemental RD&D support is needed to strengthen the basic research areas that are the wellspring of future technological breakthroughs.

Development of the full portfolio of technologies described in this study is estimated to require additional federal resources in the range of \$1.5 billion to \$2 billion. This is a preliminary estimate; actual budget decisions should be based on more detailed planning and analysis than was possible during development of this report. Initiation of that analysis and planning, which is a primary recommendation for moving forward, is discussed further in Sect. 5.2. It is anticipated that additional private-sector research effort would be leveraged by this federal increment.

There are three additional important points regarding these budget increments:

- Actual budgets should be ramped up over several years in a way consistent with sound program development.

- The necessary federal funding for most of the technology areas is seen as declining back to current levels by the third decade of the next century. The exception is carbon sequestration, which would likely require increasing budgets over the three decades as exploratory research in early years is translated into technology development activities.
- Resource requirements for the outyears obviously would be affected by developments between now and then, so these estimates are primarily valuable as preliminary indications of overall resource needs.

5.2 MOVING FORWARD

This report identifies in general terms a set of future technologies that appear to hold great promise for reducing U.S. GHG emissions. By summarizing the status and potential of a broad range of technologies relevant to reducing GHG 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, including

- an assessment of alternative programs and policies to promote deployment
- analysis of the costs and benefits of alternative technology and policy options to develop priorities
- development of technology goals and performance metrics for measuring progress
- identification of key players for pursuing these promising technology pathways
- estimation of budget requirements and appropriate allocation for each technology pathway
- mechanisms for ensuring strong ties between technology development

- activities and supporting basic sciences
- delineation of public- and private-sector responsibilities
- linkages to related ongoing activities in the United States and abroad
- a plan for managing the technology RD&D programs to be pursued over the years and decades ahead

The strong recommendation of this report is that the United States should develop and pursue a detailed and comprehensive climate change technology strategy.

Further, the planning process should begin immediately, and implementation of the strategy should occur quickly.

As the federal agency with the most involvement in the full range of technologies described in this report, the U.S. DOE should initiate and lead the planning required for implementation of this strategy. However, that planning effort must include significant participation from industry and business, the university community, Congress, and other federal agencies, as well as DOE and the national laboratories. Indeed, this planning should be a collaborative effort, just as is recommended for implementation of the technology RD&D programs.

While not all of the details of this planning and strategy implementation can be defined here, two clear needs should be explicitly addressed. The first is establishing a collaborative national planning effort to provide leadership and guidance to meet the RD&D challenges of a climate change technology strategy. The second is initiating an analysis activity to provide the information necessary for making sound decisions on the issues indicated. Both of these steps should be taken immediately.

Several other issues deserve immediate attention. One of these is the connection between developing promising technology pathways and designing policies to promote their deployment. There are many tradeoffs among how fast one pushes development, how much emphasis is placed on deployment of technologies that are ready to contribute to reduced emissions, and the timetable for achieving different reduced emission levels.

Another issue requiring study is the relationship between the implementation of promising technology pathways and the phenomenon of climate change, as well as the need for a better understanding of the phenomenon itself. This report strongly endorses the need to continue to improve our understanding of GHG emission levels, atmospheric concentrations of GHGs, climate change, and their impacts on our biosphere. A science-based understanding of the carbon cycle is essential as a framework for guiding our technology investments and ensuring their cost-effectiveness.

A third issue is consideration of the organizational structure of the technology RD&D programs. The recommendation to use strategic alliances recognizes the need to move away from the technology partnerships of the past. While there is no single organizational structure for creating strategic alliances, the traditional roles of users, industry, federal agencies, universities, states, national laboratories, and not-for-profit organizations may require redefinition as strategic alliances are formed to develop and deploy climate change technologies. Flexibility and adaptability in the structure of these partnerships is critical to the most effective pursuit of technology

development programs to reduce GHG emissions.

A fourth issue is that of relating and coupling this domestic technology strategy with related international GHG emission reduction efforts. International collaboration can provide important domestic savings and global benefits.

Finally, it is important to understand the consequences of not developing and pursuing a technology strategy. Perhaps one of the greatest risks is underestimating the magnitude of the impact we are attempting to achieve. Energy is central to development and modern civilization. We are talking about transforming a national and global infrastructure that currently includes all of the things that support combustion as a means of energy generation. This is not a trivial matter. The generation of CO₂ is embedded deeply in the social infrastructure of this nation and is being embedded in the developing world right now.

The availability of advanced technologies on a timely basis to address future GHG emission reduction commitments requires initiation of the RD&D now and a commitment to following through on all the pathways that continue to show promise. Technologies not pursued are likely to result in lost opportunities to apply them to mitigating climate change, as well as a loss of their collateral benefits.

5.3 CONCLUSION

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 GHG emissions well into the

twenty-second century. Many technology opportunities exist that could accomplish this goal without harming the nation's economy. A strategic plan that includes deployment policies to complement technology R&D will be necessary for success. Hence, development of a climate change technology strategy is the recommended next step. Based on the conclusions of this report, the strategy should specify an approach that pursues multiple technology pathways, that emphasizes public-private strategic alliances, and that is designed in close coordination with supportive government policies and deployment programs.

By delivering a portfolio of highly promising technologies, a climate change technology strategy could produce savings and revenues that far exceed the cost of an accelerated research program. The bottom line: with the help of technology and appropriate government programs and policies, we can slow GHG emissions and grow the economy. DOE's national laboratories stand ready to champion this enterprise.

5.4 REFERENCES

- Brown, M. A. 1997. "Performance Metrics for a Technology Commercialization Program," *Int. J. of Technology Management*, 13 (3): 229-244.
- EIA (Energy Information Administration) 1997. *Annual Energy Outlook 1998: With Projections to 2020*, U.S. Department of Energy, Washington D.C., December.
- Energy Innovations 1997. *Energy Innovations: A Prosperous Path to a Clean Environment*, Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, and Union of Concerned Scientists, Washington, D.C.
- Interlaboratory Working Group 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, September.
- NAS (National Academy of Sciences) 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, National Academy Press, Washington, D.C.
- OTA (Office of Technology Assessment) 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-0-482, U.S. Government Printing Office, Washington, D.C., February.
- Romm, J. J., and C. A. Ervin 1996. "How Energy Policies Affect Public Health," *Public Health Reports* 5, 390-399.

Appendix A Contributors

The following are the principal DOE National Laboratory staff participating in the committees and working groups supporting the development of this report. Many other individuals in the federal and private sector contributed but are not acknowledged here.

COORDINATING COMMITTEE

Stanley R. Bull, NREL, Co-chair
David E. Reichle, ORNL, Co-chair
William M. Babiuch, NREL
Arnold B. Baker, SNL
Lynn L. Billman, NREL
Eldon C. Boes, NREL
Marilyn A. Brown, ORNL
Brenda W. Campbell, ORNL
Michael P. Farrell, ORNL
Robert San Martin, DOE Liaison
John Sheffield, ORNL
Walter D. Short, NREL

EDITORIAL SUPPORT GROUP

Deborah M. Counce, ORNL

Vickie L. Beets, ORNL
Judy H. Benton, ORNL
Judy H. Campbell, ORNL
Vickie L. Conner, ORNL
Walter S. Koncinski, ORNL
Carolyn H. Krause, ORNL
Sandra C. Lyttle, ORNL
Jamie P. Payne, ORNL
Brenda Barlow, Lockheed Martin Energy Systems
Gloria Llanos, Temp Systems
Mary E. Marshburn, CDI
Linda O'Hara, CDI

LAB REPRESENTATIVES AND ALTERNATES

Dan E. Arvizu, SNL
Arnold B. Baker, SNL
Stanley R. Bull, NREL
Lynn L. Billman, NREL
David Cauffman, INEEL
Melinda A. Hamilton, INEEL
Harvey Drucker, ANL
David J. Hill, ANL
James M. Ekmann, FETC
Charles E. Schmidt, FETC
Mark D. Levine, LBNL
Donald F. Grether, LBNL
Leonard Newman, BNL
James W. Davenport, BNL
David E. Reichle, ORNL
John Sheffield, ORNL
Alfred P. Sattelberger, LANL
Edward L. Joyce, LANL
Robert N. Schock, LLNL
Anthony K. Chargin/Jill L. Watz, LLNL
Gerald M. Stokes, PNNL
John F. Clarke, PNNL

WORKING GROUPS

Buildings

Mark D. Levine, LBNL, Chair
John W. Andrews, BNL
Douglas Balcomb, NREL
James D. Cavallo, ANL
George E. Courville, ORNL
Richard Diamond, LBNL
Donald F. Grether, LBNL
Jeffrey P. Harris, LBNL
Jeffrey A. Johnson, PNNL
Ronald Judkoff, NREL
Marion L. Scott, LANL

Industry

Alan P. Sylwester, SNL, Chair
Dan E. Arvizu, SNL
Donald G. Foster, LBNL
Thomas D. Foust, INEEL
Michael J. Furey, BNL
Bim Gupta, NREL
Edward L. Joyce, LANL

Jeff S. Logan, PNNL
Mildred B. Perry, FETC
Anthony C. Schaffhauser, ORNL
Jill L. Watz, LLNL

Transportation

David E. Reichle/E. Kaye Johnson, ORNL, Chair
Basil A. Barna, INEEL
Larry S. Blair, LANL
Barbara Joan Goodman, NREL
Donald F. Grether, LBNL
Larry R. Johnson, ANL
Jeff S. Logan, PNNL
William J. McLean, SNL
Steven E. Plotkin, ANL
Frank J. Tokarz, LLNL
James E. Wegrzyn, BNL

Agriculture and Forestry

David P. Cauffman, INEEL, Chair
Helena L. Chum, NREL
Arthur B. Denison, INEEL
James R. Frank, ANL
Robin L. Graham, ORNL
Melinda A. Hamilton, INEEL
George R. Hendrey, BNL
Sheridan C. Johnston, SNL
Willy R. Makundi, LBNL
Gene Peterson, NREL
Norman J. Rosenberg, PNNL
Michael J. Scott, PNNL
Pat J. Unkefer, LANL

Fossil Resource Development

Robert J. Hanold, LANL, Chair
Greg A. Bala, INEEL
Edward L. Joyce, LANL
Ann F. Meinhold, BNL
Larry R. Myer, LBNL
David A. Northrop, SNL
John Reynolds, LLNL
Alfred P. Sattelberger, LANL
Tom W. Schmidt, ORNL
Alan M. Wolsky, ANL
Albert B. Yost II, FETC

Fossil Power Generation

James M. Ekmann, FETC, Chair
William A. Apel, INEEL
Steven R. Booth, LANL

Nancy J. Brown, LBNL
 Kevin R. Craig, NREL
 Robert E. Hall, BNL
 Donald R. Hardesty, SNL
 Roddie R. Judkins, ORNL
 Brady D. Lee, INEEL
 Dave K. Schmalzer, ANL
 Charles E. Schmidt, FETC

Nuclear Energy

Harvey Drucker, ANL, Chair
 William A. Barletta, LBNL
 Steven G. Hauser, NREL
 David J. Hill, ANL
 John R. Ireland, LANL
 Peter Klemkowsky, FETC
 Jim Lake, INEEL
 Gordon E. Michaels, ORNL
 Nestor R. Ortiz, SNL
 Trevor Pratt, BNL
 Keith I. Thomassen, LLNL

Renewables

Stanley R. Bull/Lynn L. Billman,
 NREL, Chair
 Marilyn A. Brown, ORNL
 Sue Jacobsen Goff, LANL
 Philip M. Goldberg, FETC
 Paul Kasameyer, LLNL
 Paul C. Klimas, SNL
 Chris Marnay, LBNL
 Paul D. Moskowitz, BNL
 Joel L. Renner, INEEL
 William W. Schertz, ANL

Carbon Management and Sequestration

Gerald M. Stokes, PNNL, Chair
 Sally M. Benson, LBNL
 David J. Borns, SNL
 Helena L. Chum, NREL
 John F. Clarke, PNNL
 Richard D. Doctor, ANL
 LaMar J. Johnson, INEEL
 Edward L. Joyce, LANL

Gregg H. Marland, ORNL
 John A. Ruether, FETC
 Meyer Steinberg, BNL
 Jill L. Watz, LLNL

Basic Research

Leonard Newman, BNL, Chair
 Joel W. Ager, LBNL
 Mark Alper, LBNL
 Anthony K. Chargin, LLNL
 John F. Clarke, PNNL
 James W. Davenport, BNL
 Deb Satyen, NREL
 Arthur B. Denison, INEEL
 Wilhelm B. Gauster, SNL
 Linda L. Horton, ORNL
 Edward L. Parsons, FETC
 Mark E. Reeves, ORNL
 Marion C. Thurnauer, ANL
 William Tumas, LANL
 Albert F. Wagner, ANL
 Leland W. Younker, LLNL

Cross-Cutting Technologies

Robert N. Schock, LLNL, Chair
 William V. Chandler, PNNL
 Anthony K. Chargin, LLNL
 Cathy Gregoire Pedro, NREL
 Jay O. Keller, SNL
 John B. Kerr, LBNL
 Gilbert V. McGurl, FETC
 Kevin Michael Myles, ANL
 James J. Reilly, BNL
 John Sheffield, ORNL
 John M. Slater, INEEL
 James Van Coevering, ORNL
 P. Henrik Wallman, LLNL
 David Watkins, LANL
 Jill L. Watz, LLNL

Analysis Team

Walter Short, NREL
 Ron A. Bradley, ORNL
 T. Randall Curlee, ORNL

TECHNOLOGY OPPORTUNITIES TO REDUCE U.S. GREENHOUSE GAS EMISSIONS

December 1997

Prepared by

**U.S. Department of Energy
National Laboratory Directors**

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.

CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	ix
ACRONYMS, ABBREVIATIONS, AND INITIALISMS	xi
EXECUTIVE SUMMARY	xiii
1. INTRODUCTION	1-1
1.1 GREENHOUSE GAS EMISSIONS AND ENERGY	1-3
1.2 THE ROLE OF TECHNOLOGY	1-5
1.3 STUDIES OF CLIMATE CHANGE AND TECHNOLOGY	1-6
1.4 ABOUT THIS STUDY	1-8
1.5 REFERENCES	1-10
2. TECHNOLOGY PATHWAYS	2-1
2.1 CARBON LEVELS: PRESENT AND FUTURE	2-3
2.1.1 Technology Approaches	2-3
2.1.2 Assumptions	2-5
2.2 ENERGY EFFICIENCY	2-7
2.2.1 Buildings	2-8
2.2.2 Industry	2-11
2.2.3 Transportation	2-16
2.2.4 Agriculture and Forestry	2-20
2.3 CLEAN ENERGY	2-23
2.3.1 Fossil Resource Development	2-23
2.3.2 Fossil Power Generation	2-28
2.3.3 Nuclear Energy	2-32
2.3.4 Renewable Energy	2-35
2.4 CARBON SEQUESTRATION AND MANAGEMENT	2-40
2.5 REFERENCES	2-44
3. BASIC AND APPLIED RESEARCH AND CROSSCUTTING TECHNOLOGIES	3-1
3.1 RESEARCH TO ADVANCE UNDERSTANDING OF THE GLOBAL CARBON CYCLE	3-3
3.1.1 Global Carbon Cycle Modeling and Measurement	3-3
3.2 BASIC RESEARCH RELATED TO GREENHOUSE GAS EMISSIONS	3-4
3.2.1 Materials Science	3-5
3.2.2 Chemical Sciences	3-6
3.2.3 Biotechnology	3-7
3.2.4 Geosciences	3-8

3.2.5 Environmental and Ecological Sciences	3-8
3.2.6 Nuclear Sciences	3-8
3.2.7 Computational Sciences	3-9
3.3 CROSSCUTTING TECHNOLOGIES SUPPORTING GREENHOUSE GAS REDUCTIONS	3-10
3.3.1 Hydrogen and Fuel Cells	3-10
3.3.2 Electrical Transmission, Distribution, and Components	3-11
3.3.3 Sensors and Controls	3-12
3.3.4 Energy Storage	3-13
3.4 REFERENCES	3-14
4. TECHNOLOGY INNOVATION APPROACHES	4-1
4.1 INTRODUCTION	4-1
4.2 APPROACHES	4-1
4.2.1 Government Led and Financed Approach	4-2
4.2.2 Industry Led and Financed Approach	4-3
4.2.3 Public-Private Strategic Alliances	4-3
4.3 STRATEGIC ALLIANCE ROLES	4-5
4.4 CONCLUSION	4-6
4.5 REFERENCES	4-7
5. SYNTHESIS AND MOVING FORWARD	5-1
5.1 SYNTHESIS	5-1
5.1.1 The RD&D Path to Carbon Stabilization	5-1
5.1.2 Factors Influencing GHG Reduction Potential	5-4
5.1.3 The Time-Line of Technology Products	5-8
5.1.4 Performance Goals	5-11
5.1.5 Basic and Applied Research Are Needed	5-12
5.1.6 Collateral Benefits and Costs	5-13
5.1.7 Research, Development, and Demonstration Resources	5-14
5.2 MOVING FORWARD	5-15
5.3 CONCLUSION	5-16
5.4 REFERENCES	5-17
Appendix A. Contributors	A-1

Appendix B. Climate Change Technology Pathways
(Forthcoming)

FIGURES

Figure	Page
1.1 Technology and policy components for a climate change strategy	1-3
1.2 The burning of fossil fuel and changing land use have resulted in human-induced alterations of the global carbon cycle	1-4
1.3 Overview of the sources of carbon emissions in the United States in 1995	1-5
2.1 Alternative technological opportunities for reducing greenhouse gas emissions	2-1
2.2 Sources of greenhouse gas emissions in the United States in 1995	2-3
2.3 Projected U.S. carbon dioxide emissions	2-6
2.4 Four technology pathways to increased industrial efficiency	2-13
2.5 Technology pathways for industry with associated benefits in carbon emission reductions	2-14
2.6 Long-term R&D in major oil companies continues to decline	2-27
2.7 Operable refineries in the United States	2-28
2.8 Relationship between CO ₂ release and electricity production in France, 1973-1996	2-32
2.9 Carbon emissions avoided under various scenarios of nuclear electricity generation	2-33
2.10 Renewables have the potential for significant reductions of U.S. carbon emissions	2-36
2.11 Renewable energy technologies are well along a path of decreasing costs	2-37
3.1 Ceramic composite hot gas candle filters can be used to remove particulates from gas streams in combined cycle fossil and biomass power facilities	3-5

3.2	This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur	3-9
3.3	Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate	3-10
4.1	Interactive model of innovation	4-5
4.2	Linear model of innovation	4-5
5.1	Illustrative time-line of anticipated technology products: 2000-2010	5-9
5.2	Illustrative time-line of anticipated technology products: 2015-2030	5-10

TABLES

Table	Page
2.1 Technology pathways.....	2-2
2.2 U.S. carbon dioxide emissions by end-use sector	2-5
3.1 Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2	3-2
4.1 Approaches to technological innovation	4-2
5.1 Potential reduction of U.S. carbon dioxide emissions from nine technology areas	5-3
5.2 Potential reduction of U.S. carbon dioxide emissions from selected sectors and technology pathways.....	5-6

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	gigatonnes of carbon (10 ³ million tonnes)*
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

*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 tonnes 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 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 the world's largest source 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, nearly 50 technology pathways are described that have significant potential to reduce greenhouse gas emissions. These technology pathways (which are described in greater detail in Appendix B, Climate Change 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 estimate 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 tonnes 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.

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. 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. 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 the United States will take 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 been convened. At the third conference in Kyoto, the parties to the FCCC will consider measures to strengthen it.

The United States faces a significant challenge in Kyoto and can play an important role in moving negotiations forward. If global atmospheric CO₂ 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 move onto a path that prevents the increase of their emissions while preserving their legitimate aspirations for economic growth.

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

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

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

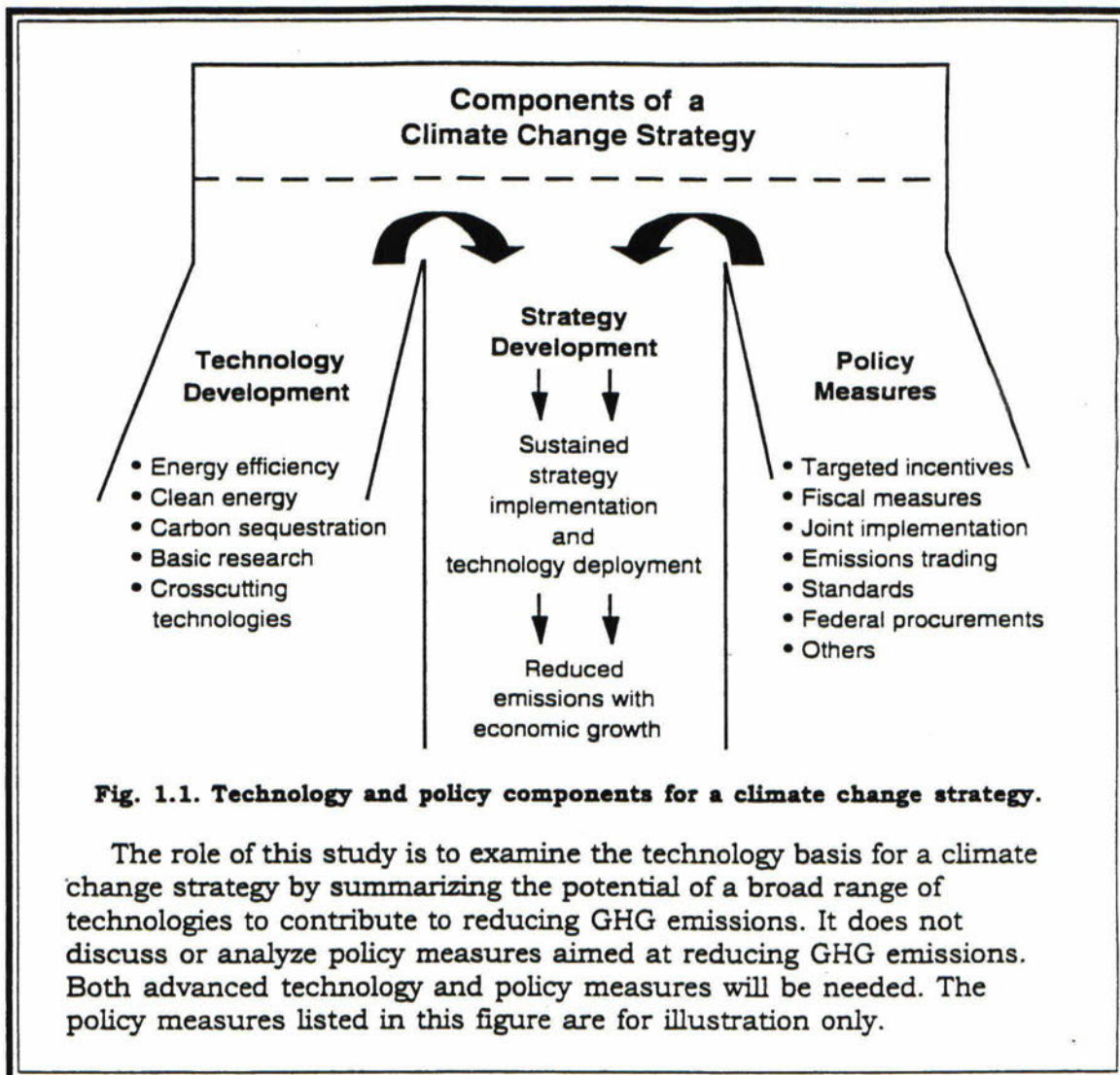
This document describes technology development efforts that need to extend through the first third of the next century. The impact of these efforts would in fact last much longer.

