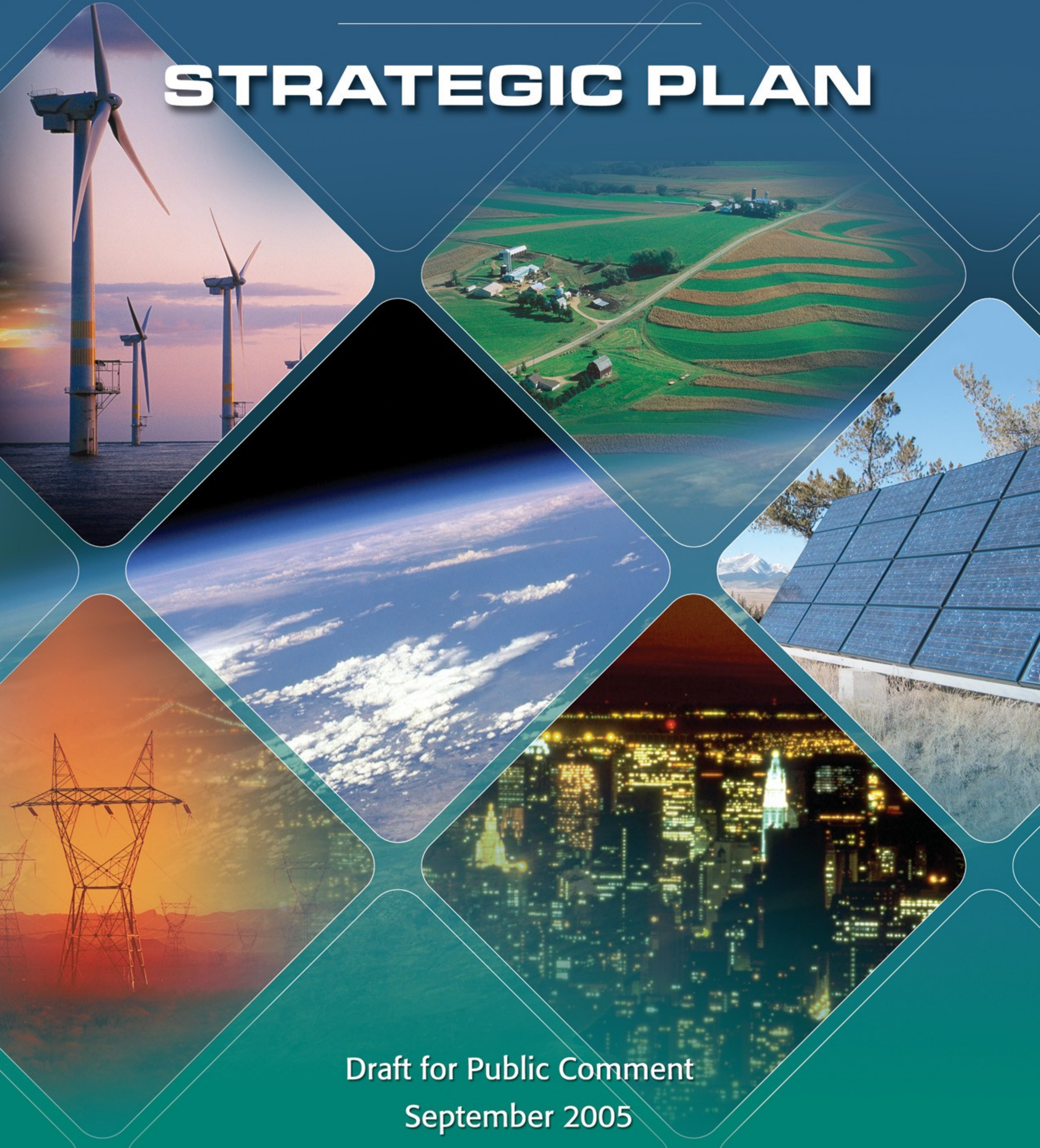
U.S. Climate Change Technology Program

STRATEGIC PLAN



Draft for Public Comment

September 2005

U.S. Climate Change Technology Program

U.S. Department of Energy (Lead Agency)
U.S. Department of Agriculture
U.S. Department of Commerce, including
National Institute of Standards and Technology
U.S. Department of Defense
U.S. Department of Health and Human Services, including
National Institutes of Health
U.S. Department of Interior
U.S. Department of State, including
U.S. Agency for International Development
U.S. Department of Transportation
U.S. Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
Other Participating Research and Development Agencies

Executive Office of the President, including
Council on Environmental Quality
Office of Science and Technology Policy
Office of Management and Budget

U.S. Climate Change Technology Program
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Washington, DC 20585
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http://www.climatetechnology.gov

U.S. Climate Change Technology Program

Strategic Plan

Draft for Public Comment

September 2005

To the Reader:

We are pleased to present for review and comment this preliminary Climate Change Technology Program (CCTP) *Strategic Plan*. This *Plan* provides strategic direction for the agencies of the Federal Government in formulating a coordinated approach to climate-change-related technology research, development, demonstration, and deployment. These CCTP activities form the technology component of a comprehensive U.S. approach to climate change that also includes undertaking short-term actions to reduce greenhouse gas emissions intensity, advancing climate science, and promoting international cooperation.

As a party to the United Nations Framework Convention on Climate Change (UNFCCC), the United States shares with many countries its ultimate goal: stabilization of greenhouse gas (GHG) concentrations in the Earth's atmosphere at a level that prevents dangerous interference with the climate system. Appropriately, this *Plan* takes a century-long look at the nature of the climate change challenge and the potential for technological solutions across a range of uncertainties. The overwhelming majority of anthropogenic GHG emissions that will occur over the course of the 21st century will arise from equipment and infrastructure that is not yet built – a circumstance that poses significant opportunities for the United States and the world to reduce or eliminate these GHG emissions.

This *Plan* articulates a vision of the role for advanced technology in addressing climate change, defines a supporting mission for the multi-agency CCTP, establishes strategic direction and a framework of guiding principles for Federal R&D agencies in formulating a CCTP research and development portfolio, outlines approaches to attain CCTP's six strategic goals, and identifies a series of next steps toward implementation. This endeavor will strengthen the U.S. research enterprise, stimulate U.S. innovation and advance technology development in many and, perhaps, unexpected ways, expanding options and reducing their costs. A sound strategic plan can help us capitalize on these innovations. It is our hope that others, at home and abroad, will be inspired by this example, launch initiatives of their own, and collaborate with us in this ambitious undertaking.

By seeking comments on this preliminary *Plan*, we hope to stimulate a thoughtful and energetic dialogue among those in the research communities, industry, agriculture, and the general public to help shape and strengthen CCTP and expand opportunities for cooperation and collaboration. To help us address comments most effectively, commenters should use the standard template found at: http://www.climatetechnology.gov. Alternatively, comments may be submitted via email to: cctp@hq.doe.gov, or in writing to: Director, U.S. Climate Change Technology Program, 1000 Independence Avenue, S.W., U.S. Department of Energy, Washington, DC 20585.

The United States is working to ensure a bright and secure energy and economic future for our Nation and a healthy planet for future generations. Through a combination of near-term actions, enhanced scientific understanding of climate change, advanced technology development, and international cooperation, this future can become a reality.

Samuel W. Bodman
Secretary of Energy

Chair, Committee on
Climate Change
Science and Technology Integration

Carlos M. Gutierrez
Secretary of Commerce

Co-Chair, Committee on
Climate Change
Science and Technology
Integration

John H. Marburger III, Ph.D.
Director, Office of Science and
Technology Policy
Executive Director, Committee on
Climate Change
Science and Technology Integration

Foreword

From the outset of his tenure as President, George W. Bush has been steadfast in his belief that America's strengths in innovation and technology should be brought to bear on the challenges of global climate change. From his White House Rose Garden speech of June 2001, which launched his National Climate Change Technology Initiative, to the communiqué coming out of the G8 Summit in Gleneagles, Scotland, in July 2005, and the Asia-Pacific Partnership for Clean Development, also in July 2005, both of which emphasize demonstration and deployment of clean energy technologies, the President has consistently championed a major role for new and advanced technology as a means to *both* reduce greenhouse gas emissions *and* spur the economic growth necessary for enabling investment in new capital and equipment.

Acting on his vision, the President initiated a Cabinet-level reorganization of Federal climate change science and technology activities and began strengthening the Federal Government's nearly $3 billion annual portfolio in climate-related technology R&D. The goal of this R&D is to expand options and lower the cost of technologies that reduce GHG emissions and further the President's vision in this area. Today, many Federal R&D agencies are working with universities, Federal laboratories, research institutions and consortia, private partners, and other governments in an ambitious technological undertaking. This undertaking has the potential to transform the primary economic activities that give rise to greenhouse gas emissions, including those that produce and use energy.

This *Strategic Plan*, therefore, affords an auspicious moment of opportunity in the climate change technology arena. Through an integrated framework of sound guidance, clear goals and next steps, the *Plan* will guide and galvanize the Federal Government's extensive and diverse technical efforts. Moreover, the *Plan* provides a long-term planning context that illuminates the nature of the challenge, as well as the opportunities for technology, which will better inform future Federal R&D planning.

The *Plan*, along with a companion document, *Vision and Framework for Strategy and Planning*[*], lays the foundation for setting priorities through its technology strategies and criteria for investment. In its sections about our current portfolio, the *Plan* highlights what we regard as the more important investment opportunities at this time. Since the *Plan* is forward-looking, and because current priorities will evolve over time, we are also seeking public input on future research directions.

Indeed, we hope this *Plan* provides a focal point for enhancing dialogue and entering into new partnerships with interested parties outside the U.S. Government. Therefore, I invite readers to avail themselves of the opportunity to comment on this document – a preliminary *Plan* – using the guidance found in the end of Chapter 1. Thank you in advance for your interest and attention.

David W. Conover, Director
U.S. Climate Change Technology Program

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[*] *Vision and Framework for Strategy and Planning*, U.S. Climate Change Technology Program, U.S. Department of Energy, DOE/PI-003, August 2005. See also: http://www.climatetechnology.gov.

U.S. Climate Change Technology Program
Strategic Plan

Table of Contents

Figures

Tables

Acronyms and Abbreviations

AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratory
AUV	Autonomous Underwater Vehicles
BC	Black Carbon
BES	Office of Basic Energy Sciences, U.S. Department of Energy
BESAC	Basic Energy Sciences Advisory Committee
BP	British Petroleum
BTU	British Thermal Unit
CCCSTI	Committee on Climate Change Science and Technology Integration
CCP	Carbon Capture Project
CCSP	U.S. Climate Change Science Program
CCTP	U.S. Climate Change Technology Program
CDIAC	Carbon Dioxide Information Analysis Centre
CEM	Continuous Emissions Monitor
CETC	Natural Resources Canada CANMET Energy Technology Center
CFC	Chlorofluorocarbon
CH_4	Methane
CHP	Combined Heat and Power (system)
CMM	Coal Mine Methane
CO_2	Carbon Dioxide
COL	Construction and Operating License
CSLF	Carbon Sequestration Leadership Forum
CSP	Competitive Solicitation Program
DG	Distributed Generation
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOS	U.S. Department of State
DOT	U.S. Department of Transportation
EIA	Energy Information Administration
EJ	Exajoule
EMF	Energy Modeling Forum, Stanford University
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
ESP	Early Site Permit
Euratom	European Atomic Energy Community

FACE	Free-Air CO_2 Enrichment
FACTS	Flexible Automated Control Transmission Systems
FCT	Fuel Cell Turbine
FES	Fusion Energy Sciences, U.S. Department of Energy, Office of Science
FHA	Federal Highway Administration
FTC	Fuel Cell Turbine
FTIR	Fourier Transform Infrared Spectroscopy
FY	Fiscal Year
Gen IV	Generation IV
GEO	Group on Earth Observations
GEO-SEQ	Geological Sequestration (project)
GEOSS	Global Earth Observation System of Systems
GHG	Greenhouse Gas
GIF	Generation IV International Forum (nuclear power)
Gt	Gigatonnes (10^9 tonnes or metric tons)
GtC	Gigatonnes (10^9 tonnes or metric tons) of Carbon
GtC-eq.	Gigatonnes (10^9 tonnes or metric tons) of Carbon Equivalent (emissions)
GWP	Global Warming Potential
H_2	Molecular Hydrogen
H_2S	Hydrogen Sulfide
HCFC	Hydroclorofluorocarbon (refrigerant)
HFC	Hydrofluorocarbon
HHS	U.S. Department of Health and Human Services
HNLC	High Nutrient, Low Chlorophyll
HTS	High-Temperature Superconductivity (e.g. wire)
HVDC	High Voltage Direct Current
IAEA	International Atomic Energy Agency
ICF	Inertial Confinement Fusion
IEA	International Energy Agency
IEOS	Integrated Earth Observation System
IFE	Inertial Fusion Energy
IGCC	Integrated Gasification Combined Cycle
IMSS	Image Multi-Spectral Sensor
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for the Hydrogen Economy
ITER	International Thermonuclear Experimental Reactor (also Latin for “the way”)
IWG	Interagency Working Group
kg	Kilogram
kW	Kilowatt
kWe	Kilowatt (electric)
kWh	Kilowatt-hour

LCCP	Life-Cycle Climate Performance
LFG	Landfill Gas
LH_2	Liquefied Hydrogen
LIBS	Laser Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging
LNLC	Low Nutrient, Low Chlorophyll
MFE	Magnetic Fusion Energy
MiniCAM	Mini Climate Assessment Model (Pacific Northwest National Laboratory)
MM	Measuring and Monitoring
MOF	Microporous Metal Organic Frameworks
mpg	miles per gallon
mph	miles per hour
MtC	Megatonnes Carbon
MWe	Megawatt electric
N_2O	Nitrous Oxide
NACP	North American Carbon Program
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NEPO	Nuclear Energy Plant Optimization (Program)
NERAC	Nuclear Energy Research Advisory Committee
NETL	National Energy Technology Laboratory
NH_3	Ammonia
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration, U.S Department of Energy
NO_x	Nitrogen Oxides
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council or Nuclear Regulatory Commission
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSCR	Non-Selective Catalytic Reduction
NSF	National Science Foundation
NSTX	National Spherical Torus Experiment
NVFEL	National Vehicle and Fuels Emission Laboratory
OC	Organic Carbon
ODS	Ozone-Depleting Substance
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
PEM	Polymer Electrolyte Membrane
PFC	Perfluorocarbons
PM	Particulate Matter
PNNL	Pacific Northwest National Laboratory

PPPL	Princeton Plasma Physics Laboratory
PV	Present Value
Quad	Quadrillion BTUs
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RDD&D	Research, Development, Demonstration, & Deployment
RFI	Request for Information
SCR	Selective Catalytic Reduction
SF_6	Sulfur Hexafluoride
SOFeX	Southern Ocean Iron Fertilization Experiment
SOIREE	Southern Ocean Iron Enrichment Experiment
SO_x	Sulfur Oxides
SRES	Special Report on Emissions Scenarios
T&D	Transmission and Distribution
TgC	Teragrams of Carbon
Tg CO_2	Teragrams Carbon Dioxide
Tg CO_2-eq.	Teragrams Carbon Dioxide Equivalent (emissions)
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
VAM	Ventilation Air Methane
VOC	Volatile Organic Compounds
W/m^2	Watts per Square Meter
WCRP	World Climate Research Program
WG	Working Group
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WRE	T. Wigley, R. Richels, and J. Edmonds (researchers who developed emissions trajectories that were projected to lead toward stabilization of CO_2 emissions over the next several hundred years at minimum economic cost)

1 Introduction

The 21st century will see substantial changes in economic and social development around the world, with accompanying transformations in the way that the world uses energy and its natural resources. The past hundred years witnessed revolutionary innovations in the technologies used to power homes and buildings, transport people and goods, and produce everyday goods and services. These innovations have been a significant source of the prosperity that the United States and many other countries currently enjoy. Continued innovations will be just as important in providing a prosperous future for countries around the world. At the same time, they will help enable and provide sound stewardship of the environment, including the Earth's climate system.

As a party to the United Nations Framework Convention on Climate Change (UNFCCC),[1] the United States shares with many other countries the UNFCCC's ultimate objective, that is, the "…stabilization of greenhouse gas[2] concentrations in Earth's atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system . . . within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." Meeting this UNFCCC objective will require a long-term commitment and international cooperation.

> *I've asked my advisors to consider approaches to reduce greenhouse gas emissions, including those that tap the power of markets, help realize the promise of technology and ensure the widest-possible global participation….Our actions should be measured as we learn more from science and build on it. Our approach must be flexible to adjust to new information and take advantage of new technology. We must always act to ensure continued economic growth and prosperity for our citizens and for citizens throughout the world.*
>
> **President Bush (6/11/01)**

In addition, the actions that countries take to address climate change will be part of an array of social, economic and environmental objectives that countries will undertake to address sustainable development. Accordingly, the United States has placed special emphasis on the fundamental importance of technology investment as a means of achieving climate goals in ways that simultaneously support broader societal goals, and in particular that will meet the world's need for abundant, clean, secure, and affordable energy to provide a continuing engine for global economic advancement in this century.

Although the scientific understanding of climate change continues to evolve, the potential ramifications of increasing accumulations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the Earth's

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[1] The UNFCCC was adopted by 157 countries in 1992; as of May 24, 2004, 189 Parties, including the European Economic Community, had ratified the UNFCCC.

[2] Greenhouse gases (GHGs) are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide (CO_2), nitrous oxide (N_2O) methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Besides CO_2, N_2O, and CH_4 the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Gases dealt with under the Montreal Protocol are excluded from the CCTP purview.

atmosphere have heightened attention on anthropogenic sources of GHG emissions and various means for their mitigation. Most long-term, prospective analyses of anthropogenic emissions of GHGs project significant increases over the next century, primarily from considerations of population growth and expansion of world's economic activity, accompanied by a continuation of existing patterns and trends in energy use (combustion of fossil fuels), land use, and industrial and agricultural production.

Climate change is a serious, long-term issue, requiring sustained action over many generations by both developed and developing countries. Solutions will likely require fundamental changes in the way the world produces and uses energy, as well as in many other GHG-emitting activities of industry, agriculture, land use, and land management. Developing innovative technologies and approaches that are cleaner and more efficient is the key to addressing our long-term climate challenge.

Under the leadership of President Bush, the United States has formulated and is implementing a comprehensive approach to climate change that anticipates and addresses this challenge. It is science-based, encourages innovation and scientific and technological breakthroughs, harnesses the power of markets, and encourages global participation. It includes elements for advancing climate change science and technology, and promoting international cooperation. It focuses on reducing emissions, while sustaining economic growth. Growth and the capital it will create are needed to finance investment in new technologies.

The technological elements of this approach, outlined in this *Strategic Plan*, build on America's strengths in innovation and technology. These longer-term elements are augmented by near-term policy measures, financial incentives, and voluntary and other Federal programs aimed at slowing the growth of U.S. GHG emissions and reducing GHG intensity.[3] These include the Climate VISION,[4] Climate Leaders,[5] Energy STAR,[6] and SmartWay Transport Partnership[7] programs, all of which work with industry to voluntarily reduce emissions. The Department of Agriculture's conservation programs provide incentives for actions that increase carbon sequestration[8] in trees and soils. Energy efficiency, alternative fuels, renewable and nuclear energy, methane capture and other GHG reduction programs and financial incentives are also underway.

The technological elements of this approach are buttressed by supporting international activities. These include bilateral agreements with 20 countries and the European Union; international partnerships to promote the advancement of renewable energy and energy efficiency, the hydrogen economy, carbon sequestration, nuclear power, methane recovery, and fusion energy (see Chapter 2). In July 2005, the United States joined with Australia, China, India, Japan, and South Korea to accelerate clean development under a new Asia-Pacific Partnership on Clean Development,[9] and embarked with other G8 countries on a far-reaching Plan of Action[10] to speed the development and deployment of clean energy technologies to

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[3] Intensity means emissions per unit of economic output. See *White House Fact Sheet on Climate Change*, www.whitehouse.gov/news/releases/2003/09/20030930-11.html.

[4] See http://www.climatevision.gov

[5] See http://www.epa.gov/climateleaders

[6] See http://www.energystar.gov

[7] See http://www.epa.gov/smartway

[8] See http://www.usda.gov/news/releases/2003/06/fs-0194.htm

[9] See http://www.whitehouse.gov/news/releases/2005/07/20050727-9.html

[10] See http://www.whitehouse.gov/news/releases/2005/07/20050708-2.html

achieve the combined goals of addressing climate change, reducing harmful air pollution and improving energy security in the U.S. and throughout the world.

The Energy Policy Act of 2005, which the President signed into law in August 2005, provides for more rigorous standards and tax credits for more energy efficient appliances and vehicles. The Act also has provisions, such as those dealing with production tax credits and loan guarantees, designed to accelerate the market penetration and deployment of advanced energy technologies that will reduce GHG emissions in the future.

The U.S. approach to climate change, which is consistent with and supports the UNFCCC's ultimate objective, forms the long-term planning context for the CCTP. Significant progress toward meeting the climate change goals can be facilitated over the course of the 21st century by new and revolutionary technologies that can reduce, avoid, capture, or sequester GHG emissions, while also continuing to provide the energy-related and other services needed to sustain economic growth. The United States is committed to leading the development of these new technologies.

This *Plan* takes a century-long look at the nature of this challenge, across a range of planning uncertainties, and explores an array of opportunities for technological solutions. The *Plan* articulates a vision for new and advanced technology in addressing climate change concerns, defines a supporting planning and coordination mission for the multi-agency CCTP, and provides strategic direction to the Federal agencies in formulating a comprehensive portfolio of related technology research, development, demonstration, and deployment (R&D).[11] The *Plan* establishes six strategic goals and seven approaches to be pursued toward their attainment and identifies a series of next steps toward implementation.

1.1 U.S. Leadership and Presidential Commitment

On June 11, 2001, the President launched the National Climate Change Technology Initiative.[12] Backed by unprecedented levels of Federal investment in R&D in climate-change-related areas, this Presidential initiative signaled Federal leadership in climate change technology development and aimed to stimulate American innovation, strengthen associated research and education, and position the United States as a world leader in pursuit of advanced technologies that could, if successful, help meet this global challenge. The President said:

> *[W]e're creating the National Climate Change Technology Initiative to strengthen research at universities and national labs, to enhance partnerships in applied research, to develop improved technology for measuring and monitoring gross and net greenhouse gas emissions, and to fund demonstration projects for cutting-edge technologies.*

In February 2002, the President reorganized Federal oversight, management and administrative control of climate-change-related activities. He established a Cabinet-level Committee on Climate Change Science and Technology Integration (CCCSTI), thereby directly engaging the heads of all relevant departments

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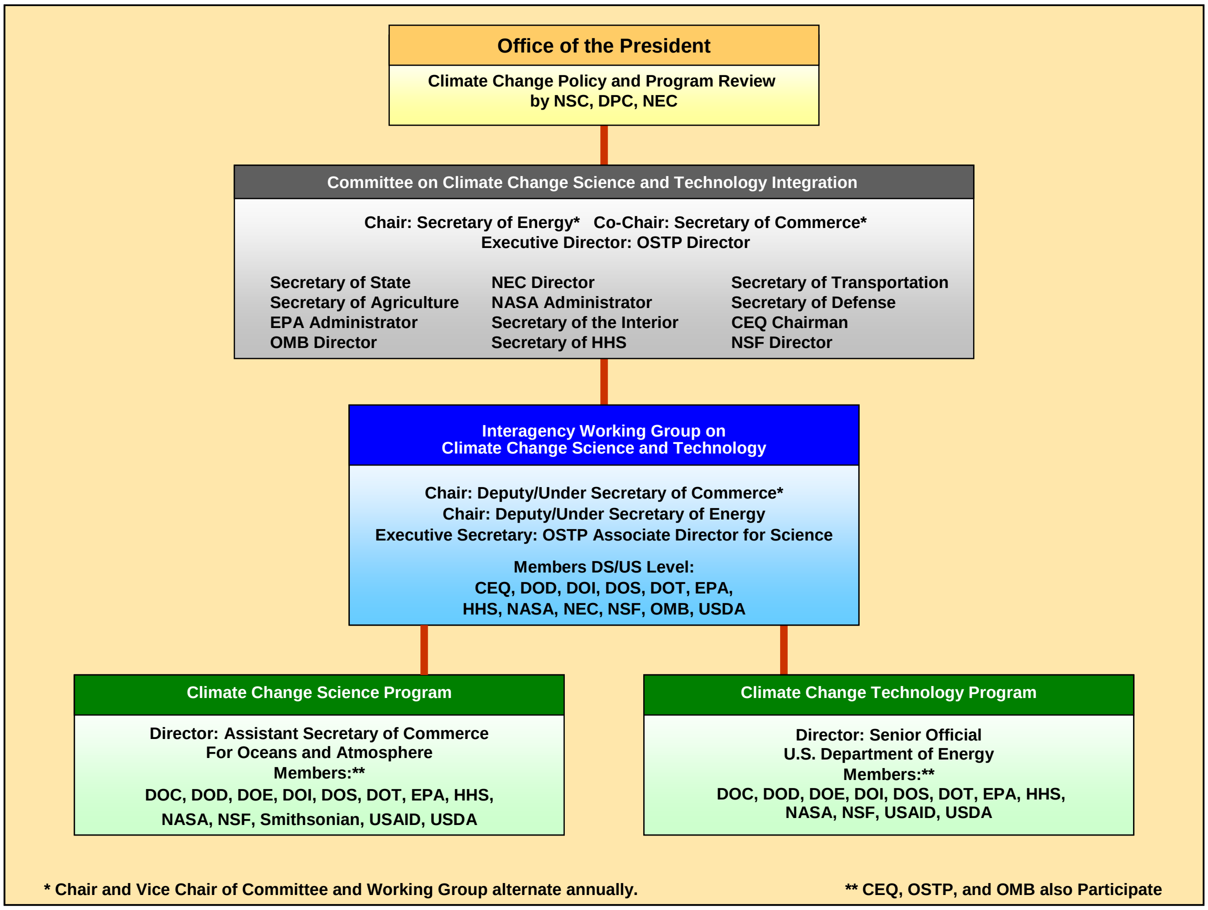
[11] Throughout this report, the use of the term "R&D" is meant generally to include research, development, demonstration, and deployment. However, where relevant, the report distinguishes research and development from demonstration and deployment, as the each activity has different rationales, different appropriate roles for the private sector, and different associated policy instruments.

[12] White House Rose Garden speech: www.whitehouse.gov/news/releases/2001/06/20010611-2.html.

and agencies in guiding and directing these activities. The President charged the CCCSTI to advance and coordinate climate change science and technology research.

In an earlier Cabinet-level climate change policy review, which gave rise to the CCCSTI, the President directed that innovative approaches for addressing climate change concerns be developed in accord with a number of basic principles: (1) be consistent with the long-term goal of stabilizing greenhouse gas concentrations in the atmosphere; (2) be measured, as more is learned from science, and build on it; (3) be flexible to adjust to new information and take advantage of new technology; (4) ensure continued economic growth and prosperity; (5) pursue market-based incentives and spur technological innovation; and (6) base efforts on global participation, including developing countries. These principles continue to apply to the development of innovative approaches under CCCSTI and its subordinate organizational elements.

Under the auspices of the CCCST, two multi-agency programs were established to coordinate Federal activities in climate change scientific research and advance the President's vision under his National Climate Change Technology Initiative. These are known, respectively, as the U.S. Climate Change Science Program, led by the U.S. Department of Commerce, and the U.S. Climate Change Technology Program, led by the U.S. Department of Energy (Figure 1-1).



* Chair and Vice Chair of Committee and Working Group alternate annually.

** CEQ, OSTP, and OMB also Participate

Figure 1-1. Cabinet-Level Committee on Climate Change Science and Technology Integration

1.2 U.S. Climate Change Science Program

The U.S. Climate Change Science Program (CCSP) is an interagency research planning and coordinating entity responsible for facilitating the development of a strategic approach to Federally supported research, integrated across the participating agencies. Collectively, the activities under CCSP constitute a comprehensive research program charged with investigating natural and human-induced changes in the Earth's global environmental system, monitoring important climate parameters, predicting global change, and providing a sound scientific basis for national and international decision-making. Its principal aim is to improve understanding of climate change and its potential consequences. Figure 1-1 shows that it operates under the direction of the Assistant Secretary of Commerce for Oceans and Atmosphere. It reports through the Interagency Working Group (IWG) on Climate Change Science and Technology, composed of agency deputies, to the CCCSTI.

Regarding climate change science, on May 11, 2001, the President asked the National Academies National Research Council (NRC) to examine the state of knowledge and understanding of climate change. The resulting NRC report concluded that "the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability." The report also noted that there are still major gaps in our ability to measure the impacts of GHGs on the climate system. Major advances in understanding and modeling of the climate system, including its response to natural and human-induced forcing; and modeling of the factors that influence atmospheric concentrations of GHGs and aerosols, as well as the feedbacks that govern climate sensitivity, are needed to predict future climate change with greater confidence.

In July 2003, CCSP released its strategic plan[13] for guiding climate research. The plan is organized around five goals: (1) improving our knowledge of climate history and variability; (2) improving our ability to quantify factors that affect climate; (3) reducing uncertainty in climate projections; (4) improving our understanding of the sensitivity and adaptability of ecosystems and human systems to climate change; and (5) exploring options to manage risks. Annually, the Federal Government spends about $2 billion on research related to advancing climate change science.[14]

A subsequent NRC review[15] of the CCSP strategic plan concluded that the Administration is on the right track, stating that the plan "articulates a guiding vision, is appropriately ambitious, and is broad in scope." The NRC's report also identified the need for a broad global observation system to support measurements of climate variables.

In June 2003, the United States hosted more than 30 nations at the inaugural Earth Observation Summit, which resulted in a commitment to establish an intergovernmental, comprehensive, coordinated, and sustained Earth observation system.[16] The data collected by the system will be used for multiple societal benefit areas, including better climate models, improved knowledge of the behavior of CO_2 and aerosols in the atmosphere, and the development of strategies for carbon sequestration.

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[13] See: http://www.climatescience.gov/Library/stratplan2003/final/default.htm

[14] See Appendix A and http://www.usgcrp.gov/usgcrp/Library/ocp2004-5/default.htm.

[15] See: http://books.nap.edu/catalog/10139.html

[16] See: http://www.earthobservationsummit.gov

Since that initial meeting, two additional ministerial summits have been held, and the intergovernmental partnership has grown to nearly 60 nations. At the most recent meeting, Earth Observation Summit III in Brussels, a Ten Year Implementation Plan for the Global Earth Observation System of Systems (GEOSS) was adopted, and the intergovernmental Group on Earth Observations was established to begin implementation of the 2-, 6-, and 10-year targets identified in the plan. The U.S. contribution to GEOSS is the Integrated Earth Observation System (IEOS). In April 2005, the USG Committee on Environment and Natural Resources (CENR) released the *Strategic Plan for the U.S. Integrated Earth Observation System*[17] that addresses the policy, technical, fiscal, and societal benefit components of this integrated system, and established the U.S. Group on Earth Observation (USGEO).

1.3 U.S. Climate Change Technology Program

The U.S. Climate Change Technology Program (CCTP) is the technology counterpart to CCSP. It is a multi-agency planning and coordinating entity, led by the Department of Energy, aimed at accelerating the development of new and advanced technologies to address climate change. It works with participating agencies (Table 1-1), provides strategic direction for the CCTP-related elements of the

Table 1-1. Federal Agencies Participating in the U.S. Climate Change Technology Program and Examples of Related Activities

Agency	Selected Examples of Climate Change-Related Technology R&D Activities
DOC	Instrumentation, Standards, Ocean Sequestration, Decision Support Tools
DoD	Aircraft, Engines, Fuels, Trucks, Equipment, Power, Fuel Cells, Lasers, Energy Management, Basic Research
DOE	Energy Efficiency, Renewable Energy, Nuclear Fission and Fusion, Fossil Fuels and Power, Carbon Sequestration, Basic Energy Sciences, Hydrogen, Bio-Fuels, Electric Grid and Infrastructure
DOI	Land, Forest, and Prairie Management, Mining, Sequestration, Geothermal, Terrestrial Sequestration Technology Development
DOS*	International Science and Technology Cooperation, Oceans, Environment
DOT	Aviation, Highways, Rail, Freight, Maritime, Urban Mass Transit, Transportation Systems, Efficiency and Safety
EPA	Mitigation of CO_2 and Non-CO_2 GHG Emissions through Voluntary Partnership Programs, including Energy STAR, Climate Leaders, Green Power, Combined Heat and Power, State and Local Clean Energy, Methane and High-GWP Gases, and Transportation; GHG Emissions Inventory
HHS*	Environmental Sciences, Biotechnology, Genome Sequencing, Health Effects
NASA	Earth Observations, Measuring, Monitoring, Aviation Equipment, Operations and Infrastructure Efficiency
NSF	Geosciences, Oceans, Nanoscale Science and Engineering, Computational Sciences
USAID*	International Assistance, Technology Deployment, Land Use, Human Impacts
USDA	Carbon Fluxes in Soils, Forests and Other Vegetation, Carbon Sequestration, Nutrient Management, Cropping Systems, Forest and Forest Products Management, Livestock, and Waste Management, Biomass Energy and Bio-based Products Development

** CCTP-related funding for the indicated agencies is not included in the totals for CCTP in the budget tables of Appendix A. However, the agencies participate in CCTP R&D planning and coordination as members of CCTP's Working Groups. Agency titles for the acronyms above are shown in Appendix A.*

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[17] See: http://ostp.gov/html/EOCStrategic_Plan.pdf

overall Federal R&D portfolio, and facilitates the coordinated planning, programming, budgeting and implementation of the technology development and deployment aspects of U.S. climate change strategy, including advancing the President's vision for the National Climate Change Technology Initiative. The CCTP operates under the direction of a senior-level official at the Department of Energy and reports through the IWG to the cabinet-level CCCSTI.

1.3.1 The Role of Technology

Analyses documented in the literature (see Chapter 3) show that accelerated advances in technology have the potential, under certain assumptions, not only to facilitate progress toward meeting climate goals, but also to reduce significantly the cost of such progress over the course of the 21st century, compared to what would be the case without accelerated advances in technology.[18] Further, it is expected that the new technologies would create substantial opportunities for economic growth.

The CCTP aims to achieve a balanced and diversified portfolio of advanced technology R&D, focusing on energy-efficiency enhancements; low-GHG-emission energy supply technologies; carbon capture, storage, and sequestration methods; and technologies to reduce emissions of non-CO_2 gases. Conducting this R&D will help resolve technological uncertainties and improve the prospects that such technologies can be adapted to market realities, better positioning them for eventual deployment.

Together, CCSP and CCTP will help lay the foundation for future progress. Advances in climate change science under CCSP can be expected to improve understanding about climate change and its impacts. Uncertainties about causes and effects of climate change will be better understood and the potential benefits and risks of various courses of action will become better known. Similarly, advances in climate change technology under the CCTP can be expected to bring forth an expanded array of advanced technology options at lower cost that will both meet the needs of society and reduce GHG emissions. CCSP progress will provide the information needed to guide and pace future decisions about climate change mitigation. CCTP will provide the means for enabling and facilitating that progress.

Three publications issued by the CCTP provide more information about CCTP and related technologies in the CCTP R&D portfolio (see Appendix A). The *Vision and Framework for Strategy and Planning* provides strategic direction and guidance to the Federal agencies developing new and advanced global climate change technologies. The *Research and Current Activities Report* provides an overview of the science, technology, and policy initiatives that make up the Administration's climate change technology strategy. Readers interested in learning about more than 85 technologies in the R&D portfolio may consult the *Technology Options for the Near and Long Term Report*.[19]

1.4 Request for Public Comment

The United States, in partnership with others, has embarked on a near- and long-term global challenge, guided by science and facilitated by advanced technology, to address climate change concerns. The

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[18] For example, see Battelle (2000) and IPCC (2000).