Energy-generating resources have lifetimes of many decades: the Grand Coulee Dam created in the 1930s continues to produce energy 60 years later. The new technologies introduced through the 30-year planning period of this report would have impacts that would extend throughout the next century.

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

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

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



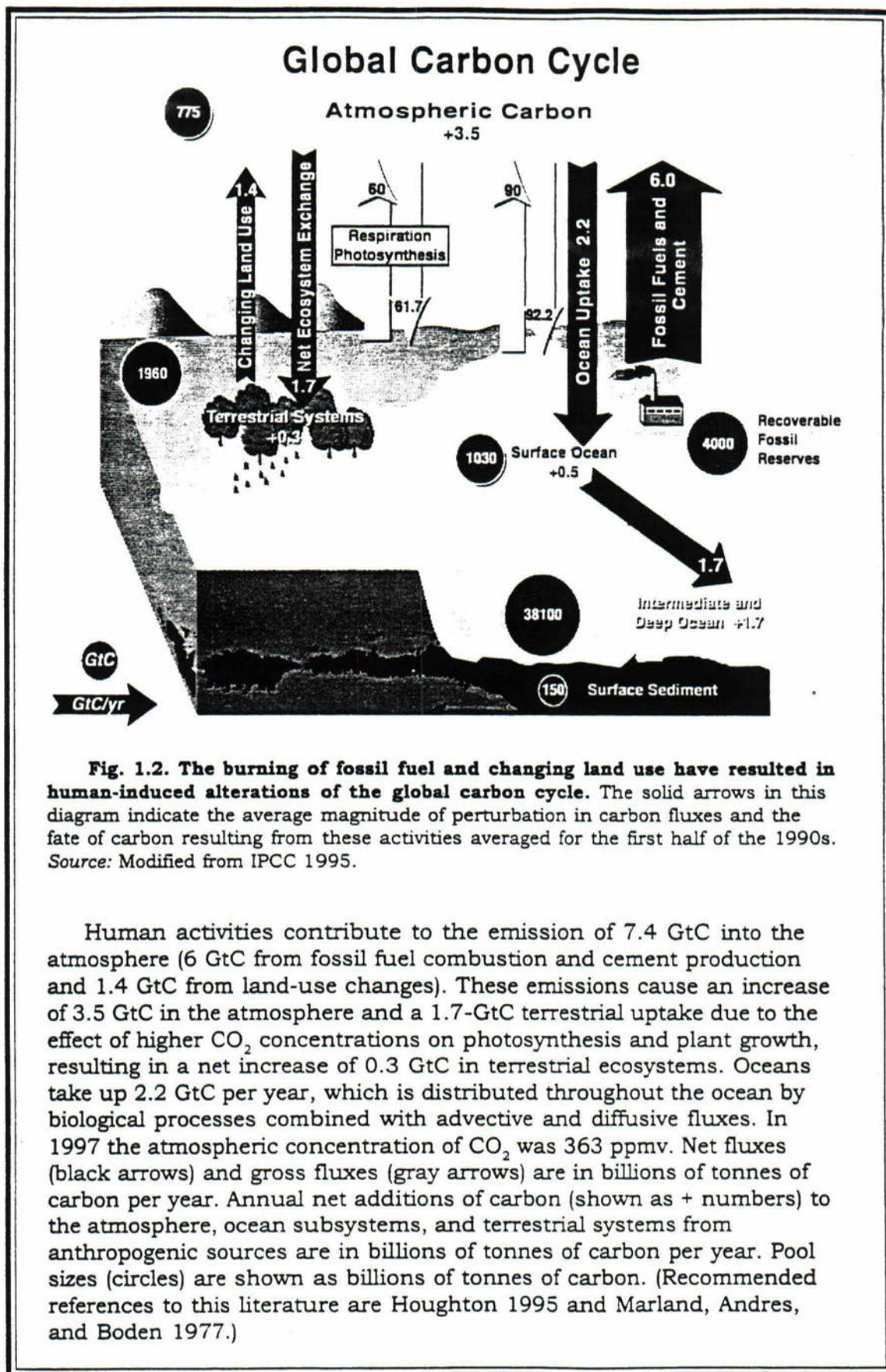
To ensure cost-effective, credible results, a climate change technology strategy also needs to be anchored in science. Much of this science base can be developed by leveraging and expanding existing efforts in the U.S. science and technology complex.

1.1 GREENHOUSE GAS EMISSIONS AND ENERGY

In 1995, human activities in the United States resulted in CO₂ 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



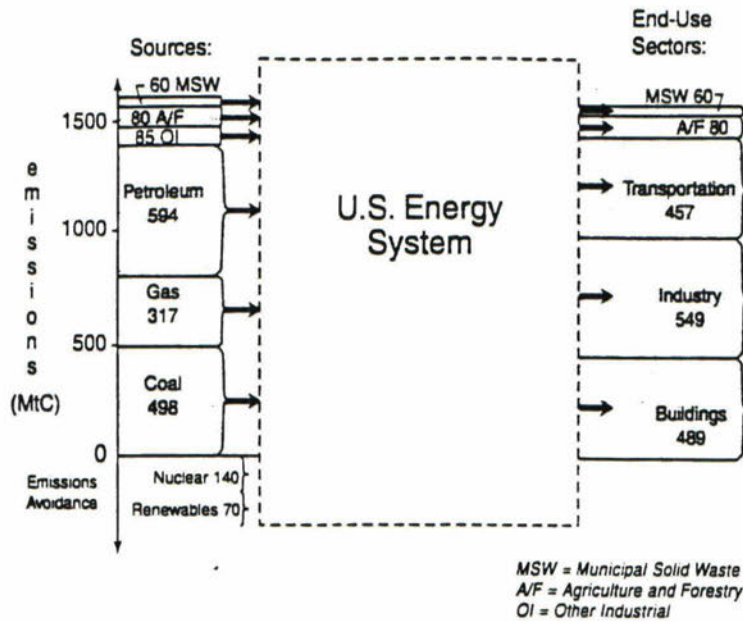


Fig. 1.3. Overview of the sources of carbon emissions in the United States in 1995 (in million tonnes equivalent and including CH_4 from MSW, A/F, and OI). Source: Based on EIA 1996a.

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:

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

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ absorption through increased carbon sequestration—may be needed. They will definitely provide valuable choices and therefore should be pursued.

1.3 STUDIES OF CLIMATE CHANGE AND TECHNOLOGY

The role that technology can play in reducing GHG emissions has significant economic implications. For example, one survey of a number of energy economic models shows that the cost of stabilizing U.S. emissions at 1990 levels by the year 2010 ranges between 0.2% and 0.75% of GDP, or roughly \$20 billion to \$75 billion per

The lab saying all technology is not ready

year in 1995 dollars. (Gaskins and Weyant 1993.) To achieve these reductions would require a carbon tax of between \$10 and \$130 per tonne, or an equivalent policy, perhaps in the form of allowance trading.¹ The cost of reducing U.S. emissions to 80% of 1990 levels by 2010 ranges between 0.9% and 1.7% of GDP (\$90 billion to \$170 billion per year). Thus controlling carbon emissions could be quite costly, and the possibility that new technologies might reduce the costs of carbon control could be very valuable to the nation and the world.

The critical role that technology can play is evident in the research literature that considers U.S. climate change strategies. One recent study (Interlaboratory Working Group 1997) documents in detail how four key sectors of the economy—buildings, transportation, industry, and electric utilities—could respond to alternative scenarios that involve directed policies to expand adoption of energy-efficient and low-carbon technologies, increase the relative price of carbon-based fuels, and launch an aggressive program of targeted research and development (R&D). The “efficiency case,” which assumes aggressive R&D and accelerated adoption of cost-effective efficiency technologies, reduces carbon emissions by 120 MtC in 2010 compared with a “business as usual” forecast. In the “high-efficiency/low-carbon case,” which assumes even more aggressive R&D and carbon valued at \$50 per tonne, carbon emissions are projected to decrease by 380 MtC relative to the business-as-usual forecast. In all cases (with reductions varying between 120 and 380 MtC/year by 2010), the projected savings from reduced energy

expenditures exceed the projected direct costs of the required technology investments. Thus this study suggests the strong role that advanced technologies can play in reducing GHG emissions without harming the economy.

The idea that the United States must marshal a wide range of technological advances to meet climate change goals is presented in a second study (Kline et al. 1997). It shows that energy efficiency measures alone will not be able to meet a target of reducing U.S. carbon emissions to 1990 levels. Low-carbon supply measures will become necessary soon after the year 2000.

The cost impact of technology is assessed directly in a third study (Edmonds, Dooley, and Wise 1997). This study examines the cost of carbon emission reduction strategies under three hypothetical technology regimes:

- a “frozen technology” case, in which technology remains at its current cost and performance level
- an intermediate case that follows the technology path in the Intergovernmental Panel on Climate Change IS92a scenario (IPCC 1992)
- an “advanced” case in which technologies progress more rapidly

The projected cost of stabilizing atmospheric CO₂ at 450 ppmv in these three cases is \$21.5 trillion, \$12.6 trillion, and \$9.4 trillion, respectively. In the advanced technology case, targets above 500 ppmv can be achieved at no net cost. Thus this study suggests that advanced technology can have a dramatic impact on the cost of reducing carbon emissions.

¹ A charge of \$50 per tonne of carbon is equivalent to \$24 per tonne of coal or \$0.12 per gallon of gasoline.

A fourth recent paper expands upon the Edmonds et al. study to relate the cost of atmospheric CO₂ stabilization to R&D expenditures (Schock et al. 1997). Assuming there is only a 1 in 4 probability that the CO₂ level in the atmosphere needs to be stabilized at or below 550 ppmv and that the effectiveness of energy R&D in developing new technologies to substantively lower emissions is only 50%, Schock et al. calculate the value of energy R&D to the United States at \$2 billion per year over the next 15 years, or a total of \$30 billion (the U.S. share of world carbon emissions is 23%). Raising the probability of the need for action to 50% and increasing the effectiveness of R&D to 80% increases the value to society by a factor of over 3, to more than \$6 billion per year, or \$90 billion over 15 years. Their examination of the DOE portfolio indicates that approximately \$1 billion of the current energy R&D budget (~\$1.3 billion) is directed at research relevant to atmospheric stabilization of CO₂.

In summary, these studies clearly support our tenets that advanced energy technologies are required to reduce GHG emissions and sustain economic growth, and that the development and use of such technologies would enable GHG reductions at relatively low net cost to the economy. The fourth study also indicates that a substantially larger R&D budget is warranted.

New technologies have frequently played key roles in resolving major issues facing the nation. Two recent examples include the catalytic converter—which has greatly reduced automobile emissions of carbon monoxide, hydrocarbons, and nitrogen oxides—and the development of alternatives to chlorofluorocarbons (CFCs) for coolants, thereby reducing

their threat to the protective stratospheric ozone layer. More broadly, the United States has realized significant environmental improvements with continued economic growth during the past 25 years by adopting environmental policies that emphasize the adoption of “best available technology economically achievable... [to] result in reasonable further progress toward [national environmental goals]” [Public Law 92-500, Federal Water Pollution Control Act Amendments of 1972; also see the Clean Air Act Amendments of 1970, Section 165 (a) (4)].

Advanced energy technologies will also provide important collateral benefits. Examples include the economic benefits that will result from exports of these technologies, enhanced environmental quality, and decreased reliance on oil imports due to the development of alternative fuels and more efficient transportation technologies.

As this report indicates, there is a solid basis for believing that pursuit of a technology strategy is an effective approach to reducing GHG emissions and stimulating economic growth.

1.4 ABOUT THIS STUDY

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 R&D and what those achievements imply for reducing GHG emissions. Fortunately, many of the advanced technologies

addressed in this report are already the subject of, at least, limited federally sponsored research, development, and demonstration (RD&D) driven by the collateral benefits they offer. In particular, DOE's applied energy technology programs, which are already supporting development of most of these technologies, should serve as the base for the expanded RD&D efforts recommended in this report.

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. The analysis of such policies and programs is the subject of a companion effort being led by DOE.

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 Council of Advisors on Science and Technology (PCAST 1997).

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.

1.5 REFERENCES

- Edmonds, J., J. Dooley, and M. Wise 1997. "Atmospheric Stabilization and the Role of Energy Technology," *Climate Change Policy, Risk Prioritization and U.S. Economic Growth*, American Council for Capital Formation, Washington, D.C.
- 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.
- Gaskins, D. W. and J. P. Weyant 1993. "Model Comparisons of the Costs of Reducing CO₂ Emissions," *American Economic Review* (AEA Papers and Proceedings), **83**(2), 318-323.
- 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.
- IPCC (Intergovernmental Panel on Climate Change) 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, ed. J. T. Houghton, B. A. Callandar, and S. K. Varney, Cambridge University Press, Cambridge, U.K.
- IPCC (Intergovernmental Panel on Climate Change) 1995. *Climate Change 1995: The Science of Climate Change*, ed. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge University Press, Cambridge, U.K.
- Kline, D. et al. 1997. "The Role of Renewable Energy in U.S. Climate Change Strategies," to be published in *Proceedings of the 8th Annual North American Conference: International Markets, Competition, and Policy*, U.S. Association of Energy Economics/International Association for Energy Economics, San Francisco, September.
- Marland, G., R. J. Andres, and T. A. Boden 1977. *Global, Regional, and National CO₂ 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.

Schock, R., W. Fulkerson, M. Brown, and R. San Martin 1997. "How Much is Energy R&D Worth?" in *Proceedings of the 32nd Intersociety Energy Conversion Conference*, Honolulu, Hawaii, July 27-August 1, 1997, Am. Inst. Chem. Engr., New York.

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.

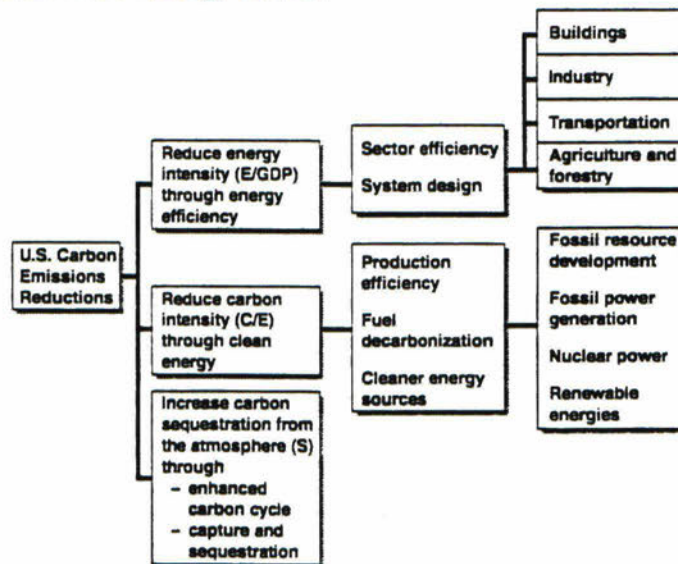


Fig. 2.1. Alternative technological opportunities for reducing greenhouse gas emissions. Electric utility technologies are covered in the fossil power generation, nuclear energy, and renewable energy areas.

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 Vehicles
 - 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 CO₂ 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
 - 9.2 Advanced Chemical and Biological Sequestration
 - 9.3 Terrestrial Storage of CO₂
 - 9.4 Carbon Sequestration in Soils
 - 9.5 Elemental Carbon Sequestration
 - 9.6 Ocean Storage
-

^aThis 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

2.1.1 Technology Approaches

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) CO₂ 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

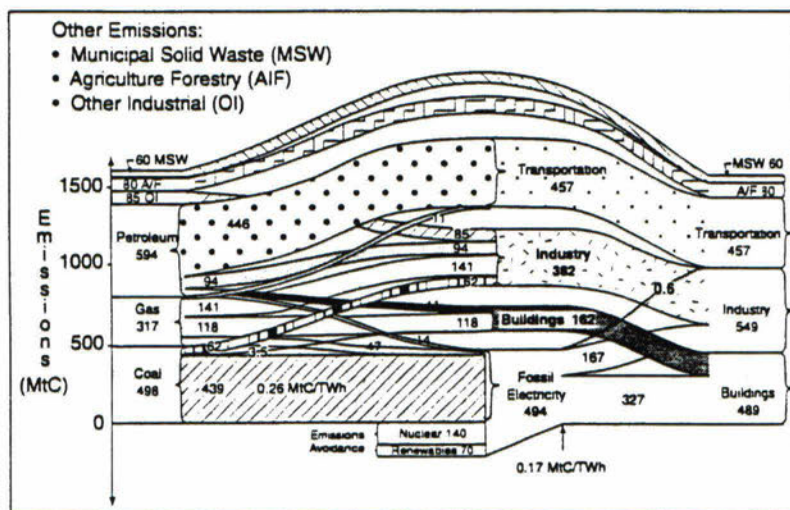


Fig. 2.2. Sources of greenhouse gas emissions in the United States in 1995 (in million metric tonnes equivalent). Note that if nuclear and renewables had not been used to generate electricity in 1995, carbon emissions would have been 210 MtC higher on each side of the chart. Source: Based on EIA 1996b.

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 CO₂ emissions captured during fossil fuel conversion processes, thus preventing their release into the atmosphere. A second approach is to increase the absorption of CO₂ 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 Chapter 5, Synthesis and Moving Forward.

2.1.2 Assumptions

Reference Case. U.S. CO₂ emissions are projected by DOE's Energy Information Administration (EIA) to increase at a rate of 1.2% per year under a "business-as-usual" scenario. This scenario assumes that some efficiency and process improvements will offset what would otherwise be a larger rate of CO₂ 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, CO₂ 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 Table 2.2 and Fig. 2.3 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.

Restructuring. The data in Table 2.2 and Fig. 2.3 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.

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

^aThe 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 CO₂ are not included.

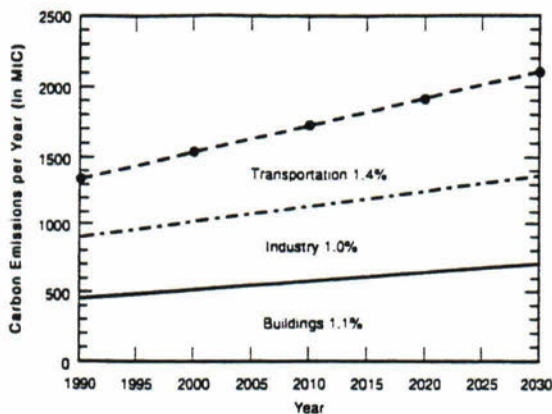


Fig. 2.3. Projected U.S. carbon dioxide emissions (in MtC per year). Source: Based on EIA 1996b.

It is also possible that deregulation will increase electrical power generation by gas turbines, making power generation by nuclear reactors and renewable energy sources less economically attractive; the result could be increases in 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 RD&D of 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. On the other hand, implementation of a renewable portfolio standard and public benefits programs might significantly promote clean power.

Federal RD&D Efforts. 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. Examples are energy efficiency improvements, development of new renewable energy technologies, coal power plant improvements, and nuclear capacity additions.

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. These additional federal resources include approximately \$1.8 billion spent in FY 1997 for the U.S. Global Change Research Program.

These existing RD&D programs form the basis of an expanded and accelerated RD&D effort to more fully address the issue of GHG emissions, including new technology pathways such as carbon sequestration. With rapidly evolving markets and technologies, it is difficult to estimate the impact of federal RD&D efforts on carbon reduction. Nonetheless, such estimates are needed to distinguish between technologies in developing a strategy. This report includes preliminary estimates of the impact of an enhanced federal RD&D program on the carbon reduction potential of technologies in the years 2010, 2020, and 2030. These estimates are the judgment of teams from the 11 participating national laboratories (in some cases in collaboration with experts from other organizations across the country). The RD&D support needed to achieve these estimates is

discussed further in Chapter 5, Synthesis and Moving Forward.

Federal RD&D is certainly not the only effort that will be needed to develop and demonstrate these technologies. Private-sector collaboration is a major element of current federal RD&D programs and will need to continue and expand along with the federal commitment to be able to achieve the advances described in this report. Supportive federal (and state and local) policies could also make a large difference.

Federal Policies. This report's estimated reductions in carbon are relative to the *Annual Energy Outlook 1997* reference (business-as-usual) case. They assume a continuation of today's existing federal programs and policies. The estimates do not presume the creation of any new incentives such as investment tax credits, a carbon charge, or a domestic or international CO₂ trading system. The carbon reduction impacts of the individual technology pathways discussed in this report could be even greater if more vigorous deployment programs and policies were implemented.

Market and Risk Factors. The effects of the market success of one technology pathway on the market success of another technology pathway were generally considered within one particular technology area, such as within nuclear energy or within buildings efficiency. Effects of competition among technology areas were not considered, however. Therefore, carbon reduction estimates from different technology areas (such as nuclear and buildings) cannot simply be summed.

The estimated carbon reductions do take into account many of the factors that can affect the performance and

market penetration of a new technology, such as

- 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
- environmental and health risks associated with the technology
- public perception and acceptance risks
- characteristics of competing technologies

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

2.2 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 subsections, by end-use sector:

- buildings
- industry
- transportation
- agriculture and forestry

2.2.1 Buildings

The Potential for Reduced Emissions

refer to 5 lab study

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.