[19] All three documents are available at www.climatetechnology.gov. The internet-based version of the report on *Technology Options* is updated periodically.

CCTP *Strategic Plan*, presented here in proposed form, seeks public input (upon release) on its overall direction and completeness, recognizing that not all potentially important technologies can be pursued simultaneously.

The ability of CCTP to effectively address comments would be facilitated if commenters could use a standard commenting process, described at http://www.climatetechnology.gov. All comments will be catalogued and addressed. Alternatively, comments may be submitted by email to CCTP@hq.doe.gov, or in writing by mailing to:

Director
U.S. Climate Change Technology Program
1000 Independence Avenue, S.W.
U.S. Department of Energy
Washington, DC 20585

1.5 References

Battelle Memorial Institute. 2000. *Global energy technology strategy: addressing climate change*. Washington, DC: Battelle Memorial Institute. http://www.pnl.gov/gtsp/docs/infind/cover.pdf

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special report on emissions scenarios*. Cambridge, UK: University Press. http://www.grida.no/climate/ipcc/emission/index.htm.

Intergovernmental Panel on Climate Change (IPCC). 2001a. *Climate change 2001: mitigation*. Working Group III to the Third Assessment Report. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/index.htm.

Intergovernmental Panel on Climate Change (IPCC). 2001b. *Climate change 2001: the scientific basis*. Working Group I to the Third Assessment Report. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg1/index.htm.

National Research Council. 2004. *Implementing climate and global change research: a review of the final U.S. Climate Change Science Program Strategic Plan*. Washington, DC: National Academies Press.

National Research Council. 2001. *Climate change science: an analysis of some key questions*, Committee on the Science of Climate Change. Washington, DC: National Academy Press.

The White House. June 11, 2001. *Climate change policy review – initial report*. www.whitehouse.gov/news/releases/2001/06/climatechange.pdf.

2 Vision, Mission, Goals, and Approaches

Within the context of a comprehensive U.S. approach to climate change that includes near-term actions to reduce greenhouse gas emissions intensity, advancements in climate science, and promotion of international cooperation, this CCTP *Strategic Plan* articulates a vision for the role of new and advanced technology in addressing climate change concerns. Following through on the President's direction, the *Plan* defines an integrated mission for the multi-agency CCTP and its participating agencies and provides strategic direction for strengthening Federal leadership of science and technical innovation in related areas. The *Plan* establishes six strategic goals and seven approaches to be pursued toward their attainment. The *Plan* outlines a process for prioritizing R&D investments and lays out a management and reporting structure for CCTP to ensure accountability and mark progress. The vision, mission, goals and approaches will guide future CCTP activities, including those related to R&D portfolio planning and coordination.

2.1 Vision and Mission

CCTP seeks to attain on a global scale, in partnership with others, a technological capability that can provide abundant, clean, secure and affordable energy and related services needed to encourage and sustain economic growth, while simultaneously achieving substantial reductions in emissions of greenhouse gases (GHGs) and mitigating the risks of potential climate change (*CCTP Vision*). With leadership in R&D and progress in technology development, CCTP aims to inspire broad interest, within and outside of government, including enhanced international cooperation, in an expanded global effort to develop, commercialize and employ such technology toward attainment of the UNFCCC's ultimate objective.

CCTP Vision

The CCTP **vision** is to attain on a global scale, in partnership with others, a technological capability that can provide abundant, clean, secure and affordable energy and related services needed to encourage and sustain economic growth, while simultaneously achieving substantial reductions in emissions of greenhouse gases and mitigating the risks of potential climate change.

CCTP Mission

The CCTP **mission** is to stimulate and strengthen the scientific and technological enterprise of the United States, through improved coordination and prioritization of multi-agency Federal climate change technology R&D programs and investments, and to provide global leadership, in partnership with others, aimed at accelerating development of new and advanced technologies that can attain the CCTP vision.

As a multi-agency R&D planning entity, CCTP will strive to stimulate and strengthen the scientific and technological enterprise of the United States, through improved coordination and prioritization of multi-agency Federal climate change technology R&D programs and investments. By conducting multi-agency planning, portfolio reviews, interagency coordination, technical assessments and other analyses, and by formulating recommendations, CCTP will provide support to the Cabinet-level CCCSTI so that it can address issues, make informed decisions, weigh priorities on related science and technology matters, and provide strategic direction. CCTP will also continue to work with and support the participating agencies in developing plans and carrying out activities needed to achieve the CCTP's vision and strategic goals (*CCTP Mission*).

2.2 Strategic Goals

The ultimate objective of the U.N. Framework Convention on Climate Change, stabilizing greenhouse gas emissions at levels that would prevent dangerous anthropogenic interference, provides a planning context for CCTP's long-term technology development strategy. Two considerations arise from this that are relevant to long-term R&D planning and guidance for technology development. First, the level of stabilized concentrations of GHGs in Earth's atmosphere implied by the ultimate objective is not known and will likely remain for some time a key planning uncertainty.[1] Accordingly, CCTP's strategic goals are not based on any hypothesized level of stabilized GHG concentrations, but rather encompass a range of levels under conditions of uncertainty. Second, stabilizing GHG concentrations, at any atmospheric concentration level, implies that global *additions* of GHGs to the atmosphere and global *withdrawals* of GHGs from the atmosphere must come into a net balance. This means that growth of *net* emissions of GHGs would need to slow, eventually stop, and then reverse, so that, ultimately, *net* emissions would approach levels that are low or near zero. The technological challenge is to enable new systems that could help achieve this goal.

In addressing this challenge, opportunities for new and advanced technologies that can address multiple societal objectives, including greenhouse gas reduction, present themselves in a number of areas: reducing emissions of CO_2 from energy end-use and infrastructure and from energy supply; capturing and storing CO_2 from various emissions sources or otherwise sequestering it from the atmosphere; and reducing emissions of non-CO_2 GHGs. In addition, the technological capacity to measure and monitor emissions of GHGs needs to be available to mark progress and guide future work. Finally, underpinning any acceleration of technology development is an array of basic research activities required to illuminate technical barriers and expand knowledge for problem solving.

Countries from all regions will work to meet their climate objectives in the context of a number of other social goals, many of which will continue to have both immediate and urgent implications. For many developing countries the overriding goal will continue to be economic development to reduce poverty and advance human well-being. Increased global energy use is needed to help lift out of poverty the nearly 2 billion people who lack even the most basic access to modern energy services. Addressing this "energy poverty" is one of the world's key development objectives, as lack of energy services is associated with high rates of disease and child mortality. All countries will continue to seek to ensure that energy sources are secure, affordable and reliable, and will also seek approaches that address other environmental concerns, in addition to climate change, such as air pollution and conservation.

These opportunities form the basis, elaborated upon below, for CCTP's six strategic goals.[2] To the extent that agency missions and other priorities allow, each participating CCTP agency will align the relevant components of its R&D portfolio in ways that are consistent with and supportive of one or more of these six CCTP goals:

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[1] The UNFCCC states that additional scientific research is required to determine the level of GHG concentrations that would prevent dangerous anthropogenic interference with the climate system. The CCSP's principal aim is to improve understanding of climate change and its potential impacts, which will inform CCTP.

[2] The CCTP *Strategic Plan* focuses on mitigation of GHG emissions and atmospheric concentrations, consistent with the context of the UNFCCC. It does not address adaptation, reducing vulnerabilities to climate change, or alternative means for reducing radiative forcing, such as modification of the Earth's surface albedo, stratospheric sunlight scattering, or geo-engineering. The public is invited to comment on this focus and these other elements.

1. Reduce emissions from energy end-use and infrastructure
2. Reduce emissions from energy supply
3. Capture and sequester carbon dioxide (CO_2)
4. Reduce emissions of non-CO_2 greenhouse gases
5. Improve capabilities to measure and monitor GHG emissions
6. Bolster basic science contributions to technology development

CCTP Goal 1

Reduce Emissions from Energy End-Use and Infrastructure

Major sources of anthropogenic carbon dioxide (CO_2) emissions are closely tied to the use of energy in transportation, residential and commercial buildings, and industrial processes. Improving energy efficiency and reducing GHG-emissions intensity in these economic sectors through a variety of technical advances and process changes present large opportunities to decrease overall GHG emissions.

In addition, application of advanced technology to the electricity transmission and distribution (T&D) infrastructure (the “grid”) can have dual effects on reducing GHG emissions. First, there is a direct contribution to energy and CO_2 reductions resulting from increased efficiency in the T&D system itself. Second, there can be an indirect contribution by enabling, through modernized systems, the expanded use of low-emission electricity generating technologies (such as wind, cogeneration of heat and power, geothermal, and solar power), including distributed energy systems; and better managing system-wide energy supply and demand. Emissions reduction from energy efficiency gains and reduced energy use could be among the most important contributors to strategies aimed at overall CO_2 emissions reduction. The types of technological advancements applicable to this goal include:

- **Efficiency, Infrastructure, and Equipment**. Development and increased use of highly efficient motor vehicles and transportation systems, buildings equipment and envelopes, industrial combustion and process technology, and components of the electricity grid can significantly reduce CO_2 emissions, avoid other kinds of environmental impacts, and reduce the life-cycle costs of delivering the desired products and services.

- **Transition Technologies**. So-called “transition” technologies, such as high-efficiency natural-gas-fired power plants, are not completely free of GHG emissions, but are capable of achieving significant reductions of GHG emissions in the near and mid terms by significantly improving or displacing higher GHG-emitting technologies in use today. Ideally, transition technologies would also be compatible with more advanced GHG-free technologies that would follow in the future.

- **Enabling Technologies**. Enabling technologies contribute indirectly to the reduction of GHG emissions by making possible the development and use of other important technologies. The example of a modernized electricity grid, mentioned above, is seen as an essential step, enabling the deployment of more advanced end-use and distributed energy resources needed for reducing GHG emissions. An intelligent electricity grid integrated with smart end-use equipment would further raise system performance. Another example is storage technologies for electricity or other energy carriers.

- **Alternatives to Industrial Processes, Feedstocks, and Materials**. Manufacturing, mining, agriculture, construction, services, and other commercial and industrial activities will require feedstocks and other material inputs to production.[3] In addition to energy efficiency improvements discussed above, opportunities for lowering CO_2 and other GHG emissions from industrial and commercial activities include replacing current feedstocks with those produced through processes (or complete resource cycles) that have lower or zero-net GHG emissions (e.g., bio-based feedstocks), reducing the average energy intensity of material inputs, and developing alternatives to current industrial processes and products.

CCTP Goal 2

Reduce Emissions from Energy Supply

Current global energy supplies are dominated by fossil fuels—coal, petroleum products, and natural gas—that emit CO_2 when burned. A transition to a low-carbon future would likely require the availability of multiple energy supply technology options characterized by low, near-net-zero, or zero CO_2 emissions. Many such energy supply technologies are available today or are under development. When combined with improved energy carriers (e.g., electricity, hydrogen), they offer prospects for both reducing GHG emissions and improving overall economic efficiency. Examples include the following:

- **Electricity**. Electricity will remain an important energy carrier in the global economy in the future. While substantial improvements in efficiency can reduce the growth of electricity consumption, the prospects of increased electrification and growing demand, especially in the developing regions of the world, still imply significant increases in electricity supply. Reducing GHG emissions from electricity supply could be achieved through further improvements in the efficiency of fossil-based electricity generation technologies, deployment of renewable technologies, increased use of nuclear energy, and development of fusion or other novel power sources.

- **Hydrogen, Bio-Based, and Low-Carbon Fuels**. The world economy will have a continuing need for portable, storable energy carriers for heat, power, and transportation. A promising energy carrier is hydrogen, which can be produced in a variety of ways, including carbon-free or low-carbon methods using nuclear, wind, hydroelectric, solar energy, biomass, or fossil fuels combined with carbon capture and sequestration. Hydrogen and other carriers, such as methanol, ethanol, and other biofuels, could serve both as a means for energy storage and as energy carriers in transportation and other applications.

CCTP Goal 3

Capture and Sequester Carbon Dioxide

Transforming fossil-fuel-based combustion systems into low-carbon or carbon-free energy processes would require further development and application of technologies to capture CO_2 and store it using safe

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[3] Producing feedstocks and materials can and does result in net emissions of GHGs.

and acceptable means, removing it from the atmosphere for the long term. In addition, large amounts of CO_2 could be removed from the atmosphere and sequestered on land or in oceans through improved land, forest, and agricultural management practices; changes in products and materials; and other means. Two focus areas are:

- **Carbon Capture and Storage**. Advanced techniques are under development that could capture CO_2 from such sources as coal-burning power plants, oil refineries, hydrogen production facilities, and various high-emitting industrial processes. Carbon capture would be linked to geologic storage — long-term storage in geologic formations, such as depleted oil and gas reservoirs, deep coal seams, saline aquifers, or other deep injection reservoirs.

- **CO_2 Sequestration**. Land-based, biologically assisted means for removing CO_2 from the atmosphere and sequestering it in trees, soils, or other organic materials have proven to be relatively low-cost means for long-term carbon storage. Ocean sequestration may also play a role as a carbon "sink," as science advances the understanding of its efficacy and the potential effects.

CCTP Goal 4

Reduce Emissions of Non-CO_2 Greenhouse Gases

GHGs other than carbon dioxide, including methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6) and others, are more potent per unit weight as radiant energy absorbers than CO_2. In addition, the atmospheric concentration of troposphere ozone (O_3), another GHG, is increasing due to human activities. The Intergovernmental Panel on Climate Change (IPCC) estimated that the cumulative effects of such gases since pre-industrial times account for about 40 percent of the anthropogenic radiative forcing[4] from GHGs. Reducing emissions of these other GHGs is an important climate change goal and key component of a comprehensive climate change technology strategy. Many categories of technologies are relevant to the attainment of this CCTP goal. Highlights include:

- **Methane Collection and Utilization**. Improvements in methods and technologies to collect methane and detect leaks from various sources, such as landfills, coal mines, natural gas pipelines, and oil and gas exploration operations, can prevent this GHG from escaping to the atmosphere. These methods are often cost-effective, because the collected methane is a fuel that can be used directly or sold at natural gas market prices.

- **Reducing N_2O and Methane Emissions from Agriculture**. Improved agricultural management practices and technologies, including altering application practices in the use of fertilizers for crop production, dealing with livestock waste, and improved management practices in rice production, are key components of the strategy to reduce other GHGs.

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[4] Radiative forcing is a measure of the overall energy balance in the Earth's atmosphere. It is zero when all energy flows in and out of the atmosphere are in balance, or equal. If there is a change in forcing, either positive or negative, the change is usually expressed in terms of watts per square meter (W/m^2), averaged over the surface of the Earth. When it is positive, there is a net "force" toward warming, even if the warming itself may be slowed or delayed by other factors, such as the heat-absorbing capacity of the oceans or the energy absorption needed for the melting of natural ice sheets.

- **Reducing Use of High Global-Warming-Potential (GWP) Gases**. Hydrofluorocarbons and perfluorocarbons have substituted for ozone-depleting chlorofluorocarbons in a number of industries, including refrigeration, air conditioning, foam blowing, solvent cleaning, fire suppression, and aerosol propellants. These and other high-GWP synthetic gases are generally used in applications where they are important to complex manufacturing processes or provide safety and system reliability, such as in semiconductor manufacturing, electric power transmission and distribution, and magnesium production and casting. Because they have high GWPs, methods to reduce leakage and use of these chemicals can contribute to UNFCCC goal attainment and include the development of lower-GWP alternatives to achieve the same purposes.

- **Black Carbon Aerosols**. Programs aimed at reducing airborne particulate matter have led to significant advances in fuel combustion and emission control technologies in both transportation and power generation sectors. Further advances can continue to reduce future black carbon aerosol emissions. Reduced emissions of black carbon, soot, and other chemical aerosols can have multiple benefits. Apart from improving public health and air quality, they can reduce radiative forcing in the atmosphere.

CCTP Goal 5

Improve Capabilities to Measure and Monitor GHG Emissions

Improved technologies for measuring, estimating, and monitoring GHG emissions and the flows of GHGs across various media and boundaries will help characterize emission levels and mark progress in reducing emissions. With enhanced means for GHG measuring and monitoring, future strategies to reduce, avoid, capture, or sequester CO_2 and other GHG emissions can be better supported, enabled, and evaluated. Key areas of technology R&D related to this goal may be grouped into four areas:

- **Anthropogenic Emissions**. Measurement and monitoring technologies can enhance and provide direct and indirect emissions measurements for various types of emissions sources using data transmission and archiving, along with inventory-based reporting systems and local-scale atmospheric measurements or indicators.

- **Carbon Capture, Storage, and Sequestration**. Advances in measurement and monitoring technologies for geologic storage can assess the integrity of subsurface reservoirs, transportation and pipeline systems, and potential leakage from geologic storage. Measurement and monitoring systems for terrestrial sequestration are also needed to integrate carbon sequestration measurements of different components of the landscape (e.g., soils versus vegetation) across a range of spatial scales.

- **Non-CO_2 Greenhouse Gases**. Monitoring the emissions of methane, nitrous oxide, black carbon aerosols, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride is important because of their high GWP and, for some, their long atmospheric lifetimes. Advanced technologies can make an important contribution to direct and indirect measurement and monitoring approaches for both point and diffuse sources of these emissions.

- **Integrated Measuring and Monitoring System Architecture**. An effective measurement and monitoring capability is one that can collect, analyze, and integrate data across spatial and temporal scales, and at many different levels of resolution. This may require technologies such as sensors and continuous emission monitors, protocols for data gathering and analysis, development of emissions accounting methods, and coordination of related basic science and research in collaboration with the Climate Change Science Program and the U.S. Integrated Earth Observation System.[5]

CCTP Goal 6

Bolster Basic Science Contributions to Technology Development

Advances arising from basic scientific research are fundamental to future progress in applied technology research and development. The dual challenges—addressing global climate change and providing the energy supply needed to meet future demand and sustain economic growth—will likely require discoveries and innovations well beyond what today's science and technology can offer. Science must not just inform decisions, but provide the underlying knowledge foundation upon which new technologies can be built. The CCTP framework aims to strengthen the basic research enterprise so that it will be better prepared to find solutions and create new opportunities. CCTP will focus on several ways to meet this goal:

- **Fundamental Research**. Fundamental research provides the underlying foundation of scientific knowledge necessary for carrying out more applied activities of research and problem solving. It is the systematic study of properties and natural behavior that can lead to greater knowledge and understanding of the fundamental aspects of phenomena and observable facts, but without prior specification toward applications, processes, or products. It includes scientific study and experimentation in the physical, biological, and environmental sciences; and many interdisciplinary areas, such as computational sciences. Related to CCTP, it is the source of much of underlying knowledge that will enable future progress in CCTP.

- **Strategic Research**. Strategic research is basic research that is inspired by technical challenges in the applied R&D programs. This is research that could lead to fundamental discoveries (e.g., new properties, phenomena, or materials) or scientific understanding that could be applied to solving specific problems or technical barriers impeding progress in advancing technologies in energy supply and end-use; carbon capture, storage, and sequestration; other GHGs; and monitoring and measurement.

- **Exploratory Research**. Innovative concepts are often too risky or multi-disciplinary for one program mission to support. Sometimes they do not fit neatly within the constructs of other mission-specific program goals. Therefore, not all of the research on innovative concepts for climate-related technology is, or should be, aligned directly to one of the existing Federal R&D mission-related programs. The climate change challenge calls for new breakthroughs in technology that could dramatically change the way energy is produced, transformed, and used in the global economy. Basic, exploratory research of innovative and novel concepts, not elsewhere covered, is one way to uncover such "breakthrough technology" and strengthen and broaden the R&D portfolio.

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[5] http://ostp.gov/html/EOCStrategic_Plan.pdf

- **Integrated Planning**. Effective integration of fundamental research, strategic research, exploratory research, and applied technology development presents challenges to and opportunities for both the basic research and applied research communities. These challenges and opportunities can be effectively addressed through innovative and integrative planning processes that place emphasis on communication, cooperation and collaboration among the many associated communities and on workforce development to meet the long-term challenges. CCTP seeks to encourage broadened application of successful models and best practices in this area.

2.3 Core Approaches

Consistent with the principles established by the President, CCTP will employ seven core approaches to stimulate participation by others and ensure progress toward attainment of CCTP strategic goals: (1) strengthen climate change technology R&D; (2) strengthen basic research at universities and federal research facilities; (3) enhance opportunities for partnerships; (4) increase international cooperation; (5) support cutting-edge technology demonstrations; (6) ensure a viable technology workforce of the future through education and training, and (7) explore and provide, as appropriate, supporting technology policy. Chapter 10 outlines next steps for CCTP for each of these core approaches.

Approach 1: Strengthen Climate Change Technology R&D

The Federal Government is engaged in a wide range of research and technology development and deployment activities that directly or indirectly contribute to meeting the President's climate change goals, investing about $3 billion in Fiscal Year 2005 in related technology R&D (Appendix A). Strengthening R&D, however, does not necessarily mean spending more money—it can also mean spending available resources more wisely by appropriately prioritizing activities and reallocating resources, or by leveraging them with the work of others.

To strengthen the current state of the U.S. climate change technology R&D, the CCTP has made, and will continue to make, recommendations to the Cabinet-level CCCSTI to sharpen the focus of and provide support for climate change technology R&D in a manner consistent with the mix and level of R&D investment required by the nature of the technical challenge.

Approach 2: Strengthen Basic Research Contributions

A base of supporting fundamental research is essential to the applied R&D for technology development. The CCTP approach includes strengthening basic research in Federal research facilities and academia by focusing efforts on key areas needed to develop insights or breakthroughs relevant to climate-related technology R&D. A strong and creative science program is necessary to support and enable technical progress in CCTP's portfolio of applied R&D programs, explore novel approaches to new challenges, and bolster the underlying knowledge base for new discoveries.

Fundamental discoveries can reveal new properties and phenomena that can be applied to development of new energy technologies and other important systems. These can include breakthroughs in our understanding of biological functions, properties and phenomena of nano-materials and structures, computing architectures and methods, plasma science, environmental sciences, and many more that are currently on the horizon.

Approach 3: Enhance Opportunities for Partnerships

Federal research is but one element of the overall strategy for development and adoption of advanced climate change technologies. Engagement in this process by private entities, including business, industry, agriculture, construction, and other sectors of the U.S. economy, as well as by non-Federal governmental entities, such as the States and non-governmental organizations, is essential to make R&D investments wisely and to expedite innovative and cost-effective approaches for reducing greenhouse gas emissions.

Public-private partnerships can facilitate the transfer of technologies from Federal and national laboratories into commercial application. Partnering can also advise and improve the productivity of Federal research. Private partners also benefit, because those who are engaged in Federal R&D gain rights to intellectual property and gain access to world-class scientists, engineers, and laboratory facilities. This can help motivate further investment in the commercialization of technology.

Today, partnering is a common mode of operation in most Federal R&D programs, but the partnering process can be improved. Opportunities exist for private participation in virtually every aspect of Federal R&D. With respect to climate change technology R&D, the CCTP seeks to expand these opportunities in R&D planning, program execution, and technology demonstrations, leading ultimately to more efficient and timely commercial deployment. The Regional Carbon Sequestration Partnerships, initiated by DOE in November 2002, are examples of ongoing public-private joint efforts.

Approach 4: Increase International Cooperation

Given the global nature of climate change concerns, and in recognition of the contributions being made by others abroad, the CCTP seeks to engage other nations—government to government—in large-scale cooperative technology research initiatives. Such cooperation can prove beneficial to the success of U.S. technology development initiatives, through leveraging of resources, partitioning of research activities addressing large-scale and multi-faceted complex problems, and sharing of results and knowledge created.

Under the auspices of the Cabinet-level CCCSTI, the U.S. Government has contributed to several multilateral cooperative agreements, such as the International Partnership for a Hydrogen Economy (IPHE); the international Carbon Sequestration Leadership Forum (CSLF); the international Methane-to-Markets Partnership; and the International Thermonuclear Experimental Reactor (ITER), an international project to develop fusion as a commercially viable power source. In certain areas of climate change technology R&D, such as advanced wind turbine design, and nuclear fission and fusion energy research, many advanced technical capabilities reside abroad, as well as in the United States. Since June 2001, the United States has launched bilateral partnerships with Australia, Brazil, Canada, China, Belize, Costa Rica, El Salvador, Germany, Guatemala, Honduras, Nicaragua, and Panama, the EU, India, Italy, Japan, Mexico, New Zealand, Republic of Korea, the Russian Federation, and South Africa on issues ranging from climate change science to energy and sequestration technologies to policy approaches. The countries covered by these bilateral partnerships account for over 70 percent of global greenhouse gas emissions. In addition, the U.S. is a leader in the 58-member country Global Earth Observations System of Systems.

In related developments in July 2005, President Bush and the G-8 Leaders agreed on a far-reaching Plan of Action to speed the development and deployment of clean energy technologies to achieve the combined goals of addressing climate change, reducing harmful air pollution, and improving energy security in the U.S. and throughout the world. The G-8 will work globally to advance climate change policies that grow economies, aid development, and improve the environment.

Also in July 2005, the United States joined with Australia, China, India, Japan, and South Korea to accelerate clean development under a new Asia-Pacific Partnership on Clean Development. This partnership will focus on voluntary practical measures taken by these six countries in the Asia-Pacific region to create new investment opportunities, build local capacity, and remove barriers to the introduction of clean, more efficient technologies. This partnership will help each country meet nationally designed strategies for improving energy security, reducing pollution, and addressing the long-term challenge of climate change.

CCTP seeks to expand on these and other international opportunities to stimulate international participation in the development of new and advanced climate change technologies, foster capacity building in developing countries, encourage cooperative planning and joint ventures and, enable the more rapid development, transfer and deployment of advanced climate change technology.

Approach 5: Support Cutting-Edge Technology Demonstrations

Demonstrations of cutting-edge climate change technologies are an important aspect of the goal to advance climate change technologies. They can help advance a technology's progress from the research phase, where a concept may have been proven in principle or shown to work in the laboratory, but where performance in an operating environment and at a larger scale is still unknown or uncertain. Such performance characteristics are important to the viability of a technology, where a substantial investment, motivated by clear and expected financial returns, depends on having confidence in technical performance.

Technology demonstrations afford unique opportunities to reduce investment uncertainty. They unveil the parameters affecting a technology's cost and operational performance. They identify areas needing further improvement or cost reduction. Federal leadership through technology demonstrations can strongly influence decisions of private-sector investors and other non-government parties.

Approach 6: Ensure a Viable Technology Workforce of the Future

The development and deployment, on a global scale, of new and advanced climate change technologies will require a skilled workforce and an abundance of intellectual talent, well versed in associated concepts and disciplines of science and engineering. Workforce development and education are integral components of any sustained and successful scientific and technological undertaking of this scope and magnitude. The CCTP mission and goals provide a unique opportunity to strengthen Federal investments across all participating agencies in science, math, and engineering education and to attract talented individuals to focus their careers on this global endeavor. Such efforts could be coordinated with other countries, and particularly in emerging economies of the developing world, where much of 21st century emissions will be concentrated.

Approach 7: Provide Supporting Technology Policy

Should widespread adoption of advanced climate change technologies be pursued, as guided by science, it would likely need to be supported by appropriate technology policy, potentially including market-based incentives. While some CCTP-supported advanced technologies may be sufficiently attractive, for a variety of reasons, to find their way into the marketplace at a large scale without supporting policy or incentives, others would not. Even with further technical progress, technologies that capture or sequester $CO_{2,}$ for example, or others that afford certain climate change-related advantages, are expected to remain more expensive than competing technologies that do not.

As Federal efforts to advance technology go forward, broadened participation by the private sector in these efforts is important to both the acceleration of innovation and the adoption of the technologies. Such participation, envisioned to extend beyond R&D partnering and demonstrations (Approaches 3 and 5 above), can be encouraged by appropriate and supporting technology policy. This is evidenced today, in part, by a number of market-based incentives already in place and by others proposed by the Administration.[6]

2.4 Prioritization Process

An important role of the CCTP is to provide strategic direction for and strengthen the Federal portfolio of investments in climate change technology R&D. The CCTP continues to prioritize the portfolio of Federally funded climate change technology R&D consistent with the President's National Climate Change Technology Initiative (NCCTI). The CCTP will also identify within its portfolio a subset of NCCTI priority activities, defined as discrete R&D activities that address technological challenges, which, if solved, could advance technologies with the potential to dramatically reduce, avoid, or sequester greenhouse gas emissions.

Prioritization of Federal technology R&D activities related to climate change is a dynamic process that has evolved over time in response to emerging knowledge. This evolution is expected to continue. Through coordinated interagency planning, the CCTP priorities will be reviewed periodically in conjunction with the Federal budget process, and recommendations will be made through the IWG to the CCCSTI.

This CCTP *Strategic Plan* provides a government-wide basis for guiding the formulation of the comprehensive Federal climate change technology R&D portfolio; identifying high priority investments, gaps, and emerging opportunities; and organizing future CCTP-related research. The CCTP planning activities will be informed by results of studies, inputs from many and diverse sources, technical workshops, assessments of technology potentials, analyses regarding long-term energy and emissions outlooks, and modeling by a number of groups of a range of technology scenarios over the next 100 years (see Chapter 3). These planning activities will be guided by several important portfolio planning principles and investment criteria.

2.4.1 Portfolio Planning Principles

The CCTP adheres to three broad principles. The first principle, given the many attendant uncertainties about the future, is that the whole of the individual R&D investments should constitute a balanced and diversified portfolio. Considerations include the realizations that (1) no single technology will likely meet the challenge alone; (2) investing in R&D in advanced technologies involves risk, since the results

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[6] Federal Climate Change Expenditures Report to Congress, March 2005 http://www.whitehouse.gov/omb/legislative/fy06_climate_change_rpt.pdf

of these investments are not known in advance, and, among successful outcomes, some are not likely to be as successful as hoped; and (3) a diverse array of technology options can hedge against risk and provide important flexibility in the future, which may be needed to respond to new and potentially strategy-changing information. The CCTP portfolio also strives to balance short- and long-term technology objectives.

A balanced and diversified portfolio must address risk in a way that hedges that risk, for example, by investing in projects that will pay off under different states of the future world. Identifying what the major sources of uncertainty are helpful in this regard, such as the degree of future GHG emissions and reductions under varying assumptions, about energy prices, technology costs and performance, and other variables. CCTP's tools in this regard are partially addressed in Chapter 3, but further work in terms of portfolio analysis, and expected benefits and costs, will be required.

The second principle is to ensure that factors affecting market acceptance are addressed. In order to enable widespread deployment of advanced technologies, each technology must be integrated within a larger technical system and infrastructure, not just as a component. Market acceptance of technologies is influenced by a myriad of social and economic factors. The CCTP's portfolio planning process must be informed by and benefit from private sector and other non-federal inputs, examine the lessons of historical analogues for technology acceptance, and apply them as a means to anticipate issues and inform R&D planning.

Third, and perhaps most importantly, the anticipated timing regarding the commercial readiness of the advanced technology options is an important CCTP planning consideration. Energy infrastructure has a long lifetime, and change in the capital stock occurs slowly. Once new technologies are available, their adoption takes time. Some technologies with low or near-net-zero GHG emissions may need to be available and moving into the marketplace decades before their maximum market penetration is achieved.

2.4.2 Portfolio Planning and Investment Criteria

Within the planning framework of vision, mission, goals, approaches, and portfolio investment principles, the CCTP's prioritization process applies four criteria (see Box 2-1). Once the individual competing investments are identified, the CCTP will consider their merits based on maximizing expected benefits versus costs (Criterion #1), subject to consideration of the distinct roles of the public and private sectors in R&D (Criterion #2). In addition, because of the risk of spreading resources across too many areas, the CCTP focuses on technologies with potential for large-scale application (Criterion #3). Technologies that are expected to have limited impact on overall GHG emissions may still be given priority if they can deliver earlier in the century and/or are particularly cost-compelling. Finally, timing of investments is an important consideration in the decision process. The CCTP planning process gives weight to considerations of logical sequencing of research (Criterion #4), where the value in knowing whether a technological advance is or is not successful can have a cascading effect on the sequencing of later investments.

2.4.3 Application of Criteria

The CCTP's review, planning and prioritization process will rely on ongoing reviews of strategies for technology development, buttressed by analysis, and of the overall R&D portfolio's adequacy to make progress toward attainment of each CCTP strategic goal. There will be an emphasis on identifying gaps

Box 2-1

CCTP Portfolio Planning and Investment Criteria

1. Maximizing Expected Return on Investment. R&D investments that have the prospect to generate maximum expected benefits per dollar of investment receive priority in investment planning. Benefits are defined with respect to expected contributions to the attainment of CCTP goals, particularly GHG reductions, but also include other considerations, such cost-effectiveness, improved productivity, and reduction of other pollutants. Climate change benefits are long-term public goods. Discount rates must be appropriate to the context, particularly when applied to very long-term impacts. This criterion includes considerations of development and deployment risks, and the hedging of risks across multiple projects. Projects with high risk, but low emissions-reduction potential should be removed from the CCTP R&D portfolio.

2. Acknowledging the Proper and Distinct Roles for the Public and Private Sectors. The CCTP portfolio recognizes that some R&D is the proper purview of the private sector; other R&D may be best performed jointly through public-private partnerships; and still other R&D may be best performed by the Federal sector alone. In cases where public support of R&D is warranted, technology development and adoption require cooperation and engagement with the private sector. History demonstrates that early involvement in technology R&D by the business community increases the probability of commercialization. A key consideration in the investment process is the means for engaging the talents of the private sector using innovative and effective approaches.

3. Focusing on Technology with Large-Scale Potential. The scope, scale, and magnitude of the climate change challenge suggest that relatively small, incremental improvements in existing technologies will not enable full achievement of CCTP goals. Every technology option has limits of various kinds. Such limits need to be identified, explored, and understood early in the planning process. Technology options should be adaptable on a global scale and have a clear path to commercialization. High-priority investments will focus on technology options that could, if successful, result in large mitigation contributions, accumulated over the span of the 21st century. For technologies on the lower end of this criterion, benefits should be deliverable earlier in the century and/or be particularly compelling from a marginal benefit/cost perspective.

4. Sequencing R&D Investments in a Logical, Developmental Order. Investments must be logically sequenced over time. Supporting a robust and diversified portfolio does not mean that all technology options must be supported simultaneously, or that all must proceed at an accelerated pace. Logical sequencing of R&D investments takes into account (i) the expected times when different technologies may need to be made available and cost-effective, (ii) the need for early resolution of critical uncertainties, and (iii) the need to demonstrate early success or feasibility of technologies upon which other technology advancements may be based.

and key opportunities for new initiatives, accompanied by periodic realignments. The process is not easily reduced to quantitative analysis due, in part, to the large number of variables and uncertainties associated with the nature of the climate change technology challenge and, in part, to the CCTP's century-long planning horizon. Nevertheless, the prioritization criteria discussed above will be applied by the participating agencies to the maximum extent practicable and augmented by inputs from various sources.

As a first step in the prioritization process, CCTP established a baseline, or inventory, of the existing portfolio of R&D activities across the participating agencies. Criteria for inclusion in this CCTP portfolio baseline are presented in Appendix A. They closely track CCTP strategic goals. As shown in Appendix A, the resulting multi-agency baseline inventory accounted for more than $3 billion in R&D activities in FY 2005. This inventory will need to be periodically updated.

The second step in the process is to identify and focus on the more important elements of a diversified strategy, assisted by insights gained from scenarios (see Chapter 3) and other analyses, and assess the portfolio both as a whole and as composed of potential contributions toward goal attainment associated with each activity in the portfolio. This assessment is intended to affirm some elements of the portfolio, challenge others, and identify gaps and promising opportunities. Once a full set of candidate investments is identified, including gaps and opportunities, the prioritization criteria can be applied to each proposed investment activity. This step will require continuing development of analytical tools and methods, including assessments of various technologies and their potentially limiting factors.

The CCTP portfolio of today reflects a "snapshot" in time of the results of a continuing and ongoing review and realignment in light of new and changing emphasis among competing national needs. In the years ahead, it is expected that the CCTP portfolio and planning emphasis will continue to evolve, as more studies and analyses are conducted, technology assessments are completed, additional gaps and opportunities are identified, and new developments and scientific knowledge emerge.

2.5 Management

The CCTP is multi-agency R&D planning and coordination activity. It accomplishes its work by engaging and assisting the Federal R&D agencies in their respective efforts to plan, prioritize, and coordinate research activities to meet CCTP goals. As the representative on CCTP-related matters of its participating agencies, CCTP also works with the Administration to formulate overall budget guidance and recommend adjustments, where appropriate, to the Federal R&D portfolio in order to better meet CCTP goals. As discussed below, the CCTP's management functions include executive direction, inter-agency planning and integration, agency implementation, external interactions, and program support.

2.5.1 Executive Direction

The CCTP exercises executive direction through the Cabinet-level Committee on Climate Change Science and Technology Integration (CCCSTI), and its associated Interagency Working Group (IWG) on Climate Change Science and Technology. The IWG is populated by agency deputies, who can adopt coordinated plans, programs, and actions that will guide their respective agencies' implementation. The IWG also provides guidance on strategy and reviews and approves CCTP strategic planning documents.

Executive direction is further facilitated by a CCTP Steering Group comprised of senior-level representatives from each participating Federal agency. The Steering Group ensures that all agencies have a means to raise and resolve issues regarding the CCTP and its functions as a facilitating and coordinating body. The Steering Group assists the CCTP Director in accessing needed information and resources within each agency. The Steering Group is briefed regularly on CCTP plans and activities and assists in developing agency budget crosscuts and proposals, conveying information and actions back to the agencies, and supporting accomplishment of the CCTP mission. The Steering Group ensures that consistent guidance and direction is given to the CCTP Working Groups, and formulates recommendations and advice back to the CCCSTI, through the IWG.

2.5.2 Interagency Planning and Integration

Six CCTP Working Groups (WGs), aligned with the six CCTP strategic goals (Box 2-2), are primarily responsible for carrying out the missions and staff functions of the CCTP in a coordinated multi-agency manner. The WGs are assisted by subgroups, as appropriate, and by technical staff drawn from the participating agencies, affiliated laboratories and facilities, and other available consulting staff. The WGs are expected to:

- Serve as the principal means for interagency deliberation and development of CCTP plans and priorities, and the formulation of guidance for supporting analyses in WG's respective areas

- Provide a forum for exchange of inputs and information relevant to planning processes, including workshops and other meetings

- Engage, cooperate with, and coordinate inputs from the relevant R&D agencies

- Identify ongoing R&D activities and identify R&D gaps, needs, and opportunities—near and long term

- Support relevant interfaces with CCSP science studies and analyses

- Formulate advice and recommendations to present to the CCCSTI

- Assist in the preparation of periodic reports to Cabinet members and the President.

2.5.3 Agency Implementation

The CCTP relies on the participating Federal agencies and their respective R&D portfolios to contribute to CCTP goal accomplishment, recognizing that the agencies must balance CCTP priorities with other mission requirements. The CCTP relies on the agencies to place appropriate priority on CCTP program implementation. Priority setting is facilitated by appointing agency heads and deputies to the CCCSTI and IWG. Top agency officials make up the CCTP Steering Group. Agency executives and senior-level managers serve as chairs and members of the CCTP Working Groups. Once CCTP plans, programs, and priorities are set and approved by the Cabinet-level CCCSTI, the agencies are expected to follow through and contribute to their execution and completion.

2.5.4 External Interactions

The CCTP accesses expert opinion and technical input from various external parties, through advisory groups, program peer-review processes, conference participation, international partnerships, and other activities. In addition, CCTP staff convenes technical workshops and meetings with experts both inside and outside the Federal Government. The CCTP activities are of interest to a number of external parties, including State and local governments, regional planning organizations, academic institutions, national laboratories, and non-governmental organizations. They are of interest, as well, to foreign

Box 2-2
CCTP Working Groups

Energy End-Use – Led by DOE
- Hydrogen End-Use
- Transportation
- Buildings
- Industry
- Electric Grid and Infrastructure

Energy Supply – Led by DOE
- Hydrogen Production
- Renewable and Low Carbon Fuels
- Renewable Power
- Nuclear Fission Power
- Fusion Energy
- Low Emissions Fossil-Based Power

CO_2 Sequestration – Led by USDA
- Carbon Capture
- Geologic Storage
- Terrestrial Sequestration
- Ocean Storage
- Products and Materials

Other (Non-CO_2) Gases – Led by EPA
- Energy & Waste – Methane
- Agricultural Methane and Other Gases
- High Global-Warming-Potential Gases
- Nitrous Oxide
- Ozone Precursors and Black Carbon

Measuring and Monitoring – Led by NASA
- Application Areas
- Integrated Systems

Basic Research – Led by DOE
- Fundamental Research
- Strategic Research
- Exploratory Research
- Integrative R&D Planning

governments, and international organizations, such as the Organization for Economic Cooperation and Development (OECD), the International Energy Agency (IEA), various global and regional compacts, and the IPCC. CCTP needs to communicate its activities to such entities and provide coordinated support, through the relevant agency programs, for enhanced external and international cooperation by engaging with and supporting activities of mutual interest.

2.5.5 Program Support

The CCTP staff will provide technical and administrative support and day-to-day coordination of CCTP-wide program integration, strategic planning, product development, communication, and representation. The CCTP staff will (1) provide support for the Working Groups and the Steering Group; (2) foster integration of activities to support the CCTP goals; (3) conduct and support strategic planning activities that facilitate the prioritization of R&D activities and decision-making on the composition of the CCTP RDD&D portfolio, including conducting analytical exercises that support planning (such as technology assessments and scenario analysis); (4) develop improved methods, tools, and decision making processes for climate technology planning and management, R&D planning, and assessment; (5) develop products that communicate the CCTP's plans, as well as the progress of the CCTP and its Federal participants toward meeting the CCTP goals; (6) coordinate interagency budget planning and reporting; (7) assist and support the Administration in representing U.S. interests in the proceedings of the United Nations' IPCC Fourth Assessment Report (AR4) process; and (8) coordinate agency support of international cooperative agreements.

2.6 Strategic Plan Outline

In the chapters that follow, CCTP provides a century-long planning context, goal-oriented strategies for technology development, and a summary of conclusions and next steps. Chapter 3 provides a synthesis assessment, based on a number of representative works in the literature on economic modeling and forecasting of future global GHG emissions. This is accompanied by a number of insights regarding opportunities for advanced technologies gained from scenarios analyses. Chapters 4 through 9 focus in some depth, respectively, on each of the CCTP's six strategic goals. Each chapter outlines elements of a technology development strategy, highlights ongoing work and suggests promising areas for future research. Chapter 10 provides a summary of conclusions regarding CCTP and its strategic goals and identifies a series of next steps within the context of each of CCTP's seven approaches. Each approach is applicable, to varying degrees, to each of CCTP's six strategic goals.

3 Synthesis Assessment of Long-Term Climate Change Technology Scenarios

In order for the Climate Change Technology Program (CCTP) to develop plans, carry out activities and help shape an R&D portfolio that will advance the attainment of its vision, mission and strategic goals, CCTP needs a long-term planning context, informed by analyses from multiple sources and aided by a variety of models and other decision support tools. An important aspect of shaping this planning context is the ability to make assessments of the potential contributions that advanced technologies could make to CCTP strategic goals if their technological potentials are realized.

Such assessments are complex and subject to many uncertainties. They require consideration of a range of assumptions about the future. Specifically, a technology strategy aimed at influencing global GHG emissions over the course of the 21st century would need to consider changing populations, varying rates of regional economic development, differing regional technological needs and interests, and availability of natural resources. In addition, the long-term costs of GHG emission reductions will depend in part on future technological innovations, many of which are presently unknown, and on other factors that could either promote or discourage the use of certain technologies in the future. Finally, both uncertainties inherent in climate science and the fact that value judgments are involved make it difficult to determine a level at which atmospheric GHG concentrations in the Earth’s atmosphere would meet the UNFCCC’s ultimate objective of achieving “stabilization of greenhouse gas concentrations in Earth’s atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system… within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.”

One approach to planning under such conditions of uncertainty is scenarios analysis. Scenarios present alternative views about the rate of future GHG emissions growth to help gauge the scope of the potential challenge, by methodically and consistently accounting for the complex interactions among economic and demographic factors, energy supply and demand, the advance of technology, and GHG emissions. Scenarios can also investigate feasible pathways to achieving varying levels and schedules of GHG emissions reductions in the future and provide a relative indication of the potential emission reduction benefits of particular classes of technology under a range of different future conditions, and a better understanding of the factors and constraints that might affect the market penetration of these classes of technology. On the other hand, results of scenarios analyses are strongly influenced by a multitude of assumptions and methodological considerations. Scenarios should not be considered predictions.

Many research organizations, university-based teams, government agencies, and other groups have engaged in scenario analysis efforts to explore these topics. This chapter reviews and synthesizes the results of these efforts to gain insights on the scope of the potential technological challenge, the potential contributions of advanced technologies, and to guide CCTP in developing an effective technology development strategy.

3.1 The Greenhouse Gases

Greenhouse gases (GHGs) are those that absorb and emit radiation at specific wavelengths, which causes the “greenhouse effect,” i.e., the trapping of heat in the atmosphere. As shown in Figure 3-1, the GHGs

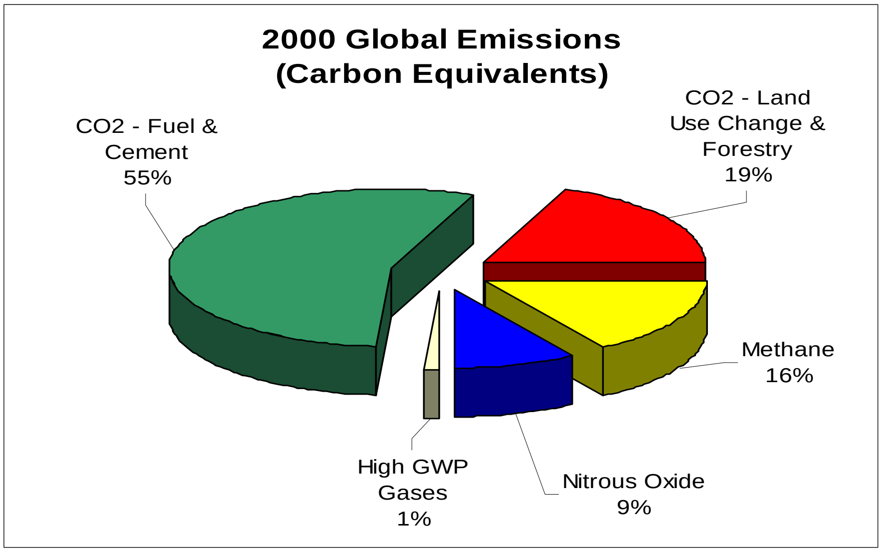

Figure 3-1. Emissions of GHGs in 2000 (% of total GtC-eq.)

Source: http://www.epa.gov/methanetomarkets/docs/methanemarkets-factsheet.pdf

include[1] carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and substances with very high global warming potential,[2] such as the halocarbons and other chlorine and bromine containing substances.[3] CO_2 emissions from the burning of fossil fuels, other industrial activity, and land use change and forestry, account for the majority of GHG emissions. The combined emissions from methane, nitrous oxide, and high-GWP gases accounted for about one-quarter of all GHG emissions (after converting the non-CO_2 gases to a CO_2-equivalency basis, in terms of gigatons carbon equivalent, or GtC-eq.) in the year 2000.

As a GHG resulting from human activities, methane's contribution is second only to CO_2. Methane, on a kilogram-for-kilogram basis, is 23 times more effective at trapping heat in the atmosphere than CO_2 over a 100-year time period. Methane is emitted from various energy-related activities (e.g., natural gas, oil and coal exploration, and coal mining), as well as from agricultural sources (e.g., emissions from cattle digestion and rice cultivation; and waste disposal facilities, landfills and wastewater treatment plants). Methane emissions have declined in the United States since the 1990s, due to voluntary programs to reduce emissions and regulation requiring the largest landfills to collect and combust their landfill gas.[4]

Another important gas is nitrous oxide (N_2O), which is emitted primarily by the agricultural sector through direct emissions from agricultural soils and indirect emissions from nitrogen fertilizers used in agriculture. Aside from CH_4 and N_2O, other non-CO_2 GHGs, including certain fluorine-containing halogenated substances (e.g., HFCs, PFCs, and SF_6), accounted for about 2 percent of total U.S. GHG

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[1] Water vapor and ozone are also GHGs.

[2] Global warming potentials (GWPs) are used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP provides a construct for converting emissions of various gases into a common measure.

[3] The ozone-depleting halocarbons and other chlorine and bromine containing substances are addressed by the Montreal Protocol and are not directly addressed by this Plan. Besides CO_2, N_2O and CH_4, the IPCC definitions of greenhouse gases include sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

[4] See http://www.epa.gov/methane/voluntary.html

emissions in 2003 (EPA 2005). These gases are used or produced by a variety of industrial processes. In most cases, emissions of these fluorine-containing halogenated substances were relatively low in 1990 but have since grown rapidly. The sources of these non-CO_2 GHG emissions are discussed in more detail in Chapter 7.

The heat-trapping capacity of GHGs varies considerably. GHGs also have different lifetimes in the atmosphere. Also, some anthropogenic emissions such as aerosols can have cooling effects. Combining these effects, the Intergovernmental Panel on Climate Change (IPCC) estimated the key anthropogenic and natural factors causing changes in warming (positive radiative forcing[5]) and cooling (negative radiative forcing) from year 1750 to year 2000,[6] as shown in Figure 3-2.

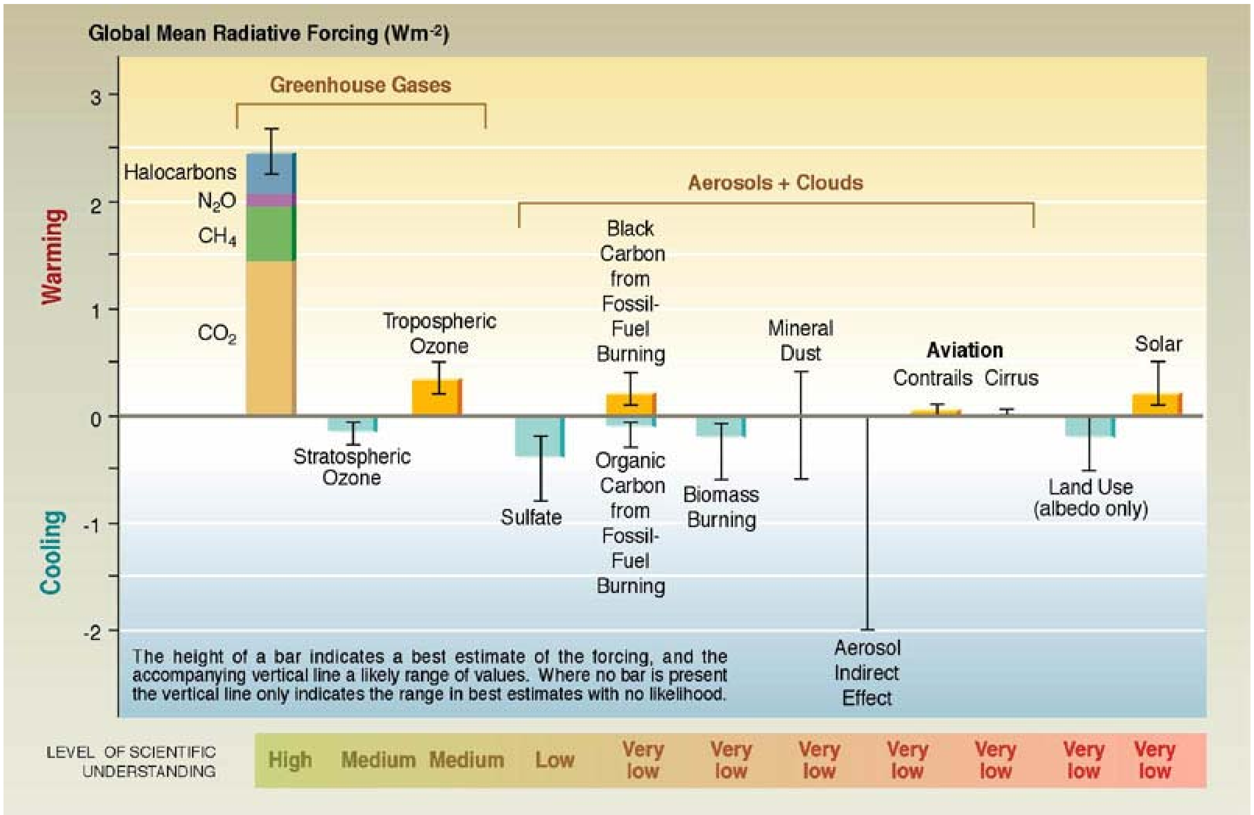

Figure 3-2. Global Mean Radiative Forcing of the Climate System for the Year 2000, Relative to 1750 (*Source: IPCC*[7]*).*

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[5] Radiative forcing is the change in the balance between radiation coming into the atmosphere and radiation going out.

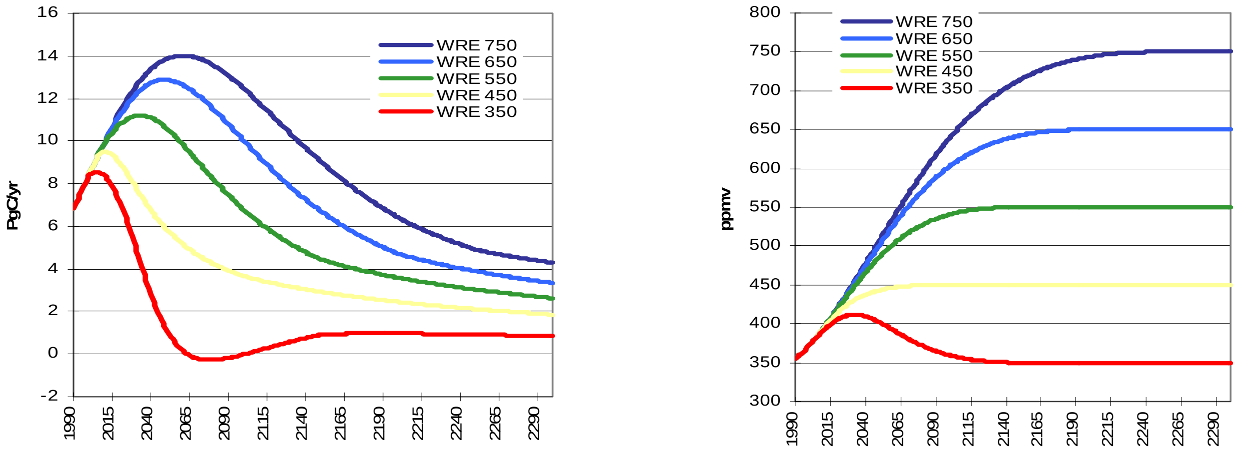
[6] A large body of work has been undertaken to understand the influence of external factors on climate using the concept of changes in radiative "forcing" due to changes in the atmospheric composition, alteration of surface reflectance by land use, and variations in solar input. Some of the radiative forcing agents are well mixed over the globe, such as CO_2, thereby perturbing the global heat balance. Others represent perturbations with stronger regional signatures because of their spatial distribution, such as aerosols. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system.

[7] Available at http://www.ipcc.ch/present/graphics/2001syr/large/06.01.jpg

The differences in the characteristics of GHGs and other radiatively important substances, as well as the potential differences in the rates of the growth their emissions over time, influence the formulation of strategies to stabilize overall GHG concentrations.

3.2 Emissions Scenarios Aimed at Stabilizing GHG Concentrations

The scenarios literature has explored the implications of a range of long-term stabilization levels, and various emissions-reduction scenarios have been explored for each stabilization level. Figure 3-3 shows one set of relationships between CO_2 emissions and CO_2 concentrations over time, across a range of CO_2 stabilization levels commonly considered in the scenarios literature.[8] This illustrative set of stabilization levels (Figure 3.3-B) does not include *all* possible stabilization levels that might be consistent with the UNFCCC ultimate objective. In addition, the set of emission curves (Figure 3.3-A) does not represent the only emissions scenarios that could theoretically lead to the corresponding stabilization levels. However, the examples illustrate that emissions trajectories leading the stabilization typically show growth of emissions slowing; and then the emissions eventually peaking, declining and, ultimately, approaching levels that are low or near zero. Uncertainty about the appropriate stabilization levels implies a wide range of possible time periods over which the emissions decrease might occur. Stabilization of CO_2 emissions has been the subject of modeling studies for over a decade. More recently, the multi-gas strategies that consider the possible tradeoffs among GHG emission reductions are being studied (e.g,, see Weyant and de la Chesnaye 2005).



A. Emissions Trajectories from Fossil Fuel Use and Industrial Activities

B. Corresponding Concentration Trajectories

Figure 3-3. Illustrative CO_2 Emissions Profiles and Their Impact on Concentration

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[8] Derived from Wigley et al. 1996. The emissions curves represent net emissions from fossil fuels (i.e., including emissions reductions from carbon dioxide capture and storage) and industrial sources. They do not include emissions from land use and land-use change. The concentration trajectories make specific assumptions regarding net emissions from land use and land-use change, and certain assumptions about the carbon cycle more generally, including assumptions regarding the rate of ocean uptake. Note that significant uncertainties remain about many aspects of the carbon cycle. Optimal emissions paths for fossil fuels and other industrial sources that lead to stabilization could differ from those shown in the figures. Other estimated relationships between emissions and concentrations can be found in the scenarios literature.

3.3 Factors Affecting Future GHG Emissions

Most of the surveyed analyses of future GHG emissions indicate that, in the absence of actions taken to mitigate climate change, increases will occur in both anthropogenic emissions of GHGs and their atmospheric concentrations. The projected rate of emissions growth is dependent on many factors that cannot be predicted with certainty. Widely read studies conducted by organizations, including the IPCC,[9] the Stanford Energy Modeling Forum (EMF),[10] and others,[11] indicate that the more significant factors affecting future GHG emissions growth include demographic change (e.g., regional population growth); social and economic development (e.g., gross world product and standard of living); increases in fossil fuel use; changes in land use; increases in other GHG-emitting activities of industry, agriculture and forestry; and the rate of technological change.

Energy generation and consumption are key determinants of CO_2 emissions. The scenarios with the highest CO_2 emissions are those that assume the highest energy demand along with the highest proportion of fossil fuels in energy production, unless that fossil energy combustion is accompanied by CO_2 capture and storage. Since 1900, global primary energy consumption has, on average, increased at more than two percent/year. The shorter-term trend from 1975 to 1995 shows a similar rate of increase. In the IPCC *SRES* scenarios of the future, 90 percent of the scenarios projected world primary energy use in 2100 to be within the range of 600 to 2800 exajoules (EJ). In 2000, by comparison, total world primary energy use was ~400 EJ. Among the many scenarios surveyed, the average annual growth rates for the century-long period from 2000 to 2100 range from 2.4 percent/year to -0.1 percent/year, with a median value of 1.3 percent/year.[12]

Other organizations, such as the U.S. Energy Information Administration (EIA), make shorter-term projections of total world energy demand. In its most recent projection (EIA 2004), EIA projected world energy demand in its reference case would be 623 EJ/year in 2025. In EIA's work, primary energy use in the developed world is projected to increase by 1.2 percent per year between 2001 and 2025, whereas primary energy consumption in the developing world is projected to grow at an average annual rate of 2.7 percent. Energy use in the emerging economies of developing Asia, which include China and India, is projected to more than double over the course of the quarter century.

At the present time, 1.7 billion people in the world have no access to electricity and 2 billion people are without clean and safe cooking fuels, relying instead on traditional biomass (UNDP 2000). Over the course of the 21st century, a greater percentage of the world's population is expected to gain access to

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[9] A key study that examined emissions growth in the absence of special initiatives directed at climate change is the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC 2000), in which six of the world's leading energy-economic models were used to explore a suite of scenarios that projected growth in global energy and GHG emissions.

[10] See http://www.stanford.edu/group/EMF/publications/index.htm

[11] See for example, *Direct and Indirect Human Contributions to Terrestrial Carbon Fluxes: A Workshop Summary* (2004) and *Human Interactions with the Carbon Cycle: Summary of a Workshop* (2002), both available from the National Academies Press.

[12] Scenarios that show low or negative energy consumption growth rates over time represent cases where technological improvement is projected to be very rapid and where population and GDP growth rates lie at the lower bounds of the projections.

commercial energy, as well as experience improvements to quality of life, resulting in increased per capita energy use. In addition, world population is expected to grow significantly, which is expected to increase further overall demand for energy.

3.3.1 CO_2 Emissions from Energy Consumption

According to EIA (2004), in the near term (between 2001 and 2025) annual global CO_2 emissions may increase by about 60 percent. For the United States, EIA projects that, by 2025, total CO_2 emissions will increase by 30 percent above the level in 2002. Higher growth rates are expected in the developing regions of the world, where CO_2 emissions may increase by a factor of two or more by 2025. In 2025, global use of petroleum products, primarily in the transportation sector, is expected to continue to account for the largest share of global emissions of CO_2. This is followed in importance by the use of coal, primarily used for electricity generation, and natural gas, which is used for power generation, residential/commercial fuel, and many other uses. Figure 3-4 shows the breakdown of global CO_2 emissions from fossil fuel combustion by end-use sector for 2002.

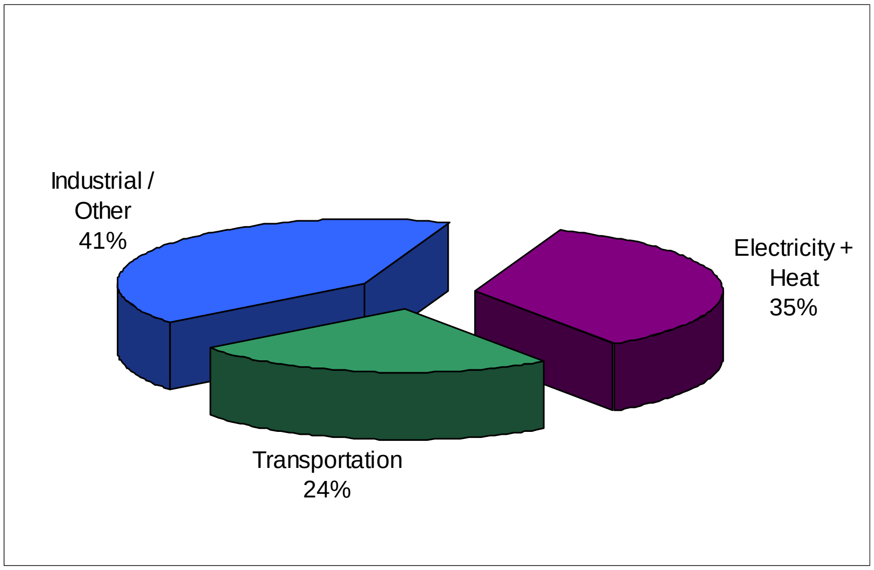

Figure 3-4. Breakdown of CO_2 Emissions from Fossil Fuel Combustion in 2002

(Source: http://www.iea.org/textbase/papers/2005/co2_fact.pdf)

Longer-term projections of CO_2 emissions were compiled during the analysis conducted by IPCC (2000) of multiple reference scenarios from six long-term modeling efforts. This compilation reveals that different assumptions about the driving forces can lead to divergent emissions trajectories. Ninety percent of the CO_2 emissions projections fall within the upper and lower bounds shown in Figure 3-5. The mean, median, and percentage bands shown in Figure 3-5 were calculated based on the range of projections across the full set of scenarios, and do not represent probabilities associated with the projections.

The upper bound is formed by scenario results that assume very high world economic growth, high per-capita energy use, and continued dominance of fossil fuels. At this upper bound, world CO_2 emissions from energy use are projected to grow from about 6 GtC/year in 2000 to more than 30 GtC/year in 2100 – a five-fold increase.

The lower bound in Figure 3-5 is formed by scenarios that assume less population growth, changes in the composition of economic activity away from energy-intensive output, lower per capita energy use, more energy efficiency, and considerably more use of carbon-neutral fuels, compared to the upper bound. At this lower bound, CO_2 emissions are projected to grow for the first half the century, but then to decline to levels about equal to those in 2000–representing no net growth by 2100. Assumptions for the various scenarios are described in Box 3-2.[13] The models used in this study include AIM,[14] ASF,[15] IMAGE,[16] MARIA,[17] MESSAGE,[18] and MiniCAM.[19]

Recent studies have explored the uncertainty in future emissions using a probabilistic approach (see for example, Webster et al. 2002).[20] While there are some differences in the upper and lower bounds of the emissions projections between the SRES scenarios and these more recent probabilistic-based analyses, the range of the SRES scenarios overlaps to a large degree with the range of emissions estimated using these probabilistic approaches.

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[13] The range of CO_2 emissions in the *SRES* has been compared to scenarios done later (post-*SRES*). In general, the ranges are not very different. The estimated CO_2 emissions in post-SRES scenarios have a higher lower bound, a similar median, and a higher upper bound of the distribution. The post-SRES scenarios use lower population estimates, both in range and median. The post-SRES economic development projections (based on market exchange rates) have approximately the same lower bound and median but a lower upper bound of the distribution. A comprehensive database of emissions scenarios is available at http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html

[14] Asian Pacific Integrated Model (AIM) from the National Institute of Environmental Studies in Japan (Morita et al. 1994).

[15] Atmospheric Stabilization Framework Model (ASF) from ICF Consulting in the USA (Lashof and Tirpak 1990; Pepper et al. 1992, 1998; Sankovski et al. 2000).

[16] Integrated Model to Assess the Greenhouse Effect (IMAGE) from the National Institute for Public Health and Environmental Hygiene (RIVM) (Alcamo et al. 1998; de Vries et al. 1994, 1999, 2000), used in connection with the Dutch Bureau for Economic Policy Analysis (CPB) WorldScan model (de Jong and Zalm 1991), the Netherlands.

[17] Multiregional Approach for Resource and Industry Allocation (MARIA) from the Science University of Tokyo in Japan (Mori and Takahashi 1999; Mori 2000).

[18] Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) from the International Institute of Applied Systems Analysis (IIASA) in Austria (Messner and Strubegger 1995; Riahi and Roehrl 2000).

[19] Mini Climate Assessment Model (MiniCAM) from the Pacific Northwest National Laboratory (PNNL) in the USA (Edmonds et al. 1994, 1996a, 1996b).

[20] There are two ways to approach forecasting the future under uncertainty. One is through the use of scenarios that illustrate different world views or a range of possible outcomes. The second is through uncertainty analysis and probabilistic forecasting. In the latter approach, critical but uncertain parameters (such as demographic or technology trends over time) are identified and quantified through the use of probability distributions. Multiple simulations are performed by sampling from those distributions to construct probability distributions of the outcomes (such as GHG emissions). One can then quantify the likelihood that an outcome falls within a specified range, such as the 90 percent upper confidence limit for CO_2 emissions. In probabilistic approaches to generating emissions scenarios, factors such as labor productivity growth, energy efficiency improvements, agricultural and industrial emissions coefficients for various GHGs, etc. are quantified by expert elicitation or from a review of the literature. These distributions are then used in assessment models to generate a distribution of results such as GHG emissions and/or climate impacts such as temperature change or sea-level rise.

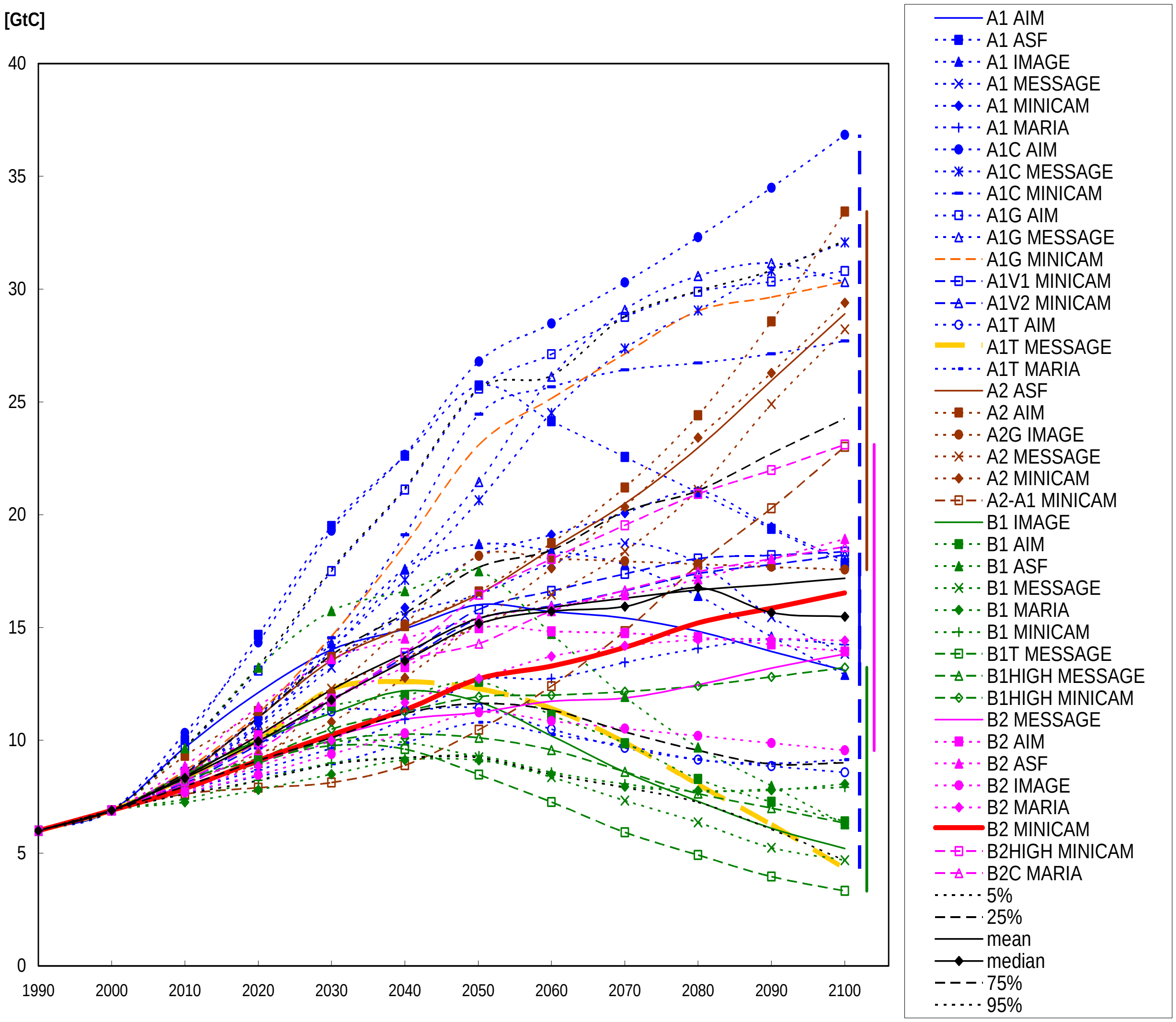

Figure 3-5. Projections of CO_2 Emissions from Energy Use, based on Various Energy-Economic Models and Assumptions

Note: The mean, median, and percentile bands in the figure are based on the range of projections, and do not represent probabilities of the projections.