2.2.2 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 (14.5 MtC) 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.

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

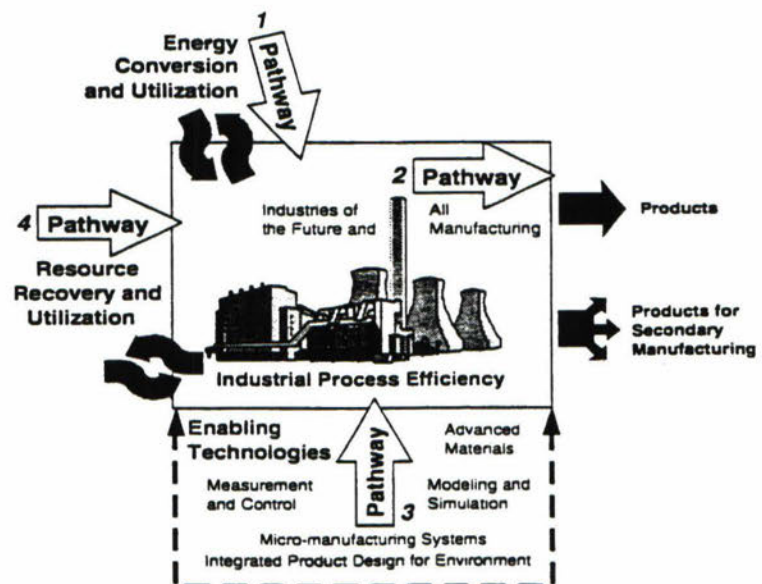


Fig. 2.4. Four technology pathways to increased industrial efficiency.

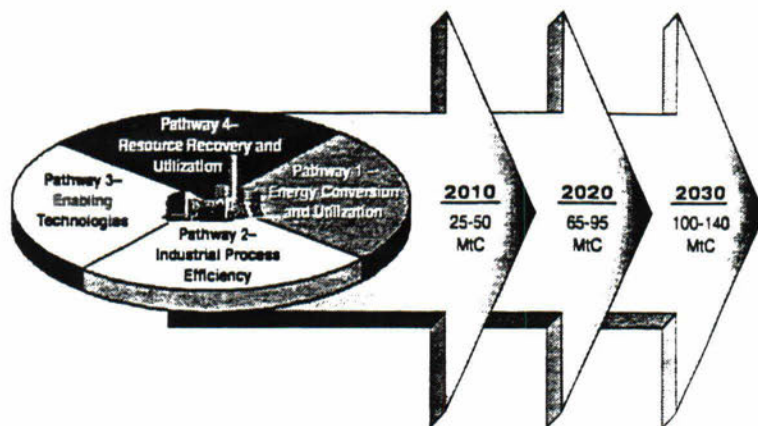


Fig. 2.5. Technology pathways for industry with associated benefits in carbon emission reductions.

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 CO₂ 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.

2.2.3 Transportation

The Potential for Reduced Emissions

Accounting for 32% of U.S. CO₂ 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. 2.3.4.)

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. 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.

2.2.4 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 CO₂ 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-bioprocess 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 CO₂ 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.

2.3 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

2.3.1 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. 2.5) 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.

Because of the desire to reduce CO₂ 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 CO₂ 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 CO₂.

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 H₂ with only a CO₂ 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.

CO₂ 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 CO₂ and minimizing fugitive gas emissions from pipelines and other remote sites. CO₂ is pumped into oil reservoirs to enhance the recovery of petroleum. Instead of present practice, CO₂ that would otherwise be emitted to the atmosphere (from fossil fuel combustors) could be captured and used to enhance energy recovery. In the future, CO₂ 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 CO₂ 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 CO₂ from nitrogen in very large-scale flows. Development of these high-throughput gas separation technologies would allow recycled CO₂ from fossil fuel combustors to replace CO₂ that is produced from dedicated production wells.

Collateral Benefits

Improved crude oil refining processes would eliminate GHGs that are considerably more damaging than CO₂. Converting coal-based synthesis gas to transportation fuels would reduce several pollutants compared with conventional fuels, as would using CO₂ 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 CO₂ 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. 2.6), which does not bode well for the implementation of new high-technology programs.

Efficiency improvements in crude oil refining and processing pose a high level of commercial risk. As shown in Fig. 2.7, 46% of domestic refineries have closed since 1981, many because of perceived environmental problems. Reconfiguring a new domestic refinery

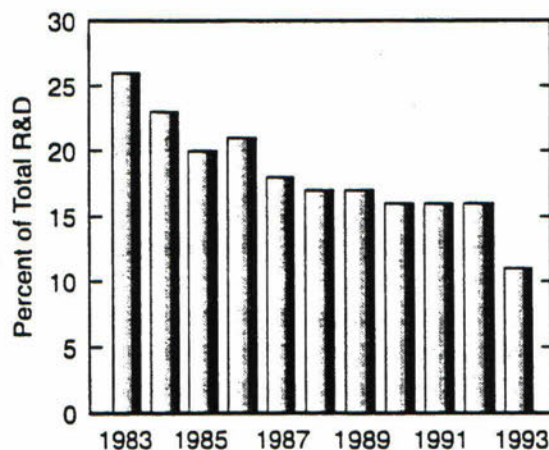


Fig. 2.6. Long-term R&D in major oil companies continues to decline.

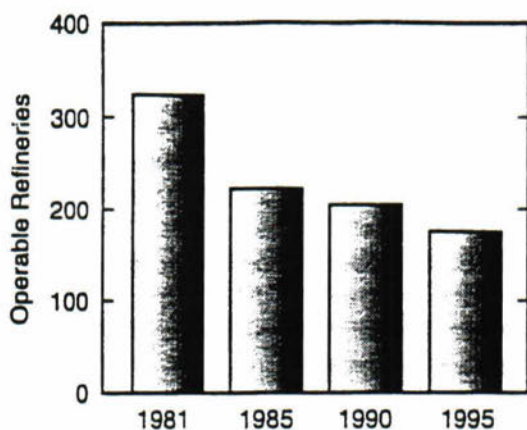


Fig. 2.7. Operable refineries in the United States.

industry will entail very significant commercial risks.

2.3.2 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 CO₂ 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 CO₂.

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 CO₂ 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 CO₂. 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 CO₂ capture methods for this pathway, including similar methods in the technologies from the first two pathways could lead to additional reductions. Typically, CO₂ may be captured by chemical, biological, or physical means. CO₂ 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 CO₂ 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 CO₂, but these are only cost effective if the CO₂ exists at a high concentration in the effluent stream.

Research needs that have been identified in CO₂ capture include (1) means to concentrate the CO₂ 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 CO₂ could include use of a blend of pure oxygen and recycled CO₂ 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 CO₂ and hydrogen. Improved separation techniques for the hydrogen would then leave a concentrated CO₂ stream, which would be available for further processing.

Currently, CO₂ 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-term carbon reduction and capture international market share arising from the 50-year service life of power plants. The low-carbon fuels pathway

faces moderate risks both technologically and commercially, although ATSS for stand-alone systems are probably low risk. The energyplex pathway faces low to moderate technical risk related to the challenges for system integration, and moderate to high risk related to the breakthroughs in capture, including those related to novel combustion configurations. The health and ecological risks are considered low to moderate.

Supporting science and crosscutting technologies needed to achieve these pathways include combustion; materials for high-temperature and corrosion-resistant performance; industrial ecology; hydrogen separation or production, transportation, and storage; improved processes for low-cost separation of oxygen; advances in fuel cells; and identification of alternative working fluids and determination of their thermodynamic properties.

Collateral Benefits

These pathways not only will reduce GHG emissions but also will provide a clean, secure energy future and help the nation respond to its international commitments. An accelerated RD&D program will enable the United States to capture a larger share of the \$1.4 trillion export market for coal technologies between now and 2010 and help the U.S. economy grow by creating an energy technology export business. An accelerated R&D program would also allow U.S. industry to take advantage of the domestic markets for ATSS and fuel cells, which are estimated to be worth tens of billions of dollars between now and 2010.

Strategy and Recommendations

For the high-efficiency coal-based pathway, about \$70 million per year is currently being spent on DOE

programs. For the low-carbon fuel pathway (fuel cells and advanced turbines), about \$90 million per year is currently being spent on DOE programs. As part of this initiative, accelerating and completing the development of these technologies is recommended. For the energyplexes pathway, relevant technical ideas (such as fuel cells and coal liquefaction) are currently being funded at various levels. Pursuing the grand challenges envisioned both for this pathway and for additional options is recommended for the next two decades.

In summary, the technology pathways described provide a range of options for using coal, natural gas, and other solid fuels—such as biomass, synthesis gas, and hydrogen—to generate power at competitive power costs, to reduce emissions of criteria pollutants and CO₂ to the atmosphere, and to develop strong positions in crucial technologies important to economic growth in the next century. Not all of these will necessarily enjoy widespread commercialization; however, they represent a family of options that spread technology risks, address fuel flexibility, and hedge against upsets in fuel prices. They include both improvements on familiar technologies, which should pose reduced commercialization risks, and bold new concepts that may pose as yet unrecognized commercialization risks.

2.3.3 Nuclear Energy

Nuclear power is deployed worldwide to produce 20% of world electrical generating capacity (in some countries, as much as 80%). Electricity generation using nuclear power results in very small emissions of GHGs, so nuclear power is an important tool in reducing global CO₂.

In the period when France converted 70% of its electricity generation to nuclear, all related emissions were reduced dramatically. CO₂ was reduced by 80%, SO₂ by 90%, NO_x by 60%, and particulates by 97% (Fig. 2.8). Today, in the United States, 109 nuclear power plants generate nearly 22% of U.S. electrical capacity (100 GWe). This nuclear generating capacity avoids the emission of about 140 MtC/year compared with generating this electrical capacity by burning fossil fuels.

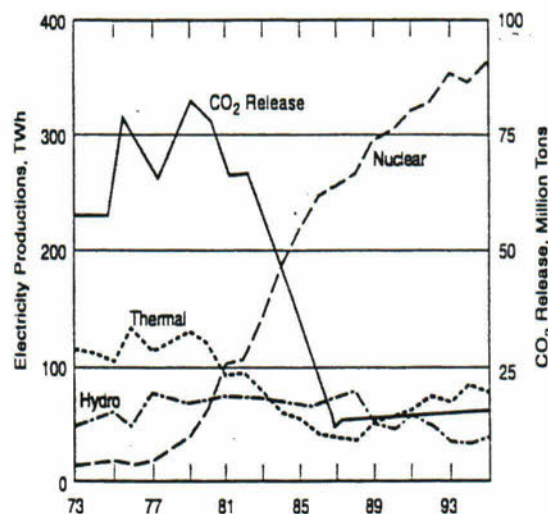


Fig. 2.8. Relationship between CO₂ release and electricity production in France, 1973-1996.

The Potential for Reduced Emissions

In the near term, the development and use of technologies for lifetime extension and for generation optimization (LEGO) of existing nuclear power plants could reduce carbon emissions by increasing nuclear electricity contributions from existing plants over the next several decades. A modest carbon reduction is also assumed for new nuclear plants in 2020 and 2030. Total potential reductions are shown in the following table.

Estimated carbon emissions reductions (MtC/year)			
	2010	2020	2030
Total nuclear	0-15	30-70	70-150

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

If the current 100 GWe of nuclear electrical generating capacity were eventually replaced by next-generation nuclear plants, the United States would continue to avoid emissions of more than 100 MtC/year. If, in addition, electrical demand in the United States continued to grow at 1.5% per year and the installed nuclear generating capacity grew along with it to maintain its current share of the U.S. market (22%), then this new nuclear capacity could result in the avoidance of about 160 MtC/year by 2030. If the market for nuclear generated electricity expanded to 30%, then the result would be an avoidance of about 250 MtC/year by 2030 (see Fig. 2.9).

In the long term, by 2030, the development and use of evolutionary

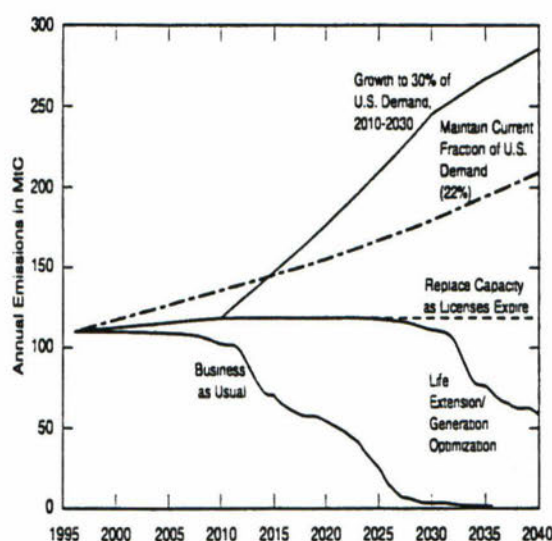


Fig. 2.9. Carbon emissions avoided under various scenarios of nuclear electricity generation.

and advanced fission reactors are projected to reduce carbon emissions by about an additional 100 MtC/year. In the longer term, the second half of the twenty-first century, fusion energy systems may become a significant economic power generation source, free of GHG emissions. The actual amount of nuclear-generated electricity will depend on the future financial viability of the nuclear option.

Technology Pathways and Opportunities

Lifetime Extension and Generation Optimization. The near-term approach to the use of nuclear energy should be to provide technologies to increase electricity generation and extend lifetimes of the existing set of 108 nuclear power plants. The initial 40-year license period for these reactors will expire roughly from 2005 to 2030. If the United States is faced with replacing this capacity with fossil-fueled generating plants, CO₂ emissions will **increase** more than 100 MtC/year. Both the renewal of plant licenses and increases in plant capacity factors can be enabled by new nuclear and nonnuclear technologies. With targeted R&D investments in monitoring, diagnostic, and materials technologies, these nuclear plant lifetimes could be extended for an additional 20 years, and the efficiency and output of the plants could be incrementally increased, thus avoiding the GHG emissions that would result from replacing this nuclear capacity with other power generation systems.

Examples of generation optimization technologies include advanced technologies for on-line monitoring of cables and conventional equipment (pumps, valves, etc.) to minimize losses of production because of unplanned

outages. In addition, improved materials measurement and diagnostic technologies could reduce scheduled downtime for diagnostics and repairs. Plants could be operated at higher net power output to the grid by using sensors and controls that more accurately measure operational parameters, thereby reducing in-plant power demands, improving the thermal-to-electric conversion efficiency, and increasing the core power.

Nuclear power plant life extension hinges on the resolution of issues related to the aging of key components, including reactor pressure vessel embrittlement, stress corrosion cracking of reactor internals, degradation of instrumentation and power cables, and steam generator tube cracking. The effort to resolve these issues could also benefit from improved instrumentation and materials characterization technologies. In addition, R&D on in situ component annealing and on materials cladding processes could provide effective and economical repair technologies. Specific examples of approaches that offer the promise of resolving these issues include gas-fired thermal annealing, water chemistry control to avoid stress corrosion cracking, and various approaches to the deposition of lining materials.

Next-Generation Fission Reactors. The mid-term approach to the use of nuclear energy is to develop and install next-generation fission reactors. Even if LEGO technologies were fully utilized, a major increase in carbon emissions could only be avoided through new nuclear capacity after 2015, which would replace existing reactors that reach the end of their lives.

Evolutionary designs for next-generation fission reactors have received Nuclear Regulatory Commission licensing certification and are available for construction today without significant research; several have been built in Japan. These designs are simple and rugged, and they incorporate passive safety features intended to provide safer, more trouble-free operation over 60-year design lifetimes. Advanced fission reactors, which use fuel cycles that are proliferation resistant, are also designed for higher efficiencies coupled with improved safety compared with currently operating plants.

The long-term (beyond 2030) approach to the use of nuclear energy would likely use nuclear reactor concepts, such as the liquid-metal cooled fast-spectrum reactor, that extract far more of the energy available in the uranium fuel than the 1% currently used and that produce less waste per GWe, thus extending the resource. In addition, efforts are under way to develop accelerator-driven systems using high-energy protons to produce nuclear energy from subcritical targets.

Finally, one can conceive of a new set of technologies that could be implemented in the next century. The concept of a hybrid nuclear-hydrogen cycle in which nuclear heat is used for production of hydrogen, with subsequent use of hydrogen as an energy source, has considerable potential. R&D on fission heat-to-hydrogen conversion technologies and on hydrogen distribution technologies has the longer-term potential to produce fundamental changes in the world's energy supply approach and make it consistent with our ecological goals.

Fusion Power. Fusion power, when developed and deployed, would be a carbon-free energy source. The U.S.

domestic fusion energy sciences program is concentrating on science and innovation supporting the development of attractive fusion systems based on toroidal magnetic configurations. It also supports a small R&D effort on driver systems for inertial fusion energy. Most of the research effort for the inertial approach to fusion energy is supported for its defense applications. The development of technologies required for fusion, and the pursuit of ignited or burning plasmas, are being pursued through international collaboration.

Collateral Benefits

One collateral benefit of the continued pursuit of nuclear power would be the economic benefit of serving as a domestic and international supplier for this major electric power technology. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. As of today, the United States has invested \$200 billion in nuclear power plants and has 400,000 nuclear-related jobs. In addition, a benefit of pursuing LEGO technologies would be enhanced safety and reduced worker radiation dose at existing plants.

Furthermore, if the United States did not pursue research into next-generation reactors, there would be several negative impacts. The first would be the loss of the technical infrastructure to support the nuclear enterprise, which also supports nuclear medicine, isotope production, and neutron science. This loss could also lead to increasing safety concerns for existing reactors. The second would be the decreased ability to design and construct fission, and eventually fusion, plants to export or to replace the existing ones in the United States at the end of their lives. Finally, with the loss of U.S. infrastructure, the

ability to influence the nuclear policy of other countries would disappear.

Technical Risks and Other Issues

Nuclear power faces environmental risks and issues, including the disposal of nuclear wastes. But most of all, the risk is economic. Nuclear power shares the same economic attributes of many renewable technologies—a high fixed cost and a low variable cost—that make market penetration difficult today in the United States. Technology R&D along the technology pathways outlined here could have a major impact on alleviating all of these risks.

Strategy and Recommendations

Nuclear technology is currently offsetting approximately 140 MtC emissions per year. Pursuit of technologies for both LEGO and next-generation nuclear power would allow this offset to continue, as well as provide additional GHG emission reductions in the future. Successful development and use of improved nuclear power technologies could also have a major impact on global GHG emissions.

This study recommends pursuit of nuclear energy R&D to provide the United States and the world with an improved nuclear technology option to help address the very challenging climate change issue. Continued support of a broad base of concepts in fusion R&D is required, and, as these concepts mature, investment will be necessary and appropriate.

2.3.4 Renewable Energy

The Potential for Reduced Emissions

Renewable energy pathways—using energy from sunlight, wind, rivers and

oceans, the hot interior of the earth (geothermal energy), and biomass (agricultural and industrial wastes, municipal solid waste, energy crops) to produce electricity, fuels, and heat—hold significant potential for reducing GHG emissions in the next century by displacing fossil-fuel-generated electricity or petroleum transportation fuels. This potential is shown in the table below and is compared with the business-as-usual carbon projections in Fig. 2.10.

Estimated carbon emissions reductions (MtC/year)			
	2010	2020	2030
Total renewable energy	30–60	75–130	135–260

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

All regions of the United States have renewable resources of one type or another. Renewable resources currently account for about 8 to 10% of the energy consumed in the United States; most of this is from hydropower and traditional biomass sources. Solar, wind, and geothermal technologies are cost-effective today in small and niche markets, which are important steps to full commercialization.

- In the electricity sector, renewable power avoids about 70 MtC emissions per year at the present emissions rate of 0.17 MtC/TWh for electricity.
- Renewable energy technologies are well along a path of decreasing cost (Fig. 2.11), making their expanded commercialization prospects very realistic for early in the next century.
- A level of 20% use in 2025 and 50% use in 2050 is foreseen for the world in a number of projected energy scenarios from, for example, Shell Petroleum Limited (1996), the World Energy Council, and the International Panel on Climate Change (1995). A group of U.S. environmental organizations has also projected the future uses of renewables in the United States in a just-released report, *Energy Innovations* (1997).

Each of the renewable energy technologies is in a different stage of research, development, and commercialization; and all have differences in current and future expected costs, current industrial base, resource availability, and potential impact on GHG emissions. Appendix B describes each of these aspects of the various technologies.

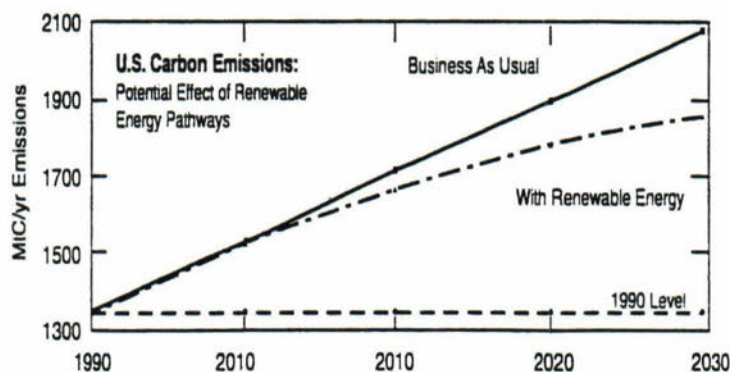


Fig. 2.10. Renewables have the potential for significant reductions of U.S. carbon emissions.