Box 3-2

The *SRES* Scenarios

The SRES scenarios are organized around four major storylines, which received the names A1, A2, B1, and B2. Each of these storylines represented different general conceptions of how the world might evolve over time, including the evolution of key drivers such as economic growth (including differences or convergence in regional economic activity), population growth, and technological change (see discussion of key drivers from above). Each driver was interpreted by the participating modeling teams in terms of quantitative assumptions about the evolution of specific model parameters. Some scenario drivers, such as economic growth, final energy, and population growth, were harmonized across many of the models, while others, such as the specific technology assumptions, were developed by the individual modeling teams to be generally consistent with the storylines. For the A1 Scenario, four basic assumptions about technology were also developed, so there are four categories of technology scenarios under the A1. The scenarios are described as follows:

A1. The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The four A1 groups are distinguished by their technological emphasis: fossil intensive (A1C – coal- and A1G – gas), non-fossil energy sources (A1T), or a balance across all sources (A1B), where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describe a convergent world with the same global population, which peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The set of harmonized drivers depended both on the scenario and the specific model. Key drivers that characterized the scenarios are summarized qualitatively in the table below. Comparison of the emissions trajectories in Figures 3-5 and 3-6 can be interpreted in terms of the relative evolution of these drivers and the discussion of these drivers above.

	A1						
Driver	**A1C**	**A1G**	**A1B**	**A1T**	**A2**	**B1**	**B2**
Population Growth	low	low	low	low	high	low	medium
GDP Growth	very high	very high	very high	very high	medium	high	medium
Energy Use	very high	very high	very high	high	high	low	medium
Land-Use Changes	low-medium	low-medium	low	low	medium/high	high	medium
Availability of Conventional and Unconventional Oil and Gas	high	high	medium	medium	low	low	medium
Pace of Technological Change	rapid	rapid	rapid	rapid	slow	medium	medium
Direction of Technological Change Favoring:	coal	oil & gas	balanced	non-fossils	regional	efficiency & dematerialization	"dynamics as usual"

3.3.2 CO_2 Emissions and Sequestration from Changes in Land Use

CO_2 emissions in the future will be influenced not only by trends in CO_2 emissions from energy use and industrial sources, but also by trends in land use that result in either CO_2 sequestration or a net increase in CO_2 emissions. CO_2 emissions and carbon sequestration associated with various land uses will be driven primarily by increasing demand for food, as well as other factors, such as demand for wood products, land management intensity, demand for biomass energy and bio-based products, and technological change.

The role of land-use change has received relatively limited consideration (compared to energy use) in prior modeling exercises aimed at developing long-run GHG emissions scenarios. To date, the most comprehensive treatment is contained in the scenarios developed for the IPCC *SRES* (IPCC 2000). In developing these scenarios, the IPCC assembled a data base of over 400 earlier emissions scenarios. Of these, 26 scenarios (all the work of three modeling groups) explicitly considered the role of land-use change on global CO_2 emissions. Differences in methodology, assumptions, and base period made comparisons of the scenarios difficult. Most of the scenarios show net global CO_2 emissions from land-use change decreasing to below current levels by 2100, with some scenarios indicating net sequestration (Figure 3-6).

A key insight to emerge from the IPCC exercise was that the link between land-use change and global CO_2 emissions is much more complex and much more uncertain than had been reflected in previous emissions scenarios. Across and within the four storylines described in Box 3.2, the scenarios produced a wide range of land-use paths that included large increases and decreases in the global areas of cropland, grassland, and forest over periods of 50 and 100 years.

In general, scenario differences in land-use patterns resulted from alternative assumptions about population and income growth (via the demands for food, meat, and environmental goods). The scenarios indicate that land-use change could be either an important source or sink of global CO_2 emissions over the next 100 years, depending on the mix of goods and services the world's population demands from its land resources. The future paths of technological change in today's land-intensive sectors—including agriculture, forestry, energy, construction, and environment quality—will help to define the role of land-use change. Many of the IPCC scenarios show that CO_2 emissions from deforestation are likely to peak after several decades and then subsequently decline.[21]

More recently, Sohngen and Mendelsohn (2003) linked global forestry models with global energy models to more explicitly explore the relationships between land-use management, land-use emissions, and global energy systems. They report a net sequestration potential of about 18 GtC in global forests, in the absence of human intervention, and suggest there might be less deforestation in tropical regions than the IPCC *SRES* study projected.

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[21] This pattern is tied to declines in the rate of population growth toward the latter half of the century and increases in agricultural productivity.

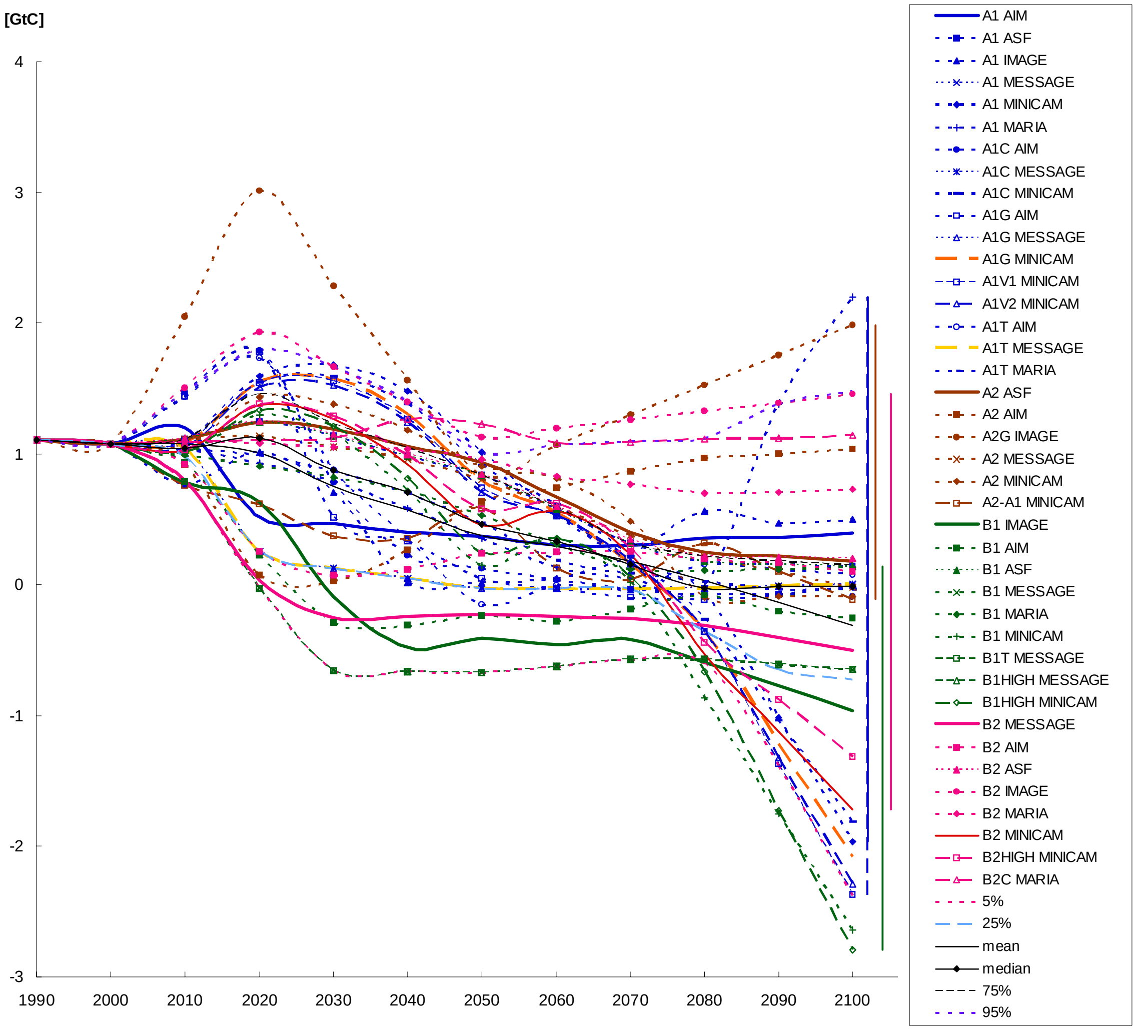

Figure 3-6. Net CO_2 Emissions from Land Use Change (Source: IPCC 2000)[22]

Note: The mean, median and percentile bands in the figure are based on the range of projections, and do not represent probabilities

3.3.3 Other Greenhouse Gases

As discussed in Section 3.1, the non-CO_2 GHGs include a diverse group of gases such as methane, nitrous oxide, chlorofluorocarbons and other gases with high global warming potential. Future growth in emissions of non-CO_2 GHGs will depend on the future level of the activities that emit these gases, as well as the amount of emissions control that occurs. Cost-effective emissions controls will depend on the trade-offs (based on relative cost and climate impact) in mitigating different GHGs.

Integrated assessment models have only recently begun to project long-term trends in non-CO_2 GHGs. In a recent international modeling exercise conducted by the Stanford Energy Modeling Forum, non-CO_2 emissions and mitigation potential were projected by 18 models of various forms (Weyant and de la

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[22] The structure of the underlying modeling exercise required harmonization in 2000. Such harmonization in the context of a modeling exercise does not necessarily reflect agreement.

Chesnaye 2005).[23] Each model ran a "reference case" scenario, in which non-CO_2 GHGs were allowed to grow in the absence of any constraints or incentives for GHG emissions mitigation.[24]

The results for methane and N_2O are shown in Figures 3-7 and 3-8, respectively. The projections vary considerably among models. On average, non-CO_2 GHGs were projected to increase from 2.7 gigatons of carbon equivalent emissions (GtC-eq) in 2000 to 5.1 GtC-eq in 2100. On average, methane emissions were projected to increase by 0.6 percent/year between 2000 and 2100; nitrous oxide by 0.4 percent/year; and the fluorinated gases by 1.9 percent/year. (By comparison, in these same scenarios, CO_2 emissions were projected to grow by 1.1 percent/year over the same time period—see Weyant and de la Chesnaye 2005.)

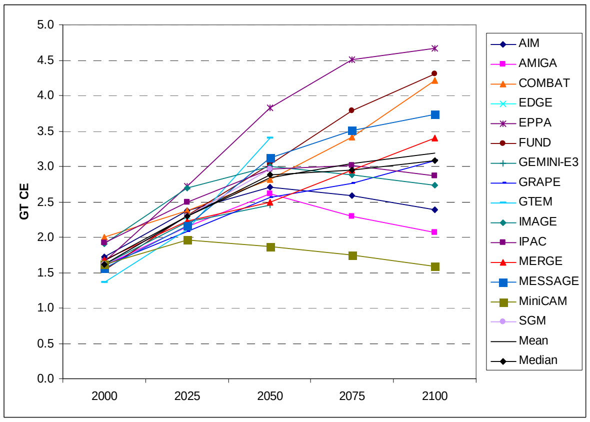

Figure 3-7 Methane Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

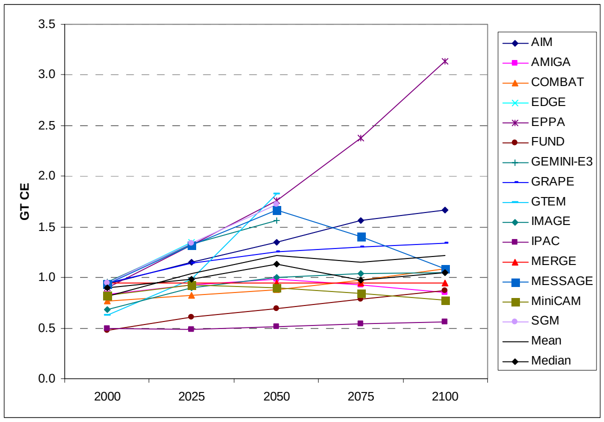

Figure 3-8. Nitrous Oxide Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

3.4 Implications for CCTP Planning

For the purposes of CCTP planning and analysis, it is useful to understand the potential contributions of advanced technologies to GHG emissions reductions over a century-long planning horizon. Although the specific stabilization path for attaining the UNFCCC objective is not known, and none is assumed, modeling the general parameters of such a hypothesized challenge across many different paths can provide useful information about a range of technologies that might contribute. This may be illustrated by one such example, shown in Figure 3-9. To meet the stabilization level in this hypothetical example, annual GHG emissions would have to be reduced by about 13 GtC-eq in 2100 from the level of an otherwise "unconstrained" illustrative case.[25] For the example shown, the cumulative emissions reduction

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[23] The models included a variety of model types, including integrated assessment models and general equilibrium models.

[24] Note, however, that some of the models (such as MiniCAM) project that some GHG-reducing technologies penetrate the market without incentives or policies. For example, methane emissions from coal and natural gas production would penetrate the market when it is cost effective to do so, based on the value of the methane (natural gas) collected, which can be used as a fuel.

[25] The "unconstrained" case in this illustrative example is based on the reference scenario developed for CCTP by PNNL; see Placet et al. (2004). The lower curve representing emissions leading to stabilization is based on the 550 ppm trajectory shown in Figure 3-3A; for more information, see Wigley et al. (1996).

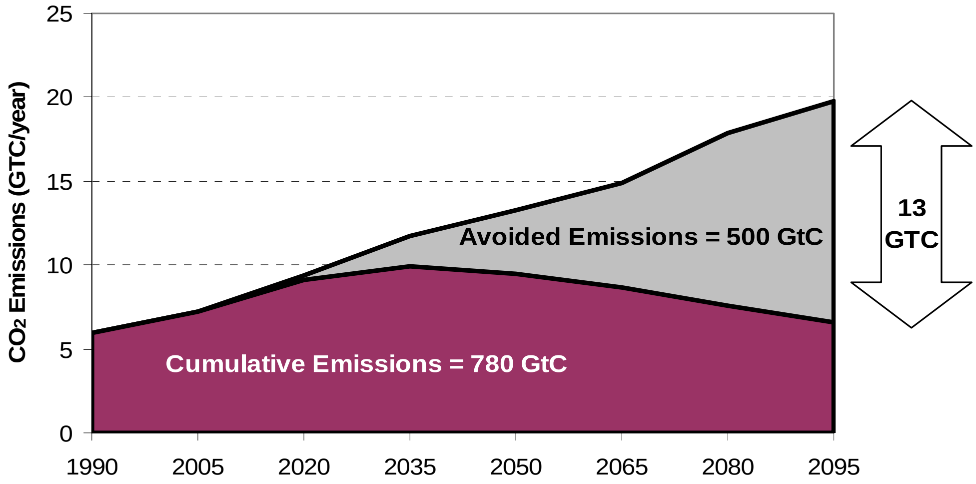

Figure 3-9. Potential Scale of CO_2 Emissions Reductions to Stabilize GHG Concentrations: Hypothetical Unconstrained and Reduced-Emissions Scenarios

over the course of the 21st century, when compared to a case with unconstrained emissions growth, would be approximately 500 GtC-eq. For various other stabilization and baseline trajectories, the cumulative emissions reductions ranged from 200GtC-eq to 800 GtC-eq.

The curves shown in Figure 3-9 represent but one of many potential emissions reductions scenarios. Many combinations of constrained and unconstrained emissions trajectories are conceivable, and many combinations of GHGs could potentially contribute to the total GHG reduction. In general, the lower the stabilization level, the larger the reduction in both CO_2 and non-CO_2 GHGs that would be required.

The specific roles of non-CO_2 GHGs would depend on factors such as the stabilization level, timeframe to stabilization, and the characteristics of the GHGs themselves (e.g., atmospheric lifetime and global warming potential). In particular, scenarios have approached methane emissions reductions in distinctly different ways because of its relatively short lifetime in the atmosphere.[26]

The example in Figure 3-9 shows a hypothetical stabilization situation that results in annual emissions reduction of about 13 GtC from the reference scenario by the year 2100. Box 3-3 provides illustrations of measures that could achieve an annual reduction of one GtC-eq/year. As the examples suggest, the technologies would have to be implemented on a significant scale. The costs of achieving such reductions using today's technology could be high. The implication for CCTP and its associated science and technology R&D programs is to develop more efficient and less costly technologies, including novel or breakthrough technologies, that could significantly reduce GHG emissions, while maintaining economic growth and ensuring safety and overall environmental quality.

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[26] Methane is generally reduced earlier in models based on GWP conversions, because its reduction is relatively less costly than reducing emissions of other GHGs. In optimization models based on radiative forcing, methane reductions are pushed back toward the point in time at which stabilization is achieved. This is because methane emitted prior to the decade immediately preceding the target would not affect the radiative forcing at the target date, because it would have already broken down in the atmosphere.

Box 3-3

How Big is a Gigaton of GHG Reduction?

Actions that provide 1 Gigaton/year of carbon-equivalent mitigation for the duration of their existence:

Coal-Fired Power Plants. Build 1,000 "zero-emission" 500-MW coal-fired power plants. Current global installed generating capacity is about 2 million MW.

Geologic Sequestration. Install 3,700 sequestration sites like Norway's Sliepner project (0.27 MtC/year)

Nuclear. Build 500 new nuclear power plants, each 1 GW in size. This would more than double the current number of nuclear plants worldwide.

Electricity from Landfill Gas Projects. Install 7,874 "typical" landfill gas electricity projects (typical size being 3 MW projects at non-regulated landfills) that collect landfill methane emissions and use them as fuel for electric generation

Efficiency. Deploy 1 billion new cars at 40 miles per gallon (mpg), instead of new cars at 20 mpg

Wind Energy. Install new wind capacity to produce 150 times the current U.S. wind generation

Solar Photovoltaics. Install new solar energy capacity to produce 10,000 times the current U.S. solar PV generation

Biomass Fuels from Plantations. Convert a barren area about 15 times the size of Iowa's farmland (about 33 million acres) to biomass crop production

CO_2 Storage in New Forest. Convert a barren area about 40 times the size of Iowa's farmland to new forest

Notes:

- All reductions for power technologies are measured relative to new coal-fired plants without CO_2 capture and storage)
- Many of these examples are adaptations from Pacala and Socolow (2004).

3.5 The Role of Technology

Reducing GHG emissions on the scale hypothesized in Section 3.4 could be achieved in many ways. It is unlikely that any single technology would be able to achieve the level of GHG emissions reductions that are likely to be required to stabilize GHG concentrations in the atmosphere. Given the diversity of the energy sector and potential constraints on the availability of resources, achieving reductions on such a scale will almost certainly require contributions from a combination of existing, improved or transitional, and advanced technologies.

The projected contribution of any technology depends in large part on assumptions about the success of scientific and technical advancements, among other factors. These types of factors are examined routinely in scenario analyses. For example, in the mitigation scenarios studied in the IPCC Working Group III,[27] as well as studies performed as part of EMF-19 (for example, van Vuuren et al. 2004 and Manne and Richels 2004), lower-carbon fuels (e.g., natural gas) and technologies such as integrated gas combined-cycle were projected to bridge the transition to more advanced fossil and zero- or low-carbon

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[27] http://www.grida.no/climate/ipcc_tar/wg3/084.htm

technologies. A theme common to many mitigation scenarios is a steady improvement in energy efficiency, as is the emergence of biomass as an important energy source throughout the next century.

In addition to technical considerations, cost considerations also are a major element of mitigation scenarios. Once the decline in costs makes them economically attractive, low-carbon-emitting technologies play a major role in many scenarios. Different technologies may mature and become cost-competitive at different times over the course of the 21st century. For example, increased energy efficiency (using today's technologies), mitigation of non-CO_2 GHGs, and terrestrial sequestration may be the more cost-effective options in the nearer term, while transformative supply-side and end-use technologies with greatly reduced GHG emissions could become commercially viable later, as technology development progresses.

Several landmark multi-model scenarios analysis studies,[28] as well as various scenarios analysis efforts based on individual models, have explored emissions reduction scenarios. Advanced technology scenarios are sometimes modeled against a range of hypothetical GHG emissions constraints (e.g., low, medium, high, and very high). The results of these, in turn, can be compared against a series of reference or baseline scenarios, where the given GHG emissions constraints are met, but with different assumptions about the advancement of technology and costs. These hypothetical results can suggest what might be possible if assumptions about technology advancement could be realized.

3.5.1 Alternative Advanced Technology Emission Reduction Pathways

A number of approaches can be pursued to explore the potential contributions of advanced technologies. One of the more direct approaches is to focus on a particular technology or genre of technology and estimate what could be achieved if it were to be fully adopted by a certain time in the future. For example, Brown et al. (1996) estimated the amount of mitigation that could be achieved with single technologies. More recently, Pacala and Socolow (2004) discussed technology "wedges," each of which represent the mitigation of one gigaton of carbon emissions in the year 2050 (see some examples in Box 3-2, some of which were adapted from Pacala and Socolow). Hoffert et al. (2002) examined technologies needed to deliver a certain amount of carbon-free energy by the end of the 21st century. Such assessments are useful for understanding the maximum technical potential of various technologies.

In reality, however, advanced technologies would need to meet a complex array of conditions before they could be successfully implemented. For instance, they would need to be cost-competitive in the market, compared to other available technologies. Other considerations include ease of use, reliability, public safety and acceptance, and policy, environmental or regulatory factors. Taking these considerations into account requires a more complex approach. Models are typically used to evaluate the competition among technologies to meet required emission reduction targets or react to various emissions taxes or policies. Such models typically simulate the deployment of technologies and approaches that could achieve a given amount of emissions reductions at the lowest cost in a given time period. If the technical potential of such technologies meets the required emissions reduction assumed in the scenario, these low or no-cost approaches may supply a large portion of the emissions reduction.[29] More costly, but feasible, advanced

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[28] For example, the IPCC "Post-SRES" report on Mitigation (IPCC 2001) and the EMF studies (Weyant 2004).

[29] The suite of technologies in the first category generally includes improvements to current systems and energy conservation–the so-called "no-regrets" strategies. Such improvements, often modeled as a general rate of energy-efficiency (or intensity) improvement, are often included in the business-as-usual (or "reference case") emissions projections.

technologies come into play more extensively in scenarios that require moderate to high levels of emissions reduction. Expensive, undeveloped, or undemonstrated technologies or others that may face non-cost barriers may enter the market later in the mitigation period. Hence, the mix of technologies in any given scenario depends on many assumptions about the costs, technical readiness, and barriers to implementation for each type of technology.

One scenarios analysis, recently completed by Pacific Northwest National Laboratory (PNNL), explored three advanced technology scenarios, each of which was designed to achieve a range of GHG emissions reductions (Placet et al. 2004).[30] The three advanced technology scenarios include:

- Scenario 1, which assumes successful development of fossil energy technologies with carbon capture and storage and high-efficiency fossil energy conversion
- Scenario 2, which assumes technological improvement and cost reduction of carbon-free energy sources such as renewable energy (wind power, energy from bio-sources, and other solar energy systems) and nuclear power
- Scenario 3, in which major advances in fusion energy and novel energy applications for solar and advanced biotechnology are assumed to occur[31]

Figures 3-10 and 3-11 provide illustrative results across the three scenarios for the high emissions constraint case. Figure 3-10 shows the contributions, over the course of the 21st century, of various energy sources to total global energy demand under the three advanced energy scenarios. Figure 3-11 shows the emissions reduction contributions from the various energy sources and technologies.

Although each scenario assumes advances in one particular class of technology, all scenarios result in a mix of energy efficiency and energy supply technologies. These results, as with the others, show the variation possible in the mix of emissions-reducing technologies under a variety of assumptions and planning uncertainties.

3.5.2 Economic Benefits of Advanced Technologies

A primary purpose of CCTP is to accelerate the advancement of promising technologies and reduce their cost. The more economically competitive of these technologies will, under the right conditions, enter the marketplace and contribute to reduced GHG emissions. They might also achieve the same emissions reductions at costs significantly lower than would be the case had they not been developed or made available.

In the aforementioned analysis by PNNL (Placet et al. 2004), the estimated costs of achieving a range of emission reductions were compared for cases with and without the use of advanced technology. The resulting cost estimates (Figure 3-12) show that the present values of the cumulative costs for meeting the hypothetical carbon constraints were significantly lower in all three advanced technology scenarios than

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[30] This study was conducted for the US CCTP.

[31] In the PNNL study, Scenarios 1, 2 and 3 are called “Closing the Loop on Carbon,” “A New Energy Backbone,” and “Beyond the Standard Suite.” Also note that all three scenarios assumed significant improvements in end-use efficiency.

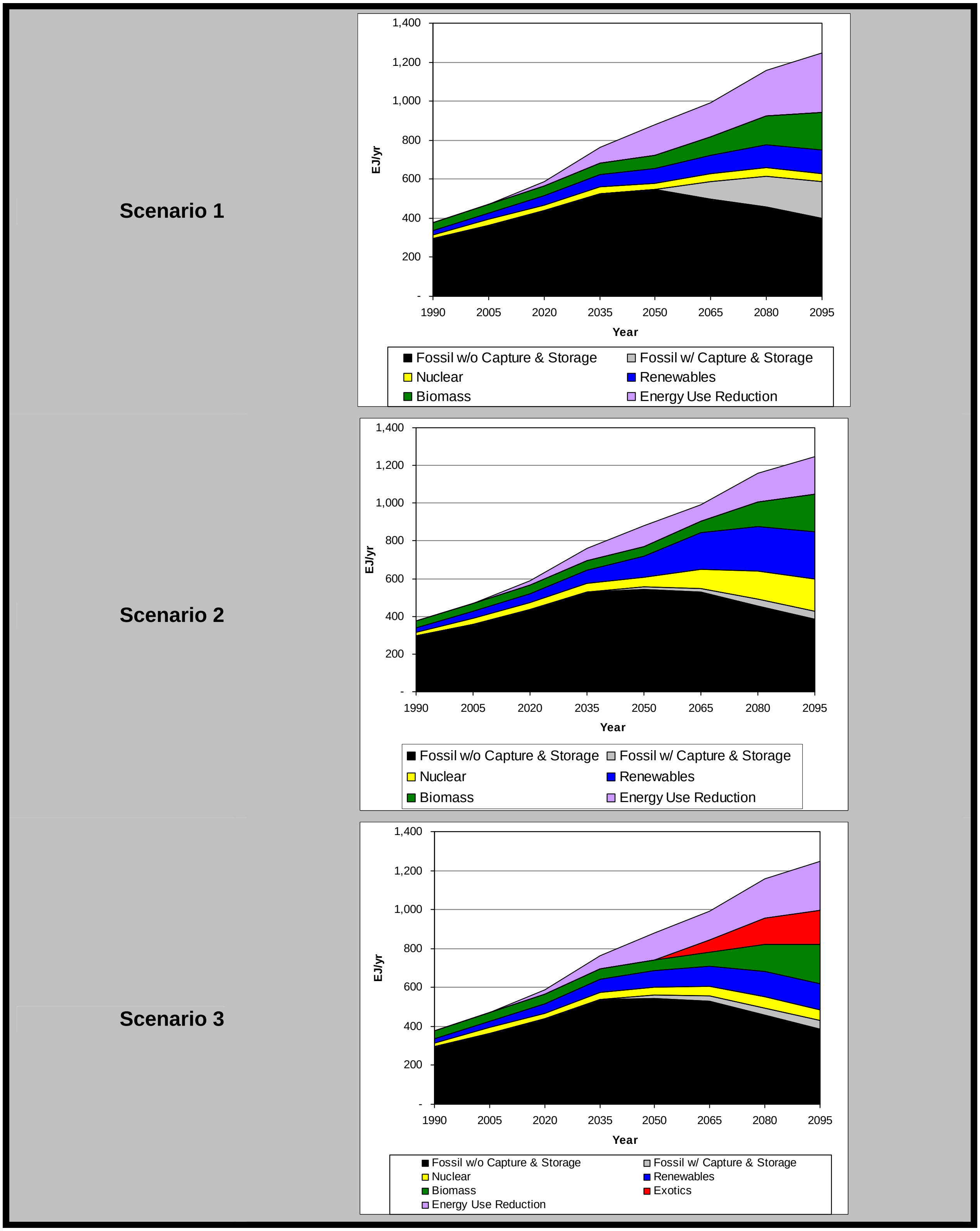

Figure 3-10. World Primary Energy Demand (Source: Placet et al. 2004)

Note: "Energy Use Reduction" is the amount of energy conserved or saved through advanced energy-efficient end-use technologies compared to a reference case, which also includes a considerable increase in energy efficiency compared to today's level. See the cited reference for more detail.

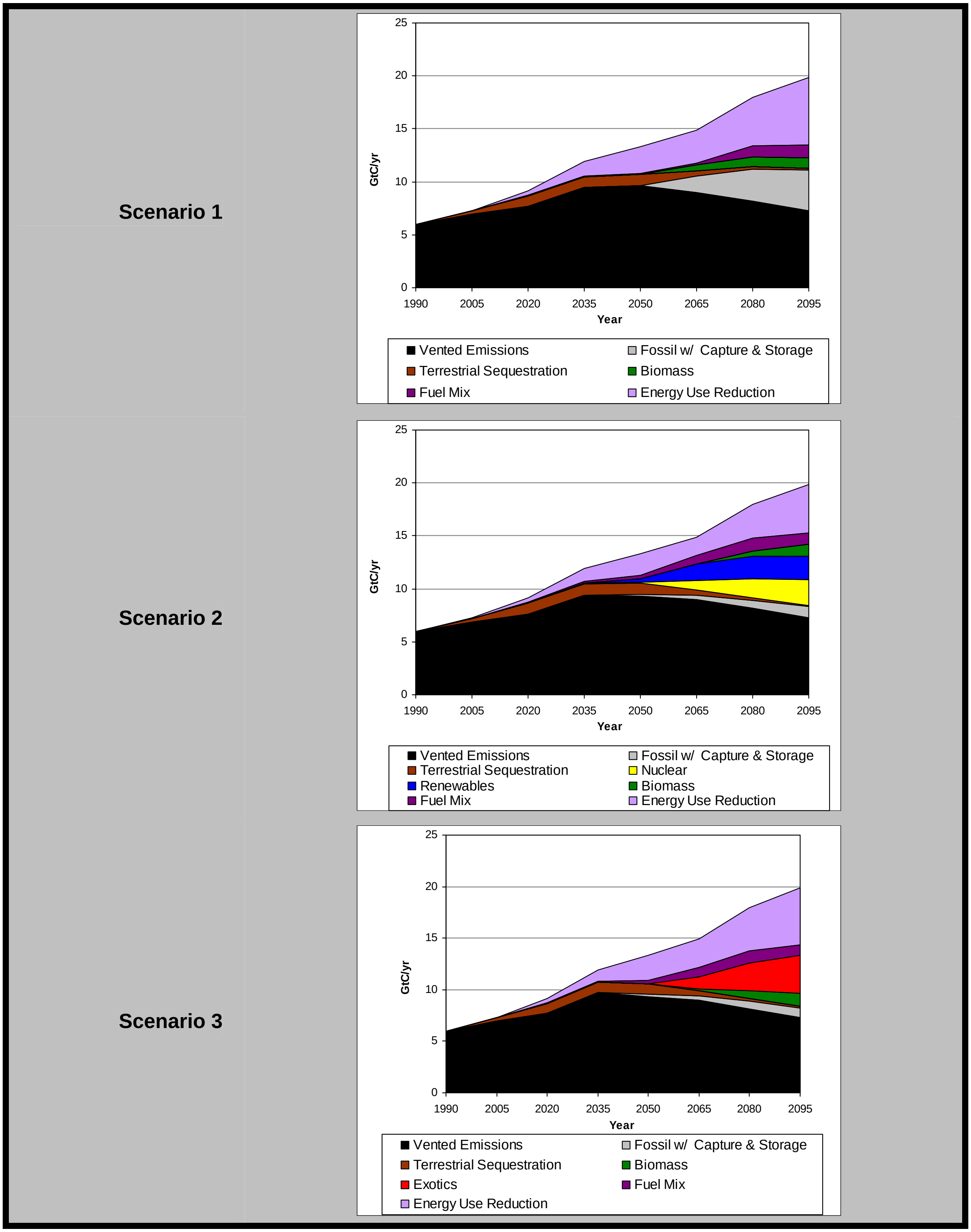

Figure 3-11. World Carbon Dioxide Emissions: Released (Vented) and Mitigated (Source: Placet et al. 2004)

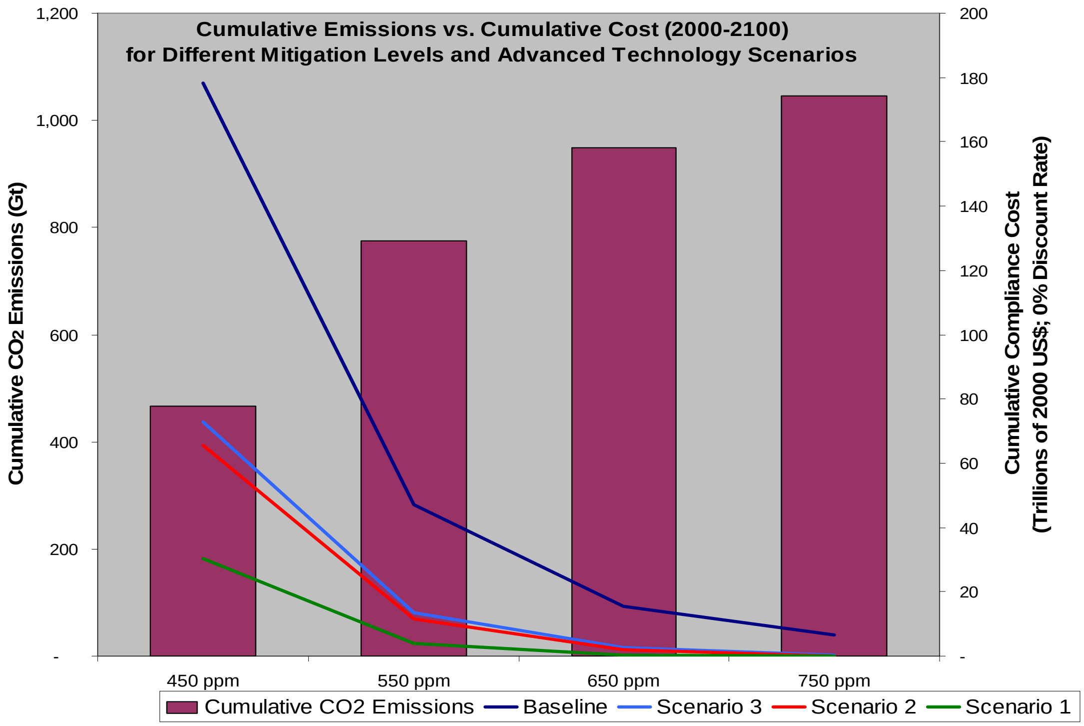

Figure 3-12. Cost Reductions of Three Advanced Technology Scenarios, Compared to Baseline Cases without Advanced Technology (Adapted from: Placet et al. 2004).

Note: Cumulative emissions (shown in the bar graphs) are highest when the emissions constraint is least stringent (750 ppm). Costs (line graphs) are highest when the emissions constraint is most stringent (450 ppm). Costs are lower (light blue, red and green lines) when advanced technology was assumed to be available, than when technology was assumed to advance only incrementally (dark blue line)

in the baseline scenario where technology advanced, but at rates more typical of historical experience.[32] Accumulated over the course of the 21st century, the potential economic benefits of such an advanced technology strategy, even without knowing which technologies would eventually emerge as most successful, would likely be significant.

Other studies in the literature reach similar conclusions. For example, Manne et al. (2004) examined limiting global temperature rise using scenarios with “optimistic” technological assumptions (i.e., assuming advanced technologies, such as fuel cells and integrated gasification combined cycle with CO_2 capture and storage, are available), compared to more “pessimistic” scenarios without such advanced technologies. The estimated costs[33] were estimated to be 2.5 times lower in the optimistic case than the pessimistic case. In another study, Edmonds et al. (2004) report that when a suite of advanced technologies (such as carbon capture and storage, biotechnology and hydrogen energy systems) are available to be

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[32] In this study, technology advancement was assumed to lead to more efficient energy technologies with lower capital and operating costs. Details on the assumptions can be found in Placet et al. (2004). The resulting cost reductions do not consider the cost associated with performing any R&D that might be necessary to achieve the improved technology performance.