While today's renewables are usually more expensive than the conventional competition on a first-cost basis, they are cost-effective in certain niche markets, especially on a life-cycle-cost basis. Several technologies produce electricity from renewable sources; those nearing

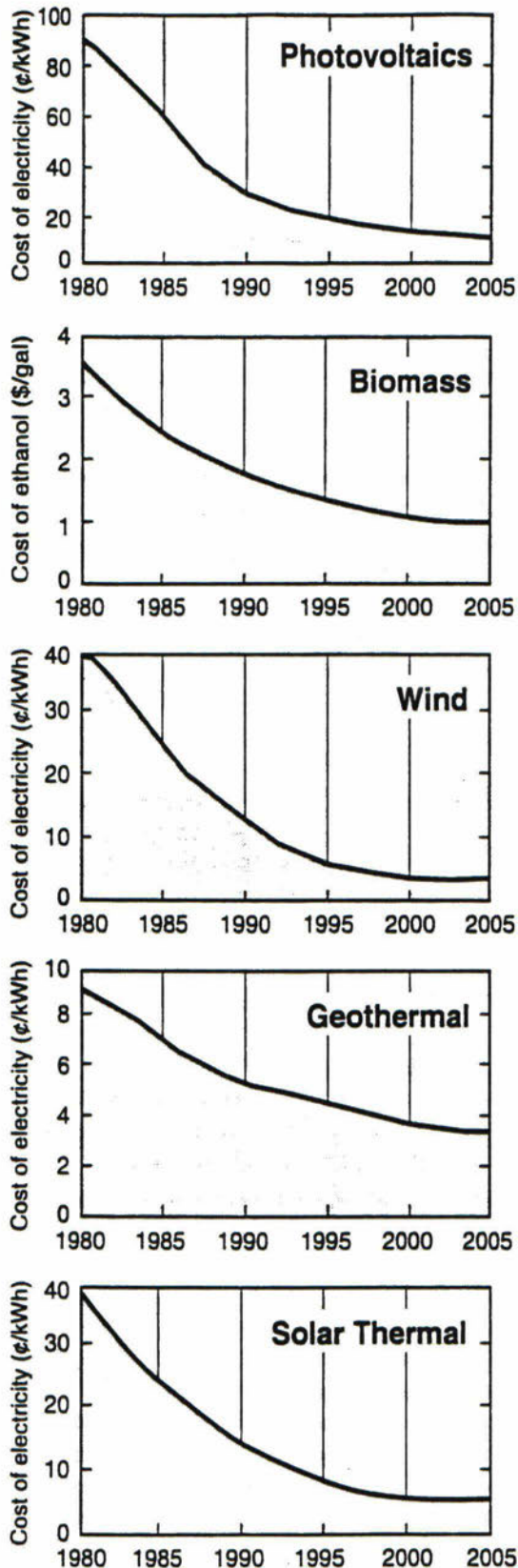


Fig. 2.11. Renewable energy technologies are well along a path of decreasing costs.

commercialization face common problems such as difficulty in obtaining capital, uncertainties related to future electric utility restructuring, and current competition from natural gas. Those technologies further from commercialization need more emphasis on R&D, from fundamental research to resolution of process scale-up issues.

Technology Pathways and Opportunities

Biomass Electric refers to technologies that generate electric power from such biomass resources as cofiring biomass with coal, using biomass as the sole fuel in new power plants, or gasifying biomass to replace natural gas. From now through 2010, new biomass electric technologies (including landfill gas) are likely to be commercialized and should have a strong impact on CO₂ emissions. Biomass cofired with coal could also replace a significant portion of coal in electricity production in the near term. Biomass gasification could have a major impact in the forest products industry during the next 10 to 15 years, when many existing boilers will be replaced. RD&D challenges include resolving issues around ash chemistry and NO_x reduction, demonstrating long-term operation of gas turbines on synthesis gas, improving materials, developing sufficient energy crops for feedstocks, and demonstrating advanced technologies.

Wind Energy systems today are very close to being cost-competitive, on a levelized cost basis, with projects at \$0.04 to \$0.07 per kWh; nearly 1800 MW are installed in the United States, and another 6000 MW in other nations. High-quality wind resources are available in 34 of the 50 states and could provide major carbon offsets

before 2010. Technology challenges to achieve lower cost and increased reliability include further advances in the understanding of wind flow, aerodynamics, structural dynamics, advanced power conversion devices, and development of durable and lightweight structural components. In the near term, up to 10 to 20% of a region's electrical capacity could be from wind power without any adverse operating or economic effects. Larger market penetrations in the mid to long term would require addressing the impact of the variation of wind through modification of systems operation, hybrids with other technologies, energy storage, transmission and infrastructure, and improved wind forecasting.

Hydropower currently generates 10% of the nation's electricity, but generation is declining. Current technology often has adverse effects on fish and downstream water quality and quantity; the goal is to generate electricity without these adverse effects. R&D challenges include quantifying the biological response of fish affected by hydropower projects, modeling the forces inside turbines to predict stress levels on fish, and demonstrating the cost-effectiveness of retrofits.

Solar Photovoltaic (PV) technology uses semiconductor-based cells and modules to directly convert the energy of sunlight to electricity. PV can be used to produce electricity on almost any scale, depending only on how many PV modules are connected together. About 100 MW of PV modules were sold in 1997; annual growth has been 15 to 20%. Hundreds of U.S. applications are currently cost-effective for off-grid electric power needs, such as powering remote telecommunications installations and utility sectionalizing switches.

International interest is also very high. PV costs are currently too high for bulk power generation, but costs are decreasing rapidly. Goals are to compete for peak power shaving by 2010, then daytime utility electricity by 2020. RD&D challenges include improving the fundamental understanding of materials and processes to provide a technology base for advanced PV options, optimizing cell and module materials and design, scaling up cells to product size, validating performance in outdoor and accelerated conditions, and improving manufacturing processes.

Geothermal Energy technologies use energy from within the earth to produce electricity or provide heat for industrial processes. Geothermal heat pumps use the thermal mass of the earth as a heat sink for air-conditioning and heating. Hydrothermal reservoirs produce about 2100 MWe in the United States and about 6000 MWe worldwide. In the United States, direct-use applications produce about 400 MWt; heat pumps produce 4000 MWt and are increasing by 25% per year. Only a small fraction of the huge geothermal resource can be used economically today. With research and policy support, electricity production could be doubled, and thermal production (including heat pumps) could be tripled or more. Geothermal RD&D challenges include improved methods for predicting reservoir performance and lifetime, innovative low-cost drilling technologies, new concepts to expand the use of the resource, improved energy conversion through thermal and fluids science and modeling, and lowering costs through thermal science and process chemistry.

Solar Thermal Electric and Buildings includes technologies that concentrate the heat of the sun to generate

electricity or use the heat directly. Solar thermal electric technologies have been successfully demonstrated in nine commercial plants (354 MW) operating in California. Using existing, relatively conventional technology, including unique cost-effective storage, hundreds of additional megawatts of peaking power could be on-line by 2005; and evolutionary R&D improvements will allow bulk power market penetration by 2020. Solar hot water systems are commercially available, and ventilation preheat systems using unglazed transpired collectors have made significant progress in commercial/industrial markets. RD&D challenges include improving performance and lifetime and reducing manufacturing costs with improved designs and manufacturing technologies, and addressing commercialization challenges similar to those facing wind energy.

Biomass Transportation Fuels include methanol, ethanol, and hydrogen, which can displace petroleum in internal combustion engines. Biomass sources, including agricultural and other wastes, energy crops, and microalgae, are converted to fuels through biotechnology methods (using microbes) or through thermochemical processes. R&D goals are to demonstrate a biomass waste-to-fuels process with an industrial partner by 2000 and larger-scale production and conversion technologies by 2005. By 2010, energy crops should begin to be available, allowing biofuels to compete with petroleum for direct fuel replacement. R&D challenges include low-cost production of enzymes, development of microorganisms for consolidated processes, improved performance of thermochemical processing, and advances in energy crop productivity, cultivation, and harvesting. Biomass transportation

fuels are also discussed in Transportation Sect.. 2.2.3.

Solar Advanced Photoconversion technologies use the energy of sunlight to directly produce fuels, materials, chemicals, and electricity from renewable sources such as water, CO₂, and nitrogen. Most of these technologies—involving photobiological, photochemical, and photoelectrochemical approaches—are in the fundamental research stage where technical feasibility must be demonstrated. Examples of these natural and artificial photosynthesis processes include producing hydrogen from water or biomass and producing biodiesel, methane, and methanol from water, waste, and CO₂.

Collateral Benefits

A significant increase in the use of renewable energy pathways would provide benefits beyond reducing GHGs, such as lessening the reliance on foreign oil (especially biomass for transportation fuels), contributing little to waste storage or safety problems, and reducing pollutants. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies.

Technical Risks and Other Issues

The technical risks vary among the pathways, but there are clear R&D paths to address these risks. Overall, ecological and human health risks are low. Commercial, regulatory, and economic risks are generally moderate to high. In many cases, first costs are higher than for conventional energy choices, while the benefits of renewables do not currently motivate and reward private investment. Mechanisms are required that

acknowledge the public value of renewables and help to attract private capital to develop these technologies. Small renewable energy companies in the United States face very strong international competition. Finally, decisions made under utility restructuring will have a major impact on market penetration for renewable electricity technologies.

Supporting R&D is needing in a variety of basic science and crosscutting areas, such as photosensitive materials, innovative semiconductors, corrosion-resistant and higher-temperature materials, biotechnology, catalysts and separations systems, sustainable agriculture, sensors and controls, electrical components, and computational modeling. A wide range of energy storage and transmission systems—along with the production of hydrogen as transportation fuel—would broaden the opportunities for the deployment of intermittent renewable energies, such as wind, solar photovoltaic, and solar thermal electric.

Strategy and Recommendations

Eventually, the private sector is likely to complete the development and commercialization of renewable energy technologies. But well-considered and sustained government investments, both in the underlying R&D and in actions that will remove deployment barriers, are critical. This is the most important step in realizing the full potential that renewable energy pathways can contribute to reducing carbon emissions early in the next century.

Significant investment would be required from both the private and the public sectors. Currently, the annual federal investment is about \$250 million for these pathways. Increased federal investments to

reduce carbon emissions would also return additional environmental benefits and the opportunity for U.S. companies involved in the area to be key players in the \$1 trillion global energy market and the \$400 billion market for environmental technologies.

2.4 CARBON SEQUESTRATION AND MANAGEMENT

This subsection discusses the reduction of net carbon emissions by capturing and sequestering CO₂ after combustion, decarbonizing fuel before combustion, or increasing the absorption of CO₂ from the atmosphere. These approaches are required for the continued use of fossil fuels as energy sources with reduced impacts on concentrations of atmospheric CO₂. For both approaches, there are a number of technological options, ranging from storage of CO₂ in the ocean or in geologic formations to chemical or biological stimulation of the absorption of CO₂ from the atmosphere.

The eventual path to stabilization of atmospheric CO₂ concentrations would require portfolios of GHG reduction technologies, portfolios that would vary from nation to nation and require systems-level analysis. Risks associated with any one pathway suggest that developing an effective approach to large-scale carbon sequestration would require evaluation of a number of alternatives as described in this report. These ideas and technologies should have a sound basis in science, both for understanding each technology and for evaluating the effectiveness of the technologies in actually ameliorating the atmospheric carbon loading. Thus it is imperative that we have a science-based model of the carbon cycle (atmospheric, oceanic, and terrestrial ecosystems) and that we verify the

actual effectiveness of our model through measurements. One set of essential elements are models of each part of the carbon cycle, anchored with georeferenced measurements and verified by checking performance predictions against data gathered using remote sensing technologies on local, regional, and global scales. The resulting science-based program would permit us to direct our investments with greater confidence and with improved cost-effectiveness.

The Potential for Reduced Emissions

The developmental status of the carbon sequestration technologies discussed in this report varies widely. For example, the injection of CO₂ into oil wells or coal seams to enhance oil or methane production is a commercial practice today, whereas the understanding of soil biochemistry is not yet adequate to identify the most promising means for increasing soil uptake of atmospheric CO₂. Therefore, estimating the potential impacts of these carbon sequestration technologies on net carbon emissions is difficult. It is generally believed that net carbon emission reduction from carbon sequestration could be very high in the time frame of the late 2030s and beyond. In the nearer term, carbon sequestration potentials are uncertain, but they may range from low to medium. All of these estimates should be considered possible targets and should only be considered within an order of magnitude indication of what might be likely to result from R&D on these technologies.

Technology Pathways and Opportunities

CO₂ and Carbon Storage Technologies.

Promising concepts for reducing CO₂ emissions are the storage of CO₂ in the ocean or in geologic formations. The technical feasibility of both of these

storage concepts has been established, and it is believed that the CO₂ escape rates in both cases could be low enough to consider the carbon as permanently sequestered. However, the ecological impacts of various specific approaches—which are likely to depend on the location and type of storage media—are not known, nor are the economics of different oceanic or terrestrial CO₂ injection technologies.

For ocean storage, the most critical R&D questions include the stability of CO₂ clathrates and hydrates at various temperatures and ocean depths, as well as the diffusivity of CO₂ in the ocean, again as a function of temperature, depth, and concentration. In addition, the biological impacts of oceanic injection need to be studied.

Terrestrial storage of CO₂ in depleted oil or gas wells, coal seams, or underground aquifers deserves analysis. For the injection of CO₂ into oil or gas wells or coal seams, which has enhanced oil and gas production (as well as, perhaps, mine safety), to be commercially motivated, the critical research questions center on understanding the total potential storage capacity and the economics of different specific candidate sites. Answers to these questions will depend on proximity to CO₂ sources, as well as on the size and other characteristics of the site.

For storage in underground aquifers, the critical research questions include fluid, thermal, geological, and chemical properties of aquifers and the implications of that environment for injected CO₂. For example, would the formation of complex carbonates result from CO₂ injection, and at what rate? The economics of such CO₂ storage also needs to be analyzed.

A third approach to reducing net emissions through storage is the

terrestrial storage of elemental carbon. This concept basically entails removing some or all of the carbon from a fossil fuel and then storing the carbon as a solid. For this approach, the challenge is primarily economic, because the carbon component of the starting fossil resource represents a major part of the energy value of that resource. Not using the carbon fraction in effect increases the energy cost of the remaining hydrogen-rich energy fraction. The advantage of this approach is that it should be less expensive to store carbon than to store CO₂. It may also be possible to market the carbon as a materials commodity to offset the increased energy cost. If carbon is placed in retrievable storage, the carbon energy may be used at a later date under less severe CO₂ emission control conditions.

Currently, storage is believed to be relatively less expensive than capture technologies, but neither is being employed on a large scale. This, however, will change with time as combustion processes are reengineered to facilitate capture. As the cost of capture comes down, storage becomes a greater part of the cost equation. Managing this cost suggests that storage near the point of combustion is advantageous because it reduces the transportation cost of the waste carbon.

Which of the storage pathways is best matched to any single combustion or conversion location will vary, so parallel development is required. As discussion of the individual technology pathways highlights, it is important to emphasize that very clear technological and environmental risks are associated with these technologies. The R&D agenda must therefore be very aggressive if cost-effective technologies are to be in place in time.

Advanced Chemical and Biological Sequestration. There are also several advanced chemical and biological concepts for CO₂ sequestration, including

- chemical sequestration as a mineral carbonate
- direct solar conversion of CO₂ to methanol or other benign products
- reducing the carbon/hydrogen ratio of fossil fuels and capturing the excess carbon
- microalgae sequestration

Advanced chemical and biological sequestration is aimed at permanent stable sequestration and at recycle of carbon to new fuels and chemical feedstocks. Reduction of emissions is accomplished through converting CO₂ into an environmentally benign product, reducing atmospheric CO₂ while generating liquid fuels, generating hydrogen as a fuel from coal without CO₂ emissions, and converting CO₂ into organic compounds. The major advantage of these technologies is that they eliminate the hazards to humans and to the environment that are intrinsic in the disposal of gaseous CO₂. Carbonate disposal accomplishes this by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products. All of these are at a research stage, with conceptual engineering design currently being completed. A better understanding of the basic processes is needed before practical achievable technology performance or cost levels can be estimated. However, because of the inherent attractiveness of these sustainable solutions, further work is merited.

Technologies for Removing CO₂ from the Atmosphere. The annual exchange of CO₂ between the

atmosphere and the combination of the ocean and terrestrial biosphere is very large (IPCC 1995):

- gross annual atmosphere-ocean exchange—approximately 92 GtC
- gross annual atmosphere-terrestrial exchange—approximately 63 GtC (IPCC 1995)
- oceans currently hold 44,000 GtC

By comparison, the total annual anthropogenic emissions of CO₂ are only around 7 GtC. This suggests that small increases in the absorption of CO₂ as a manipulation of the global carbon cycle could have a very significant effect on net GHG emissions.

Dissolved CO₂ in the oceans is removed by the growth of phytoplankton. When carbon is thus removed, it is ultimately replaced by CO₂ drawn from the atmosphere. Two concepts have been proposed for enhancing oceanic uptake of atmospheric CO₂. These are iron enrichment or nitrogen enrichment, both targeted at stimulating the growth of phytoplankton. The general understanding of these approaches is in its infancy. While some experiments on iron fertilization have been conducted, no such studies of nitrogen fertilization exist. Key questions include what rates of CO₂ uptake can be achieved, what the biological impacts are, and to what extent the gains would be offset by carbon or methane emissions resulting from increasing harvests or decay of higher levels of the food chain. The economics of these approaches, which depend directly on the costs and efficacy of different fertilization approaches and rates, also need to be studied. An important risk factor is that of anoxia, or oxygen depletion, which needs to be understood as a function of site characteristics and fertilization rates.

An important component of terrestrial uptake of CO₂ is plant growth, which is treated in the Agriculture and Forestry technology pathway. However, carbon sequestration in soils is also a key of the carbon cycle. The fundamental concept here is the level of "soil organic matter" (SOM). Many agricultural practices, such as breaking of grasslands for crop farming or draining of wetlands, tend to decrease SOM. Technologies that can increase SOM include minimum tillage agriculture, increased return of crop residues to the soil, use of irrigation and fertilizers at levels that maximize crop and root biomass, and return of lands to forests or perennial plants. The most critical R&D needs include research on soil productivity (including the interactions of fertilization levels), tillage practices, water management practices, different plant species, regional soil biochemistry and climate, and the implications of these for affecting SOM. A better understanding of these factors and their interactions can then enable the analysis of the economics of specific technological approaches to increasing SOM.

Collateral Benefits

The most important benefit of successes with these carbon sequestration technologies would be that they could help to enable the continued extensive use of fossil fuels without harm to the climate. Thus they could indirectly have a major impact on global economics, given that economic growth is highly dependent on energy use, about 75% of which is derived from fossil fuels.

Technical Risks and Other Issues

The most important risks for these carbon sequestration technologies are environmental and economic. Each

has the potential for environmental damage, and developing means to prevent that is a primary research need in each case. The economics for all of these technologies should be analyzed to determine their actual carbon sequestration potential and their associated costs.

The risks that are difficult to quantify today, however, are those associated with scaling up limited but promising field experiments to full-scale practice. The global infrastructure requirements for realizing large net carbon sequestration rates from carbon sequestration technologies would require a system of technologies that match or exceed the infrastructure requirements of the fossil fuel combustion enterprise of the next century. It will only be through an aggressive R&D program that we can develop a fundamental understanding of these risks.

2.5 REFERENCES

- Cramer-Kresselt Research 1996. *Facilities and Real Estate Strategies*, prepared for the National Summit on Building Performance, November.
- EIA (Energy Information Administration) 1996a. *Annual Energy Outlook 1997: with Projections to 2105*, DOE/EIA-0383 (97), U.S. Department of Energy, Washington, D.C., December.
- EIA (Energy Information Administration) 1996b. *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573 (95), U.S. Department of Energy, Washington, D.C.
- Energy Innovations 1997. *Energy Innovations: A Prosperous Path to a Clean Environment*, Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, and Union of Concerned Scientists, Washington, D.C.
- Interlaboratory Working Group 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, September.
- IPCC (Intergovernmental Panel on Climate Change) 1995. *Climate Change 1995: The Science of Climate Change*, ed. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge University Press, Cambridge, U.K.
- Shell Petroleum Limited 1996. *World's Energy Systems*, Group Internal Affairs, Shell Centre, London.
- The National Corn Growers Association and Inverizon International, Inc. 1997. *Plant/Crop Biobased Renewable Resources 2020*.

3. BASIC AND APPLIED RESEARCH AND CROSSCUTTING TECHNOLOGIES

Scientific research and the technological advances associated with it have been the basis for a multitude of new technologies that have appeared in the last 20 years. Many of the most successful and globally competitive industries in the United States (e.g., semiconductors, pharmaceuticals, aeronautics, biotechnologies) have strong ties to the products of U.S. R&D. The future security of our energy resources, the quality of our lives and health, and the competitiveness of our industries increasingly depend on further scientific and technological advances (*R&D Magazine* 1997). To create the innovative technologies required for energy systems with reduced carbon emissions requires (1) a broad interdisciplinary and visionary research program that develops the scientific understanding of the problem and (2) a strong industrial base.

Are there critical paths forward that require technological advances? If so, what types of research will enable those advances? At a workshop on R&D integration, Dr. Mary Good, until recently an undersecretary for technology for the U.S. Department of Commerce, concluded that basic research is the major factor that will determine the long-term outcomes of the technologies used to control carbon emissions. But reducing the levels of carbon emissions in the United States will require a commitment to both basic and application-driven research. In addition, disparate technologies for emissions control often will require work in the same critical basic research areas. Advances in both crosscutting basic research and enabling technologies are required to provide technological options like those outlined in Chap. 2 to reduce GHG emissions (Table 3.1).

This chapter addresses basic research needs and identifies a set of enabling technologies that will support the development of a wide range of technology pathways. Basic research needs and crosscutting technology developments are aggregated in the following list.

Table 3.1. Most pressing research and enabling technology needs identified for each of the technology pathways presented in Chapter 2.

Shaded boxes indicate a strong need for specific basic science or enabling technologies to advance a specific technology pathway. White boxes indicate that work in that basic research or technology area could be useful to develop a technology pathway

	Energy efficiency				Clean energy				CS
	Bld	Ind	Trn	A&F	FRD	FPG	Nuc	Ren	
Modeling and measurements									
Materials									
Chemical sciences									
Biotechnology									
Geosciences									
Environmental and ecological sciences									
Nuclear sciences									
Computational sciences									
Hydrogen and fuel cells									
Electrical transmission distribution, and components									
Sensors and controls									
Energy storage and retrieval									

Bld = buildings, Ind = industry, Trn = transportation, A&F = agricultural and forestry, FRD = fossil resource development, FPG = fossil power generation, Ren = renewables, CS = carbon sequestration.

- basic research to understand the global carbon cycle (i.e., computational modeling and measurements to understand the ocean-atmosphere-terrestrial-biosphere interactions)
- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, nuclear sciences, and computational sciences)
- enabling technologies supporting GHG reduction technologies (i.e., hydrogen and fuel cells; electrical transmission, distribution and components; sensors and controls; and energy storage)

The sections of this chapter of the report draw heavily upon the draft white paper, *Carbon Management: Fundamental Research Needs Assessment* (August 6, DOE-OER) and the report of the Secretary of Energy Advisory Board (SEAB 1995).

3.1 RESEARCH TO ADVANCE UNDERSTANDING OF THE GLOBAL CARBON CYCLE

CO₂ emissions from fossil fuels are divided among the atmosphere, ocean, and terrestrial biosphere.

Measurements indicate that the atmosphere is storing carbon at a rate roughly equivalent to 60% of the emissions being produced by fossil-fuel consumption. Additional quantities of the excess carbon emissions are being stored in the ocean, where they do not affect the earth's radiation balance. Carbon storage changes in the terrestrial biosphere are difficult to measure and/or model; but there is reason to suspect that, while some areas are losing their ability to store carbon as a result of land-use changes, carbon storage is

increasing in other areas. Therefore, a satisfactory balance of the contemporary global carbon budget has not yet been reached. In order to plan, assess, and verify the performance of CO₂ sequestration strategies, the fate of emitted CO₂ must be understood and quantified on a global scale.

Verification of the fate of anthropogenic CO₂ via direct measurement programs is now technically feasible in both the atmosphere and the oceans. It is becoming possible to infer changes in terrestrial carbon storage using tracer methodologies, remote sensing, and modeling.

In general, CO₂ sequestration strategies and scenarios must be based on the assumption that the natural carbon cycle will function largely as it has over the past several thousand years. However, in the context of elevated CO₂ levels and perhaps of altered climates in the future, this assumption is not necessarily valid. Basic research is therefore required to identify and evaluate possible feedback on future atmospheric levels of CO₂. This feedback could arise from either direct effects (e.g., CO₂ fertilization of terrestrial plant growth, ocean ecosystem changes due to CO₂-related pH changes) or indirect effects (e.g., climate-related changes in deep-ocean circulation that might alter the sequestration of fossil-fuel CO₂).

3.1.1 Global Carbon Cycle Modeling and Measurement

Coupled atmospheric, terrestrial, and oceanic models are required for basic understanding of the integrated response of the global environmental system and for predicting changes in the global carbon cycle (see Fig. 1.1). This level of complex systems modeling demands high-performance computing (e.g., Accelerated Strategic Computing

Initiative) and fundamental research in the earth and ecological sciences. High-performance computing is critical to increase spatial and temporal resolution, to implement coupling between subsystems, and include important processes in the global systems model needed to assess carbon mitigation strategies. Research is necessary to quantify feedback among the terrestrial, atmospheric, and oceanic subsystems—including the implications of global changes for local and regional environments and economies and, conversely, local and regional inputs to the global systems. These models can be used to evaluate the effectiveness of carbon mitigation technologies and, through integrated assessments, to determine the cost-effectiveness and ecological impacts of carbon mitigation strategies.

In conjunction with the modeling activities, observations of the global environment are critical to document changes in the carbon cycle and to provide the basis for how and why changes are occurring. The strategy for systematic monitoring of CO₂ storage is now based on direct measurements of changes in atmospheric CO₂, oceanic storage of CO₂, and the inferred terrestrial carbon storage. The atmospheric and oceanic measurements should be continued, and measurement systems that directly estimate terrestrial storage must be developed. These measurements must then be used to verify the predictions and to suggest continuous improvement of the models.

The U.S. Global Change Research Program (USGCRP) is implementing a global observing and monitoring system for certain key physical measurements. This should be augmented with global and regional measurements that are especially pertinent to the global carbon cycle. These efforts should be coordinated

and should take advantage of all available technologies and measurement systems in addition to those of the USGCRP.

3.2 BASIC RESEARCH RELATED TO GREENHOUSE GAS EMISSIONS

Scientific discovery is difficult to mandate or even predict. It can, however, be stimulated by the nature of basic R&D. The returns on investments in basic research have been immense. Who could have anticipated the profound impacts on society of the revolutionary technologies enabled through the development of, for example, antibiotics, gene therapy, transistors, structural polymers, nuclear fission, and superconductivity. Areas of visionary research that could be profitably explored to reduce GHG emissions might include developing a hydrogen-based economy, producing electric power from nuclear energy without any radioactive by-products, developing global electrical transmission using high-temperature superconductors, and significantly increasing photosynthesis processes via genetic engineering.

Scientific understanding from basic research efforts will provide the United States with a sound basis to advance technological options. Creating a strong science base makes it likely that the United States will be capable of developing a portfolio of technological options to meet GHG reduction targets. Discoveries resulting from basic research will almost certainly provide the United States with technologies that today might seem highly uncertain and unrealistic but that tomorrow might be essential problem-solving tools. Our long history of scientific progress has shown that basic scientific research alters the technological options available for

responding to threats to our environment, security, and quality of life.

The following examples of progress in the areas of materials science, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences could offer vastly improved or completely new technologies for reducing GHG emissions. We have already seen the pull of technology in Chap. 2; here is the push of basic science and its promise for the future.

3.2.1 Materials Science

Improvements in materials can significantly impact the production of GHGs and wastes. Materials found in systems that produce energy (e.g., combustors and turbines), store energy (e.g., batteries and fuel cells), and use energy (e.g., vehicles and industrial/chemical processing) can improve system efficiencies, extend component lifetimes, and increase performance or capacity (Fig. 3.1). Furthermore, the production and processing of materials consumes the largest fraction of the energy used by U.S. industry. Reducing the energy required to supply materials is essential to reducing GHG production.

Basic research into materials synthesis and processing is needed to provide new ways to produce the materials currently used and enable the creation of new materials for energy systems. Areas in which breakthroughs are needed include nonequilibrium thermodynamics, microstructure-properties characterization, interface science, optical and electronic property optimization, and computational modeling of materials processes. Examples of potential near-

term improvements include high-temperature-tolerant materials that allow improvements in the efficiency of combustion processes, heterogeneous catalysts that increase yields and selectivity, high-temperature superconductors to reduce energy losses in electrical systems, lightweight materials to decrease vehicle weight, improved magnets for sensors and motors, improved coatings and surface treatments to reduce wear and surface degradation, improved insulation to reduce heat loss, and miniaturization of equipment to improve efficiency and reduce cost.

Interdisciplinary theoretical and experimental research in condensed matter physics, metallurgy, bioscience, and materials chemistry are key components of a long-term research strategy. For example, cross-disciplinary efforts are needed to develop bio-inorganic composite



Fig. 3.1. Ceramic composite hot gas candle filters can be used to remove particulates from gas streams in combined cycle fossil and biomass power facilities. The filter is made up of an oxide fiber structure into which silicon carbide is deposited by a chemical vapor infiltration process.

materials systems or "smart" materials that are self-constructing or self-adapting. Interdisciplinary biological and materials research is needed to create biomimetic materials—materials patterned after nature. The development of materials engineered at the nano-scale requires the merger of materials science and condensed matter physics; the result will be opto-electronic, organic-electronic, thin film, and semiconductor materials for use in energy generation and distribution (e.g., solar cells, sensors in power plants, and power grid control circuits) and in energy-efficiency applications (e.g., engine sensors and processors, solid-state lighting and displays, advanced windows).

3.2.2 Chemical Sciences

Chemistry is central to the design and synthesis of a wide range of useful materials, as well as to the conversion of energy into heat, work, and light. Advances in the chemical sciences in key areas of separations, catalysis, and combustion are necessary for significant GHG reductions.

Separation processes are used to purify raw materials, separate by-products, and remove contaminants. The membrane materials market alone is currently \$1 billion. Improved separation techniques using membranes, novel separating agents, or hybrid processes could make many industrial processes more efficient while enhancing productivity and reducing environmental impacts. For example, distillation, which consumes more than 40% of the energy used in chemicals and petroleum manufacturing, seldom exceeds a thermodynamic efficiency of 10%. It would benefit greatly from improved separations technology. Other industries, such as microelectronics,

require new standards in separation performance to improve the purity of the components and materials used. Adsorption and ion exchange processes are attractive for removing and recovering materials from dilute systems. Pharmaceuticals, biotechnology, food processing, and pulp and paper processing use separation technologies for product preparation or waste recovery and reuse. Waste treatment and recovery constitute another potentially large market for membrane and adsorption or ion exchange systems.

Catalysts and catalytic processes account for nearly 20% of the U.S. gross domestic product and nearly 20% of consumer products. Improved catalysts could increase efficiency to shrink energy requirements, while increasing product selectivity and thereby decreasing wastes and emissions. New catalytic processes could also reduce GHG emissions in alternative fuel resources, electricity production, transportation, and carbon sequestration. Several studies (e.g., the Council on Chemical Research's Vision 2020 document) have cited critical areas for innovation in catalysis including

- the development of theoretical and experimental tools to improve understanding of catalytic processes at the molecular level, and to enhance predictive capabilities and the ability to design catalysts and develop industrial catalytic processes to increase yield, selectivity, and reliability
- methods to improve the speed of catalyst discovery
- novel reactors and reaction engineering including reactive separation concepts
- low-temperature selective oxidation of fuel-value feedstocks to high-value chemicals

- conversion of gases (e.g., methane) to liquid fuels and chemical feedstocks
- novel methods for producing recyclable polymers and other materials with specific designed properties
- new catalyst systems for achieving high regio- and/or stereo-selectivity, including supported catalysts
- biomimetic synthesis of chemicals and materials,
- fuel cells for cogeneration of chemicals and energy
- new, more economical abatement technologies
- on-line monitoring and in situ catalyst characterization technologies

Combustion is employed in the conversion of 90% of primary energy to end uses in the United States. It powers practically all electric power and provides most heating and process heating (either directly or indirectly, by electricity). Key R&D needs include improved basic understanding and advanced analysis of combustion processes; nonintrusive (e.g., laser and microwave) diagnostics to improve understanding of the chemical, heat transfer, and fluid mechanics relationships that characterize combustion processes; understanding of processes that control flame shape and stability under different conditions; and flame chemistry to control emissions.

3.2.3 Biotechnology

Biotechnology as a crosscutting technology affects four of the nine major technology impact areas shown in Table 3.1: industry, agriculture/forestry, renewables, and carbon sequestration. However, under the broad realm of biotechnology as it applies to reducing carbon emissions,

the status of research and technology-development efforts varies greatly.

The range of technological areas where biotechnology could have an impact on GHG/global carbon cycle issues is broad and includes crop improvement (including energy crops), alternative fuels other than biomass (noncellulosic), carbon cycle manipulation/sequestration, bioprocessing for fuels and chemicals, and biological/biochemical hydrogen production. Energy crop production and efficiencies in the agriculture and forest products sectors will result from advances in genetics and cropping systems. In addition to biomass energy crops, biotechnological approaches offer promise for production of other alternative fuels, including oils/lipids from algae and certain higher plants, and hydrogen from photosynthesis or enzymatic conversion of cellulosic biomass. The recent discovery of a one-photon photosynthesis system and protein engineering of the carboxylase/decarboxylase pathway offers the promise of increases in the efficiencies of carbon fixation by plants.

Fundamental studies of global carbon cycles and the importance of the biosphere as a major sink could lead to major breakthroughs in deploying biological phenomena in strategies to sequester CO₂. Bioprocessing of cellulosic biomass into alternative fuels is necessary in order to realize the full value of biomass-based energy. In addition, cells and enzymes are capable of synthesizing many organic chemicals of industrial interest. Because of mild reaction conditions, unique specificity, and selectivity, biocatalytic conversions are now being considered for many industrial uses. Organic-phase bioprocessing, a particularly promising application,

employs microorganisms and enzymes in nonaqueous media such as organic liquids, gases, or supercritical fluids. This technique could provide alternatives for processing fossil fuels, synthesizing organic chemicals, and converting alternative feedstocks to fuels and chemicals.

3.2.4 Geosciences

The geosciences play a central role in understanding and mitigating the impacts of carbon emissions. A better understanding of the terrestrial, atmospheric, and ocean carbon cycles—and the interactions among them—will lead to new ideas for managing excess carbon and provide the foundation for comparing alternative technologies that could contribute to carbon emissions reductions. Moreover, evaluating the feasibility of most of the mitigation technologies under consideration today will require new knowledge in such disciplines as geophysics, flow and transport, geomechanics and geochemistry. For example, the geosciences are critical for developing or enhancing technologies to inject CO₂ into oil reservoirs, aquifers, and the deep oceans; increasing production of clean fuels such as natural gas; tapping into the huge natural gas supplies found in methane hydrates; and enhancing the natural carbon cycle to capture and sequester more carbon. In addition, closing the nuclear fuel cycle through geologic disposal of nuclear waste is critical to the widespread future use of nuclear power generation.

A fundamental research program in the geosciences would include studies of transport phenomena and the movement of fluids, the kinetics of geochemical systems, and the modeling of complex interactive systems.

3.2.5 Environmental and Ecological Sciences

Ecological and environmental sciences provide the fundamental knowledge of the structure and function of ecosystems (carbon and nutrient cycling) and, therefore, understanding of the responses of ecosystems to the effects of increased GHG emissions. Ecological science is fundamental to quantify the role of the world's ecosystems as net carbon sources or sinks, and to predict ecosystem response to future climate change events and/or carbon mitigation strategies.

Key research goals in ecological and environmental science include

- quantifying current carbon sequestration potential in both managed and unmanaged ecosystems, including soils
- understanding the response of ecosystems to increased atmospheric concentrations of CO₂
- understanding how future changes in climate variables will affect ecosystems and their role in carbon cycling
- developing carbon cycle models to predict future carbon sequestration
- understanding how land use changes and land management options affect carbon storage and exchange
- developing biological productivity potentials to offset fossil fuel usage with biomass energy

3.2.6 Nuclear Sciences

From the birth of nuclear power to the present, the United States has been the technological and policy leader. U.S. technology has been exported and adapted for use throughout the world. U.S. nuclear plant technology is among

the safest and most reliable of nuclear technologies available worldwide.

Nuclear science and engineering is a discipline that is rapidly disappearing in the United States. If the United States is to maintain nuclear fission as an option for its future energy generation and is committed to avoiding additional carbon emissions, then a vital nuclear science basic research program is essential. It is likely that nuclear power will continue to be developed globally, with or without U.S. technology.

Research on nucleonics, new fission reactor concepts, proliferation-resistant technologies, fusion and fission-fusion hybrids, hybrid accelerator-driven subcritical systems, advanced fuel cycle technologies, advanced component design, waste transmutation (both accelerator and reactor based) and fast neutron burning, and systems safety are all vital to a successful industry in the future and to U.S. viability in this important area. In addition, research reactors form a vital component in this system and in our national research and educational infrastructure. They are essential and critical to many national priorities in addition to reducing carbon emissions, such as health care, environmental science and education, and technology transfer. Perhaps the most important goal of nuclear science is to improve the acceptance—by the public and by industry—of nuclear energy as a safe, reliable, and cost-effective resource for a sustainable future.

3.2.7 Computational Sciences

Advanced energy technologies with low carbon emissions can benefit greatly from modern simulation technology, particularly in the areas of combustion modeling, airborne

particulates, and global carbon cycle modeling. High-fidelity simulations of manufacturing and power generation operations and the distribution of gases resulting from internal combustion engines (Fig. 3.2) can be used to predict the behavior of pollutants in the atmosphere at scales ranging from a few rooms in a building all the way to global simulation of the buildup of GHGs. Process design and optimization using simulations including social and economic components can result in improved processes and reduced environmental impact, without the expense of trial-and-error experimental designs. These tools can aid development of advanced energy technologies by allowing advanced modeling and visualization where direct experimentation or prototyping is very expensive, inaccessible, or otherwise unfeasible.

Predictive modeling and simulation involves the use of the most advanced parallel computers—in speed, memory capacity, and I/O capability. By the

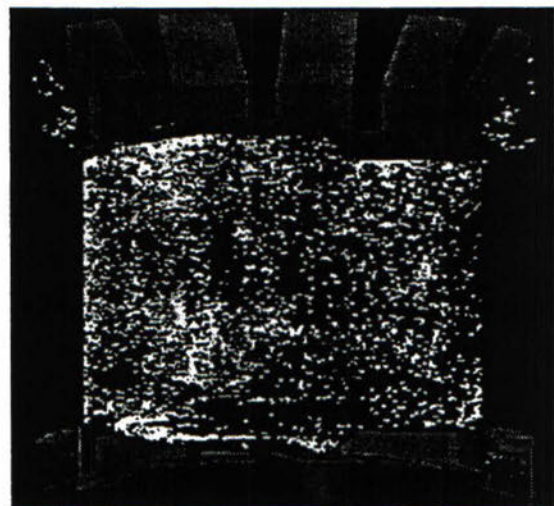


Fig. 3.2. This KIVA prototype 3-D simulation of an advanced diesel engine includes the regions where gas exchange and combustion occur. The simulation includes the flow of gases, heat transfer, combustion, and creation of pollutants.

year 2000, U.S. vendor systems will be capable of 10 thousand billion floating point operations per second. Advanced visualization and analysis techniques, including virtual reality, will be necessary for scientists and decision makers to understand the huge amounts of data generated by these simulations and to compare these simulations with observational and experimental data. Advanced network communications will allow the establishment of national and international collaborations, as well as enabling the remote operation of unique experimental facilities.

Effective use of this immense capability will require development of new mathematical models of relevant physical, biological, social, and economic processes; stable programming paradigms that support—over a decade or more—changing hardware capabilities; algorithms and computational techniques that can efficiently make use of parallel, distributed computing resources; software frameworks that allow rapid prototyping of new capabilities; and, perhaps most important, a verification and validation methodology that provides both qualitative and quantitative assurance of what can and cannot be predicted.

3.3 CROSSCUTTING TECHNOLOGIES SUPPORTING GREENHOUSE GAS REDUCTIONS

In addition to the broad portfolio of technological opportunities for reducing GHG emissions presented in Chap. 2, a number of technologies crosscut a wide range of applications, including those which impact U.S. carbon emissions. Advancing these enabling technologies integrates the pull of technology with the push of basic science.

This subsection presents four crosscutting technology areas: hydrogen and fuel cells; electrical transmission, distribution, and components; sensors and controls; and energy storage.

3.3.1 Hydrogen and Fuel Cells

Hydrogen is a carbon-free energy carrier that can be used to fuel every aspect of society. For example, it can fuel transportation vehicles (air and ground), provide process heat for industrial processes, supply domestic heating needs through cogeneration or heat recovery systems, and fuel power plants for centralized or distributed electrical generation (Fig. 3.3).

Hydrogen is an energy carrier that must be produced efficiently from a primary energy source. Depending on the source, its production may or may not involve CO₂ emissions. Hydrogen also burns cleanly and efficiently, an advantage that lowers the operating

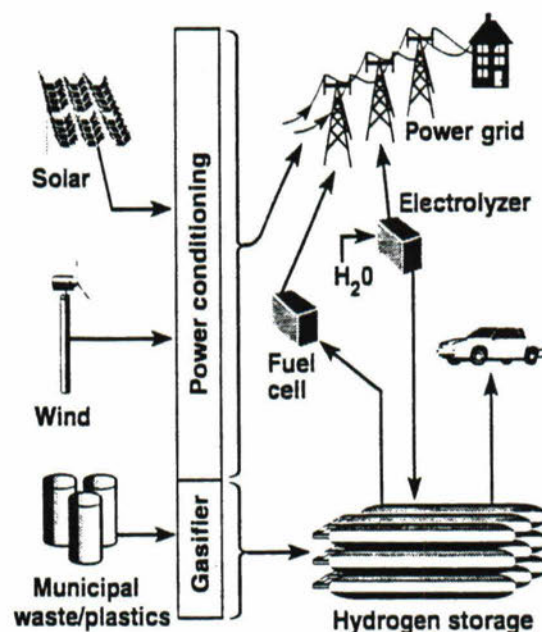


Fig. 3.3. Integrating utilities with the hydrogen transportation fuel system would enable greater penetration of renewables into the marketplace at a faster rate.

cost. Expanded production-related R&D is needed on biological, thermochemical, and electrochemical processes. Goals of the RD&D for production include a 10 ton/day process demonstration using municipal solid waste by 2000 and the development of advanced steam electrolysis, photobiological, and photoelectrochemical processes by 2010.

Hydrogen can be used in modified conventional combustion energy conversion devices (e.g., engines) to ease the transition to a completely new energy infrastructure where hydrogen will be used in fuel cells for energy conversion. Fuel cells promise potentially higher system efficiency and solid-state operation with water as the only effluent.

Lack of suitable hydrogen storage technologies is the greatest obstacle to its use as a transportation fuel. For 2000, the RD&D goals are to develop an automotive on-board hydrogen storage system capable of a 300 to 400 mile range and to demonstrate a fuel cell or hydrogen-powered internal combustion engine hybrid vehicle fleet with associated infrastructure. For 2010, the goals are to develop (1) advanced solid-state storage systems based upon such innovative materials as carbon fibers and structures and metal hydrides and (2) a conversion system for waste and biomass capable of producing hydrogen at a cost of \$10/GJ (lower heat value of hydrogen).

Fuel cells convert chemical energy directly into electrical energy; no combustion is involved. They are significantly more efficient than other power-generation technologies or internal combustion engines operating on conventional fuels. Individual cells produce less than 1 V and are stacked

in electrical series to produce higher voltages for utility, industrial, transportation, and residential use. Fuel cells span all important energy use sectors. Molten carbonate and phosphoric acid fuel cells target power generation, both large-scale and distributed power production. Solid-oxide fuel cells, which in stacks have recently reached the 100-kW size, are mostly considered for stationary application. Proton exchange membrane fuel cells target transportation as well as distributed power applications.

Key targets for R&D are materials and fabrication issues concerning the catalyst/electrode/membrane designs, as well as the cell stacking design. Future improvements in manufacturability will strive to reduce the currently high cost of fuel-cell fabrication to levels competitive with combustion devices.

3.3.2 Electrical Transmission, Distribution, and Components

Many proposed GHG reduction technologies involve alternative ways of producing electricity. In most cases, the U.S. electric transmission and distribution system is the means by which these alternative approaches will be made available to energy users. Almost 40% of the capital investment currently required to produce and deliver electricity goes to construct transmission and distribution facilities, and the availability of reasonably priced transmission capacity will be crucial in determining the commercial success of alternative generation strategies. This is particularly a concern for large-scale development of such remote resources as renewable generation, which could require significant investments in new transmission capacity because of the

distances between the best resource areas and load centers. At the same time, public opposition to the construction of conventional transmission lines for environmental reasons has focused attention on opportunities for increasing the capacity of existing corridors, as well as on development of transmission technologies that are compatible with public concerns and therefore present a minimum of permitting risk. In addition, the importance of other collateral benefits of these technologies cannot be overlooked, especially their contribution to improving power quality.