[33] In the study, costs included those associated with fuel switching (to fuels or technologies with lower emissions), changes in domestic and international fuel prices, and price-induced conservation activities.

deployed at a large scale, the effective "tax" on GHG emissions that would be required to achieve the assumed reduction was 60 percent lower than when the advanced technologies were not available.

Other studies that explore the dynamics of technical change (e.g., Manne and Richels 2004, van Vuuren et al. 2004) show lower total abatement cost or lower mitigation costs through deployment of advanced technology. One of the major conclusions drawn at the recent IPCC Expert Meeting on Emission Scenarios was: "Technological change is fundamental for (reducing) stabilization (costs)."[34]

3.5.3 Key Technology R&D Areas

Review of scenario analyses indicates that, given the scale of the challenge, no single technology or class of technology would be likely to provide, by itself, the quantity of GHG emissions reductions needed to achieve most of the stabilization levels typically hypothesized and examined in the technology scenarios literature. Instead, these studies show that under a wide range of differing assumptions and planning uncertainties, technological advances aimed at the following four broad areas are likely to be needed *in combination* in order to contribute to the needed GHG emissions reductions: [35]

1. Energy End Use and Infrastructure
2. Low- and Zero-Emissions Energy Supply
3. CO_2 Capture/Storage and Sequestration
4. Non-CO_2 Greenhouse Gases

3.5.3.1 Energy End-Use Efficiency

Ultimately, global CO_2 emissions are driven by the demand for services (heating, cooling, transportation, etc.) that energy can provide. Technological advancement that can reduce the energy required to meet these services is one of the key levers for reducing GHG emissions. Scenarios analyses suggest that increased use of highly energy-efficient technologies and other means of reducing energy end use could play a major role in contributing to cost-effective emissions reduction within any given energy supply strategy.

In published scenarios, increasing demand for energy services, driven by population and economic growth, drives growth in GHG emissions over the 21st century. If gross world product were to grow by only 2.0 percent/year over the 21st century, and the demand for energy services were to grow at a commensurate 2.0 percent rate, then energy demand would grow seven-fold over the course of the century. Many published scenarios assume gross world product growth well above these rates. For example, at the top of the range of the IPCC's *Special Report on Emissions Scenarios (SRES)* scenarios, gross world product grows at over 3.0 percent/year from 1990 through 2100.

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[34] Meeting Report of the IPCC Expert Meeting on Emission Scenarios, 12-14 January 2005, Washington DC. http://www.ipcc.ch/meet/washington.pdf

[35] CCTP also includes two supporting technology areas. These are measuring and monitoring technologies, and application of basic science to applied technology R&D. These supporting areas are not discussed in this chapter, though they are integral elements of the overall CCTP technology strategic plan.

However, in virtually all published scenarios, the demand for final energy[36] and, therefore, the emissions of CO_2 grow at a rate lower than gross world product growth, because improvements in end-use efficiency, along with structural economic changes, drive down the energy requirements associated with increasing global prosperity.[37] In 1990, global final energy intensity (energy used per dollar of gross world product) was roughly 17 billion joules per dollar. In the IPCC's *SRES* scenarios, final energy intensities in 2100 ranged from 1.4 billion joules per dollar of GDP to 5.9 billion joules per dollar of GDP.[38] Without these reductions in energy intensity, which are significant, energy demand growth, and therefore GHG emissions, would be significantly higher. This point is illustrated in Figure 3-13, which shows the relationship between global CO_2 emissions and final energy consumption in 2100 in the *SRES* scenarios. Although Figure 3-13 shows variation across multiple scenarios, in general, the greater the demand for final energy, the higher the CO_2 emissions and the more challenging the task of stabilizing CO_2 concentrations.[39]

This context demonstrates the benefits that would accrue from increasingly efficient end-use technologies. If R&D efforts were to increase the rate of final energy intensity improvement by only a

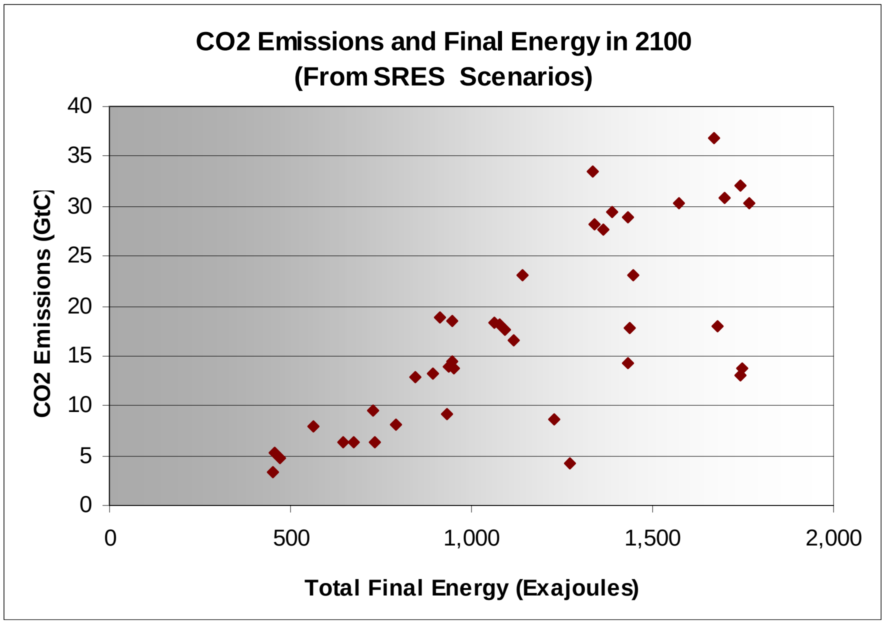

Figure 3-13. Relationship between CO_2 Emissions and Final Energy in the IPCC *SRES* Scenarios

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[36] Final energy refers to energy used at the point of end-use as opposed to energy used as an input to, for example, electricity generation. Final energy is lower than primary energy, because primary energy includes the efficiency losses required to transform primary energy to final energy.

[37] See the Greenhouse Gas Emissions Scenario Database at http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html

[38] Range based on the illustrative scenarios from IPCC (2000).

[39] Variations in the relationship are due to, among other things, differences in final energy mixes (e.g., ratio of electricity, solid, liquid, and gaseous fuels) and the deployment of zero-emitting technologies. Note that these scenarios all assume no attempts to constrain carbon emissions.

quarter of a percent/year over the 21st century in a “middle-of-the-road” scenario, the required CO_2 emissions reductions would decrease by 3.5 GtC/year by 2100. This is roughly half of the total global CO_2 emissions today.[40]

Several scenario analyses point to the benefits of developing and deploying advanced end-use technologies. For example, the advanced technology scenarios in the recent PNNL report on climate change technology strategies assumed that advanced energy-efficiency technologies decreased final energy requirements by ten percent globally by 2100 (Placet et al. 2004). These reductions alone were responsible for a decrease of roughly 2.0 GtC/yr by 2100, in a scenario without any climate-change-related initiatives. Energy-efficiency improvements were also a critical driver of the decreased costs of stabilization across the board in these scenarios. Similarly, the IPCC’s *SRES* included a scenario (A1T) with advanced end-use technologies. In the simulation of this scenario using the Asian Pacific Integrated Model (AIM), the reductions from end-use efficiency alone (through reduced final energy intensity) were responsible for roughly 4.0 GtC/yr by 2100.[41] Hanson and Laitner (2004) incorporated advanced end-use technology assumptions, along with advanced supply-side assumptions and a range of policy levers to encourage technology deployment and reduce emissions, into the AMIGA integrated assessment model. In this study, approximately one-third of the U.S. carbon emissions reductions in 2050—roughly one GtC—are due to the deployment of more efficient end-use technologies.[42]

Providing technological options to reduce the energy required for production of goods and services demanded in a growing global economy can provide a fundamental way to achieve emissions reductions and lowering the need for GHG-free energy supply. This is true across the full spectrum of technology futures—whether these futures emphasize fossil fuels combined with CO_2 capture and storage, renewable or nuclear power, or novel technologies such as fusion and advanced bio-technology.

3.5.3.2 Low- and Zero-CO_2 Energy Supply Technologies

Supplying the world’s energy needs while achieving substantial reductions in GHG emissions may also require large contributions from energy supply technologies with near-zero emissions. These include renewable sources of electricity, such as wind, solar and hydroelectric power, biomass-based energy systems, and nuclear power, as well as the use of these technologies to produce hydrogen. These could also include novel advanced technologies such as fusion and advanced biotechnologies.

A number of scenario analyses have shown the importance of low- and zero-energy supply technologies in reducing emissions to achieve a given climate policy through the use of integrated assessment models. For example, Akimoto et al. (2004)[43] show that for a hypothetical climate policy, the share of the world’s primary energy in 2100 met by biomass and wind energy increased by more than 70 percent from their

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[40] This calculation is based on the illustrative B2 scenario from IPCC (2000). It assumes that lower final energy requirements would not alter the relative proportions of energy provided from different sources.

[41] Result based on the illustrative scenarios for the A1 set. It was calculated based on a comparison of the illustrative A1T scenario with the illustrative A1B scenario, assuming no change in the primary energy mix between the two. While not identical to A1T, A1B is similar in terms of the emissions per unit of primary energy and therefore serves as an effective reference.

[42] Note that many of the assumptions in this study followed from the study, *Scenarios for a Clean Energy Future* (see Brown et al. 2001).

[43] The study used an updated version of the DNE21 model, an integrated assessment model which hard-links macroeconomic, energy systems, and climate change models, and seeks optimal development of the world’s energy system for a given climate policy based on maximizing macroeconomic consumption.

reference case contributions of 10 percent and 4 percent, respectively. In addition, solar power supplied almost 5 percent of the world's primary energy demand by 2100,[44] and nuclear, biomass and renewable energy accounted for about 30 percent of the emissions reduction in 2100, in approximately equal shares. Similarly, Edmonds et al. (2004) report increasing contributions from solar and nuclear energy under carbon constraints, especially when fossil-based generation technologies and CO_2 capture and storage technologies are not assumed to advance.[45]

As discussed in previous sections, Placet et al. (2004) examined several advanced technology scenarios to achieve a range of emissions reduction targets. Low- and zero-emissions energy technologies (including solar, wind, biomass, nuclear fission, and novel concepts such as nuclear fusion and advanced biotechnology) contribute between 23 percent and 34 percent of world primary energy demand by 2100, depending on the scenario.

In several scenarios, renewable sources are also important sources for generating hydrogen and other secondary fuels for different end-use sectors. For example, Edmonds et al. (2004) show that, under a medium carbon constraint, the preferred feedstock for hydrogen production switches from fossil feedstock to biomass, because the application of carbon dioxide capture and storage (CCS) to biomass-based H_2 production can have net negative emissions. Alternatively, Mori and Saito (2004) report that H_2 production from fast breeder reactors can supply nearly all of the final energy demand for hydrogen and can be a cost-effective way to achieve significant emissions reductions.[46]

3.5.3.3 Carbon Capture/Storage and Sequestration

The CCTP technology area related to capturing and sequestering CO_2 has two main thrusts: (1) engineered capture and storage of CO_2 from power plants and other industrial sources of CO_2 emissions, and (2) terrestrial sequestration of CO_2 in trees, soils, and other terrestrial systems.

3.5.3.3.1 Capture and Storage of Carbon Dioxide

Carbon dioxide capture and storage (CCS) refers to the capture of carbon dioxide emitted from power generation or industrial processes, and subsequent storage in suitable deep geologic or deep ocean reservoirs. The benefits of CCS technologies stem from their ability to continue to make use of abundant and therefore relatively inexpensive fossil energy resources while simultaneously delivering substantial and sustained CO_2 emissions reductions. CCS could also be applied to bio-based electricity-generation systems.

A number of recent studies using integrated assessment models have examined the potential of CCS to lower future CO_2 emissions. For example, Edmonds et al. (2004) report that fossil energy technologies with CCS can supply approximately 55 percent of the global electricity generation by the end of the

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[44] The upper limit of the world total nuclear production assumed in this scenario was 920 GW in 2050 and 1450 GW in 2100, so nuclear energy was not a major contributor in this analysis.

[45] This study used the MiniCAM model and the IPCC *SRES* B2 Scenario to examine the role of advanced technologies under a climate policy aimed at stabilizing atmospheric CO_2 concentrations at 550 ppmv.

[46] This study used the MARIA integrated assessment model to examine the role of nuclear technology and hydrogen use under different climate policies, and different technology advancement assumptions.

century in an advanced technology scenario with high emissions reductions.[47] This was more than twice the contribution as compared to a modeling case when CCS (and other advanced energy technologies) were not assumed to advance as rapidly. McFarland et al. (2004) find fossil-based power systems with CCS account for approximately 70 percent of global electricity production under a high GHG emissions constraint, when CCS systems and other advanced fossil energy systems are allowed to deploy to their full market potential, as compared to ~10 percent under a reference scenario with no climate policy.[48] Placet et al. (2004) show fossil systems with CCS contributing up to 50 percent more of the world's total primary energy consumption in 2100 in scenarios featuring technology advancement in CCS and fossil generation, as compared to scenarios where advancement occurs in other types of technologies.[49]

Several studies have also examined the economic implications of using CCS, either in isolation or along with other technological advancements. By allowing for abundant fossil energy stocks to be used while simultaneously delivering reductions in CO_2 emissions, CCS technologies help to constrain the rate of increase and ultimate peak of carbon prices (an indication of the overall cost of achieving the emission reductions[50]). For example, Edmonds et al. (2004) show that, through the large-scale adoption of CCS and other advanced fossil energy technologies, peak carbon permit prices were 62 percent lower than if those technologies were not allowed to deploy to their full market potential. In the study by McFarland et al. (2004), CCS reduces carbon prices by 33 percent at the end of the century.

While the studies summarized here use comparable costs for CCS (especially in their advanced technology scenarios), they employ different modeling approaches, technology representations and climate policies. However, they have all shown that CCS has the potential to play a significant role in emissions mitigation during the 21st century, and that technology advancement magnifies this contribution while delivering substantial economic savings. Early technical resolution of the viability of various CCS options could have significant implications for subsequent R&D investment strategies.

3.5.3.3.2 Terrestrial Sequestration

Land-use change that results in net CO_2 release to the atmosphere accounts for about 22 percent of today's global CO_2 emissions (IPCC 1996). At the same time, terrestrial systems in many parts of the world are being managed in ways that remove carbon from the atmosphere and sequester it in soils and biomass. Over the next several decades the potential exists to achieve significant reductions in global CO_2 emissions by managing the world's terrestrial systems to accumulate and store additional carbon.

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[47] This analysis used the PNNL MiniCAM model, with implementation of the IPCC SRES B2 scenario was used as the reference case, and compared with an advanced technology case with more efficient and economical CCS, higher efficiency fossil generation, and hydrogen energy systems, to examine the role of advanced technologies like CCS in a stabilization strategy.

[48] This study used the MIT EPPA model, a recursive dynamic multi-regional general equilibrium model of the world economy. Bottom-up information about coal and natural gas based generation systems with CCS were used in a top-down energy economics model to examine the effect of CCS on different climate policies.

[49] This study used the PNNL MiniCAM model to examine energy and economic implications of different technology futures and different levels of emissions reductions. One future assumes CCS technologies meet aggressive technical, economic, and environmental goals for application on fossil and biomass-based energy systems, along with higher-efficiency fossil generation and greater end-use efficiency gains.

[50] Since the cost of compliance is the total area under the marginal abatement curve, the last two metrics are strongly correlated i.e., the higher the reduction in the carbon price, the greater the reduction in the cost of compliance.

How much of this potential can be realized, however, is very uncertain and will depend on the development and diffusion of advanced technologies in a variety of economic sectors.

Globally, the goods and services derived from land resources—including food, water, shelter, energy, and recreation—are basic to human existence and quality of life. One insight that has emerged in the literature on long-run GHG emissions scenarios is that future changes in cropland, grassland, and forest land areas—regionally and globally—will be driven by the ability of land resources to provide these basic goods and services. Hence, the potential to use terrestrial systems to sequester carbon and mitigate global GHG emissions will be directly affected by the development of advanced technologies that reduce human pressures on land by increasing land productivity across a range of economic sectors—including (but not limited to) agriculture, forestry, and energy.

In agriculture, advanced technologies could enhance terrestrial carbon sequestration by enabling the development of new food and fiber products, production processes, and distribution systems that reduce the amount of land needed to feed and clothe the world's population. In forestry, advanced technologies could accelerate the processes of reforestation and afforestation, as well as increase the quantity of wood products that could be obtained from a unit of forest land. Advanced energy technologies could increase terrestrial sequestration by reducing deforestation pressures in developing countries and shifting cropland to bioenergy crop systems that not only increase soil carbon levels but also shift energy production toward technologies that recycle atmospheric CO_2.

In the absence of any human intervention, Sohngen and Mendelsohn (2003) suggest that global forests have a net sequestration potential of about 18 GtC in the coming century (see Section 3.2.1.2). In a more recent study performed as part of EMF-21, this potential was projected to increase by an additional 48 to 147 GtC by 2100 under different climate policies (Sohngen and Sedjo forthcoming). The cost of land-use and forest sequestration has been estimated to range between $10-$200 per ton of carbon stored (Richards and Stokes 2004).

3.5.3.4 Non-CO_2 GHG Emissions

Non-CO_2 GHGs play an important role in the CCTP framework because of the high reduction potential over the next 100 years and the potential for reducing the overall cost of stabilization. These gases are particularly important because a variety of scenario analyses show that a significant level of reduction is achievable in the first half of the 21st century.

Potential reductions and cost savings are illustrated in the Energy Modeling Forum multi-gas scenario study – EMF-21 (Weyant and de la Chesnaye 2005), and other long-term multi-gas studies (e.g., Manne and Richels 2000, 2001; Reilly et al. 2002). The various models exercised in the EMF-21 study used a range of assumptions about technology development, leading to a range of reductions of non-CO_2 GHGs. The studies suggest that, between 2000 and 2100, emissions of non-CO_2 "well mixed" gases (methane, nitrous oxide, and the fluorinated gases) in a moderately constrained case[51] could be reduced by as much as 48 percent, and the cost of stabilization could be lowered by 30 to 60 percent compared to a CO_2-only scenario.

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[51] The constrained case was defined as 4.5 W/m^2 stabilization target by 2100.

In addition to the long-term EMF-21 multi-gas scenarios, two other studies illustrate maximum technology potential of non-CO_2 mitigation options over the medium term. Delhotal and Gallaher (2005) projected the reduction potential of technological improvements out to 2030 in the three major methane emitting sectors—landfills, natural gas, and coal—for selected countries. By 2030, cost-effective technologies could reduce methane emission to less than 50 percent of current levels in the United States, and could potentially reduce emissions by a factor of two in countries such as China, Mexico, and Russia in the same time frame. Another study by the International Institute for Applied Systems Analysis (IIASA) (Cofala et al. 2005) shows the "maximum potential reductions" out to 2030. This study concluded that if all currently available technologies were applied to landfills, agriculture, the natural gas sector, the coal sector, and oil and gas extraction, without consideration of cost, global CH_4 emissions would stabilize and continue to be stable up to 2030.

The scenario analyses above do not explicitly include new non-CO_2 mitigation technologies. An analysis conducted by the U.S. Environmental Protection Agency in cooperation with PNNL assumed the development of advanced technologies in areas such as methane emissions from waste and energy sectors, methane and nitrous oxide emissions from agriculture, and high-GWP emissions from the industrial sector (Placet et al. 2004). Compared to a reference scenario with no emissions constraints and no new non-CO_2 mitigation technologies, the study suggests that reductions in emissions from other GHGs could potentially contribute 120 to 160 GtC-eq in cumulative emissions reductions over the century. The assumptions underlying the advanced technology scenario are based on the currently known methods to achieve emissions reduction, as well as detailed "bottom-up" analyses of the technical potential to reduce non-CO_2 GHGs further. Results from this analysis for a high carbon-constrained case are shown in Figure 3-14.

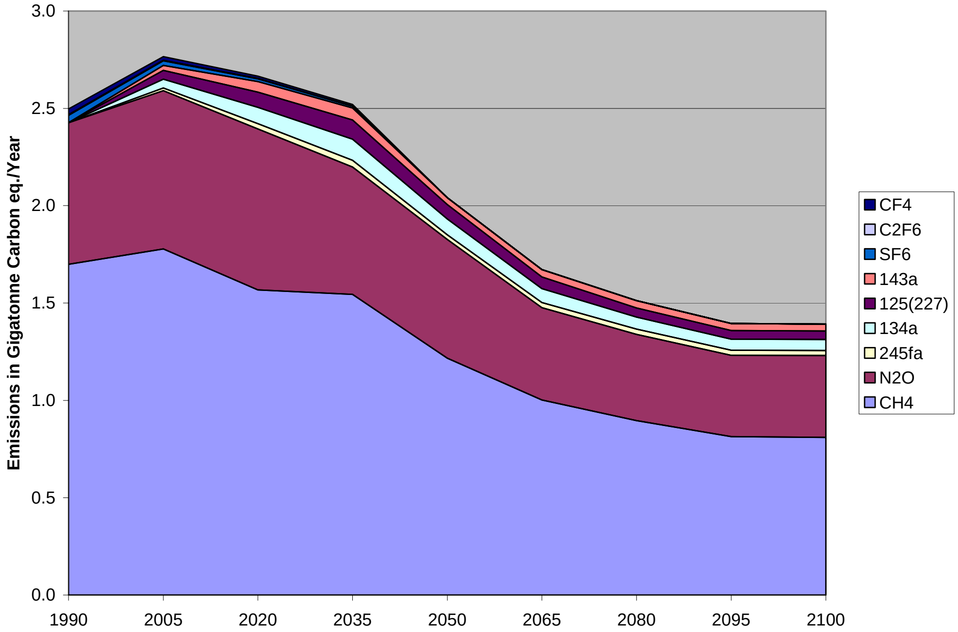

Figure 3-14. World Non-CO_2 GHG Emissions in a High Carbon-Constrained Case[52]

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[52] This figure was based on the *A New Energy Backbone* scenario (Scenario 2).

3.5.3.5 Summary: Relative Contributions of the Four CCTP Goals

As described in the sections above, a variety of scenarios analyses conducted by different research groups show the importance of technology advancement consistent with each of the four core CCTP emissions-reduction goals:

1. Reduce emissions from energy end use and infrastructure
2. Reduce emissions from energy supply
3. Capture and sequester CO_2
4. Reduce emissions of non-CO_2 greenhouse gases

In general, scenario analyses typically indicate that no single technology option is able to provide sufficient emissions reductions to meet stabilization objectives.

This point is illustrated by the results of the PNNL study, in which each of the four technology areas was shown to make contributions toward stabilizing concentrations. Based on the assumptions used in this set of scenarios, no one area was markedly more or less important than others. Figure 3-15, redrawn from

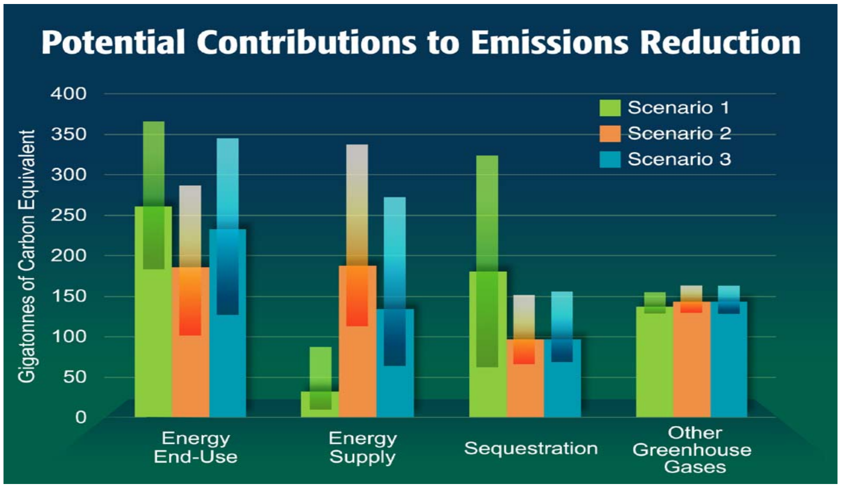

Figure 3-15. Cumulative Contributions between 2000 and 2100 to the Reduction, Avoidance, Capture and Sequestration of Greenhouse Gas Emissions for the Three Advanced Technology Scenarios, Under Varying Carbon Constraints[53]

Note: The thick bars show the contribution in the high emission reduction case and the thinner bars show the variation in the contribution between the very high emission reduction case and the low emission reduction case.

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[53] The figure shows the cumulative contributions between 2000 and 2100 to the reduction, avoidance, capture/ storage and sequestration of greenhouse gas emissions under the three Advanced Technology Scenarios, based on varying emissions constrained cases. The thick bars show the contribution under the high emission constraint and the thinner, semi-transparent bars show the variation in the contribution between the very high emissions constraint and the low emissions constraint. "Energy End-Use" includes emission reductions due to energy efficiency measures. "Energy Supply" includes emissions reductions from the substitution of non-fossil energy supply technologies with low or zero CO_2 emissions for fossil-based power generation without capture and storage of CO_2. "Sequestration" includes carbon capture and storage from fossil-based technologies, as well as terrestrial sequestration.

that analysis, shows the contributions of four technology categories (directly linked to the four CCTP goals stated above) to cumulative GHG emissions reductions over the 100-year scale, across a range of different scenarios. The figure represents one set of possible scenario outcomes based on a particular set of assumptions about advanced technologies over the next century. It offers a glimpse of the range of emissions reductions new technologies might make possible through reduced energy end use; low-or zero-emission energy supply; carbon capture, storage and sequestration; and reduction of other greenhouse gases – on a 100-year scale and across a range of uncertainties.

3.6 Summary of Insights

Many studies have examined long-term GHG emissions trends under a range of assumptions about the rate of change of population, economic growth, and technology change, and the potential role for advanced technology in mitigating emissions growth. Although the rate of GHG emissions growth over the 21st century is uncertain and will depend on many variables, the synthesis assessment of scenarios analyses suggests that significant increases in GHG emissions are projected in most scenarios that assume no specific climate-change-related initiatives. Further scientific study must be undertaken to determine the amount and timing of emissions reductions that would be needed to stabilize concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Many scenarios analyses have shown that the necessary cumulative emissions reductions over the course of the century could be on the order of 200 GtC-eq to 800 GtC-eq (or more).

Emissions reductions of that scale potentially could be achieved through combinations of many different technologies. A large number of scenarios analyses conducted by different research groups show the importance of technology advancement in each of the four core CCTP technology areas. An important insight that can be drawn from these studies is that under a wide range of differing assumptions, advanced technologies associated with energy end use; energy supply; carbon capture, storage and sequestration; and controlling emissions of non-CO_2 GHGs could all potentially contribute significantly to overall GHG emission reductions. This suggests the importance of a diversified approach to technology R&D.

Scenarios analyses also suggest that successful development of advanced technologies could result in potentially large economic benefits. When the costs of achieving different levels of emission reductions were compared for cases with and without advanced technologies, many of the advanced technology scenarios projected that the cost savings would be significant over the course of 100 years.

Finally, scenarios analyses suggest that the timing of the commercial readiness of advanced technology options is an important planning consideration for all scenarios, and particularly for the tighter GHG emissions constraints. Looking over a 100-year planning horizon, and allowing for capital stock turnover and other inertia inherent in the energy system, technologies with zero or near-net-zero GHG emissions would need to be available and moving into the marketplace many years before the emissions "peaks" occur in the hypothetical GHG-constrained cases. Allowing for appropriate lead-in periods for technology development and commercialization, in most of the GHG-constrained cases, some new technologies may need to be commercially ready for widespread implementation between 2020 and 2040, with initial demonstrations between 2010 and 2030.

The following chapters focus in depth on various technological means for making progress toward, and eventually achieving, each of the CCTP strategic goals. Guided, in part, by the insights gained through the review and synthesis of the scenarios analyses, each chapter's discussion addresses the rationale and technology strategy that would guide investments in the current technology portfolio and identifies candidate areas for future research directions that could accelerate technology development and contributions to CCTP goals.

3.7 References

Akimoto, K., T. Tomoda, Y. Fujii, and K. Yamaji. 2004. Assessment of global warming mitigation options with integrated assessment model DNE21. *Energy Economics* 26(4):635-653. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Alcamo, J., R. Leemans, and E. Kreileman, eds. 1998. *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. London: Elsevier Science.

Ausubel, J.H., A. Grübler, and N. Nakicenovic. 1988. Carbon dioxide emissions in a methane economy. *Climatic Change* 12:245-263.

Brown, S., J. Sathaye, M. Cannell, and P.E. Kauppi. 1996. Mitigation of carbon emissions to the atmosphere by forest management. *Commonwealth Forestry Review* 75:80-91.

Cofala, J. Markus Amann, and Reinhard Mechler. 2005. Scenarios of world anthropogenic emissions of air pollutants and methane up to 2030. Laxenburg, Austria: International Institute for Applied Systems Analysis. http://www.iiasa.ac.at/rains/global_emiss/Global%20emissions%20of%20air%20pollutants%20.pdf

Delhotal, K.C., and M. Gallaher. In press. Estimating technical change and potential diffusion of methane abatement technologies for the coal-mining, natural gas, and landfill sectors. Conference proceedings, IPCC Expert Meeting on Industrial Technology Development, Transfer and Diffusion. http://arch.rivm.nl/env/int/ipcc/docs/ITDT/ITDT%20Meeting%20Report%20Open%20website%20version.pdf

De Jong, A., and G. Zalm. 1991. Scanning the future: a long-term scenario study of the world economy 1990-2015. In *Long-term prospects of the world economy*, 27-74. Paris: OECD.

De Vries, H.J.M., J.G.J. Olivier, R.A. van den Wijngaart, G.J.J. Kreileman, and A.M.C. Toet. 1994. Model for calculating regional energy use, industrial production and greenhouse gas emissions for evaluating global climate scenarios. *Water, Air Soil Pollution* 76:79-131.

De Vries, B., M. Janssen, and A. Beusen. 1999. Perspectives on global energy futures—simulations with the TIME model. *Energy Policy* 27:477-494.

De Vries, B., J. Bollen, L. Bouwman, M. den Elzen, M. Janssen, and E. Kreileman. 2000. Greenhouse gas emissions in an equity-, environment- and service-oriented world: An IMAGE-based scenario for the next century. *Technological Forecasting & Social Change* 63(2-3).

Edmonds, J., J. Clarke, J. Dooley, S.H. Kim, S.J. Smith. 2004. Stabilization of CO_2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies. *Energy Economics* 26(4):517-537. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Edmonds, J., M. Wise, and C. MacCracken. 1994. *Advanced energy technologies and climate change. an analysis using the Global Change Assessment Model (GCAM)*. PNL-9798, UC-402. Richland, WA: Pacific Northwest Laboratory. http://sedac.ciesin.columbia.edu/mva/MCPAPER/mcpaper.html

Edmonds, J., M. Wise, H. Pitcher, R. Richels, T. Wigley, and C. MacCracken. 1996a. An integrated assessment of climate change and the accelerated introduction of advanced energy technologies: an application of MiniCAM 1.0. *Mitigation and Adaptation Strategies for Global Change* 1(4):311-339.

Edmonds, J., M. Wise, R. Sands, R. Brown, and H. Kheshgi. 1996b. *Agriculture, land-use, and commercial biomass energy. a preliminary integrated analysis of the potential role of biomass energy for reducing future greenhouse related emissions*. PNNL-11155. Washington, DC: Pacific Northwest National Laboratories.

Energy Information Administration (EIA). 2004. *International energy outlook 2004*. DOE/EIA-0484. Washington, DC: U.S. Department of Energy. http://www.eia.doe.gov/oiaf/ieo/index.html

EPA (See U.S. Environmental Protection Agency)

Grübler, A., and N. Nakicenovic. 1996. Decarbonizing the global energy system. *Technological Forecasting and Social Change* 53(1):97-110.

Hanson, D., and J. Laitner. 2004. An integrated analysis of policies that increase investments in advanced energy-efficient/low-carbon technologies, Energy Economics 26(4):739-755. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Hoffert, Martin L. et al. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298:981-987.

IIASA-WEC (International Institute for Applied Systems Analysis-World Energy Council). 1995. *Global energy perspectives to 2050 and beyond*. London: WEC.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate change 1995: the science of climate change. Contribution of Working Group I to the Second Assessment Report*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special report on emissions scenarios*. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc/emission/index.htm

Intergovernmental Panel on Climate Change (IPCC). 2001. C*limate Change 2001. Mitigation: a report of Working Group III of the Intergovernmental Panel on Climate Change*. Bert Metz, Ogunlade Davidson, Rob Swart and Jiahua Pan, eds. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/index.htm

IPCC (See Intergovernmental Panel on Climate Change).

Lashof, D., and D.A. Tirpak. 1990. Policy options for stabilizing global climate. 21P-2003. Washington, DC: U.S. Environmental Protection Agency.

Manne, A., and R. Richels. 2000. A multi-gas approach to climate policy—with and without GWPs. http://www.stanford.edu/group/MERGE/multigas.pdf

Manne, A., and R. Richels. 2001. An alternative approach to establishing trade-offs among greenhouse gases. *Nature* 410:675-677.

Manne, A., and R. Richels. 2004. The impact of learning-by-doing on the timing and costs of CO_2 abatement. *Energy Economics* 26(4):603-619. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

McFarland, J.R., J.M. Reilly, and H.J. Herzog. 2004. Representing energy technologies in top-down economic models using bottom-up information. *Energy Economics* 26(4):685-707. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Messner, S., and M. Strubegger. 1995. *User's guide for MESSAGE III*. WP-95-69. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Mori, S. 2000. The development of greenhouse gas emissions scenarios using an extension of the MARIA model for the assessment of resource and energy technologies. *Technological Forecasting & Social Change* 63(2-3).

Mori, S., and M. Takahashi. 1999. An integrated assessment model for the evaluation of new energy technologies and food productivity. *International Journal of Global Energy Issues* 11(1-4):1-18.

Mori, S., and T. Saito. 2004. Potentials of hydrogen and nuclear towards global warming mitigation—expansion of an integrated assessment model MARIA and simulations. *Energy Economics* 26(4):565-578. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Morita, T., Y. Matsuoka, I. Penna, and M. Kainuma. 1994. Global carbon dioxide emission scenarios and their basic assumptions: 1994 survey. CGER-1011-94. Tsukuba, Japan: Center for Global Environmental Research, National Institute for Environmental Studies.

Pacala, S., and R. Socolow. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 305:968-972.

Pepper, W.J., J. Leggett, R. Swart, J. Wasson, J. Edmonds, and I. Mintzer. 1992. Emissions scenarios for the IPCC. An update: assumptions, methodology, and results. Support document for Chapter A3. In *Climate change 1992: supplementary report to the IPCC scientific assessment*, J.T. Houghton, B.A. Callandar, and S.K. Varney, eds. Cambridge, UK: Cambridge University Press.

Placet, M., K.K. Humphreys, and N. Mahasenan. 2004. Climate change technology scenarios: energy, emissions, and economic implications. PNNL-14800. Richland, WA: Pacific Northwest National Laboratory. http://www.pnl.gov/energy/climate/climate_change-technology_scenarios.pdf

Reilly, J., M. Mayer, and J. Harnisch. 2002. The Kyoto Protocol and non-CO_2 greenhouse gases and carbon sinks. *Environmental Modeling and Assessment* 7(4):217-229.

Riahi, K., and R.A. Roehrl. 2000. Greenhouse gas emissions in a dynamics-as-usual scenarios of economic and energy development. *Technological Forecasting & Social Change* 63:175-206.

Richards, K. and C. Stokes. 2004. A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research. *Climatic Change*. 63 (1-2): 1-48.