R&D is needed on automated system control technologies that better use the capacity of existing systems, as well as advanced composite-reinforced high-strength overhead line conductors to increase the capacity of individual lines. Developments in power electronics—including wide-bandgap semiconductors for high-power switching devices and advanced converter designs—are needed to improve power management on existing systems and to enable high-voltage DC transmission for long-distance power transfers.

Improvements in superconducting materials and associated refrigeration technologies will lead to development of superconducting cables and power transformers that offer half the energy losses and many times the capacity of conventional devices while taking up less space and reducing environmental impact.

While electrical transmission and distribution system improvements are essential to enable deployment of alternative electrical generating strategies, power system component development also offers significant opportunities to reduce GHG production. Energy losses in U.S. transmission and distribution systems

were 7.2% in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC of carbon emissions. Roughly 70% of these losses are due to the resistance of the conductors used on transmission and distribution lines, while 20% are in the distribution transformers used by utilities and commercial building owners to provide the last step of voltage reduction for customer equipment. In addition, the bulk of U.S. electricity production goes to drive motors—most commonly the ubiquitous polyphase induction motor, whose limited speed control reduces associated process efficiency by as much as 30%.

Research needed to improve the efficiency of power system components includes the development of superconducting generators, motors, and transmission cables, as well as low-cost methods for manufacturing amorphous metal materials for high-efficiency distribution transformers. R&D on advanced power electronic converters and controls for variable-speed motor drives, integrated with high-efficiency motors, could substantially improve industrial process efficiency and product quality.

3.3.3 Sensors and Controls

Sensors and controls will play a significant role in any technological advances for reducing CO₂ emissions and in CO₂ sequestration processes. Each primary area of clean energy production, energy efficiency, and carbon-cycle/carbon sequestration, will require sensors and controls technology for ensuring maximum efficiency at minimal cost.

R&D is needed to develop sensors that can improve the efficiency of primary energy production. For example, chemical sensors capable of operation in boreholes can improve fossil fuel

recovery. Both refining processes and fossil fuel reforming for CO₂ sequestration require substantial chemical processing that can be enhanced through real-time process sensors and controls. Sensors and controls that more accurately measure operational parameters can be used to increase the output of nuclear power plants.

In the area of energy efficiency, transportation remains a major factor in energy consumption. Novel sensors are needed to enable the use of more efficient engine technologies. Almost all industrial processes depend on sensors and controls to ensure the quality of goods produced, and advanced sensors can help to reduce wasted energy and thus CO₂ emissions. In carbon cycle/carbon sequestration, innovative sensors for analyzing photochemical processes and carbon fixation are needed. They may also be required for efficient biomass energy production.

Often a single fundamental sensor technology will meet the needs of different applications, so sensors are a true crosscutting technology. The best example is the solid-state oxygen sensor developed for the space program in the 1960s. This sensor is now universally used in gasoline engine control and is common in industrial combustion control, touching virtually every major energy-consuming industry.

A large variety of novel sensor technologies that are robust, sensitive, cost-effective, and capable of supporting real-time control will be required in a successful climate change technology development program, as will commensurate methods of data analysis and fusion for control. Across the industrial arena, sensors are needed that can be used in harsh environments and that will

measure such on-line process parameters as viscosity, moisture, chemical composition, density, flow, temperature, and pressure. Research is also needed in the development of multi-analyte sensors and in the integration of sensors and microtechnologies, such as microflow devices. Further RD&D is necessary in the development of "smart controllers" that couple a multitude of sensors and/or sensor arrays to sophisticated data analysis systems that can provide real-time on-line process control and improve process efficiencies.

3.3.4 Energy Storage

Stationary energy storage is now primarily in the form of bulk storage of fossil fuels (piles of coal, oil in tanks, gas in pipelines) and water in reservoirs. Reversible energy storage technologies in use today include pumped hydropower, compressed air, and chemical batteries for small uninterruptible power. Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), and purely electrical (ultracapacitors, superconducting magnetic storage). The major hurdle for all storage technologies is cost reduction.

In transportation, hybrid powertrains that use batteries, flywheels, or ultracapacitors in conjunction with engines allow the reduction of engine size. A hybrid powertrain can increase overall efficiency by up to 100% without a loss in vehicle performance (acceleration, range, and passenger capacity). When combined with other vehicle improvements, such as weight reductions, aerodynamic improvements, and rolling friction, this efficiency increase results in up to three times the equivalent mileage of

current direct-drive automobiles, which is the current goal of the PNGV.

Key R&D needs for energy storage include developing

- new electrocatalysts, electrode materials, and structural materials for electrochemical systems
- higher specific-energy composite rotors, magnetic bearings, fail-safe designs, and lightweight containment for flywheels
- better corrosion-resistant materials for higher power-density batteries
- commercial high-temperature superconductors (operating at liquid nitrogen temperatures) for superconducting magnetic energy systems
- higher energy-density ultracapacitors for light-duty vehicles
- improved power conditioning systems.

The greatest value of advanced energy storage for electric utilities is that it can enable better use of intermittent renewable energy sources, such as solar PVs and wind, that produce no direct CO₂.

3.4 REFERENCES

- Carbon Management: Fundamental Research Needs Assessment* 1997. (Draft), DOE-Office of Energy Research, August 6.
- R&D Magazine 1997. "Basic Research White Paper: Defining Our Path to the Future," *R&D Magazine*, A. Cahn's Publication, Des Plaines, Ill.
- 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.

4. TECHNOLOGY INNOVATION APPROACHES

4.1 INTRODUCTION

Previous chapters of this report identified a set of technology pathways that we believe offer the United States affordable options to reduce GHG emissions to sustainable levels. We have emphasized that R&D, both fundamental and applied, needs to be continued and/or initiated to advance the technologies identified within the pathways, thereby moving them closer to the goal of deployment in the marketplace. This section discusses three technology innovation approaches and presents several factors for consideration in deciding which approach to use to develop a particular technology. While each of the approaches provides a viable option; we believe that in most cases public-private strategic alliances are the best approach for developing and deploying these technologies.

4.2 APPROACHES

In this section, we evaluate the pros and cons of three approaches for advancing the RD&D of GHG reduction technologies. These approaches can be characterized as

- government led and financed
- industry led and financed
- public-private strategic alliances

Although we recommend public-private strategic alliances as the best approach for developing and deploying most of the technologies discussed in the technology pathways section, in some cases one of the other approaches may be more appropriate.

When selecting an approach to pursue the RD&D of a technology, we recommend the following factors be considered:

- national strategic value of the technology
- target market of the technology
- return on private-sector investment

A technology has *strategic value to the nation* when it provides a significant benefit to national security, economic well-being, environmental quality, and/or public health. National defense is the casebook example of high strategic value to the nation. Historically, the strategic value criterion has also been a justification for government support of technologies in the areas of space, health, energy, and agriculture.

The *target market* factor refers to the expected end-user or consumer of the technology. In some cases, a technology is developed for a specific target market or end-user (e.g., the federal government), and the technology has little application beyond that market. For example, technologies to process uranium have had little application beyond the nuclear industry. In other cases, a technology, such as the transistor, has applications in multiple markets and industries. Technologies that are applicable to a variety of markets and industry are sometimes referred to as "generic technologies" (Bloch 1991).

The third criterion refers to whether the private sector believes it can attain a large enough *return on its RD&D investment* within a reasonable time frame and at acceptable levels of risk to warrant supporting the innovation process. The complexity and the length of time needed to develop and deploy a technology are key variables considered by private industry when it

is deciding whether to invest in a technology, because both factors can increase the risk of not receiving the expected return on investment. Of the three factors presented, expected return on investment is the key factor companies consider when deciding whether to invest in the development of a technology. Although this factor is of primary importance to the private sector, it is not necessarily mutually exclusive from the national strategic value criterion. In many cases, companies have led and financed the development of technologies that have underpinned the formation of industries with a high strategic value to the nation (e.g., computer software, drug, and automobile industries).

The following sections discuss the characteristics and relationship among the three approaches to technology innovation in an effort to provide selection criteria for determining the optimum approach to achieving the RD&D goals for individual technologies (Table 4.1).

4.2.1 Government Led and Financed Approach

The government typically leads and finances projects throughout the RD&D process when a technological innovation has a high strategic value to the nation, the public sector is the intended end-user of the technology, and the expected return on investment is too low to warrant the private sector's

Table 4.1. Approaches to technological innovation

	National strategic value	Target market	Return on private sector investment
Government led and financed	High	Public sector	Low
Industry led and financed	Low-medium	Specific market	High
Public-private alliance	Medium-high	Multiple markets	Low-medium

bearing the RD&D costs (Table 4.1). Examples of projects led and financed primarily by the federal government include the Manhattan Project, which developed the atomic bomb in World War II, and the Apollo Project, which put a man on the moon in 1969. Government led and financed projects have been very successful in meeting their goals when the conditions warrant government leadership and it has been able to focus the best resources of the nation on solving a problem with clearly defined technological goals and large public benefits and support.

The government led and financed approach could be applied to reducing GHGs, but it contains some inherent barriers to full effectiveness. In contrast to the examples given earlier, the government is not the primary target market for GHG reduction technologies, and there is no single technological solution to stabilizing atmospheric concentrations of CO₂. Therefore, significant GHG reductions will be achieved only if a number of technologies penetrate a broad spectrum of commercial target markets. In addition, some of the GHG technologies will have economic benefits in reduced fuel use, higher productivity, and reduced waste generation. Therefore, we expect the private-sector return on investment in the innovation process to be at a sufficiently high level for some of the technologies to warrant private-sector RD&D cost sharing.

4.2.2 Industry Led and Financed Approach

The private sector typically leads and finances projects throughout the RD&D process when a technological innovation has a high potential return on investment from specific commercial markets, regardless of its

national strategic value. Historically, technological innovation leading to products for the commercial market has been primarily the responsibility of the private sector. Numerous examples exist of technology innovation led and financed primarily by industry, including plastics, pharmaceuticals, scientific instrumentation, information systems, and robotics. These technologies were driven by the demands of consumers in target markets, not by the federal government. Market-driven technology development is critical to continued economic growth because it enables companies, through the deployment of technological innovations, to profit by meeting the demands of consumers.

The strong relationship between technological development and quality of life in America in the twentieth century is a testament to the value of the industry led and financed approach to innovation. However, for this to be the primary approach for developing and deploying GHG reduction technologies, carbon mitigation would have to be highly valued in the marketplace to enable private companies to profit from their RD&D investments. Some technologies that result in GHG reduction may attract sufficient private-sector investment because they offer additional benefits that consumers are willing to pay for to amortize the RD&D costs and to provide adequate profits. However, short of policies that create a large economic incentive for reducing carbon emissions, industry is not likely to lead and finance RD&D on a broad spectrum of GHG reduction technologies.

4.2.3 Public-Private Strategic Alliances

Public-private alliances are typically established to share the costs of RD&D and deployment of technologies that

have a strategic value to the nation and have value for multiple markets and industries, but do not promise sufficient return on investment to motivate the private sector to bear all the RD&D costs. Many of the technology pathways for reducing GHGs have these characteristics, making public-private strategic alliances the optimum approach for promoting their development and deployment.

Numerous examples of public-private alliances exist, such as SEMATECH, PNGV, IOF, the International Energy Agency Greenhouse Gas R&D Programme, the Clean Coal Technology program, the Advanced Light Water Reactor program, and PVMaT. In the case of PNGV, technologies to increase the fuel efficiency of automobiles have a *high strategic value to the nation* because they reduce our consumption of oil, thereby increasing our economic and national security, and mitigate GHG emissions, thereby reducing global warming and improving the quality of the air we breathe. In addition to being deployed in the automobile industry, many of the technologies being developed by the PNGV consortia are likely to be deployed in *multiple markets*. For example, one of the goals of PNGV is to increase fuel economy threefold. In order to meet this goal the vehicle weight must be reduced 40%; therefore, a significant portion of the steel and cast iron components in these vehicles must be replaced with aluminum and polymer composites. These new lightweight, high-strength materials will be deployed in other transportation markets (e.g., aircraft and rail), as well as multiple segments of our infrastructure (e.g., bridges, buildings, energy). Finally, although the technologies being developed by PNGV have a high strategic value, the *market return* on fuel efficiency investments is currently very small

because the cost of gasoline in the United States has been decreasing at an average annual percentage rate of 1.8% (in constant dollars) since 1978.

The combination of high strategic value, multiple target markets, and expected low return on investment makes public-private strategic alliances the optimal approach for developing and deploying GHG reduction technologies. This approach will allow sharing of costs and pooling of resources, thereby motivating private companies to invest in the technology even though the return on investment is likely to be low in the short term, and encouraging government agencies to support the RD&D process even though the public sector may not be the targeted end-user of the technology.

The interactive nature of the innovation process is another reason to use public-private alliances to develop and deploy GHG reduction technologies. It is now widely recognized (Kline 1991; OTA 1995; Branscomb et al. 1997; *R&D Magazine* 1997) that most complex technological innovations advance through a nonlinear, interactive innovation process (Fig. 4.1), in which there is synergy between scientific research, technology development, and deployment activities. The interactive process is a more effective model for developing and deploying technology than the linear model that depicts the innovation process as starting with basic scientific research and then advancing sequentially through the technology development and deployment phases (Fig. 4.2). This linear approach can take longer and can result in potential innovations being delayed or never making it to the marketplace. The interactive process has several advantages in that it provides the following:

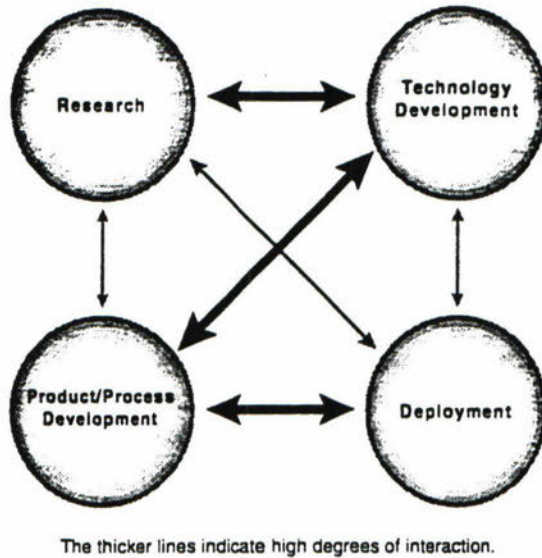


Fig. 4.1. Interactive model of innovation.

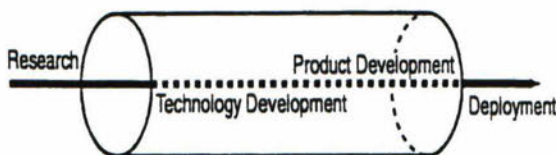


Fig. 4.2. Linear model of innovation.

- a continuous feedback loop for development and use of new scientific capabilities and facilities that can expedite the innovation cycle
- effective dialog between the research and user communities on innovation needs
- an effective basis for focusing research in the highest priority areas and evaluating progress along the technology pathways

4.3 STRATEGIC ALLIANCE ROLES

One of the major benefits of strategic alliances is that they help maximize the efficiency of the innovation process by bringing together an interdisciplinary team of scientists, engineers, and analysts (e.g., market, social, and financial) from industry, government laboratories, universities,

and nongovernment organizations who can ensure that the scientific, technical, and commercial challenges that arise throughout the innovation process are successfully resolved. We recognize that there will be many stakeholders in a climate change technology strategy and that over the course of time, some of the technology pathways will dramatically restructure the nation's energy, buildings, industrial, and transportation sectors. International customers and suppliers will be concerned about their costs and their markets. The financial community, insurance industry, and standards organizations all have a stake in the process; the list is long. Their input will be important for formulating effective public-private alliances, monitoring progress toward GHG reductions, and sustaining interest in the climate change technology strategy over the decades that will be required to implement it.

In many respects, the whole is greater than the sum of its parts in strategic alliances, for while private companies, universities, federal laboratories, government organizations, and nongovernment organizations each have unique capabilities, a synergy results when their resources are applied strategically toward a common goal, such as developing technologies to reduce GHG emissions. For example,

- Private companies and industrial consortia, such as the Electric Power Research Institute and the Gas Research Institute, play a key role in the innovation process by identifying requirements for technologies that help ensure their commercial viability, by performing R&D in collaboration with federal laboratories and universities, and eventually by demonstrating and deploying the technologies.

- Government laboratories and nongovernment research organizations provide scientific staff who have conducted and managed research for more than 50 years. These laboratories have conducted much of the research that provides the scientific underpinning for many technological breakthroughs. This scientific resource can provide new approaches to reducing emissions in the future. The national laboratories also provide unique facilities for use by researchers from industry and academia, as well as by their own researchers, in the development of these technologies.
- Universities provide a wealth of scientific talent to undertake the scientific research required to understand the role of GHGs in global climate change and to understand the basic mechanisms of biological and chemical processes that might be used to reduce GHG emissions. The linking of science and technology in the interactive process of innovation makes the scientific resources of universities and laboratories critical throughout the innovation process. In addition to providing scientific resources, universities are the training ground for future scientists and engineers needed for a sustained national effort to minimize the effect of GHGs on climate change.

Along with private companies, federal laboratories, and universities, it is important that government agencies, international organizations, and other nongovernmental organizations that are stakeholders in global climate change have a role in strategic alliances.

- Government agencies at the federal, state, and local levels contribute financial resources that are critical

for advances in scientific research and basic technologies, as well as legislative mechanisms that can play an important role in removing barriers to the deployment of climate change technologies. In addition, government institutions can help educate the American public about climate change and can provide a forum for stakeholders to express their views on this subject.

- Climate change is a global issue, and international collaborative RD&D efforts will be needed. Japan has recently announced a national program to support international R&D on technologies to mitigate global climate change and pollution. Other efforts involving the U.S. federal government and U.S. companies are under way (e.g., the International Energy Agency Greenhouse Gas R&D Programme).
- Nongovernment organizations, including end-users, environmental organizations, financial institutions, and other interest groups, possess expertise that can be valuable to scientists, engineers, and market analysts as they work to better understand climate change and market issues.

4.4 CONCLUSION

Three specific approaches for implementing RD&D and deployment activities on GHG technologies are considered: (1) government led and financed, (2) industry led and financed, and (3) public-private strategic alliances. In selecting an implementation approach, we encourage the consideration of three factors: strategic value to the nation, target market, and expected return on private-sector investment. A systematic assessment of the relationship between the technology being developed and the three implementation approaches

will allow selection of the optimum approach.

For most of the GHG emission reduction technologies discussed in this report, we believe that the public-private strategic alliance approach is the best choice. Although many of these technologies will be able to compete cost-effectively in the marketplace in the future, industry may not be willing to lead and finance the innovation process for many of these technologies 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. Additional factors favoring public-private strategic alliances include the *interactive nature* of the innovation process and the need to develop and deploy a variety of technologies in a number of target markets to reduce GHG emissions significantly. A public-private alliance will enhance the efficiency of the innovation process by bringing together stakeholders who can meet the scientific, technical, and commercial challenges involved in developing and deploying the required technologies. In this context, institutional efforts, such as collaborative RD&D enterprises, that help bring together industries, government laboratories, universities, government agencies, and nongovernment organizations to focus on common technological issues will be of great value in fostering the development of public-private alliances.

While public-private strategic alliances are only one part of the nation's climate change technology strategy, we feel they are a vital element if we hope to efficiently and effectively develop and deploy the GHG reduction technologies discussed in this report.

4.5 REFERENCES

- Bloch, Erich 1991. "Science and Technology: The False Dichotomy," *Powernomics: Economic and Strategy After the Cold War*, ed. Clyde Prestowitz Jr., Ronald Morse, and Alan Tonelson, Economic Strategy Institute, Washington, D.C.
- Branscomb, Lewis et al. 1997. *Investing in Innovation: Creating a Research and Innovation Policy That Works*, MIT Press, Cambridge, Mass., in press.
- Kline, Stephen 1991. "Styles of Innovation and Their Cultural Basis," *Chemtech*, 473-480, August.
- OTA (Office of Technology Assessment) 1995. *Innovation and Commercialization of Emerging Technologies*, U.S. Government Printing Office, OTA-BP-ITC-165, Washington, D.C., September.
- R&D Magazine 1997. "Basic Research White Paper: Defining Our Path to the Future," *R&D Magazine*, A. Cahners Publication, Des Plaines, Ill.

5. SYNTHESIS AND MOVING FORWARD

5.1 SYNTHESIS

In this report to Secretary of Energy Peña, the directors of 11 DOE national laboratories conclude that

1. 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.
2. Success will require the pursuit of multiple technology pathways, providing choices and flexibility for reducing GHG emissions.

One cost-effective strategy for reducing long-term GHG emissions while continuing economic growth is to develop and deploy a portfolio of new and improved technologies (as described in Chapter 2). Successful development of these technologies would require advances in many fields of basic science (as described in Chapter 3) along with strong public-private strategic alliances (as described in Chapter 4). Rapid and widespread deployment may also require the development and implementation of supportive programs and policies. The features of such programs and policies are not specified in this report.

5.1.1 The RD&D Path to Carbon Stabilization

Chapter 2 described the broad menu of technology pathways that could significantly reduce U.S. carbon emissions over the next three decades. If a vigorous, accelerated RD&D program were pursued, these pathways would enable the transformation of our nation's energy system. Given the breadth of technology options, this transformation could take place in an orderly fashion. Industry and consumers would be able to recover their investments in the nation's current energy infrastructure, while new energy and carbon sequestration technologies were gradually absorbed, as they became profitable, through the normal process of capital stock turnover.

By offering a technology-based, evolutionary—not revolutionary—path to a sustainable energy future, this report outlines the possibility of a transition that could be profitable to a wide array of potential constituents.

Over a 30-year planning horizon, implementing a climate change technology strategy could quickly expand the portfolio of options available for reducing U.S. GHG emissions. The three decades of this planning horizon appear to be distinct in terms of the dominant climate change technology opportunities.

- In the first decade, significant advances in energy efficiency technologies would reduce carbon emissions substantially by reducing the energy intensity (E/GDP) of the U.S. economy. Based on the five-laboratory study, the increased use of these technologies could offer energy-savings benefits that exceed their implementation costs (Interlaboratory Working Group 1997). Clean energy technologies would continue to gain market share, and carbon sequestration technologies could begin to emerge.
- Along with continued improvements in energy efficiency, research-based advances in clean energy technologies would begin to reduce the carbon intensity (C/E) of the U.S. energy economy significantly during the second decade. A wide range of renewable, fossil, and nuclear technologies could be introduced and widely deployed in this period. These clean energy options could begin to overshadow the impact of increased end-use efficiencies by the year 2030.
- 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. We assume that these would not be widely available until the 2020 to 2030 time frame; however, successful introduction earlier could result in significantly greater reductions in carbon emissions. Success in this technology area could enable the nation to continue its extensive use of fossil fuels without changing the climate.

This technological progression can be seen in Table 5.1, which summarizes the carbon reduction estimates of each of the nine technology areas described in Chapter 2. Estimates of carbon-saving potential are difficult because of the many factors that can affect the performance and market penetration of a new technology. Consistent with these uncertainties, the values shown in Table 5.1 are provided in five ranges from low to high.

These estimates of carbon reduction potential were made relative to the *Annual Energy Outlook 1998* reference (business-as-usual) case (EIA 1997). They assume an accelerated federal RD&D program and a continuation of current federal programs and policies. The estimates do not presume the creation of any new incentives. The carbon reduction estimates were made individually for each technology area; competition between technologies and other effects of one technology on the success of another were not fully considered.

Because of the uncertainties associated with the carbon impacts of each pathway and the complexities associated with aggregation across pathways, our estimate of the combined potential effects of all of the pathways has a wide range. In total, it is estimated that an accelerated RD&D effort could provide advanced

**Table 5.1. Potential reduction of U.S. carbon dioxide emissions
from nine technology areas**
(in MtC)

	2010	2020	2030
Energy efficiency			
Buildings	L/M	M/H	H
Industry	L/M	M/H	H
Transportation	M	H	H
Agriculture and forestry	L	L	L/M
Clean energy			
Fossil resource development	L	M/H	H
Fossil power generation	L	M	H
Nuclear energy ^a	L	M	H
Renewables	L/M	H	H
Carbon sequestration	NA	NA	NA

L = 0–25 MtC, L/M = 25–50 MtC, M = 50–75 MtC, M/H = 75–100 MtC, and H = 100+ MtC. Shaded areas show significant additions to the technology routes to reducing greenhouse gases. NA = Not applicable because the carbon reductions require policy changes.

^aThe 2020 and 2030 estimates for nuclear energy (M and H, respectively) are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010. By extending the operation of one-third to one-half of these plants, significant carbon emissions can be avoided.

technologies with the potential to reduce U.S. carbon emissions by 400 to 800 MtC/year in the year 2030. This represents a significant portion of the carbon emission reductions that may be targeted by the United States for 2030.

Table 5.1 and the discussions of each pathway in Chapter 2 also indicate that no single area or pathway can deliver sufficient GHG emission reductions; success will require pursuit of multiple technology pathways. The lower range of the estimated impact (400 MtC per year) could result from major technological advances and market success in several of the pathways. Achieving the upper range (800 MtC per year) would require technological breakthroughs and market success in a wider spectrum of pathways. This higher, more optimistic range is viewed as unlikely without also strengthening the policies and deployment programs that exist today. We did not attempt to quantify the potential reductions from a combination of accelerated RD&D

and more vigorous deployment programs, policies, and financial incentives. However, it is believed that such a combination could drive U.S. carbon emissions down much further than the 400 to 800 MtC range described in this report.

This report's estimates of carbon reduction potential are quite modest compared with the estimates produced by many other studies. The smaller overall impacts estimated by this report are due primarily to our focus on the potential of accelerated RD&D within the context of today's policies and programs.

The 1991 report by the Office of Technology Assessment titled *Changing by Degrees* (OTA 1991) analyzed the potential for energy efficiency to reduce carbon emissions by the year 2015, starting with the base year of 1987. Its "moderate" scenario results in a 15% rise in carbon emissions, from 1300 MtC/year of carbon in 1987 to 1500 MtC/year of

carbon in 2015 (compared with a business-as-usual forecast of 1900 MtC/year). Its "tough" scenario results in a 20% to 35% reduction in emissions relative to 1987 levels, or emissions levels of 850 to 1000 MtC/year of carbon in 2015.

Scenarios of U.S. Carbon Reductions by the Interlaboratory Working Group (1997) modeled three scenarios of carbon emissions in the year 2010 based on an array of assumptions about increased RD&D efforts, supporting policies, and deployment programs (see Chapter 1 for further details). The results were carbon reduction estimates of 120, 230, and 390 MtC in the year 2010. The most aggressive scenario reduces carbon emissions in 2010 to their levels in 1990 and reduces energy consumption in 2010 to 1997 levels.

Energy Innovations (1997) provides a third point of comparison. It estimates the levels of carbon emissions that are possible in 2010 and 2030 as the result of vigorous RD&D, deployment, and policies. It estimates that by 2010, carbon emissions could drop to a level that is 10% below emissions in 1990. By 2030, it suggests, carbon emissions could possibly be reduced to 728 MtC per year, which is almost half of the 1990 benchmark and well below the estimates provided in this report.

A fourth study by the National Academy of Sciences (NAS), *Policy Implications of Greenhouse Warming* (1992), identified a set of energy conservation technologies that would have either a positive economic return or a cost of less than \$2.50 per tonne of carbon. Altogether, NAS concluded that these technologies offer the potential to reduce carbon emissions by 463 million tonnes, with more than half of the reductions arising from cost-effective investments in building

energy efficiency. The NAS study characterized the current technological potential available at the time; thus it did not take into account stock turnover rates and other factors that prevent the instantaneous, full market penetration of technologies. Nor did it describe the role of RD&D in expanding future technology opportunities.

5.1.2 Factors Influencing GHG Reduction Potential

Many factors influence the ability of technology development efforts to reduce future U.S. GHG emissions. These include the magnitude of available R&D resources, technological risk, market size, stock turnover rates, and public acceptance issues. While this study has not attempted to analyze the effects of all of these various factors, it has compiled a considerable amount of information on them in its review of nearly 50 technology pathways. That information can be found in Appendix B, which includes a two-page description of each pathway that explains many of the factors.

Table 5.2 summarizes some of this information for technology areas grouped as energy efficiency, transportation fuels, electricity, and carbon sequestration. The table expands on the information in Table 5.1 in two ways. First, it includes information for those specific sectors and technologies that at this time appear to represent the largest potential carbon emission reductions over the 30-year planning period. For example, in the transportation sector, light-duty vehicles represent 58% of the CO₂ emissions in the transportation sector. Therefore, one entry in Table 5.2 summarizes information for the two technology pathways that address light-duty vehicles:

(1) advanced conventional technologies for light-duty vehicles and (2) hybrid, battery-electric, and fuel cell vehicles.

Second, Table 5.2 provides information on several of the key factors that will influence future carbon emission reductions. This includes a column listing some of the significant issues or opportunities that will impede or enable the realization of potential carbon reductions. These issues and opportunities are selected from a more comprehensive accounting in Appendix B.

Altogether, Table 5.2 provides the reader with an indication of the most important results of this study in the form of the sectors and technologies that can play the largest role, as well as the factors and considerations that will determine their future contributions to GHG emission reductions.

The key factors that are used in Table 5.2 are defined as follows:

- Total market size: current total market in terms of carbon emissions (MtC/year) that is relevant to the technology
- Turnover rate: rate of retirement of the current stock of energy equipment or systems displaceable by this technology, with
 - “Fast” corresponding to less than 10 years average lifetime
 - “Moderate” corresponding to 11 to 20 years average lifetime
 - “Slow” corresponding to greater than 20 years average lifetime
- Estimates of carbon emissions reductions: best estimate of the carbon emissions reductions (in MtC/year) that are likely to be achieved given this accelerated RD&D effort and continuing

government deployment programs and policies. The estimates are based on the overall market size, the stock turnover rate, some consideration of the expected competitive position of the technology, and so on. For energy efficiency and clean energy technologies, the estimates assume no new fiscal incentives such as a carbon charge. See Sect. 2.1.2 for a more complete description of the study's assumptions. The entries are defined as follows:

“High” corresponding to
>100 MtC/year

“Medium” corresponding to
50 to 100 MtC/year

“Low” corresponding to
0 to 50 MtC/year

- Technological risk: subjective estimate of the risk that the technology will not be developed to the point that it can compete in its market as expected with
 - “High” reflecting research that is still at the basic sciences level or involves complex systems integration
 - “Moderate” reflecting research that is currently at both the basic research and technology prototype level
 - “Low” reflecting development activities for technologies at the prototype or more advanced stage
- Significant issues or opportunities: illustrative major factors particularly noteworthy for this technology

The estimates of potential GHG reductions shown in Table 5.2 are consistent with the conclusions that were offered in conjunction with Table 5.1; that is, substantial reductions are available by 2030, and many technology areas can be

Table 5.2. Potential reduction of U.S. carbon dioxide emissions from selected sectors and technology pathways

Sector/area ^a	Technologies	Market size (MtC in 1995) ^b	Turnover rate	Estimated carbon emission reductions ^c			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Efficiency— Buildings (1)		489	Mod	L/M	M/H	H	Lo	• minimal private sector R&D • slow adoption of innovations • CFC ban accelerates chiller turnover
	Building Equipment and Appliances (1.1)	489	Mod to Fast	L/M	L/M	L/M	Lo	
Efficiency— Industry (2)		463	Mod	L/M	M/H	H	Med	• short payback periods required • pollution prevention often saves energy
	Industrial Energy Conversion (2.1)	463	Mod	L	L/M	L/M	Med	
Efficiency— Transportation (3)		457	Mod	M	H	H	Med	• cost of lightweight materials • consumer preference for power and size over high mpg
	Light-Duty Vehicles (includes trucks through class 6) (3.1 and 3.3)	265	Mod	L/M	M/H	H	Med to High	
Transportation fuels (5.2 and 8.7)		457	Fast	L	L/M	L/M	Med	• distribution infrastructure barriers • limited stocks at competitive prices
	Biomass Fuels (8.7)	457	Fast	L	L/M	L/M	Med	
Electricity— Fossil (6)		494	Slow	L	M	H	Med	• large domestic coal resources
	Accelerated Development of High-Efficiency Power Generation (6.1)	494	Mod	L	L/M	M/H	Lo	
Electricity— Nuclear ^d (7)		494	Slow	L	M	H	Med	• public acceptance • nuclear waste storage • competition with natural gas
	Lifetime Extension and Generation Optimization (7.1)	113	Mod	L	L/M	M/H	Lo	

Table 5.2. (continued)

Sector/area ^a	Technologies	Market size (MtC in 1995) ^b	Turnover rate	Estimated carbon emission reductions ^c			Technical risk	Significant issues and opportunities
				2010	2020	2030		
Electricity— Renewables (8)		494	Slow	L/M	H	H	Med	• competition with natural gas • large domestic resources • biomass resource limitations at competitive prices • price penalty for intermittent power
	Biomass Electric (8.1)	494	Mod	L	L	L/M	Lo	
	Wind and Photovoltaics (8.2, 8.4)	247	Slow	L	L/M	M	Med	
Carbon Sequestration (9)		>6200	NA	NA	NA	NA	High	• small potential impact without regulations, incentives, or growth in markets for CO₂ • extends fossil fuel use • ecological risk • stability of clathrates and hydrates • diffusivity of CO₂ in the ocean • permanency
	Enhanced Carbon Cycle (4.3, 9.1, 9.4)	>6200	NA	NA	NA	NA	High	
	Capture and Sequestration (9.2, 9.3, 9.4, 9.5, 9.6)	1400	NA	NA	NA	NA	High	

NA=not applicable because the carbon reductions require policy changes. The carbon sequestration pathways could enable the nation to continue its extensive use of fossil fuels without changing the climate.

^aTechnology pathways identified in () are cross-referenced to Table 2.1

^bThe technologies and sectors shown in this table overlap in terms of the carbon reductions they can deliver. For instance, decarbonization of the electricity sector through the introduction of clean energy technologies will reduce the potential carbon reductions from end-use sector efficiency technologies. As a result, it is not valid to simply add either the market size or the carbon reduction estimates.

^cL=0–25 MtC, L/M=25–50 MtC, M=50–75 MtC, M/H=75–100, and H=100+ MtC. These estimates assume an enhanced federal RD&D program aimed at developing GHG reduction technologies. They do not presume the creation of any new financial incentives for reducing carbon emissions. The technologies covered in this table could deliver even greater GHG reductions if incentives, such as a carbon emissions trading program, or more vigorous deployment programs and policies, were implemented.

^dEstimated carbon emission reductions are relative to the reference case in the *Annual Energy Outlook 1998* (EIA 1997), extended to 2020 and 2030 by extrapolating current carbon emission growth rates. The exceptions are the 2020 and 2030 estimates for nuclear energy (M and H, respectively). These are relative to an adjusted reference case forecast, which takes into account the large capacity of nuclear power scheduled for retirement after 2010.

contributing to these savings at that point.

Table 5.2 also shows that technology areas face different challenges, opportunities, and issues. Many of the technology issues can be addressed by the technology RD&D outlined in this report.

Technical risks are low to moderate in each of the energy efficiency areas and especially in the buildings sector. Counterbalancing this advantage in terms of delivering carbon impacts is the low level of private-sector R&D, the slow pace of adoption of innovations by builders, and the moderate rate of stock turnover in the buildings sector. The transportation and industrial sectors face generally moderate levels of technical risk. In transportation, economic risk is increased by consumer preferences for power and size over efficiency; and in industry, economic risk results from high discount rates that impede investments in efficient equipment.

Many of the clean energy options for generating electricity are threatened by the uncertainty of utility industry restructuring and competition with inexpensive natural gas combined-cycle technology. Nuclear power also has the additional institutional risks of a long-term waste repository solution and concerns over proliferation.

Carbon sequestration technologies face high technical risks because of the exploratory stage of their development. In addition, environmental and economic issues need to be resolved. However, these technologies hold the potential to extend the continued use of fossil fuel.

In most cases, risk can be reduced by technology and basic research programs that include analysis of

economic and social consequences. Modeling tools and analyses are needed to complement the technology RD&D process to assess the potential acceptance of developmental technologies, identify likely concerns, and develop mechanisms to address those concerns. Such efforts to understand the social and economic risks are critical.

5.1.3 The Time-Line of Technology Products

Consistent with the notion of an orderly technology evolution, the products of a vigorous RD&D program to develop GHG reduction technologies could be adopted and implemented in time frames that mirror the typical pace of capital stock turnover. As a result, improvements in energy efficiency, clean energy, or carbon sequestration technologies would typically be available long before their impact on carbon emissions could be discerned. Thus, it is useful to forecast when different incremental improvements and breakthrough technologies will be available as cost-effective alternatives, recognizing that many years will typically be required before they are mature technologies.

Figures 5.1 and 5.2 present time lines of selected technology products. They illustrate the steady stream of important accomplishments that the vigorous RD&D program could produce. (Many more technology products are identified in Appendix B.) The technology products shown in these figures are consistent with the trend in carbon savings from energy efficiency gains in the first decade, to significant contributions by a variety of clean energy technologies in the second decade, followed by the emergence of carbon sequestration technologies in the third decade.

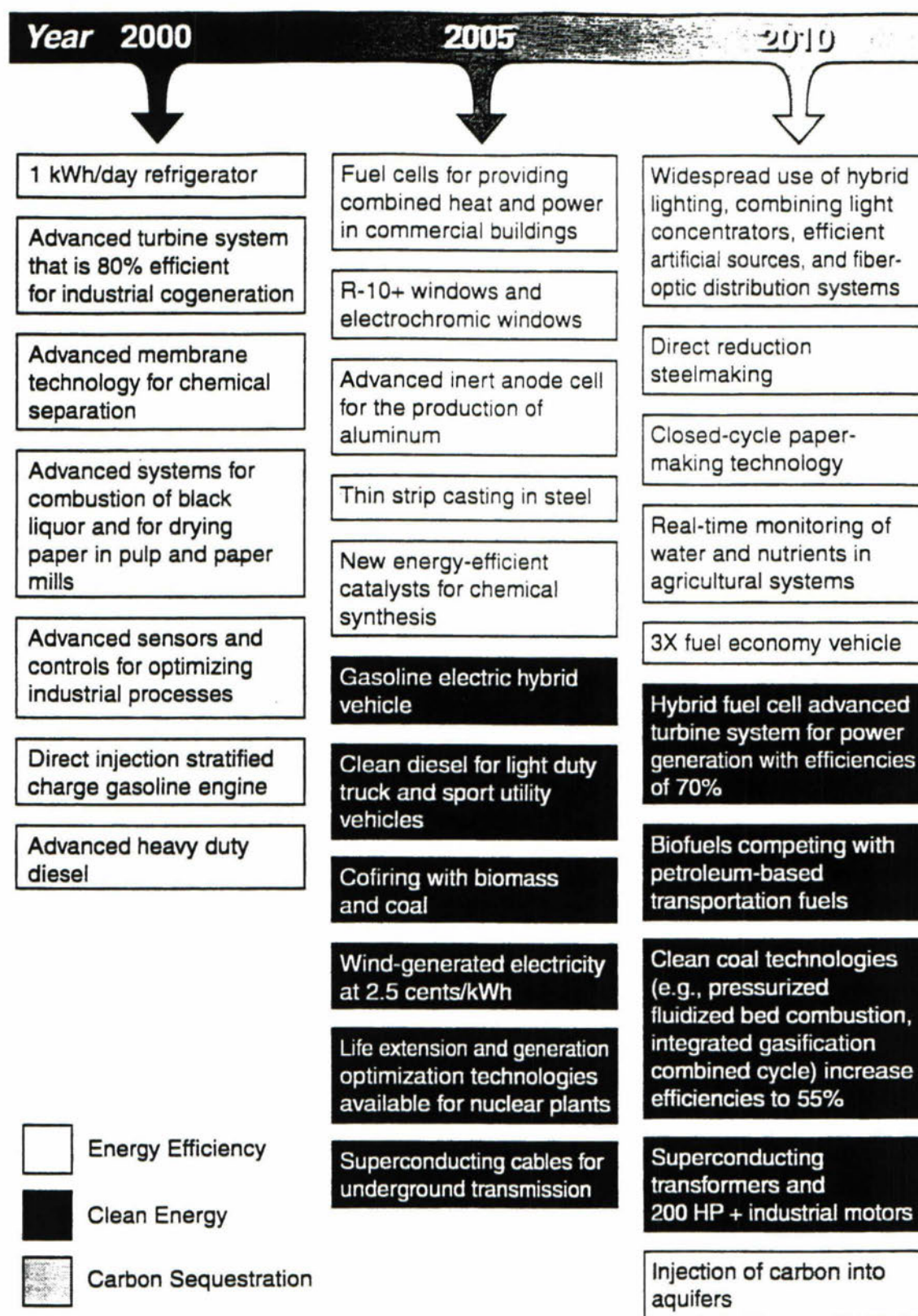


Fig. 5.1. Illustrative time-line of anticipated technology products: 2000–2010.

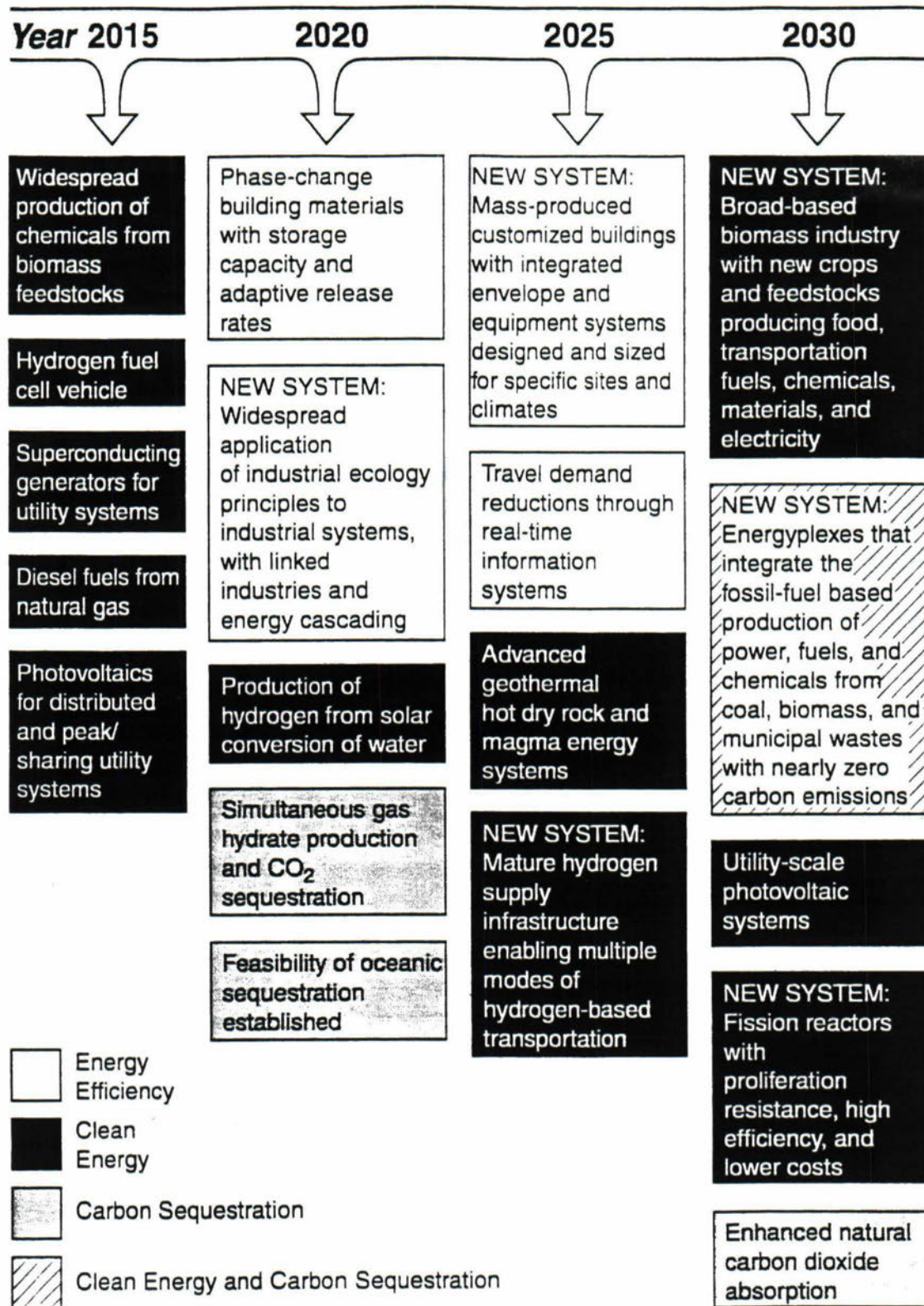


Fig. 5.2. Illustrative time-line of anticipated technology products: 2015-2030.