Richels, R.G., A.S. Manne, and T.M.L. Wigley. 2004. Moving beyond concentrations: the challenge of limiting temperature change. Working Paper 04-11. AEI-Brookings Joint Center for Regulatory Studies. http://www.aei-brookings.org/admin/authorpdfs/page.php?id=937

Sankovski, A., W. Barbour, and W. Pepper. 2000. Quantification of the IS99 emission scenario storylines using the atmospheric stabilization framework (ASF). *Technological Forecasting & Social Change* 63(2-3).

Sohngen, B., and R. Sedjo (forthcoming). Carbon Sequestration Costs in Global Forests. *Energy Journal*. Special Edition on Multi-gas Scenarios and Climate Change (forthcoming).

Sohngen, B. and R. Mendelsohn. 2003. An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics*, 2003, Volume 85, Issue 2, pp. 448-457.

United Nations Development Program (UNDP). 2000. World Energy Assessment. New York.

U.S Climate Change Science Program. 2003. *Strategic plan for the U.S. Climate Change Science Program*. http://www.climatescience.gov/Library/stratplan2003.default.htm

U.S. Environmental Protection Agency. 2005. *U.S. emissions inventory: inventory of u.s. greenhouse gas emissions and sinks: 1990-2003*. EPA 430-R-05-003. Washington, DC: U.S. Environmental Protection Agency. http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html

van Vuuren, D.P., B. de Vries, B. Eickhout, and T. Kram. 2004. Responses to technology and taxes in a simulated world. *Energy Economics* 26(4):579-601. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.

Webster, M.D., M. Babiker, M. Mayer, J.M. Reilly, J. Harnisch, R. Hyman, M.C. Sarofim, and C. Wang. 2002. Uncertainty in emissions projections for climate models. *Atmospheric Environment* 36 (2002) 3659–3670.

Wexler, L. 1996. *Improving population assumptions in greenhouse emissions models*. WP-96-099. Laxenburg, Austria: International Institute for Applied Systems Analysis. http://www.iiasa.ac.at/Publications/Documents/WP-96-099.pdf

Weyant, J.P., ed. 2004. *Energy Economics* 26(4): Special Issue EMF 19 Alternative technology strategies for climate change policy.

Weyant, J.P., and F. de la Chesnaye. 2005. Multigas scenarios to stabilize radiative forcing. *Energy Journal*. Special Edition on Multi-gas Scenarios and Climate Change (forthcoming).

Wigley T., R. Richels, and J. Edmonds. 1996. “Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations.” *Nature*, Volume 379, Number 6562, pp. 240-243.

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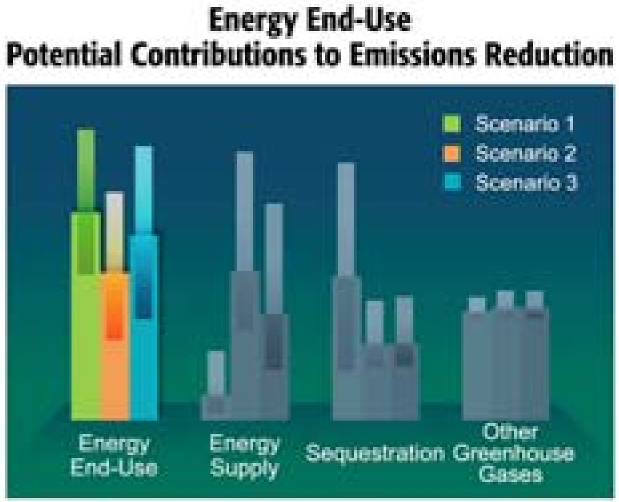
4 Reducing Emissions from Energy End Use and Infrastructure



Potential contributions of Energy End Use reduction to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

Emissions of carbon dioxide (CO_2) from energy consumption in the end-use sectors (industry, residential and commercial buildings, and transportation) of the global economy can be lowered through energy conservation practices,[1] technological and other economic productivity improvements that lead to increased energy efficiency, and shifts in the composition of output in the economy. Historically, global energy productivity – loosely measured in terms of economic output per unit of energy input – has shown steady increases, averaging gains of about 0.9 percent per year over the period 1971 to 2002 (IEA 2004). Use of more energy-efficient processes and replacement of older, less-efficient capital stock are important contributors to these gains. Another factor in reducing individual country measures of energy intensity, especially in industrialized countries, has been a shift over the past several decades in the composition of economic output toward less energy-intensive goods and services.

In published scenarios, increasing demand for energy services, driven by population and economic growth, results in growth of CO_2 emissions over the 21st century in the absence of GHG emissions constraints. And, in almost all scenarios that explore pathways to emission reductions, energy use reduction[2] plays a key role in achieving future CO_2 emissions reductions. In one set of scenarios, energy end-use reductions led to a decrease of between 3 and 18 thousand exajoules (EJ) of global energy, and between about 100 and 370 gigatons of carbon (GtC) of global carbon emissions, compared to the reference case used in the study (see Chapter 3).

In the United States, the largest end-use sources of CO_2 emissions (see Table 4-1) are the following:

- electricity and fuel use in buildings
- transportation fuels
- electricity and fuel use in industry
- a few industrial processes not related to combustion

This chapter explores energy end-use and carbon emission-reduction strategies and opportunities within each of these end-use categories. Sections 4.1 through 4.3 address transportation, buildings, and industry, respectively. Section 4.4 deals with technology strategies for the electric grid and infrastructure that can facilitate CO_2 emissions reductions in all sectors. All sections provide background information on each of their respective sectors and explain the current and evolving strategy for reducing CO_2 emissions. Note

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[1] In this context, "energy conservation" refers to practices that reduce energy waste, such as turning off lights, equipment, etc., when not in use.

[2] End-use reduction includes improvements in energy efficiency in the end-use sectors, as well as improvements in efficiency of energy conversion, e.g., increased efficiency in electricity generation.

Table 4-1. CO_2 Emissions in the United States by End-Use Sector, 2003 (GtC)

End-Use Sector	Emissions from Electricity	Emissions from Combustion of Fuels	Emissions, Total	% of Total
Transportation	0.009	0.485	0.493	31.1%
Residential and Commercial Buildings	0.410	0.169	0.579	36.5%
Industrial Energy Use	0.211	0.258	0.468	29.5%
Industrial Processes			0.040	2.5%
Waste Disposal Activities		0.005	0.005	0.3%
Total	**0.630**	**0.957**	**1.586**	

Source: EPA 2005, Tables 2-16, 3-44, and 4-1.
Note: Values may not sum to total due to independent rounding of values.

that this chapter focuses on reducing and avoiding CO_2 emissions. Many industrial processes and energy end uses produce significant quantities of other non-CO_2 greenhouse gases (GHGs), which are addressed separately in Chapter 7, "Reducing Emissions of Other Greenhouse Gases." The descriptions of the technologies in this section include active Internet links to an updated version of the CCTP report *Technology Options in the Near and Long Term* (CCTP 2005) at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

4.1 Transportation

The transport of people, goods, and services accounts for a significant share of global energy demand, mostly in the form of petroleum, and is among the fastest growing sources worldwide of emissions of GHGs, mainly CO_2. In the developing parts of Asia and the Americas, emissions from transportation-related use of energy are expected to increase dramatically during the next 25 years. In the United States, from 1991 to 2000, vehicle miles traveled, a measure of highway transportation demand, increased at an average rate of 2.5 percent per year (DOT 2002a), outpacing population growth. In 2003, the U.S. transportation sector accounted for 39 percent of total CO_2 emissions, with the highway modes accounting for more than 82 percent of these (see Table 4-2). Through 2025, future growth in U.S. transportation energy use and emissions is projected to be strongly influenced by the growth in light-duty trucks (pickup trucks, vans, and sport-utility vehicles, under 8,500 lb gross vehicle weight rating) (see Figure 4-1). According to the Federal Highway Administration's *Freight Analysis Framework*, freight tonnage will grow by 70 percent during the first two decades of the 21st century (DOT 2002b).

4.1.1 Potential Role of Technology

Advanced technologies can make significant contributions to reducing CO_2 emissions from transportation activity. In the near term, advanced highway vehicle technologies, such as electric-fuel-engine hybrids ("hybrid-electric" vehicles) and clean diesel engines, could improve vehicle efficiency and, hence, lower CO_2 emissions. Other reductions might result from modal shifts (e.g., from cars to light rail) or higher load factors, improved overall system-level efficiency, or reduced transportation demand. Improved intermodal connections could allow for better mode-shifting and improved efficiency in freight transportation. Application of developing technology will reduce idling and the concomitant emissions

Table 4-2. CO_2 Emissions in the United States from Transportation, by Mode, in 2003 (GtC)

	Emissions	% of Total
Passenger Cars	0.173	35.6%
Light-Duty Trucks	0.131	26.9%
Other Trucks	0.093	19.2%
Aircraft[(a)]	0.047	9.6%
Other[(b)]	0.013	2.6%
Boats and Vessels	0.016	3.2%
Locomotives	0.012	2.4%
Buses	0.002	0.5%
Total [(c)]	**0.477**	**100.0**

(a) Aircraft emissions consist of emissions from all jet fuel (less bunker fuels) and aviation gas consumption.
(b) "Other" CO_2 emissions include motorcycles, pipelines, and lubricants.
(c) Percentages may not sum to 100 percent due to independent rounding of values.

Source: EPA 2005.

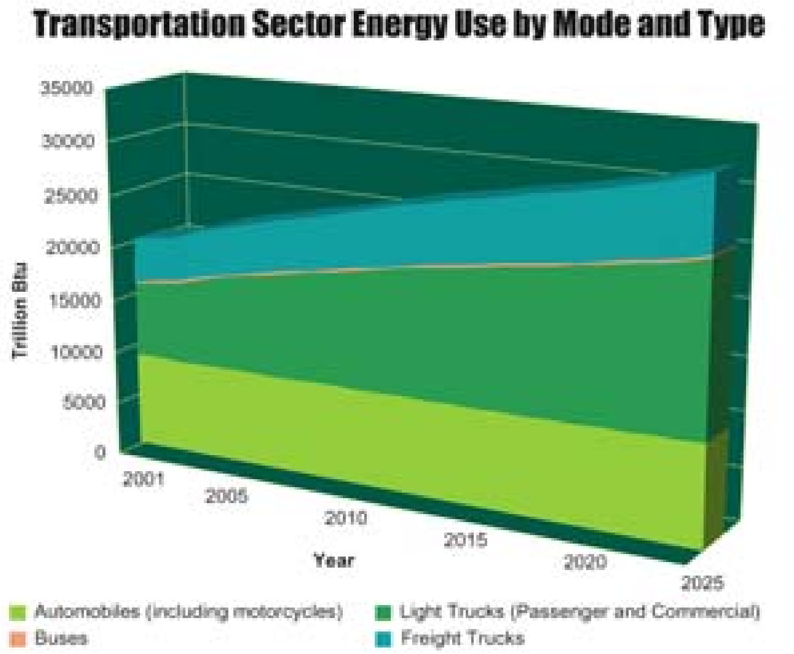

Figure 4-1. Projected Energy Consumption in U.S. Highway Vehicles
(*Source:* EIA 2004)

from heavy-duty vehicles, including vessels, trains, and long-haul trucks. Intelligent transportation systems can reduce congestion, resulting in decreases in fuel use. In the long term, technologies such as cars and trucks powered by hydrogen, bio-based fuels, and electricity show promise for transportation with either no highway CO_2 emissions or no net-CO_2 emissions.

In addition, new communications technologies may alter our concepts about individual mobility. Work locations may be centered near or in residential locations, and work processes and products may be more commonly communicated or delivered via digital media. With global trends toward increasing urbanization in both population concentrations and opportunities for employment, there may be more reliance in the future on improved modes of local, light-rail or intra-city passenger transport, coupled with other advances in electrified intercity transport that would curb the growth of fuel use and emissions from transportation.

4.1.2 Technology Strategy

Realizing these opportunities requires a research portfolio that embraces a combination of advanced vehicle, fuel, and transportation system technologies. Within constraints of available resources, a balanced portfolio needs to address major sources of CO_2 emissions in this sector, including passenger cars, light trucks, and other trucks; key modes of transport, including highway, aviation, and urban transit; system-wide planning and enhancements; and both near- and long-term opportunities.

In the near term, CO_2 emissions and transportation energy use can be reduced through improved vehicle efficiency, clean diesel engines, hybrid propulsion, and the use of hydrogenated low-sulfur gasoline. Other fuels, such as ethanol, natural gas, electricity with storage, and biodiesel, can also provide attractive means for reducing emissions of CO_2. These efficiency gains and fuel alternatives also provide other benefits, such as improving urban and regional air quality and enhancing energy security.

In aviation, emissions could be lowered through new technologies to improve air-traffic management. An example is RVSM – Reduced Vertical Separation Minimums. RVSM has been used for transatlantic flights since 1997, and it became standard in U.S. airspace in January 2005. Full implementation of RVSM may reduce fuel use by ~500 million gallons each year.

In the long term, hydrogen may prove to be a low- or no-net-carbon energy carrier, if it can be cost-effectively produced with few or no GHG emissions, such as with renewable or nuclear energy, or with fossil fuels in conjunction with carbon capture and storage. Hydrogen and biofuels as substitutes for petroleum-based fuels in the transportation and other sectors also offer significant national security benefits. Hydrogen and alternative fuels are discussed in more depth in Chapter 5, "Reducing Emissions from Energy Supply." Hydrogen can be used in internal combustion engines; but use in highly efficient fuel-cell-powered vehicles is considered a very important future option. In aviation, new engines and aircraft will feature enhanced engine cycles, more efficient aircraft aerodynamics, and reduced weight – thereby improving fuel efficiency. Research sponsored by the Federal Government through NASA, in collaboration with the Next Generation Air Transportation System (NGATS) plan, could enable these enhancements. NGATS is a multiagency-integrated effort to ensure that the future air transportation system meets air transportation security, mobility, and capacity needs while reducing environmental impacts.

4.1.3 Current Portfolio

Across the current Federal portfolio of transportation-related R&D, Federal activities are focused on a number of major programs:

- Research on **light vehicles**, organized primarily under the FreedomCAR Partnership program, focuses on materials; power electronics; hybrid vehicles operating on gasoline, diesel, or alternative fuels; high-efficiency, low-emission advanced combustion engines, enabled by improved fuels; and high-volume, cost-effective production of lightweight materials.

  The vehicle technologies research programs have a number of specific goals. They include: (a) electric propulsion systems with a 15-year life capable of delivering at least 55 kW for 18 seconds and 20 kW continuous at a system cost of $12/kW peak; (b) internal combustion engine powertrain systems costing $35/kW, having peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards; (c) electric drivetrain energy storage with a 15-year life at 200 Wh with discharge power of 25kW for 18 seconds and $20/kW; (c) material and manufacturing technologies for high volume production vehicles, which enable/support the simultaneous attainment of 50 percent reduction in the weight of vehicle structure and subsystems, affordability, and increased used of recyclable/renewable materials; and (d) internal combustion engine powertrain systems, operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards. For more information, see Section 1.1.1 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-111.pdf
  See also: http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/transportation.html, and http://www.epa.gov/otaq/technology

- Research areas for **heavy vehicles**, organized primarily under the 21st Century Truck Partnership, include lightweight materials, aerodynamic drag, tire rolling resistance, electrification of ancillary equipment, advanced high efficiency combustion propulsion systems (including energy-efficient emissions reduction), fuel options (both petroleum and nonpetroleum based), hybrid technologies for urban driving applications, and onboard power units for auxiliary power needs. The research objectives are to (1) reduce energy consumption in long-haul operations, (2) increase efficiency and reduce emissions during stop-and-go operations, and (3) develop more efficient and less-polluting energy sources to meet truck stationary power requirements (i.e. anti-idling). By 2007, the goals for heavy vehicles include a commercially viable 5 kW, $200/kW, diesel-fueled, internal combustion engine auxiliary power unit. By 2010, the goals include a laboratory demonstration of an emissions-compliant engine system that is commercially viable for Class 7-8 highway trucks, which improves the system efficiency by 32 percent (37 percent by 2013) from the 2002 baseline. By 2012, the goals include advanced technology concepts that reduce the aerodynamic drag of a Class 8 tractor-trailer combination by 20 percent. See Section 1.1.2 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-112.pdf See also:
  http://www.epa.gov/otaq/technology

- **Fuels research** encompasses the development of new fuel blend formulations that will enable more efficient and cleaner combustion and the development of renewable and nonpetroleum-based fuels that could displace 5 percent of petroleum used by commercial vehicles. See Section 1.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-113.pdf

- Research on **intelligent transportation systems** infrastructure includes sensors, information technology, and communications to improve efficiency and ease congestion. Intelligent transportation systems goals include improved analysis capabilities that properly assess the impact of ITS strategies and strategies that will improve travel efficiency resulting in lower delays, thereby reducing emissions. See Section 1.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-114.pdf

- Research on **aviation fuel efficiency** includes engine and airframe design improvements. Aviation fuel efficiency goals include improved aviation fuel efficiency per revenue plane-mile by 1 percent per year through 2008, and new technologies with the potential to reduce CO_2 emissions from future aircraft by 25 percent within 10 years and by 50 percent within 25 years. See Section 1.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-115.pdf

- Research on **transit buses** and other urban-driving heavy vehicles focuses on hybrid-electric propulsion, weight reduction, and advanced combustion engine concepts to improve efficiency and reduce emissions. By 2012, research program goals for transit buses include development of heavy hybrid propulsion technology that achieves a 60 percent improvement in fuel economy, on a representative driving cycle, while meeting regulated emissions levels. See Section 1.1.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-116.pdf

4.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Strategies and technologies to increase freight transfer and movement efficiency (tons of freight moved 1 mile by a particular unit of energy) in anticipation of large growth in freight volumes.

- Studies of advanced urban-engineering concepts for cities to reduce vehicle miles traveled.

- Concept and engineering studies for large-scale institutional and infrastructure changes required to manage CO_2, electricity, and hydrogen systems reliably and securely.

- Technologies for large-scale hydrogen storage and transportation and electricity storage

In addition, supporting or crosscutting areas for future research include:

- Advanced thermoelectric concepts to convert waste heat from combustion into power.

- New combustion regimes and fuels designed to achieve very high efficiencies, near-zero regulated emissions, and reduced carbon emissions in conventional vehicle propulsion systems.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

4.2 Buildings

The built environment – consisting of residential, commercial, and institutional buildings – accounts for about one-third of primary global energy demand (IPCC 2000) and represents a major source of energy-related GHG emissions, mainly CO_2. Growth in global energy demand in buildings averaged 3.5 percent per year since 1970 (IPCC 2001).

Over the long term, buildings are expected to continue to be a significant component of increasing global energy demand and a large source of CO_2 emissions. Energy demand in this sector will be driven by growth in population, by the economic expansion that is expected to increase the demand for building services (especially electric appliances, electronic equipment, and the amount of conditioned space per person), and by the continuing trends toward world urbanization. As urbanization occurs, energy consumption increases, because urban buildings usually have electricity access and have a higher level of energy consumption per unit area than buildings in more primitive rural areas. According to a recent projection by the United Nations, the percentage of the world's population living in urban areas will increase from 49 percent in 2005 to 61 percent by 2030 (UN 2005).

In the United States, energy consumption in buildings has been increasing proportionately with increases in population, although this trend masks significant increases in efficiency in some building components that are being offset by new or increased energy uses in others. In the United States in 2003, CO_2 emissions from this sector, including those from both fuel combustion and use of electricity derived from CO_2-emitting sources, accounted for nearly 37 percent of total CO_2 emissions (see Table 4-1). These emissions have been increasing at 1.9 percent per year since 1990 (EIA 2005). Table 4-3 shows a breakdown of emissions from the buildings sector, by fuel type, in the United States.

Table 4-3. Residential and Commercial CO_2 Emissions in the United States, by Source, in 2003 (GtC)

	Emissions	%
Residential		
Electricity	0.2121	66.9
Natural gas	0.0756	23.8
Petroleum	0.0291	9.2
Coal	0.0003	0.1
Total Residential	0.3171	100.0
Commercial		
Electricity	0.2005	76.2
Natural gas	0.0466	17.5
Petroleum	0.0147	5.4
Coal	0.0025	0.9
Total Commercial	0.2643	100

Source: EPA 2005, Tables 2-16 and 3.3.
Note: Percentages may not sum to 100 percent, due to independent rounding of values.

4.2.1 Potential Role of Technology

Many opportunities exist for advanced technologies to make significant reductions to energy-related CO_2 emissions in the buildings sector. In the near term, advanced technologies can improve efficiency of energy-using equipment in the primary functional areas of energy use. In residential buildings, these functional areas include space heating, appliances, lighting, water heating, and air conditioning. In commercial buildings, functional areas are lighting, space heating, cooling and ventilation, water heating, office equipment, and refrigeration. Through concerted research, major technical advances have occurred during the past 20 years, with many application areas seeing efficiency gains of 15 percent to 75 percent. (See Figure 4-2 for an example of technological improvements that have occurred in refrigerators as an illustration of the kind of gains that have been achieved.)

Over the longer term, more advances can be expected in these areas, and significant opportunities also lie ahead in the areas of new buildings design, retrofits of existing buildings, and the integration of whole building systems and multibuilding complexes through use of sensors, software, and automated maintenance and controls.

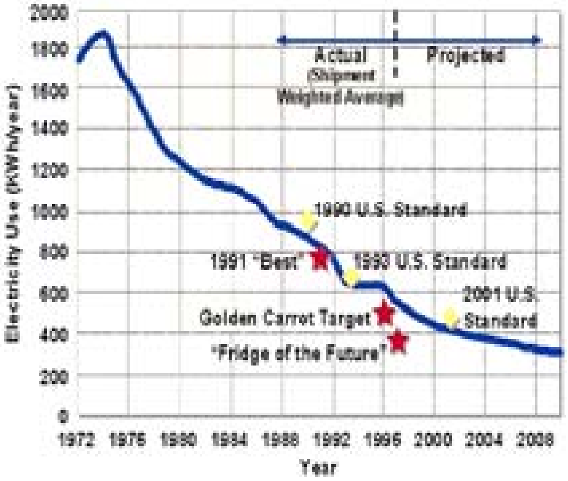

Figure 4-2. Refrigerator Energy Efficiency

(*Source*: Brown 2003)

Note: The curve applies to 18-20 cu. ft. top-mount refrigerator/freezers, which capture the largest market share in the United States. The term,"1991 Best" stands for the 1991 top-mount model with lowest energy use. "Golden Carrot Target" was an EPA/electric utility program in the early 1990s to develop a model that was 25% more efficient than the current technology at the time. "Fridge of the Future" is a refrigerator that had a target energy use of 365 kWh/yr or 1 kWh/day for 18-20 cu. ft. top-mount models based on an cooperative research agreement between Oak Ridge National Laboratory (ORNL) and the Association of Home Appliance Manufacturers; this target was exceeded in a test unit (0.93 kWh/day) in FY 1996.

By 2025 – with advances in building envelopes, equipment, and systems integration – it may be possible to achieve up to a 70 percent reduction in a building's energy use, compared to the average energy use in an equivalent building today (DOE 2005). If augmented by on-site energy technologies (such as photovoltaics or distributed sources of combined heat and power), buildings could become net-zero GHG emitters and net energy producers.

4.2.2 Technology Strategy

While the built environment is a complex mix of heterogeneous building types (commercial, service, detached dwelling, apartment buildings) and functional uses, all have common features, each of which may benefit from technological research, both as individual components and as integrated systems. Within constraints of available resources, a balanced portfolio needs to address four important aspects of buildings that affect their CO_2 emissions, including the building envelope, building equipment, integrated building design, and the urban heat island effect. The portfolio should look at both near- and long-term opportunities.

In the near term, building energy use and CO_2 emissions could be lowered through building environment-control systems and advanced materials such as insulation, foams, vacuum panels, and optical coatings. Technology to improve the efficiency of lighting, appliances, heating, cooling, and ventilation are other options. Intelligent building systems (such as load balancing and automated sensors and controls) help ensure the comfort, health, and safety of residents, as well as aid in the reduction of CO_2.

In the long term, more advanced research on the building envelope – including panelized housing construction, integration of photovoltaics, and new storage technologies – can drive CO_2 emissions even lower. Distributed power systems, advanced refrigeration and cooling technologies, heat pumps, and solid-state lighting technology are among some of the more promising options for equipment. Among the alternatives, building integration should focus on including sensors and controls, community-scale integration tools, and urban engineering.

4.2.3 Current Portfolio

The current Federal portfolio focuses on four major thrusts. In combination, these activities aim to achieve net-zero energy residential buildings by 2020 and commercial buildings by 2025.

- Research on the **building envelope** (the interface between the interior of a building and the outdoor environment) focuses on systems that determine or provide control over the flow of heat, air, moisture, and light in and out of a building; and on materials that can affect energy use, including insulation, foams, vacuum panels, optical control coatings for windows and roofs, thermal storage, and related controls (such as electrochromic glazings). A major new initiative is a re-engineered attic/roof assembly, which has an equivalent performance of R-50.

  Research program goals in the building envelope area include the following: By 2008, demonstrate dynamic solar control windows (electrochromics) in commercial buildings; and by 2010, demonstrate windows with R10 insulation performance for homes. By 2025, the program goal is to develop marketable and advanced energy systems capable of achieving "net-zero" energy use in new residential and commercial buildings. The long-term goal is to achieve a 30 percent decrease in the average envelope thermal load of existing residential buildings and a 66 percent decrease in the average thermal load of new buildings. See Section 1.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-122.pdf

- Research on **building equipment** focuses on means to significantly improve efficiency of heating, cooling, ventilating, thermal distribution, lighting, home appliances, on-site energy and power devices, and a variety of miscellaneous consumer products. This area also includes a number of crosscutting elements, including geothermal heat pumps with enhanced earth-heat exchangers, advanced refrigerants and cycles, solid-state lighting, smart sensors and controls, small power supplies, microturbines, heat recovery, and other areas.

Specific goals include: (a) for distributed electricity generation technologies (including microturbines), by 2008, enable a portfolio of equipment that shows an average 25 percent increase in efficiency; (b) for solid-state lighting in general illumination applications, by 2008, develop equipment with luminous efficacy of 79 lumens per watt (LPW); and for laboratory devices by 2025, luminous efficacy of 200 LPW. The long-term goals are: (a) by 2025, develop and demonstrate marketable and advanced energy systems that can achieve "net-zero" energy use in new residential and commercial buildings through a 70 percent reduction in building energy use; and (b) by 2030, enable the integrations of all aspects of the building envelope, equipment, and appliances with on-site micro-cogeneration and zero-emission technologies. See Section 1.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-121.pdf

- Research on **whole building integration** focuses on load balancing and automated sensors and controls, sometimes referred to as intelligent building systems. Such systems continuously monitor building performance, detect anomalies or degradations, optimize operations across all building systems, guide maintenance, and document and report results. They can also be extended to coordinate on-site energy generation and internal loads, with external power (grid) demands and circumstances, allowing responsiveness to time-variant cost savings, system efficiencies, and grid contingencies. They also ensure occupant comfort, health, and safety, met at lowest possible cost.

  Whole building integration goals include fully and seamlessly integrated building design tools that support all aspects of design and provide rapid analysis of problems. Also included are the development of automatic operation of buildings systems that require little operator attention and highly efficient combined cooling, heating, and power systems that use waste heat from small-scale, on-site electricity generation to provide heating and cooling for the buildings, as well as export excess electricity to the grid. See Section 1.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-123.pdf

- Research related to the **urban "heat island"** includes the causes of, and mitigation strategies for, the heating and energy loading effects of the built environment in this paved and often treeless environment. Urban heat island goals include improved understanding and quantification of the impacts heat island reduction measures have on local meteorology, energy use and expenditures, greenhouse gas emissions, and air quality. Specific products include a GIS application that predicts heat island outcomes from different development scenarios (e.g., benefits from large-scale tree planting) and cool materials for roofs and pavements. See Section 1.2.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-124.pdf

4.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Building Envelope**. Improved panelized housing construction; methods for integrating photovoltaic systems in building components such as roofs, walls, skylights, and windows, and with building loads and utilities; and exploration of fundamental properties and behaviors of novel materials for the storage and release of energy.

- **Building Equipment**. Fuel cells, microturbines, and reciprocating engines; advanced commercial refrigeration display cases, refrigerants, and materials; advanced desiccants and commercial chiller improvements, including absorption systems; advanced magnetic or solid-state cooling technologies, highly efficient geothermal heat pumps, residential heat pump water heater and hot water circulation improvements; solid-state lighting technology and improved lighting distribution systems.

- **Whole Building Integration**. Further development and widespread implementation of building design tools for application in new and retrofit construction; tools and technologies for systems integration in buildings, with a particular focus on sensors and controls for supply and end-use system integration; development of pre-engineered, optimized net-zero energy buildings; community-scale design and system integration tools; and urban engineering to reduce transport energy use and congestion.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

4.3 Industry

Industrial activities were estimated to account for about 41 percent of primary global energy consumption in 1995 (IPCC 2000) and a commensurate share of global CO_2 emissions. Certain activities are particularly energy-intensive, including metals industries, such as iron, steel, and aluminum; petroleum refining; basic chemicals and intermediate products; fertilizers; glass; pulp, paper, and other wood products; and mineral products, including cement, lime, limestone, and soda ash. Others are less energy-intensive, including the manufacture or assembly of automobiles, appliances, electronics, textiles, food and beverages, and others. Each regional or national economy varies in the structure, composition, and growth rates of these industries; shaped, in part, by its state of economic development and, in part, by regional advantages in international trade. The industrial sector worldwide is expected to expand in the future and will likely continue to account for a substantial portion of future CO_2 emissions.

In the United States in 2003, industry accounted for about one-third of total U.S. CO_2 emissions (see Table 4-1). These are attributed to combustion of fuels (51 percent), use of electricity derived from CO_2-emitting sources (41 percent), and industrial processes that emit CO_2 (8 percent). (See Table 4-4[3]).

4.3.1 Potential Role of Technology

The industrial sector presents numerous opportunities for advanced technologies to make significant contributions to the reductions of CO_2 emissions to the Earth's atmosphere. In the near term, advanced

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[3] Emissions of GHGs other than CO_2 from industry and agriculture are discussed in Chapter 7, "Reducing Emissions of Other Greenhouse Gases."

Table 4-4. CO_2 Emissions in the United States from Industrial Sources in 2003 (GtC)
(Excludes Indirect Emissions from Industrial Use of Centrally Generated Electric Power)

	Emissions 10^9 Tonnes C	**Share of Industry Total (%)**	**Share of Industrial Processes (%)**
Industrial Fuel Combustion	**0.258**	**50.7**	
Coal	*0.034*	6.6	
Petroleum	*0.087*	17.1	
Natural Gas	*0.111*	21.9	
Industrial Electricity	**0.211**	**41.4**	
Industrial Processes (excluding fuel combustion emissions above)	**0.040**	7.9	(See Breakout Below)
Total Industrial CO_2	**0.509**	**100.0**	
Breakout of Emissions from Industrial Processes:			
Iron and Steel Production	0.0147		36.5
Cement Manufacture	0.0117		29.2
Ammonia Manufacture & Urea Application	0.0043		10.6
Lime Manufacture	0.0035		8.8
Limestone and Dolomite Use	0.0013		3.2
Aluminum Production	0.0011		2.9
Soda Ash Manufacture and Consumption	0.0011		2.8
Petrochemical Production	0.0008		1.9
Titanium Dioxide Production	0.0005		1.4
Phosphoric Acid Production	0.0004		1.0
Ferroalloy Production	0.0004		1.0
Carbon Dioxide Consumption	0.0004		0.9
Total Industrial Process CO_2	**0.0402**		**100.0**

Source: EPA 2005, Tables 2-14, 2-16, 3-44, and 4-1.
Note: Percentages may not sum to 100 percent due to independent rounding of values.

technologies can increase the efficiency with which process heat is generated, contained, transferred, and recovered. Process and design enhancements can improve quality, reduce waste, minimize reprocessing, reduce the intensity of material use (with no adverse impact on product or performance), and increase in-process material recycling. Cutting-edge technologies can significantly reduce the intensity with which energy and materials (containing embedded energy) are used. Industrial facilities can implement direct manufacturing processes, which can eliminate some energy-intensive steps, thus both avoiding emissions and enhancing productivity. On the supply side, industry can self-generate clean, high-efficiency power and steam; and create products and byproducts that can serve as clean-burning fuels. The sector can also make greater use of coordinated systems that more efficiently use distributed energy generation, combined heat and power, and cascaded heat.

In the long term, fundamental changes in energy infrastructure could affect significant CO_2 emissions reductions. Revolutionary changes may include novel heat and power sources and systems, including renewable energy resources, hydrogen, and fuel cells. Innovative concepts for new products and high-efficiency processes may be introduced that can take full advantage of recent and promising developments in nanotechnology, micro-manufacturing, sustainable biomass production, biofeedstocks, and bioprocessing. As global industry's existing, capital-intensive equipment stock nears the end of its useful service life – and as industry expands in rapidly emerging economies in Asia and the Americas – this sector will have an opportunity to adopt novel technologies that could revolutionize basic manufacturing. Advanced technologies will likely involve a mix of pathways, such as on-site energy generation, conversion, and utilization; process efficiency improvements; innovative or enabling concepts, such as advanced sensors and controls, materials, and catalysts; and recovery and reuse of materials and byproducts (See Figure 4-3). In the United States, the development and adoption of advanced industrial technologies can provide not only GHG benefits but also help to maintain U.S. competitiveness.

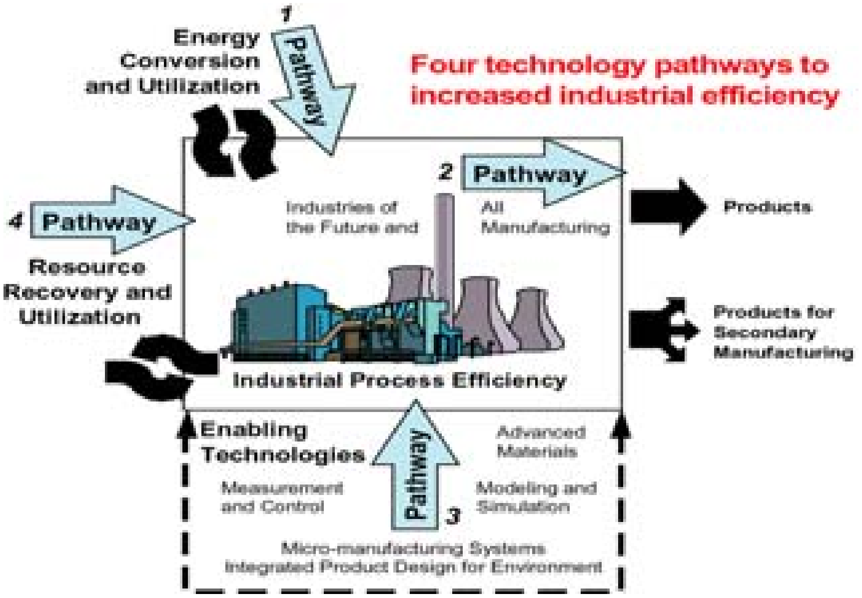

Figure 4-3. Four Possible Pathways to Increased Industrial Efficiency
(*Source:* DOE 1997)

4.3.2 Technology Strategy

Within constraints of available resources, a balanced portfolio needs to address the more important current and anticipated sources of CO_2 emissions in this sector. Some of the largest sources of CO_2 emissions today, and expected in the future, arise from energy conversion to power industrial processes, inefficiencies in the processes themselves, and ineffective reuse of materials or feedstocks; and, in some cases, the intensive use of fossil fuels, especially natural gas.