A second trend illustrated in these figures is the transition from the development of individual components to the emergence of novel, integrated systems. Over the next two decades, many components will be designed and engineered that can be woven into existing technology and capital infrastructures to improve their performance while reducing carbon emissions. Ultimately, these components will overhaul many of the systems that exist today. Such orderly sequencing of component development, with the ultimate goal of creating entirely new systems, can minimize the costs of capital displacement and economic disequilibrium. Two examples are provided below.

- The gasoline/electric hybrid vehicle (envisioned for development before 2005) is a precursor to the hydrogen fuel cell vehicle, which could be available by 2015. Following breakthroughs in hydrogen production, such as the manufacture of hydrogen from the solar conversion of water (perhaps by 2020), we envision a transformed transportation system by 2025 with a mature hydrogen supply infrastructure fueling multiple modes of transportation
- By 2010, we envision that biofuels could be cost-competitive with transportation fuels and that they could be distributed by the existing infrastructure of filling stations (worth hundreds of billions of dollars) with only modest modifications. By 2015, RD&D could enable the widespread production of chemicals from biomass feedstocks. Ultimately, 2030 could see a broad-based biomass industry with new crops, feedstocks, and distribution systems producing food, transportation fuels, chemicals,

materials, and electricity, and possibly an entirely new distribution system at the wholesale and retail levels

The two examples illustrate the need for pursuing multiple technology pathways in critical areas (e.g., for alternative transportation fuels), because the success of any single pathway cannot be guaranteed. In addition, no single pathway appears able to deliver the amount of GHG reductions that may be needed.

Figures 5.1 and 5.2 portray a possible time line for the commercial introduction of new technology. The technologies themselves will endure much longer than the 30-year horizon indicates. They will become the legacy of the technology strategy that eventually is followed. With many of these technologies is an infrastructure and a whole economic system. Just as the introduction of the mass-produced Model-T Ford and the interstate highway system transformed transportation, these technologies will have comparable enduring effects.

Of course, RD&D programs by their very nature cannot guarantee that anticipated outcomes will result. Many technical and market risks prevent laudable efforts from producing successful technologies. However, there will also be important technological successes not foreseen at this time. If we invest in a portfolio of RD&D activities, historic data indicate that the winners will more than compensate for the cost of the failures (Brown 1997).

5.1.4 Performance Goals

Another way of viewing the products of the proposed technology pathways is by specifying performance goals they

could achieve. These goals do not rely on particular technology developments; rather, they specify performance criteria that could be met by many alternative technologies. Recommended goals are presented, along with some of the technologies that could contribute to meeting 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 the 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 IGCC 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 the use of sources with higher generating efficiencies and lower emissions—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 GHGs 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

- Sequester CO₂ in large-capacity geological formations in deep oceans.
- Efficiently remove CO₂ from combustion emissions before they reach the atmosphere.
- Increase the rate at which oceans, forests, and soils naturally absorb atmospheric CO₂.
- Develop carbon storage technologies sufficient for geologic times.

5.1.5 Basic and Applied Research Are Needed

Meeting the goals described above also depends upon incremental improvements and breakthroughs in the basic sciences. These basic research needs include

- basic research 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

- basic research supporting GHG reduction technologies (i.e., materials, chemical sciences, biotechnology, environmental and ecological sciences, geosciences, nuclear sciences, and computational sciences)

To support multiple technology pathways, enabling technologies also must be improved, especially those that enhance the utilization of energy carriers and systems. Relevant enabling technologies include

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

5.1.6 Collateral Benefits and Costs

In addition to the benefits of GHG avoidance, the technology pathways described in this report could have significant secondary effects, as such pathways have in the past. For example, in the buildings area, there is a remarkable record of success in federally supported RD&D leading to products in the marketplace that have generated energy savings far exceeding their costs of development. In addition to reducing energy costs, the pathways would lead to improved environmental quality and public health, reduced U.S. dependence on imported oil, and increased exports of U.S. technologies to help other nations reduce GHG emissions, all of which will sustain economic growth.

The environmental and public health benefits of new and improved GHG reduction technologies could be very large. Clean energy options for generating electricity offer the prospect

of significantly reducing air pollution. The development of efficient low-carbon transportation fuels would reduce pollutant emissions and abate ground-level ozone. Pollution prevention and waste minimization are important hallmarks of improved industrial process efficiencies. These collateral benefits would lead directly to major improvements in public health (Romm and Ervin 1996).

These environmental and public health benefits would not be limited to the United States. Better technology options would help to control the GHG emissions of other countries for many decades to come. They could also position the United States as the provider of choice for these new energy and environmental systems, with major economic growth consequences. The global energy market is estimated at \$1 trillion, and the market for environmental technologies is estimated to be

\$400 billion. Renewable resources are widespread around the world, are highly attractive to developing countries, and represent a huge potential market for U.S. companies. An important collateral benefit of continued pursuit of nuclear power is the economic benefit of serving as an international supplier. The increased use of nuclear energy is foreseen around the developing world, especially in the Pacific Rim countries. The international market for ATSS and fuel cells is also likely to grow rapidly. Thus, implementation of a technology strategy would help to grow the U.S. economy by creating an energy technology export business.

The reductions in petroleum use that would result from the technology pathways would cut U.S. oil import dependence and could lower oil prices to consumers (Interlaboratory Working Group 1997, p. 5.47). It is estimated

that efficiency improvements and alternative fuels in the transportation sector could result in reductions of one billion barrels per year by 2010.

Some of the pathways might also spawn significant collateral costs. For instance, increased nuclear waste might result in negative environmental repercussions, large-scale biomass production might cause soil and water contamination, and ocean fertilization might precipitate ecosystem damage. Regions that flourish in today's energy economy might be negatively impacted by shifts in the resource and labor requirements of new energy systems. The workplace requirements associated with advanced energy technologies might strain the nation's capacity to train and educate its labor force. History has shown that such challenges often can be managed. Further, if multiple pathways are pursued, those judged unacceptable can be set aside in favor of those that are preferred.

5.1.7 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 GHG 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. However, to be consistent with the technology RD&D focus on this study, we have estimated the magnitude of only the associated technology RD&D resources, excluding deployment program or policy costs.

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

- The annual federal RD&D budget for the development of advanced energy technologies would need to grow to produce a sufficient number of the technological solutions.
- Additional resources are needed to initiate research into carbon sequestration technologies, which would also require supporting research on carbon cycle modeling, monitoring, and ecosystems.
- Supplemental RD&D support is needed to strengthen the basic research areas that are the wellspring of future technological breakthroughs.

Development of the full portfolio of technologies described in this study is estimated to require additional federal resources in the range of \$1.5 billion to \$2 billion. This is a preliminary estimate; actual budget decisions should be based on more detailed planning and analysis than was possible during development of this report. Initiation of that analysis and planning, which is a primary recommendation for moving forward, is discussed further in Sect. 5.2. It is anticipated that additional private-sector research effort would be leveraged by this federal increment.

There are three additional important points regarding these budget increments:

- Actual budgets should be ramped up over several years in a way consistent with sound program development.

- The necessary federal funding for most of the technology areas is seen as declining back to current levels by the third decade of the next century. The exception is carbon sequestration, which would likely require increasing budgets over the three decades as exploratory research in early years is translated into technology development activities.
- Resource requirements for the outyears obviously would be affected by developments between now and then, so these estimates are primarily valuable as preliminary indications of overall resource needs.

5.2 MOVING FORWARD

This report identifies in general terms a set of future technologies that appear to hold great promise for reducing U.S. GHG emissions. By summarizing the status and potential of a broad range of technologies relevant to reducing GHG 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, including

- an assessment of alternative programs and policies to promote deployment
- analysis of the costs and benefits of alternative technology and policy options to develop priorities
- development of technology goals and performance metrics for measuring progress
- identification of key players for pursuing these promising technology pathways
- estimation of budget requirements and appropriate allocation for each technology pathway
- mechanisms for ensuring strong ties between technology development

- activities and supporting basic sciences
- delineation of public- and private-sector responsibilities
- linkages to related ongoing activities in the United States and abroad
- a plan for managing the technology RD&D programs to be pursued over the years and decades ahead

The strong recommendation of this report is that the United States should develop and pursue a detailed and comprehensive climate change technology strategy.

Further, the planning process should begin immediately, and implementation of the strategy should occur quickly.

As the federal agency with the most involvement in the full range of technologies described in this report, the U.S. DOE should initiate and lead the planning required for implementation of this strategy. However, that planning effort must include significant participation from industry and business, the university community, Congress, and other federal agencies, as well as DOE and the national laboratories. Indeed, this planning should be a collaborative effort, just as is recommended for implementation of the technology RD&D programs.

While not all of the details of this planning and strategy implementation can be defined here, two clear needs should be explicitly addressed. The first is establishing a collaborative national planning effort to provide leadership and guidance to meet the RD&D challenges of a climate change technology strategy. The second is initiating an analysis activity to provide the information necessary for making sound decisions on the issues indicated. Both of these steps should be taken immediately.

Several other issues deserve immediate attention. One of these is the connection between developing promising technology pathways and designing policies to promote their deployment. There are many tradeoffs among how fast one pushes development, how much emphasis is placed on deployment of technologies that are ready to contribute to reduced emissions, and the timetable for achieving different reduced emission levels.

Another issue requiring study is the relationship between the implementation of promising technology pathways and the phenomenon of climate change, as well as the need for a better understanding of the phenomenon itself. This report strongly endorses the need to continue to improve our understanding of GHG emission levels, atmospheric concentrations of GHGs, climate change, and their impacts on our biosphere. A science-based understanding of the carbon cycle is essential as a framework for guiding our technology investments and ensuring their cost-effectiveness.

A third issue is consideration of the organizational structure of the technology RD&D programs. The recommendation to use strategic alliances recognizes the need to move away from the technology partnerships of the past. While there is no single organizational structure for creating strategic alliances, the traditional roles of users, industry, federal agencies, universities, states, national laboratories, and not-for-profit organizations may require redefinition as strategic alliances are formed to develop and deploy climate change technologies. Flexibility and adaptability in the structure of these partnerships is critical to the most effective pursuit of technology

development programs to reduce GHG emissions.

A fourth issue is that of relating and coupling this domestic technology strategy with related international GHG emission reduction efforts. International collaboration can provide important domestic savings and global benefits.

Finally, it is important to understand the consequences of not developing and pursuing a technology strategy. Perhaps one of the greatest risks is underestimating the magnitude of the impact we are attempting to achieve. Energy is central to development and modern civilization. We are talking about transforming a national and global infrastructure that currently includes all of the things that support combustion as a means of energy generation. This is not a trivial matter. The generation of CO₂ is embedded deeply in the social infrastructure of this nation and is being embedded in the developing world right now.

The availability of advanced technologies on a timely basis to address future GHG emission reduction commitments requires initiation of the RD&D now and a commitment to following through on all the pathways that continue to show promise. Technologies not pursued are likely to result in lost opportunities to apply them to mitigating climate change, as well as a loss of their collateral benefits.

5.3 CONCLUSION

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 GHG emissions well into the

twenty-second century. Many technology opportunities exist that could accomplish this goal without harming the nation's economy. A strategic plan that includes deployment policies to complement technology R&D will be necessary for success. Hence, development of a climate change technology strategy is the recommended next step. Based on the conclusions of this report, the strategy should specify an approach that pursues multiple technology pathways, that emphasizes public-private strategic alliances, and that is designed in close coordination with supportive government policies and deployment programs.

By delivering a portfolio of highly promising technologies, a climate change technology strategy could produce savings and revenues that far exceed the cost of an accelerated research program. The bottom line: with the help of technology and appropriate government programs and policies, we can slow GHG emissions and grow the economy. DOE's national laboratories stand ready to champion this enterprise.

5.4 REFERENCES

- Brown, M. A. 1997. "Performance Metrics for a Technology Commercialization Program," *Int. J. of Technology Management*, 13 (3): 229-244.
- EIA (Energy Information Administration) 1997. *Annual Energy Outlook 1998: With Projections to 2020*, U.S. Department of Energy, Washington D.C., December.
- Energy Innovations 1997. *Energy Innovations: A Prosperous Path to a Clean Environment*, Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, and Union of Concerned Scientists, Washington, D.C.
- Interlaboratory Working Group 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, September.
- NAS (National Academy of Sciences) 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, National Academy Press, Washington, D.C.
- OTA (Office of Technology Assessment) 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-0-482, U.S. Government Printing Office, Washington, D.C., February.
- Romm, J. J., and C. A. Ervin 1996. "How Energy Policies Affect Public Health," *Public Health Reports* 5, 390-399.

Appendix A Contributors

The following are the principal DOE National Laboratory staff participating in the committees and working groups supporting the development of this report. Many other individuals in the federal and private sector contributed but are not acknowledged here.

COORDINATING COMMITTEE

Stanley R. Bull, NREL, Co-chair
David E. Reichle, ORNL, Co-chair
William M. Babiuch, NREL
Arnold B. Baker, SNL
Lynn L. Billman, NREL
Eldon C. Boes, NREL
Marilyn A. Brown, ORNL
Brenda W. Campbell, ORNL
Michael P. Farrell, ORNL
Robert San Martin, DOE Liaison
John Sheffield, ORNL
Walter D. Short, NREL

EDITORIAL SUPPORT GROUP

Deborah M. Counce, ORNL

Vickie L. Beets, ORNL
Judy H. Benton, ORNL
Judy H. Campbell, ORNL
Vickie L. Conner, ORNL
Walter S. Koncinski, ORNL
Carolyn H. Krause, ORNL
Sandra C. Lyttle, ORNL
Jamie P. Payne, ORNL
Brenda Barlow, Lockheed Martin Energy Systems
Gloria Llanos, Temp Systems
Mary E. Marshburn, CDI
Linda O'Hara, CDI

LAB REPRESENTATIVES AND ALTERNATES

Dan E. Arvizu, SNL
Arnold B. Baker, SNL
Stanley R. Bull, NREL
Lynn L. Billman, NREL
David Cauffman, INEEL
Melinda A. Hamilton, INEEL
Harvey Drucker, ANL
David J. Hill, ANL
James M. Ekmann, FETC
Charles E. Schmidt, FETC
Mark D. Levine, LBNL
Donald F. Grether, LBNL
Leonard Newman, BNL
James W. Davenport, BNL
David E. Reichle, ORNL
John Sheffield, ORNL
Alfred P. Sattelberger, LANL
Edward L. Joyce, LANL
Robert N. Schock, LLNL
Anthony K. Chargin/Jill L. Watz,
LLNL
Gerald M. Stokes, PNNL
John F. Clarke, PNNL

WORKING GROUPS

Buildings

Mark D. Levine, LBNL, Chair
John W. Andrews, BNL
Douglas Balcomb, NREL
James D. Cavallo, ANL
George E. Courville, ORNL
Richard Diamond, LBNL
Donald F. Grether, LBNL
Jeffrey P. Harris, LBNL
Jeffrey A. Johnson, PNNL
Ronald Judkoff, NREL
Marion L. Scott, LANL

Industry

Alan P. Sylwester, SNL, Chair
Dan E. Arvizu, SNL
Donald G. Foster, LBNL
Thomas D. Foust, INEEL
Michael J. Furey, BNL
Bim Gupta, NREL
Edward L. Joyce, LANL

Jeff S. Logan, PNNL
Mildred B. Perry, FETC
Anthony C. Schaffhauser, ORNL
Jill L. Watz, LLNL

Transportation

David E. Reichle/E. Kaye Johnson,
ORNL, Chair
Basil A. Barna, INEEL
Larry S. Blair, LANL
Barbara Joan Goodman, NREL
Donald F. Grether, LBNL
Larry R. Johnson, ANL
Jeff S. Logan, PNNL
William J. McLean, SNL
Steven E. Plotkin, ANL
Frank J. Tokarz, LLNL
James E. Wegrzyn, BNL

Agriculture and Forestry

David P. Cauffman, INEEL, Chair
Helena L. Chum, NREL
Arthur B. Denison, INEEL
James R. Frank, ANL
Robin L. Graham, ORNL
Melinda A. Hamilton, INEEL
George R. Hendrey, BNL
Sheridan C. Johnston, SNL
Willy R. Makundi, LBNL
Gene Peterson, NREL
Norman J. Rosenberg, PNNL
Michael J. Scott, PNNL
Pat J. Unkefer, LANL

Fossil Resource Development

Robert J. Hanold, LANL, Chair
Greg A. Bala, INEEL
Edward L. Joyce, LANL
Ann F. Meinhold, BNL
Larry R. Myer, LBNL
David A. Northrop, SNL
John Reynolds, LLNL
Alfred P. Sattelberger, LANL
Tom W. Schmidt, ORNL
Alan M. Wolsky, ANL
Albert B. Yost II, FETC

Fossil Power Generation

James M. Ekmann, FETC, Chair
William A. Apel, INEEL
Steven R. Booth, LANL

Nancy J. Brown, LBNL
 Kevin R. Craig, NREL
 Robert E. Hall, BNL
 Donald R. Hardesty, SNL
 Roddie R. Judkins, ORNL
 Brady D. Lee, INEEL
 Dave K. Schmalzer, ANL
 Charles E. Schmidt, FETC

Nuclear Energy

Harvey Drucker, ANL, Chair
 William A. Barletta, LBNL
 Steven G. Hauser, NREL
 David J. Hill, ANL
 John R. Ireland, LANL
 Peter Klemkowsky, FETC
 Jim Lake, INEEL
 Gordon E. Michaels, ORNL
 Nestor R. Ortiz, SNL
 Trevor Pratt, BNL
 Keith I. Thomassen, LLNL

Renewables

Stanley R. Bull/Lynn L. Billman,
 NREL, Chair
 Marilyn A. Brown, ORNL
 Sue Jacobsen Goff, LANL
 Philip M. Goldberg, FETC
 Paul Kasameyer, LLNL
 Paul C. Klimas, SNL
 Chris Marnay, LBNL
 Paul D. Moskowitz, BNL
 Joel L. Renner, INEEL
 William W. Schertz, ANL

Carbon Management and Sequestration

Gerald M. Stokes, PNNL, Chair
 Sally M. Benson, LBNL
 David J. Borns, SNL
 Helena L. Chum, NREL
 John F. Clarke, PNNL
 Richard D. Doctor, ANL
 LaMar J. Johnson, INEEL
 Edward L. Joyce, LANL

Gregg H. Marland, ORNL
 John A. Ruether, FETC
 Meyer Steinberg, BNL
 Jill L. Watz, LLNL

Basic Research

Leonard Newman, BNL, Chair
 Joel W. Ager, LBNL
 Mark Alper, LBNL
 Anthony K. Chargin, LLNL
 John F. Clarke, PNNL
 James W. Davenport, BNL
 Deb Satyen, NREL
 Arthur B. Denison, INEEL
 Wilhelm B. Gauster, SNL
 Linda L. Horton, ORNL
 Edward L. Parsons, FETC
 Mark E. Reeves, ORNL
 Marion C. Thurnauer, ANL
 William Tumas, LANL
 Albert F. Wagner, ANL
 Leland W. Younker, LLNL

Cross-Cutting Technologies

Robert N. Schock, LLNL, Chair
 William V. Chandler, PNNL
 Anthony K. Chargin, LLNL
 Cathy Gregoire Pedro, NREL
 Jay O. Keller, SNL
 John B. Kerr, LBNL
 Gilbert V. McGurl, FETC
 Kevin Michael Myles, ANL
 James J. Reilly, BNL
 John Sheffield, ORNL
 John M. Slater, INEEL
 James Van Coevering, ORNL
 P. Henrik Wallman, LLNL
 David Watkins, LANL
 Jill L. Watz, LLNL

Analysis Team

Walter Short, NREL
 Ron A. Bradley, ORNL
 T. Randall Curlee, ORNL

Rosina M. Bierbaum

02/05/98 10:17:02

AM

Record Type: Record

To: T J. Glauthier/OMB/EOP

cc: Peter R. Orszag/OPD/EOP, Todd Stern/WHO/EOP

Subject: Latest version of the DOE 11-Lab study

TJ--- The biggest

problem is the report can be used to undermine the Kyoto agreement. I still wonder what it to be gained by putting this report out as a public document. If there is use as an internal DOE document, fine. This was not requested by anyone. Pena initiated it himself. If others vote the report deserves to be public, then a WH review such as you required for the 5 Lab study is certainly warranted as you mentioned to me yesterday. Below are a few additional important comments/examples.

Rosina

ANALYSIS: There is no analysis in the report, nor a discussion of what methodology was used, nor references as to where any sort of explanation might be found. Tables of estimated carbon savings are indicated in Chapter 2, but there is no explanation as to how these projected savings were arrived at or even what the actual baseline is that they are compared to. Further, the projected savings are said to be in the absence of policy changes, but no explanation is provided of what that means_ is this tapping all cost-effective opportunities even though there are many cost-effective opportunities today that are not taken advantage of today? Further, the projected impact of these estimates can be added up to produce a figure (now removed, but there is still a summary table with the same info) similar to that in the previous draft which would suggest that the Kyoto targets are not attainable. This may or may not be true, but there is no basis in the eleven lab report to make any such judgment. Finally, the eleven-lab study does not even show as great a reduction as the five lab study (which did have documentation and a description of its methodology) in the 2010 timeframe.

Page 1-8: What do they mean (citing the Schock paper) that there is only one chance in four that CO2 needs to be stabilized at or below 550 ppmv? This is done to advance an argument about how much should be invested in energy R&D, but it also seems to be giving credence to a totally unsupportable position that could be easily taken out of context and used against the administration's position. The Administration is not assigning probabilities to a concentration target!

p.5-3, Table 5-1: In 2010, using the classification provided, the maximum savings possible is 300 MtC which falls well short of what is likely to be required to meet the Kyoto commitment. This could pose substantial problems with Congress and will require an

extensive dialogue to explain what the report means concerning it being a technology development effort only, with no policy changes. With no discussion of the methodology used to arrive at these numbers (is there an appendix as was done for the five-lab study?) this seems likely to create much confusion without any means of clarifying the basis for these estimates.