In the near term, industrial energy use and CO_2 emissions could be lowered through improvements in the industrial use of electricity and fuels to produce plant process heat and steam, including steam boilers, direct-fired process heaters, and motor-driven systems, such as pumping and compressed air systems. Opportunities for reducing emissions in these areas lie with the adoption of best energy-management practices; adopting more modern and efficient power and steam generating systems; integrated approaches that combine cooling, heating, and power needs; and capture and use of waste heat. Other areas of opportunity include improvements in specific energy-intensive industrial processes, including hybrid distillation systems; process intensification by combining or removing steps, or designing new processes altogether while producing the same or a better product; the recovery and utilization of waste and feedstocks, which can reduce energy and material requirements; and crosscutting opportunities, such as improved operational capabilities and performance.

In the long term, highly efficient coal gasifiers coupled with CO_2 sequestration technology could provide an alternative to natural gas, and even export electricity and hydrogen to the utility grid and supply pipelines. Bioproducts could replace fossil feedstocks for manufacturing fuels, chemicals, and materials; while biorefineries could utilize fuels from nonconventional feedstocks to jointly produce materials and value-added chemicals. Furthermore, integrated modeling of fundamental physical and chemical properties, along with advanced methods to simulate processes, will stem from advances in computational technology.

4.3.3 Current Portfolio

The current Federal portfolio focuses on four major thrusts.

- Research on **energy conversion and utilization** focuses on a diverse range of advanced and integrated systems. These include advanced combustion technologies, gasification technologies, high-efficiency burners and boilers, thermoelectric technologies to produce electricity using industrial waste heat streams, co-firing with low-GHG fuels, advanced waste heat recovery heat exchangers, and heat-integrated furnace designs. Integrated approaches include combined-cycle power generation, and cogeneration of power and process heat or cooling.

  The overall research program goal in this area is to contribute to a 20 percent reduction in the energy intensity (energy per unit of industrial output, as compared to 2002) of energy-intensive industries by 2020. Several specific goals include: (1) by 2006, demonstrate a greater than 94 percent packaged boiler; and by 2010, the packaged boilers will be commercially available with thermal efficiencies of 10-12 percent higher than conventional technology; (2) by 2008, demonstrate high-efficiency pulping technology in the pulp and paper industry that redirects green liquor to pretreat pulp and reduce lime kiln load and digester energy intensity; and (3) by 2011, demonstrate isothermal melting technology, which could improve efficiency significantly in the aluminum, steel, glass, and metal-casting industries. See Section 1.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-141.pdf

- Research on **specific, energy-intensive and high-CO_2-emitting industrial processes** focuses on identifying (compared to theoretical minimum energy requirements) and removing process inefficiencies, lowering overall energy requirements for heat and power, and reducing CO_2 emissions. One example under development is a means to produce high-quality iron without the use of metallurgical coke, which – under current methods of steelmaking – is a significant source of CO_2 emissions. Other areas of research focus on processes that may also improve product yield, including oxidation catalysis, advanced processes, and alternative processes that take a completely different route to the same end product, such as use of noncarbon inert anodes in aluminium production.

  Industrial process efficiency goals are focused on industry partnerships. The overall research program goal in this area is to realize, before 2020, a 20 percent improvement in energy intensity by the energy-intensive industries through the development and implementation of new and improved processes, materials, and manufacturing practices. Specific goals for the pulp and paper industry include, by 2010, to assist efforts to implement advanced water-removal technologies in papermaking, resulting in an energy efficiency improvement of 10 percent in paper production. For the iron and steel industry, by 2010, assist efforts to develop a commercially viable technology that will eliminate the use of blast furnaces and natural gas-driven iron-making processes. More generally, in the separations area, demonstrate advanced hybrid separations technology by 2016, including separations combined with distillation (membranes, adsorption, and extraction), reactive separations, and separative reactors for use across various industries (chemicals, refining, pulp and paper). See Section 1.4.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-143.pdf

- Research on **enabling technologies** includes an array of advanced materials that resist corrosion degradation and deformation at high temperatures and pressures; inferential sensors, controls, and automation, with real-time nondestructive sensing and monitoring; and new computational techniques for modeling and simulating chemical pathways and advanced processes.

  Research program goals for this area target new enabling technologies that meet a range of cost goals depending on the technologies and on the applications where they are to be used. Specific goals include: (a) by 2010, demonstrate production and application for nano-structured diamond coatings and composites and other ultra-hard materials for use in wear-intensive industrial applications; and develop materials for use in a wide array of severe industrial environments (corrosive, high temperature, and pressure); (b) by 2012, demonstrate the generation of efficient power from high-temperature waste heat using systems with thermoelectric materials; and (c) by 2017, develop and demonstrate integration of sensing technologies with information processing to control plant production. See Section 1.4.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-144.pdf

- Research on **resource recovery and utilization** focuses on separating, capturing, and reprocessing materials for feedstocks. Recovery technologies include materials designed for recyclability, advanced separations, new and improved process chemistries, and sensors and controls. Reuse technologies include recycling, closed-loop process and plant designs, catalysts for conversion to suitable feedstocks, and post-consumer processing.

  Research program goals in this area target a range of improved recycling/recovery efficiencies. For example, in the chemicals industry the goal is to improve recyclability of materials by as much as 30 percent. Additional goals target new and improved processes to use wastes or byproducts; improve separations to capture and recycle materials, byproducts, solvents, and process water; identify new markets for recovered materials, including ash and other residuals such as scrubber sludges. For more information, see Section 1.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-142.pdf

4.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Industrial Alternatives to Natural Gas**. Research could be conducted to develop coal gasification systems for large industrial plants (e.g., 100 megawatts [MW]). The coal gasifiers would be highly integrated into complex manufacturing plants (e.g., chemical or glass plants). The industrial plant's feedstock, process heat, and power requirements could be accommodated from the coal gasifier, which could also export electricity, hydrogen, or other fuels to the utility grid and gas supply pipelines.

- **Cement and Related Products**. Research could focus on various means to reduce or eliminate CO_2 emissions from high-emitting industrial processes, including the cement, lime, limestone, and soda ash industries. Worldwide infrastructure building over the 21st century can be expected to create high demands for these mineral products, the production of which releases CO_2 as a consequence of the calcining process. In the United States in 2003, CO_2 emissions from these sources accounted for 44 percent of the non-energy related industrial emissions and about 1 percent of total U.S. emissions. Research could be focused on carbon capture and sequestration and on the exploration of substitutes for the end product. Carbon matrixes for construction, for example, might be lighter and stronger than concrete and would provide a means for carbon sequestration.

- **Computational Technology**. Process simulation enables more effective design and operation, leading to increased efficiency and improved productivity and product quality. Integrated modeling of fundamental physical and chemical properties can enhance understanding of industrial material properties and chemical processes.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

4.4 Electric Grid and Infrastructure

Large reductions in future CO_2 emissions may require that a significant amount of electricity be generated from carbon-free or carbon-neutral sources, including nuclear power and renewable electricity producers such as wind energy, geothermal energy, and solar-based power generating systems. Some renewable energy resources are concentrated in regions of the country that are distant from large urban markets. To accommodate such sources, the future electricity distribution infrastructure (the "grid") would need to extend its capacity and evolve to an intelligent and flexible system that enables the use of a wide and varied set of base load, peaking, and intermittent generation technologies.

In recent years, the demand for electricity in the United States has increased at a rate such that it could eventually exceed current transmission capacity. Demand is projected to increase by 19 percent from 2003-2012 (EIA 2005); only a 6 percent increase in transmission is planned for 2002-2012 (DOE 2002). There have been few major new investments in transmission during the past 15 years. Outages experienced in parts of the country – including the August 2002 blackout in the Midwest and Northwest – highlighted the need to enhance grid reliability.

Enhancements for grid reliability will likely go hand in hand with improved efficiency of electricity transmission. Energy losses in the U.S. transmission and distribution (T&D) system were 5.5 percent in 2003, accounting for 201 billion kilowatt hours of electricity generation and 133 million metric tons of

CO_2 emissions (EIA 2005, Table A8 and EPA 2005 Table 2-14). About 10 percent of GHG emissions resulting from transmission and distribution are SF_6 emissions from certain specified high-voltage transmission equipment. The remainder of GHG emissions is from increased operations needed to compensate for energy losses.

4.4.1 Potential Role of Technology

There are many T&D technologies that can improve efficiency and reduce GHG emissions. In the near term, these include high-voltage DC (HVDC) transmission, high-strength composite overhead conductors, solid-state transmission controls such as Flexible AC Transmission System (FACTS) devices that include fault current limiters, switches and converters, and information technologies coupled with automated controls (i.e., a "Smart Grid"). High-efficiency conventional transformers – commercially available although not widely used – also could have impacts on distribution system losses.

Advanced conductors integrate new materials with existing materials and other components and subsystems to achieve better technical, environmental, and financial performance – e.g., higher current carrying capacity, more lightweight, greater durability, lower line losses, and lower installation and operations and maintenance costs. Improved sensors and controls, as part of the next-generation electricity T&D system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the GHG emissions intensity associated with the electric grid. Outfitting the system with digital sensors, information technologies, and controls could further increase system efficiency, and allow greater use of more efficient and low-GHG end-use and other distributed technologies. High-temperature superconductors may be able to be utilized in key parts of the T&D system to reduce or eliminate line losses and increase efficiency. Energy storage allows intermittent renewable resources, such as photovoltaics and wind, to be dispatchable.

Advanced storage concepts and particularly high-temperature superconducting wires and equipment represent longer-term solutions with great promise. Digital sensors, information technologies, and controls may eventually enable real-time responses to system loads. HTS electrical wires might be able to carry 100 times the amount of electricity compared to the same-sized conventional copper wires. Such possibilities may create totally new ways to operate and configure the grid. Power electronics will be able to provide significant advantages in processing power from distributed energy sources using fast response and autonomous control.

4.4.2 Technology Strategy

Realizing these opportunities requires a research portfolio that focuses on balance of advanced transmission grid and distributed-generation technologies. Within constraints of available resources, a balanced portfolio needs to address conductor technology, systems and controls, energy storage, and power electronics to help reduce CO_2 emissions in this sector.

Early research is likely to focus on ensuring reliability, e.g., establishing "self-healing" capabilities for the grid, including intelligent, autonomous device interactions, and advanced communication capabilities. Additional technologies would be needed for wide-area sensing and control, including sensors, secure communication and data management; and for improved grid-state estimation and simulation. Simulation linked to intelligent controllers can lead to improved protection and discrete-event control. Digitally enabled load-management technologies, wireless communications architecture and algorithms for system automation, and advanced power storage technologies will allow intermittent and distributed energy resources to be efficiently integrated.

Longer-term research is likely to focus on the development of fully operational, pre-commercial prototypes of energy-intensive power equipment that, by incorporating HTS wires, will have greater capacity with lower energy losses and half the size of conventional units. Over the long term, the T&D system would also be enhanced by integrating storage and power electronics.

4.4.3 Current Portfolio

Across the current Federal portfolio of electric infrastructure-related R&D, multiagency activities are focused on a number of major thrusts in high-temperature superconductivity, T&D technologies, distributed generation and combined heat and power, energy storage, sensors, controls and communications, and power electronics. For example:

- Research on **high-temperature superconductivity** (HTS) is focused on improving the current carrying capability of long-distance cables; its manufacturability; and cost-effective ways to use the cable in equipment such as motors, transformers, and compensators. More reliable and robust HTS transmission cables that have three to five times the capacity of conventional copper cables and higher efficiency – which is especially useful in congested urban areas – are being developed and built as pre-commercial prototypes. Through years of Federal research in partnership with companies throughout the nation, technology has developed to bond these HTS materials to various metals, providing the flexibility to fashion these ceramics into wires for use in transmission cables; bearings for flywheels; and coils for power transformers, motors, generators, and the like.

  Research program goals in this area include HTS wires with 100 times the capacity of conventional copper/aluminum wires. More broadly, the program aims to develop and demonstrate a diverse portfolio of electric equipment based on HTS, such that the equipment can achieve a 50 percent reduction in energy losses compared to conventional equipment and a 50 percent size reduction compared to conventional equipment with the same rating. Low-cost, high-performance second-generation coated conductors are expected to become available in 2008 in kilometer-scale lengths. Cost goals include: (a) for the conducting wire, the aim for \$0.01/ampere-meter; (b) equipment premium cost payback (efficiency savings) to be achieved in 2-5 years of operation; and (c) equipment total cost payback to be achieved during the operating lifetime. For coated conductor goals for applications in liquid nitrogen, the wire-cost goal is to be less than \$50/kA-m; while for applications requiring cooling to temperatures of 20-60 degrees K, the cost goal is to be less than \$30/kA-m. By 2010, the cost-performance ratio will have improved by at least a factor of 2. See Section 1.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-131.pdf

- Research on **transmission and distribution technologies** is focused on real-time information and control technologies; and systems that increase transmission capability, allow economic and efficient electricity markets, and improve grid reliability. Examples include high-strength composite overhead conductors, grid-status measurement systems that improve reliability by giving early warning of unstable conditions over major geographic regions, and technologies and regulations that enable the customer to participate more in electric markets through a demand response.

Research program goals in this area include, by 2010, demonstrated reliability of energy-storage systems; reduced cost of advanced conductors systems by 30 percent; and operation of a prototype smart, switchable grid on a region on the U.S. transmission grid. See Section 1.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-132.pdf

- Research on **distributed generation** (DG) includes renewable resources (e.g., photovoltaics), natural gas engines and turbines, energy-storage devices, and price-responsive loads. These technologies can meet a variety of consumer energy needs, including continuous power, backup power, remote power, and peak shaving. They can be installed directly on the consumer's premises or located nearby in district energy systems, power parks, and mini-grids (see Figure 4-4).

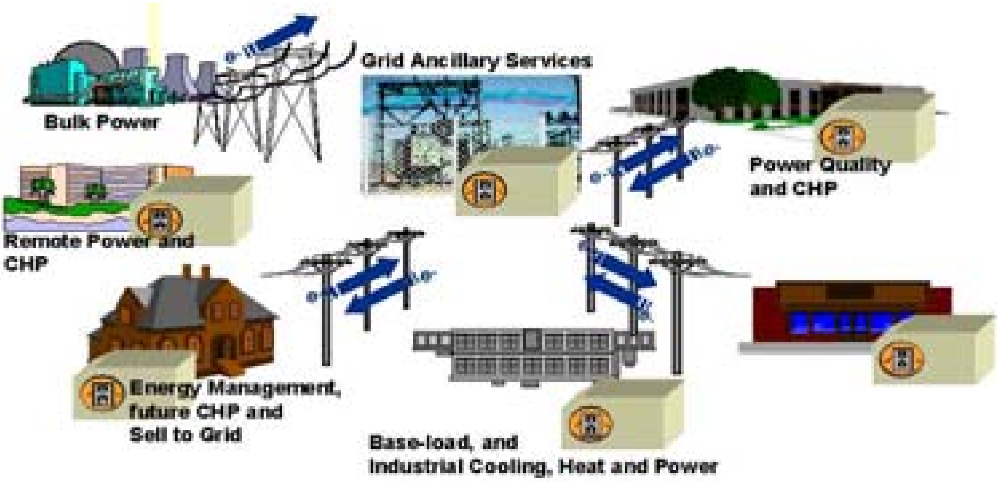

Figure 4-4. A Distributed Energy Future
(*Source:* Personal communication from M.A. Brown, ORNL, Oak Ridge, Tennessee)

Current research focuses on technologies that are powered by natural gas combustion and are located near the building or facility where the electricity is being used. These systems include microturbines, reciprocating engines and larger industrial gas turbines that generate from 25 kW to 10 MW of electricity that is appropriate for hotels, apartment buildings, schools, office buildings, hospitals, etc. Combined cooling, heating, and power (CHP) systems recover and use "waste heat" from distributed generators to efficiently cool, heat, or dehumidify buildings or make more power.

Research is needed to increase the efficiency and reduce the emissions from microturbines, reciprocating engines, and industrial gas turbines to allow them to be sited anywhere, even in nonattainment areas. These technologies can meet a variety of consumer energy needs, including continuous power, backup power, remote power, and peak shaving. Microturbines and reciprocating engines can also be utilized to burn opportunity fuels such as landfill gases or biogases from wastewater-treatment facilities or other volatile species from industrial processes that would otherwise be an environmental hazard. See Section 1.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-133.pdf

Combined heat and power technologies have the potential to take the DG technologies one step further in GHG reduction by utilizing the waste heat from the generation of electricity for making steam, heating water, or producing cooling energy. The average power plant in the United States converts approximately one-third of the input energy into output electricity and then discards the remaining two-thirds of the energy as waste heat. Integrated DG systems with CHP similarly produce electricity at 30 percent to 45 percent efficiency, but then capture much of the waste heat to make steam, heat, or cool water – or meet other thermal needs and increase the overall efficiency of the system to greater than 70 percent. Research is needed to increase the efficiency of waste-heat-driven absorption chillers and desiccant systems to overall efficiencies well above 80 percent.

The overall research goal of the Distributed Energy Program is to develop and make available, by 2015, a diverse array of high-efficiency, integrated distributed generation and thermal energy technologies, at market-competitive prices, so to enable and facilitate widespread adoption and use by homes, businesses, industry, communities, and electricity companies that may elect to use them. If successful, these technologies will enable the achievement of a 20 percent increase in a building's energy utilization, when compared to a building built to ASHRAE 90.1 standards, using load management, CHP, and energy-storage technologies that are replicable to other localities.

- Research on **energy storage** is focused in two general areas. First, research is striving to develop storage technologies that reduce power-quality disturbances and peak electricity demand, and improve system flexibility to reduce adverse effects to industrial and other users. Second, research is seeking to improve electrical energy storage for stationary (utility, customer-side, and renewable) applications. This work is being done in collaboration with a number of universities and industrial partners. This work is set within an international context, where others are investing in high-temperature, sodium-sulfur batteries for utility load-leveling applications and pursuing large-scale vanadium reduction-oxidation battery chemistries.

  The research program goals in this area focus on energy-storage technologies with high reliability and affordable costs. For capital cost, this is interpreted to mean less than or equal to those of some of lower-cost new power generation options ($400–$600/kW). Battery storage systems range from $300-$2,000/kW. For operating cost, this figure would range from compressed gas energy storage (which can cost as little as $1 to $5/kWh) to pumped hydro storage (which can range between $10 and $45/kWh). See Section 1.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-134.pdf

- Research on **sensors, controls, and communications** focuses on developing distributed intelligent systems to diagnose local faults and coordinate with power electronics and other existing, conventional protection schemes that will provide autonomous control and protection at the local level. This hierarchy will enable isolation and mitigation of faults before they cascade through the system. The work will also help users and electric power-system operators achieve optimized control of a large, complex network of systems; and will provide remote detection, protection, control, and contingency measures for the electric system.

  The initial research program goals for sensors, controls, and communications will be to develop, validate, and test computer simulation models of the distribution system to assess the alternative situations. Once the models have been validated on a sufficiently large scale, the functional requirements and architecture specifications can be completed. Then more specific technology solutions can be explored that would conform to the established architecture. See Section 1.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-135.pdf

- Research on **power electronics** is focused on megawatt-level inverters, fast semiconductor switches, sensors, and devices for Flexible AC Transmission Systems (FACTS). The Office of Naval Research and DOE have a joint program to develop power electronic building blocks. The military is developing more electricity-intensive aircraft, ships, and land vehicles, which are providing power electronic spinoffs for infrastructure applications.

  The research program goal in this area is to build a power electronic system on a base of modules. Each module or block would be a subsystem containing several components, and each one has common power terminals and communication connections. See Section 1.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-136.pdf

4.4.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **High-Temperature Superconducting Cables and Equipment**. The manufacture of promising HTS materials in long lengths at low cost remains a key program challenge. New, continuously scanning analytical systems are necessary to ensure uniformly high superconductor characteristics over kilometer lengths of wire. R&D could help develop highly reliable, high-efficiency cryogenic systems to economically cool the superconducting components including materials for cryogenic insulation and standardized high-efficiency refrigerators. Scale-up of national laboratory discoveries for "coated conductors" could be another promising area for the laboratories and their industry partners.

- **Energy Storage**. Energy storage that responds over timescales from milliseconds to hours – and outputs that range from watts to megawatts – is a critical enabling technology for enhancing customer reliability and power quality, more effective use of renewable resources, integration of distributed resources, and more reliable transmission system operation.

- **Real-Time Monitoring and Control**. Introduction of low-cost sensors throughout the power system is needed for real-time monitoring of system conditions. New analytical tools and software must be developed to enhance system observability and power flow control over wide areas.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

4.5 Conclusions

The development of advanced technologies that can reduce, avoid, substitute for, or improve the efficiency of energy use provides the foundation for most scenarios aimed at achieving significant reductions in CO_2 emissions over the long term. Many technologies discussed in this chapter are under development in the transportation, buildings, and industrial sectors to reduce energy consumption and lower CO_2 emissions. The relative size of the contribution of energy end-use reduction toward GHG emissions reductions would depend on many factors, but is generally considered large.

The scenarios suggest, however, that there are a number of important challenges to be met. The first challenge would be achieving advances in technology to sustain progress in energy productivity improvement during the next 100 years at the historical rate of 1 percent or more per year. Additional energy efficiency improvements would need to be made, above and beyond the historic rate, to make the additional contributions built into the three CCTP scenarios. World transportation energy use is expected to grow substantially, and low-emission technology would have significant leverage in that sector. Another challenge is reducing emission rates from several key CO_2-emitting industrial processes, including the coking, cement, lime, and soda-ash industries. Finally, in the long run, new technologies using new fuels or energy forms derived from low- or near-net-zero CO_2 emitting sources would need to be introduced to achieve further reductions in CO_2 emissions from energy end use and infrastructure.

4.6 References

Brown, M.A. 2003. *What Are the Administration Priorities for Climate Change Technology?* Testimony before the Energy Subcommittee of the U.S. House of Representatives' Committee on Science. Hearing on November 6, 2003. http://www.house.gov/science/hearings/energy03/nov06/brown.pdf

CCTP (See U.S. Climate Change Technology Program)

DOE (See U.S. Department of Energy)

DOT (See U.S. Department of Transportation)

Energy Information Administration (EIA). 2004. *Annual energy outlook 2004: with projections to 2025*, DOE/EIA-0383(2004). Washington, DC: U.S. Department of Energy.

Energy Information Administration (EIA). 2005. *Annual energy outlook 2005: with projections to 2025*, DOE/EIA-0383(2005). Washington, DC: U.S. Department of Energy.

EPA (See U.S. Environmental Protection Agency)

Intergovernmental Panel on Climate Change (IPCC). 2000. *Special report on emissions scenarios*. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc/emission/

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001: mitigation*. Working Group III to the Third Assessment Report. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/index.htm

International Energy Agency (IEA). 2004. *World energy outlook*. Paris: International Energy Agency.

United Nations (UN) Population Division. 2005. *World Population Prospects: The 2004 Revision Population Database*. http://esa.un.org/unpp/

U.S. Climate Change Technology Program (CCTP). 2003. *Technology options for the near and long term*. DOE/PI-0002. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm
Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 1997. *Technology opportunities to reduce U.S. greenhouse gas emissions*. Washington, DC: U.S. Department of Energy. http://www.ornl.gov/~webworks//cppr/y2003/rpt/110512.pdf

U.S. Department of Energy (DOE). 2002. *National transmission grid study*. Washington, DC: U.S. Department of Energy. http://www.pi.energy.gov/pdf/library/TransmissionGrid.pdf

U.S. Department of Energy (DOE). 2005. *Hydrogen fuel cells & infrastructure technologies multi- year research, development and demonstration plan: 2003-2010* (Draft). Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy (EERE). 2005. *FY 2006: budget-in-brief*. http://www.eere.energy.gov/office_eere/pdfs/fy05_budget_brief.pdf

U.S. Department of Transportation (DOT). 2002a. *Highway statistics 2001*. Washington, DC: Federal Highway Administration.

U.S. Department of Transportation (DOT). 2002b. *Freight analysis framework*. Washington, DC: Federal Highway Administration.

U.S. Environmental Protection Agency (EPA). 2005. *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2003*. EPA 430-R-05-003. http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69V4ZS/$File/05_complete_report.pdf

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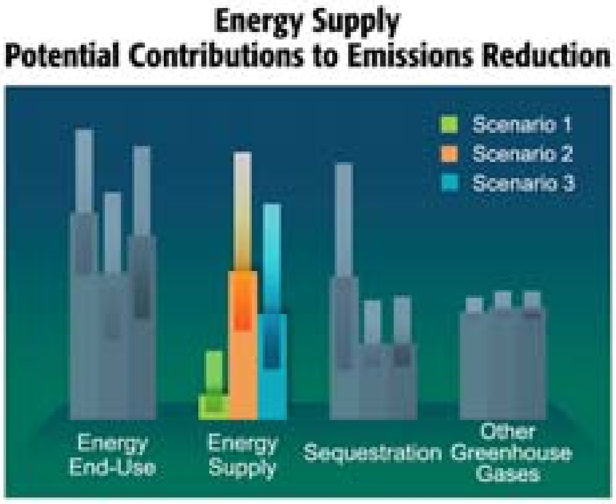
5 Reducing Emissions from Energy Supply

As discussed in Chapters 3 and 4, global energy demand is projected to grow significantly by the year 2100. Some projections show energy demand over the century growing by a factor of 6 or more (from about 400 exajoules [EJ] in 2000 to 2800 EJ in 2100), and mid-range scenarios project an increase of about a factor of 3 or more from today's level, even under scenarios in which energy efficiency is assumed to improve steadily over time. Of this growth, global demand for *electricity* is projected to increase faster than direct use of *fuels* in end-use applications.



Potential contributions of Energy Supply to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

Today, a range of technologies using fossil fuels, nuclear power, hydroelectric power, and a relatively small (but fast-growing) amount of renewable energy, supplies the world's electricity demand. Most of global transportation demand is met with petroleum products (see Figures 5-1 and 5-2).

The development of advanced technologies that can significantly reduce emissions of carbon dioxide (CO_2) from energy supply is a central component of the overall climate change technology strategy. Many opportunities exist for pursuing technological options for energy supply that are characterized by low or near-net-zero emissions and whose development can be facilitated by a coordinated Federal R&D investment plan.

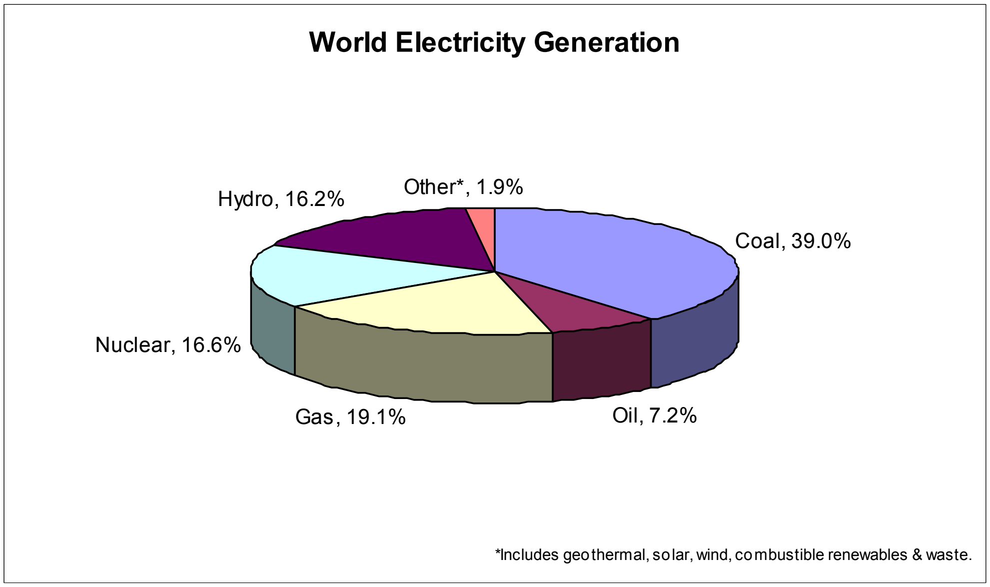


Figure 5-1. World Electricity Generation
(Source: IEA 2004)

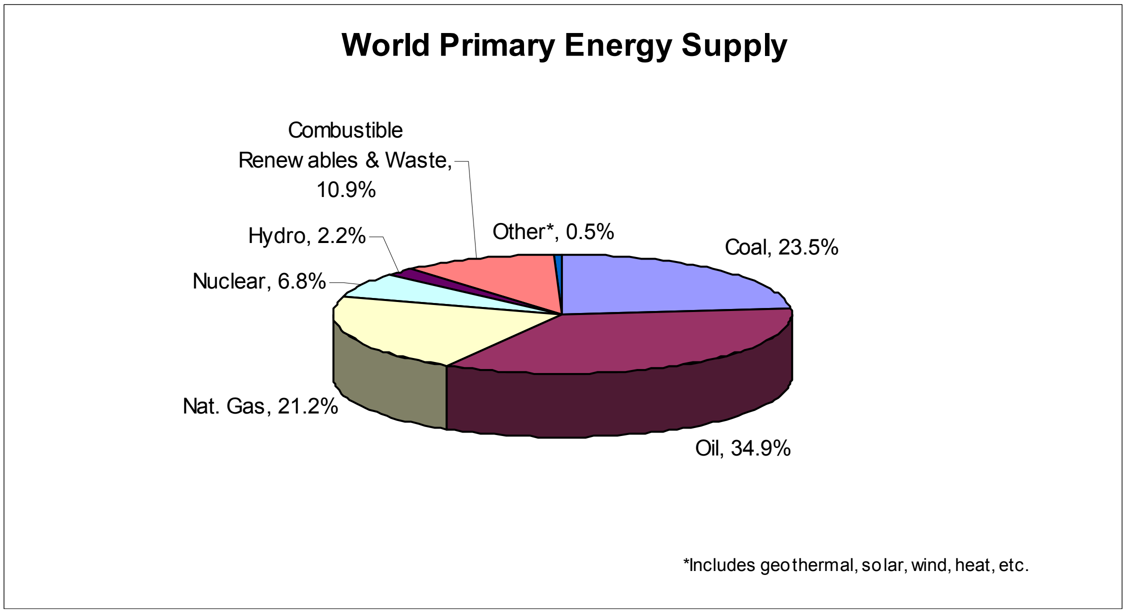


Figure 5-2. World Primary Energy Supply
(Source: IEA 2004)

Some advanced energy supply technologies build on the existing energy infrastructure, which is currently dominated by coal and other fossil fuels. One set of technologies that would allow continued use of coal and other fossil fuels—even under scenarios calling for substantial CO_2 emission limitations—is contained in an advanced coal-based production facility. It is based on coal gasification and production of syngas, which can generate electricity, hydrogen, and other valued fuels and chemicals and would be combined with CO_2 capture and storage and have very low emissions of other pollutants. Some of the emissions-reduction scenarios examined (see Chapter 3) project that if CO_2 capture and storage and improvements in fossil energy conversion efficiencies are achieved, fossil-based energy could continue to supply a large percentage of total energy and electricity in the future (e.g., up to 70 percent of global electricity demand in some scenarios), even under a high carbon constraint. In addition to this mid- to long-term opportunity, lowering CO_2 emissions from fossil fuel combustion in the near term can be achieved by increasing the energy efficiency of combustion technology and by increasing the use of combined heat and power.

Advances in low- and zero-emission technologies have also been identified in a number of scenario analyses as important for reducing GHG emissions. These technologies include advanced forms of: renewable energy, such as wind, photovoltaics, solar thermal applications, and others; biologically based open and closed energy cycles, such as enhanced systems for biomass combustion, biomass conversion to biofuels and other forms of bioenergy; refuse-derived fuels and energy; and various types of nuclear energy, including technologies that employ spent fuel recycling. Variations of these advanced technologies can also be deployed in the production of hydrogen, which may play a big role in reducing emissions from the transportation sector, as well as potentially being used to supply fuel cells for electricity production. Several studies showed that biomass, nuclear, and renewable (solar and wind) energy, combined, would contribute approximately 30 percent of the total reduction in GHG emissions from a "reference case"[1] (see Chapter 3).

Novel energy supply technologies, including breakthrough designs in fusion energy that reduce its cost and increase its rate of deployment; advanced fuel cycles based on combinations of nanotechnology and new forms of bio-assisted energy production, using bioengineered molecules for more efficient photo-synthesis; and hydrogen production or photon-water splitting, may also make important contributions toward reduced GHG emissions. Other possibilities include advanced technologies for capturing solar energy in Earth orbit, on the moon, or in the vast desert areas of Earth—enabled, in part, by new energy carriers and/or low-resistance power transmission over long distances. In one scenario (see Chapter 3), these novel forms of energy were projected to lower cumulative CO_2 emissions by more than 100 GtC over the course of 100-year period, under a very high emission-constraint scenario.

Because outcomes of various ongoing and planned technology development efforts are not known, a prudent path for science and technology policies in the face of uncertainty is to maintain a diverse R&D portfolio. The current Federal portfolio supports R&D activities important to all three of the general technology areas discussed above. The analysis of the advanced technology scenarios suggests that, through successful development and implementation of these technologies, stabilization trajectories could be met across a wide range of hypothesized concentration levels—and the goal could be accomplished both sooner and at significant cost savings, compared to the case without such dramatic technological advances.

This chapter explores energy supply technologies. For each technology area, the chapter examines the potential role for advanced technology; outlines a technology-development strategy for realizing that potential; highlights the current research portfolio, replete with selected technical goals and milestones; and invites public input on considerations for future research directions. The chapter is organized around the following five energy supply technology areas:

- Low-Emission, Fossil-Based Fuels and Power
- Hydrogen as an Energy Carrier
- Renewable Energy and Fuels
- Nuclear Fission
- Fusion Energy

In each of these technology sections, there is a sub-section describing the current portfolio, where the technology descriptions include an internet link to the updated version of the CCTP report, *Technology Options for the Near and Long Term* (DOE/PI-0002) (CCTP 2003). The updated report is available at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

5.1 Low-Emission, Fossil-Based Fuels and Power

Today, fossil fuels are an integral part of the U.S. and global energy mix. Because of its abundance and current relative low cost, coal now accounts for more than half of the electricity generated in the United States, and it is projected to continue to supply one-half of U.S. electricity demands through the year 2025 (EIA 2005). EIA also projects that natural gas will continue to be the "bridge" energy resource, as it offers significant efficiency improvements (and emissions reductions) in both central and distributed electricity generation and combined heat and power (CHP) applications.

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[1] In Chapter 3, the 30 percent value is associated with a hypothesized high emissions constraint.

5.1.1 Potential Role of Technology

Because coal is America's most plentiful and readily available energy resource, the U.S. Department of Energy (DOE) has directed a portion of its research and development (R&D) resources toward finding ways to use coal in a more efficient, cost-effective, and environmentally benign manner, ultimately leading to near-zero atmospheric emissions. Even small improvements in efficiency of the installed base of coal-fueled power stations can result in a significant lowering of carbon emissions. For example, increasing the efficiency of all coal-fired electric-generation capacity in the United States by 1 percentage point would avoid the emission of 14 million tons of carbon per year.[2] That reduction is equivalent to replacing 170 million incandescent light bulbs with fluorescent lights or weatherizing 140 million homes. New U.S. government-industry collaborative efforts are expected to continue to find ways to improve the ability to decrease emissions from coal power generation at lower costs. The objective for future power plant designs is to both increase efficiency and reduce environmental impacts. The focus is on designs that are compatible with carbon sequestration technology, including the development of coal-based, near-zero atmospheric emission power plants.

5.1.2 Technology Strategy

The current U.S fossil research portfolio is a fully integrated program with mid- and long-term market-entry offerings. The principal objective is a zero-emission, coal-based electricity generation plant that has the ability to coproduce low-cost hydrogen. In the midterm, that goal is expected to be accomplished through the FutureGen project. This $1 billion venture, cost-shared with industry, will combine electricity and hydrogen production from a single facility with the elimination of virtually all emissions of air pollutants, including sulfur dioxide, nitrogen oxides, mercury, and particulates—as well as almost complete elimination of atmospheric CO_2 emissions, through a combination of efficiency improvements and carbon capture and storage (called "sequestration" in Figure 5-3). This prototype power plant will

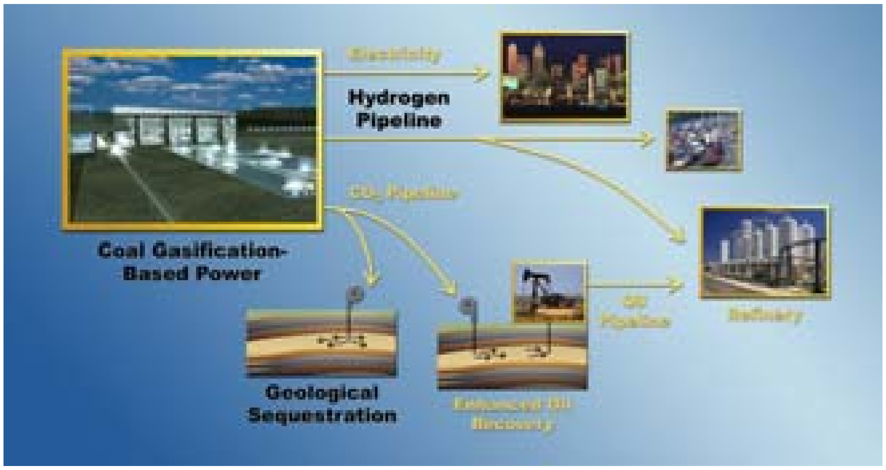

Figure 5-3. Coal-Based Energy Complex
(*Source:* DOE 2004)

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[2] Avoided carbon emissions were calculated based on current coal consumption and power plant efficiencies from the Energy Information Administration's *Annual Energy Outlook 2002*. Using the published efficiencies, 0.574 quads of energy were saved with a 1 percent improved efficiency, which would result in 14.8 MMT of carbon avoided.

serve to demonstrate the most advanced technologies, such as hydrogen fuel cells. See http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_report_march_04.pdf.

5.1.3 Current Portfolio

The low-emissions, fossil-based power system portfolio has three focus areas:

- **Advanced Power Systems**: Advanced coal-fired, power-generation technologies can achieve significant reduction in CO_2 emissions, while providing a reliable, efficient supply of electricity.

  Significant reductions in atmospheric CO_2 emissions have been demonstrated via efficiency improvements and co-firing of coal with biomass. While current average power plant efficiencies are about 33 percent, increasing efficiencies to 45-50 percent in the midterm, and ultimately to 60 percent (with the integration of fuel cell technology), will nearly halve emissions of CO_2 per unit of electricity. Development and deployment of CO_2 capture and storage technology could reduce atmospheric carbon emissions to near-zero levels. Recent R&D activities have focused on integrated gasification, combined-cycle (IGCC) plants. Two U.S. IGCC demonstration plants are in operation.

  The research program goal in the Advanced Power Systems area is to increase efficiency of new systems to levels ranging from 48-52 percent by 2010, and to more than 60 percent by 2020, while also achieving an overall electricity production cost that is between 75 percent and 90 percent of current pulverized-coal-based power generation. Additionally, emissions of criteria pollutants are targeted to be much less than one-tenth of current new source performance standards. See Section 2.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-212.pdf

- **Distributed Generation/Fuel Cells**: The fuel cell (FC) program is focused on reducing the cost of fuel cell technology by an order of magnitude.

  In the near- and midterm, fuel cell cost reductions could enable the widespread deployment of natural-gas-fueled distributed generation in gas-only, combined heat and power, and fuel cell applications. In the midterm to long-term, this technology, along with others being developed as part of the Distributed Generation effort, will also support coal-based FutureGen/central-station applications. The goal is to develop a modular power system with lower cost and significantly lower carbon dioxide emissions than current plants. Examples of current R&D projects in this area include (1) low-cost fuel cell systems development, (2) high-temperature fuel cell scale-up and aggregation for fuel cell turbine (FCT) hybrid application, and (3) hybrid systems and component demonstration.

  Research program goals in the natural gas fuel cell and hybrid power systems include demonstrating a gas aggregated FC module larger than 250 kW that can run on coal syngas, while also reducing the costs of the Solid-State Energy Conversion Alliance fuel cell power system to $400/kW by 2010. Additionally, by 2012-2015, the program aims to (1) demonstrate a megawatt-class hybrid system at FutureGen with an overall system efficiency of 50 percent on coal syngas, (2) demonstrate integrated fuel cell and turbine systems achieving efficiencies of 55 percent on coal; and (3) integrate optimized turbine systems into zero-emission power plants. See Section 2.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-213.pdf

- **Coproduction/Hydrogen**: This research area focuses on developing technology to coproduce electricity and hydrogen from coal and, perhaps, using coal and biomass blends, resulting in very large reductions in CO_2 emissions when compared to present technologies. This technology will use synthesis gas generated from coal gasification to produce hydrogen.

  Zero-Emission Power and H_2 coproduction research goals target a 10-year demonstration project (FutureGen) to create the world's first coal-based, zero-emissions electricity and hydrogen power plant. The near-term goals of the program are to (1) design, by 2010, a near-term coproduction plant, configured at a size of 275-MW, which would be suitable for commercial deployment; (2) demonstrate pilot-scale reactors using ceramic membranes for oxygen separation and hydrogen recovery; and (3) demonstrate a $400/kW solid-oxide fuel cell. A longer-term goal, by 2020, is to design a long-term coproduction plant at a scale of 275-MW or larger. See Section 2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-211.pdf

  Carbon emissions from fossil fuel-based power systems can be reduced in the near term principally by improving process efficiency and, in the longer term, via more advanced system components, such as high-efficiency fuel cells. In both the near and long terms, incorporating CO_2 capture into the systems' processes, accompanied by long-term CO_2 storage, will be required to achieve low or near-zero atmospheric emissions from these energy sources. Current research activities focus on (1) ion transport oxygen separation membranes, (2) hydrogen separation membranes, and (3) early-entrance coproduction plant designs. These activities are discussed in more detail in Chapter 6.

5.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Enhancing the hydrogen production technology effort;
- Adding advanced hybrid gasification/combustion, which offers an alternative path to achieve many of the program goals;
- Broadening advanced research in materials development, which offers potential benefits in system efficiency, durability, and performance.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.2 Hydrogen

As discussed above, in a long-term future characterized by low or near-net-zero emissions of GHGs, global energy primary supply can continue its reliance on fossil fuels, provided there are suitable means for capturing and storing the resulting emissions of CO_2. Alternatively, the world could increase reliance on low-carbon and nonfossil energy sources. These approaches share a need for carbonless energy carriers, such as electricity or some alternative, to store and deliver energy on demand to end users. Electricity is increasingly the carbonless energy carrier of choice for stationary energy consumers, but hydrogen could prove to be an attractive carrier for the transportation sector (e.g., highway vehicles and aircraft), as well as stationary applications. If successful, hydrogen could enable reductions in petroleum use and potentially eliminate concomitant air pollutants and CO_2 emissions on a global scale.

Today, hydrogen is used in various chemical processes and is made largely from natural gas, producing CO_2 emissions. However, hydrogen can be produced in a variety of ways that do not emit CO_2, including renewable energy-based electrolysis; various biological and chemical processes; water shift reactions with coal and natural gas, accompanied by CO_2 capture and storage; thermal and electrolytic processes using nuclear energy; and direct photoconversion. Hydrogen can be stored as a pressurized gas or cryogenic liquid, or absorbed within metal hydride powders or physically absorbed onto carbon-based nanostructures. If progress can be made on a number of technical fronts—and costs of producing hydrogen can be reduced—hydrogen could play a valuable, enabling, and synergistic role in heat and power generation, transportation, and energy end use.

5.2.1 Potential Role of Technology

As a major constituent of the world's water, biomass, and fossil hydrocarbons, the element hydrogen (H_2) is ubiquitous. It accounts for 30 percent of the fuel-energy in petroleum, and more than 50 percent of the fuel-energy in natural gas. A fundamental distinction between H_2 and fossil fuels, however, is that the production of H_2, whether from water, methane or other hydrocarbons, is a net-energy consumer. This makes H_2 not an energy source, per se, but a carrier of energy, similar to electricity.

Like electricity, the life-cycle GHG emissions associated with H_2 use would vary depending on the method to produce, store, and distribute it. H_2 can be generated at various scales, including central plants, fuel stations, businesses, homes, and perhaps onboard vehicles. In principle, the diversity of scales, methods, and sources of production make H_2 a highly versatile energy carrier, capable of transforming transportation (and potentially other energy services) by enabling compatibility with many primary energy sources. This versatility opens up possibilities for long-term dynamic optimization of CO_2 emissions, technology development lead times, economics, and other factors. In a future "hydrogen economy," H_2 may ultimately serve as a means of linking energy sources to energy uses in ways that are more flexible, secure, reliable, and responsive to consumer demands than today, while also integrating the transportation and electricity markets.

While its simple molecular structure makes H_2 an efficient synthetic fuel to produce, use, and/or convert to electricity, the storage and delivery of hydrogen are more challenging than for most fuels. Consequently, most H_2 today is produced at or near its point of use, consuming other fuels (e.g., natural gas) that are easier to handle and distribute.

Large H_2 demands at petroleum refineries or ammonia (NH_3) synthesis plants can justify investment in dedicated H_2 pipelines, but smaller or variable demands for H_2 are usually met more economically by truck transport of compressed gaseous H_2 or cryogenic and liquefied hydrogen (LH_2) produced by steam methane reforming. These methods have evolved over decades of industrial experience, with H_2 as a niche chemical commodity, produced in amounts (8 billion kg H_2/yr) equivalent to about 1 percent

(~1 EJ/yr) of current primary energy use in the United States. For H_2 use to scale up from its current position to a global carbonless energy carrier (alongside electricity), new energetically and economically efficient technical approaches would be required for H_2 delivery, storage, and production.

Hydrogen production can be a value-added complement to other advanced climate change technologies, such as those aimed at the use of fossil fuels or biomass with CO_2 capture and storage. As such, hydrogen may be a key and enabling component for full deployment of carbonless electricity technologies (advanced fission, fusion, and/or intermittent renewables).

In the near term, initial deployment of H_2 fleet vehicles and distributed power systems may provide early adoption opportunities and demonstrate the capabilities of the existing H_2 delivery and on-site production infrastructure. This will also contribute in other ways, such as improving urban air quality and strengthening electricity supply reliability. This phase of H_2 use may also serve as a commercial proving ground for advanced distributed H_2 production and conversion technologies using existing storage technology, both stationary and vehicular.

In the midterm, light-duty vehicles likely will be the first large mass market (10-15 EJ/yr in the United States) for hydrogen. Fuel cells may be particularly attractive in automobiles, given their efficiency versus load characteristics and typical driving patterns. Hydrogen production for this application could occur either in large centralized plants or using distributed production technologies on a more localized level.

In the long term, production technologies must be able to produce H_2 at a price competitive with gasoline for bulk commercial fuel use in automobiles, freight trucks, aircraft, rail, and ships. This would likely require efficient production means and large quantities of reasonable-cost energy supplies, perhaps from coal with CO_2 sequestration, advanced nuclear power (high-efficiency electrolysis and thermochemical decomposition of water), fusion energy, renewables (wind-powered electrolysis, direct conversion of water via sunlight, and high-temperature conversion of water using concentrated solar power), or a variety of methods using biomass. Other important factors in the long term include the cost of H_2 hydrogen storage and transportation. Finally, advances in basic science associated with direct water-splitting and solid-state H_2 storage could possibly permit even lower-cost H_2 production; and safer storage, delivery, and utilization in the context of low or near-net-zero emission futures for transportation and electricity generation.

5.2.2 Technology Strategy

Introducing H_2 into the mix of competitive fuel options and building the foundation for a global hydrogen economy will require a balanced technical approach that not only envisions a plausible commercialization path, but also respects a triad of long-run uncertainties on a global scale: (1) the scale, composition, and energy intensity of future worldwide transportation demand, and potential substitutes; (2) the viability and endurance of CO_2 sequestration; and (3) the long-term economics of carbonless energy sources. The influences of these factors shape the urgency, relative importance, economic status, and ideal end state of a future H_2 infrastructure.

The International Partnership for the Hydrogen Economy (IPHE) was formed in November 2003 among 15 countries (Australia, India, Brazil, Italy, Canada, Japan, China, Republic of Korea, Norway, France, Russia, Germany, United Kingdom, United States, and Iceland) and the European Commission. The

IPHE provides a mechanism to organize, evaluate, and coordinate multinational research, development, and deployment programs that advance the transition to a global hydrogen economy. The Partnership leverages limited resources, brings together the world's best intellectual skills and talents, and develops interoperable technology standards.

The IPHE has reviewed actions being pursued jointly by participating countries and is identifying additional actions to advance research, development, and deployment of hydrogen production, storage, transport, and distribution technologies; fuel cell technologies; common codes and standards for hydrogen fuel utilization; and coordination of international efforts to develop a global hydrogen economy. More about the IPHE is available at http://www.iphe.net.

The Department of Energy's Hydrogen Fuel Cells and Infrastructure Technologies Program plans to research, develop, and demonstrate the critical technologies (and implement codes and standards for safe use) needed for H_2 light-duty vehicles (see Figure 5-4). The program operates in cooperation with automakers and related parties experienced in refueling infrastructure to develop technology necessary to enable a commercialization decision by 2015 (DOE 2005). Current research program goals call for validation by 2015 of technology for:

- H_2 storage systems enabling minimum 300-mile vehicle range while meeting identified packaging, cost, and performance requirements.

- H_2 production to safely and efficiently deliver H_2 to consumers at prices competitive with gasoline and without adverse environmental impacts.

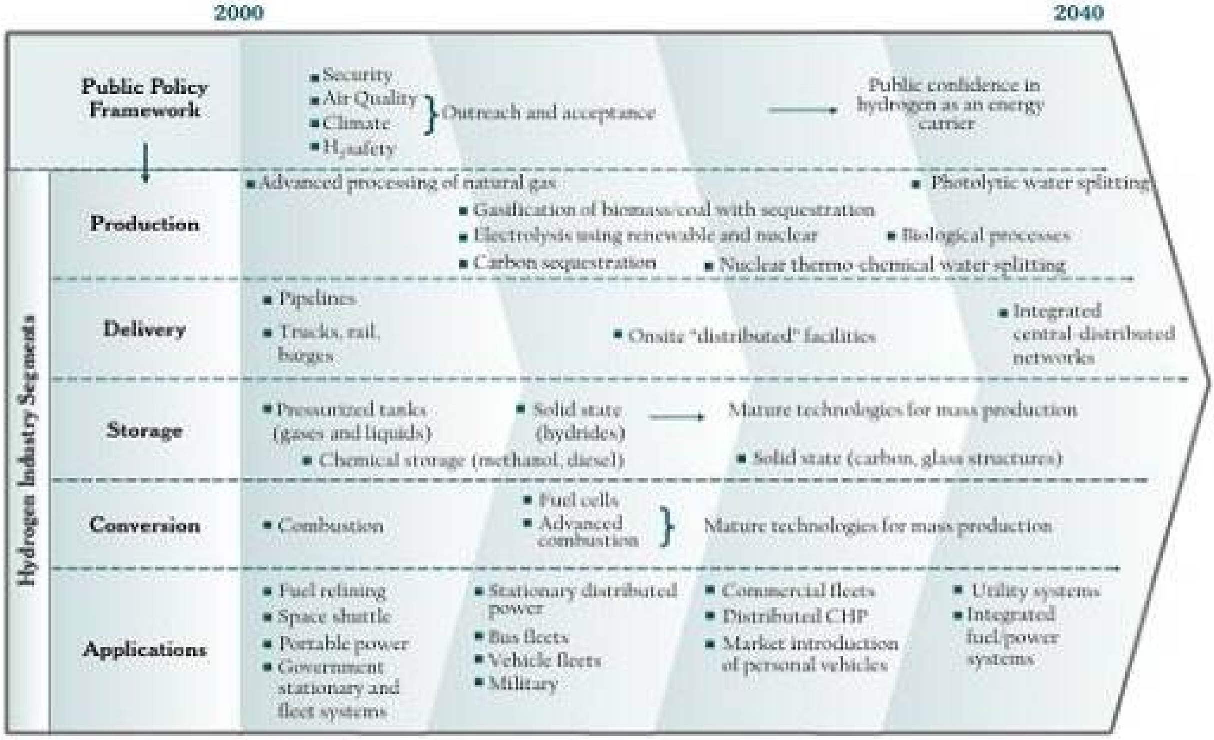


Figure 5-4. Possible Hydrogen Pathways
(*Source:* DOE 2004)

- Fuel cells to enable engine costs of less than \$50/kW (in high volume production) while meeting performance and durability requirements.

DOE requested a study by the National Research Council (NRC) and the National Academy of Engineering (NAE) to assess the current state of technology for hydrogen production and use, and to review and provide feedback on the DOE RD&D hydrogen program, including recommendations for priorities and strategies to develop a hydrogen economy. The resulting report (NRC/NAE 2004) addressed implications for national goals, R&D priorities, and criteria for transition to a hydrogen economy. It provided recommendations in the areas of systems analysis, fuel cell vehicle technology, infrastructure, transition, safety, CO_2-free hydrogen, carbon capture and storage, and DOE's hydrogen RD&D program. In addition to research being conducted within DOE's Hydrogen, Fuel Cells and Infrastructure Program, the NRC report also addressed DOE's programs for hydrogen production from nuclear and fossil energy sources.

5.2.3 Current Portfolio

Within the constraints of available resources, the current Federal hydrogen technology research portfolio balances the emphasis on near-term technologies that will enable a commercialization decision for H_2 automobiles by 2015, with the longer-term ultimate development of a mature hydrogen economy founded on advanced H_2 production, storage, and delivery technologies. Elements of the portfolio include

- **Hydrogen Production From Nuclear Fission and Fusion**. High-efficiency, high-temperature fission power plants are projected to produce H_2 economically without CO_2. Hydrogen would be produced by cyclic thermochemical decomposition of water or high-efficiency electrolysis of high-temperature steam.

  Hydrogen production from nuclear power RDD&D goals target high-temperature, high-efficiency fission and, when available, fusion power plants to produce electricity to generate hydrogen from water economically and without generation of CO_2. Major research areas include support for the development of high-temperature materials, separation membranes, advanced heat exchangers, and supporting systems relating to hydrogen production using the sulfur-iodine (S-I) thermochemical cycle and high-temperature electrolysis. Alternative processes having significantly more technical risk (because less is known about them) continue to be evaluated because their expected lower temperature requirements and, in some cases, reduced complexity could render them more economical in the longer term. The RDD&D program goal is to reduce thermochemical facility costs by two-thirds by 2030 and high-temperature electrolysis facility costs by 85 percent in the same time frame. Another goal is a decrease in operating costs by three-fourths in 2030 for both technologies, while thermal efficiency would increase from levels as low as 30 to 40 percent to more than 50 percent by 2030. See Section 2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-221.pdf

- **Hydrogen Production and Distribution Using Electricity and Fossil/Alternative Energy**. Research and development of small-scale steam reformers, alternative reactor technologies, and hydrogen membrane/separation technologies are aimed at improving the economics of hydrogen production from fossil fuels. Demonstration of on-site electrolysis integrated with renewable electricity and laboratory-scale direct water-splitting by photoelectrochemical and photobiological methods are planned.

Near-term research program goals in this area include, by 2006, (1) completion of research of small-scale steam methane reformers with a projected cost of $3.00/kg hydrogen at the pump; (2) development of alternative reactors, including auto-thermal reactors; and (3) evaluation of whether renewable energy—when integrated with hydrogen production by water electrolysis—can achieve 64 percent net energy efficiency at a projected cost of $5.50/kg, delivered at 5,000 psi. Midterm goals call for demonstrating, by 2010, at the pilot-plant scale, (1) membrane separation and reactive membrane separation technology for hydrogen production from coal, and (2) distributed hydrogen production from natural gas with a projected cost of $2.50/kg hydrogen at the pump. Longer-term goals call for demonstrating, by 2015, at laboratory-bench scale, (1) a photo-electrochemical water-splitting system and (2) a biological system for water-splitting (or other substrates) that shows potential to achieve long-term costs that are competitive with conventional fuels—and reduce the cost of hydrogen distribution to $1/kg. See Section 2.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-223.pdf

- **Hydrogen Storage.** Four methods of high-density, energy-efficient storage of hydrogen are being researched: (1) composite pressure vessels, which will contain the hydrogen as a compressed gas or cryogenic vapor, (2) physical absorption on high-surface-area lightweight carbon structures, (3) reversible metal hydrides, and (4) chemical hydrides. Improving hydrogen compression and/or liquefaction equipment—as well as evaluating the compatibility of the existing natural gas pipeline infrastructure for hydrogen distribution—are also planned.

  The research program goals of hydrogen storage are to, by 2010, develop and verify hydrogen storage systems with 6 weight-percent, 1,500 watt-hrs/liter energy density, and at a cost of $4/kWh of stored energy; and, by 2015, develop associated technologies and verify hydrogen storage systems with 9 weight-percent, 2,700 watt-hrs/liter energy density, and at a cost of $2/kWh of stored energy. See Section 2.2.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-224.pdf

- **Hydrogen Use**. DOE aims to demonstrate high-efficiency, solid-oxide fuel cell/turbine hybrid-electric generation systems operating on coal with carbon capture and storage, and to develop efficient and durable polymer electrolyte membrane (PEM) fuel cells appropriate for automotive and stationary applications.

  The research program goals in this area are: (1) by 2010, develop a 60 percent peak-efficient, durable, PEM fuel cell power system for transportation at a cost of $45/kW; and a distributed generation (50-250 kW) PEM fuel cell system operating on natural gas or propane that achieves 40 percent electrical efficiency and 40,000 hours durability at $400-750/kW; and, (2) by 2015, reduce the cost of PEM fuel cell power systems to $30/kW for transportation systems. See Section 2.2.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-225.pdf

- **Hydrogen Systems Technology Validation**. A systems approach is needed to demonstrate integrated hydrogen production, delivery, and storage, as well as refueling of hydrogen vehicles and use in stationary fuel cells. This could involve providing hydrogen in gaseous and liquid form.

  The overall goal in this area is to validate, by 2015, integrated hydrogen and fuel cell technologies for transportation, infrastructure, and electric generation in a systems context under real-world operating conditions. Specific goals include: (1) by 2005, demonstrate that an energy station (coproduction of hydrogen as fuel for a stationary fuel cell and for a fuel-cell vehicle) can produce electricity for 8 cents/kWh and $3.60/gallon gasoline equivalent; (2) by 2008, demonstrate stationary fuel cells with a durability of 20,000 hours and 32 percent efficiency; (3) by 2009, demonstrate vehicles with greater than 250-mile range and 2,000-hour fuel cell durability; and (4) by 2009, demonstrate hydrogen production at $3/gallon gasoline equivalent. By 2015, the research program aims to provide critical statistical data that demonstrate that fuel cell vehicles can meet targets of 5,000-hour fuel cell durability, storage systems can efficiently meet 300+ mile range requirements, and H_2 fuel can cost less than $2.50/gallon gasoline equivalent. The technology-validation effort also provides information in support of technical codes and standards development of infrastructure safety procedures. See Section 2.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-222.pdf

- **Hydrogen Infrastructure Safety**. The approach to safely expand the hydrogen infrastructure is expected to build on current delivery approaches. DOE is working with the U.S. Department of Transportation (DOT) to test and refine existing hydrogen technologies in compliance with Federal Standards while developing new technologies that can improve hydrogen distribution, as well as reduce or eliminate leaks or other risks.

  Hydrogen infrastructure safety goals are to work within the Federal government and with industry to develop, test, and approve new hydrogen storage and monitoring technologies; and conduct a thorough and comprehensive transportation and storage hydrogen infrastructure assessment. This research would address capacity, safety, security, reliability, operations, and environmental compliance, evaluating scenarios for near-term and long-term development and implementation of hydrogen infrastructure including a risk analysis for each technology and application. Additionally, researchers would investigate future systems that offer improved safety, security, reliability, and functionality vs. the current transportation and storage systems. See Section 2.2.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-226.pdf

5.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Commercial Transportation Modes**. If efficient hydrogen-fueled or hybrid-electric vehicles begin to dominate the light-duty passenger vehicle market (beyond 2025), commercial transportation modes (freight trucks, aircraft, marine, and rail) may become the dominant sources of transportation-related CO_2 emissions later in the 21st century. Therefore, the future CCTP portfolio should aim at reducing the cost of hydrogen production *and* liquefaction of H_2 for these modes and explore the infrastructure implications of H_2 production and/or liquefaction on-site at airports, harbors, rail yards, etc. In the case of hydrogen aircraft, the average length of future flights – and whether significant demand for supersonic passenger aircraft that would use hydrogen develops over the 21st century – will be important in determining the relative fuel economy advantages of hydrogen over conventional jet fuel. Research and development programs that support scenarios that include a worldwide shift toward hydrogen aircraft and substitutes for shorter trips (high speed rail) could be considered.

- **Integration of Electricity and H_2 Transportation Sectors.** Eventual full deployment for optimal use of solar, wind, biomass, and nuclear electricity may require significant H_2 storage or increased flexibility in electricity demand. Electrolytic coproduction of H_2 for transportation fuel would provide such a demand profile. This important possibility needs to be examined to determine the economic and technical parameters for electricity demand, generation, and storage; and for hydrogen production, storage and use to achieve a synergistic effect between H_2 vehicles and carbonless electricity generation.

- **Develop Fundamental Understanding of the Physical Limits to Efficiency of the Hydrogen Economy**. Finally, the fundamental electrochemistry and material science of electrolyzers, fuel cells, and reversible devices needs to be fully explored. For example, the theoretical limits on electrolyte conductivity bound the power density and efficiency of both fuel cells and electrolyzers. Advancing the knowledge of these limits should allow efficiency gains in the conversion of electricity to hydrogen (and reconversion to electricity) to approach theoretical limits before hydrogen technology is deployed on a global scale.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.3 Renewable Energy and Fuels

Renewable sources of energy include the energy of the sun, the kinetic energy of wind, the thermal energy inside the Earth itself, the kinetic energy of flowing water, and the chemical energy of biomass. These sources of energy, available in one or more forms across the globe, are converted and/or delivered to end users as electricity, direct heat, fuels, hydrogen, and useful chemicals and materials. Box 5-1 lists the 11 renewable energy technologies discussed in *Technology Options for the Near and Long Term.* In the United States in 2003, of the 71.42 quads of net energy supply and disposition (98.22 quads total energy consumption), renewable resources contributed 5.89 quads (8 percent of supply, or 6 percent of the total). Of the renewable energy, 2.78 quads came from hydropower, 2.72 quads from burning biomass (wood and waste), 0.28 quads from geothermal energy, and 0.12 quads from solar and wind energy combined. An additional 0.24 quads of ethanol were produced from corn for transportation (EIA 2005).

The suite of renewable energy technologies is in various states of market readiness. For example, hydropower is well established, but improvements in the technology could increase its efficiency and widen its applicability. Geothermal technologies are established in some areas and applications, but significant improvements are needed to tap broader resources. The installation of wind energy has been rapidly and steadily expanding during the past several years. In the past decade, the global wind energy capacity has increased tenfold—from 3.5 GW in 1994 to almost 50 GW by the end of 2004. Technology improvements will continue to lower the cost of wind energy onshore and will enable access to the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets. The next generations of solar—with improved performance and lower cost—are in various stages of concept identification, laboratory research, engineering development, and process scale-up. Also, the development of integrated and advanced systems involving solar photovoltaics, concentrating solar power, and solar buildings are still in quite early stages.

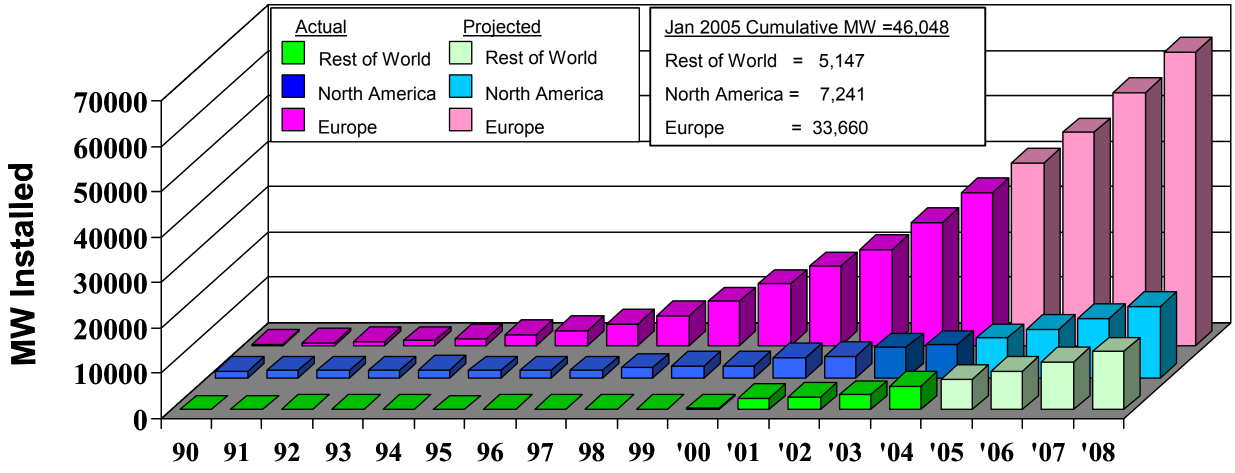
Biochemical and thermochemical conversion technologies also range broadly in their stages of development, from some that need only to be proved at an industrial scale, to others that need more research, to others in early stages of scientific exploration. In the general category of photo-conversion, most technical ideas are at the earliest stages of concept development, theoretical modeling, and laboratory experiment.

The energy-production potential and siting of the various types of renewable energy facilities is dependent on availability of the applicable natural resources. Figures 5-5 through 5-9 show availability of key U.S. renewable resources as estimated by the National Renewable Energy Laboratory (NREL) at the Renewable Resource Data Center (see http://rredc.nrel.gov/).

Box 5-1

Renewable Energy and Fuels Technologies

- Wind Energy
- Solar Photovoltaic Power
- Solar Buildings
- Concentrating Solar Power
- Biochemical Conversion of Biomass
- Thermochemical Conversion of Biomass
- Biomass Residues
- Energy Crops
- Photoconversion
- Advanced Hydropower
- Geothermal Energy



Sources: BTM Consult Aps, March 2003
Windpower Monthly, January 2005
*NREL Estimate for 2005

Figure 5-5. Global Wind Capacity Growth

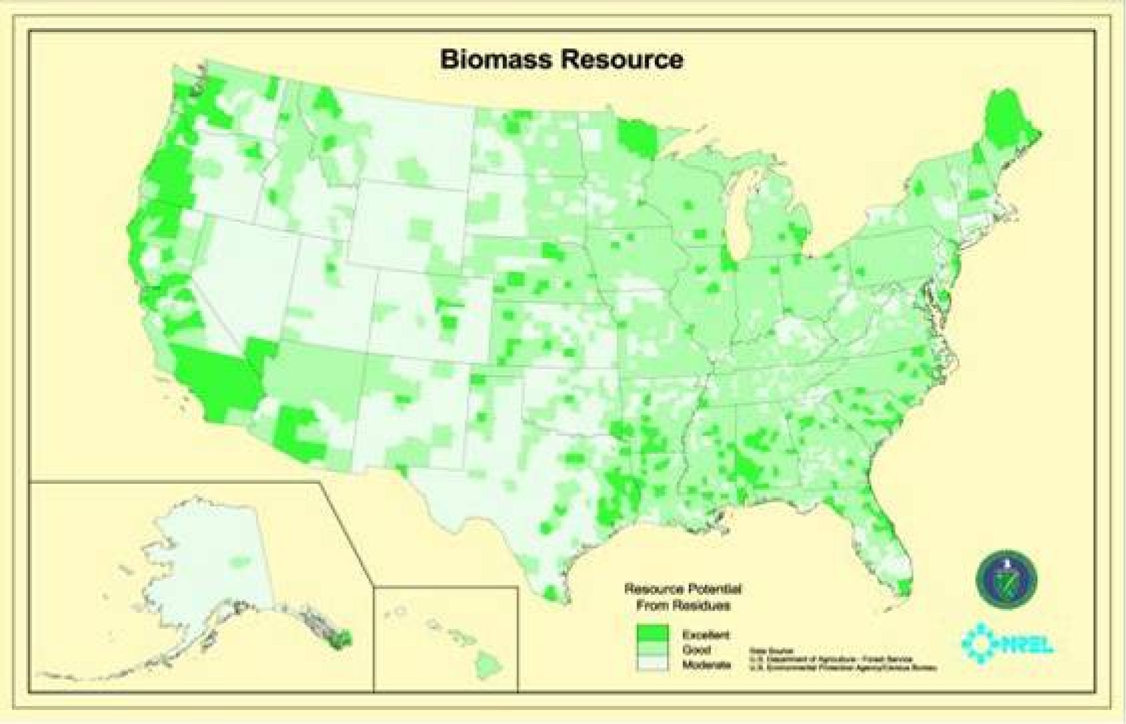


Figure 5-6. U.S. Biomass Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

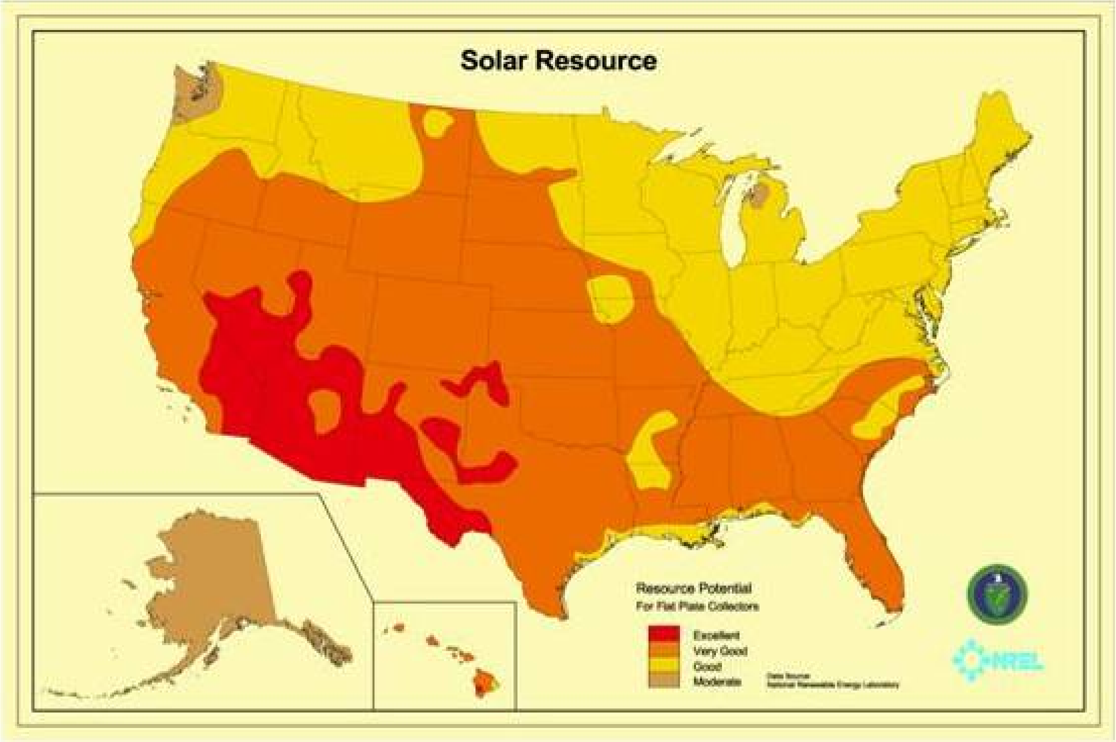


Figure 5-7. U.S. Solar Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

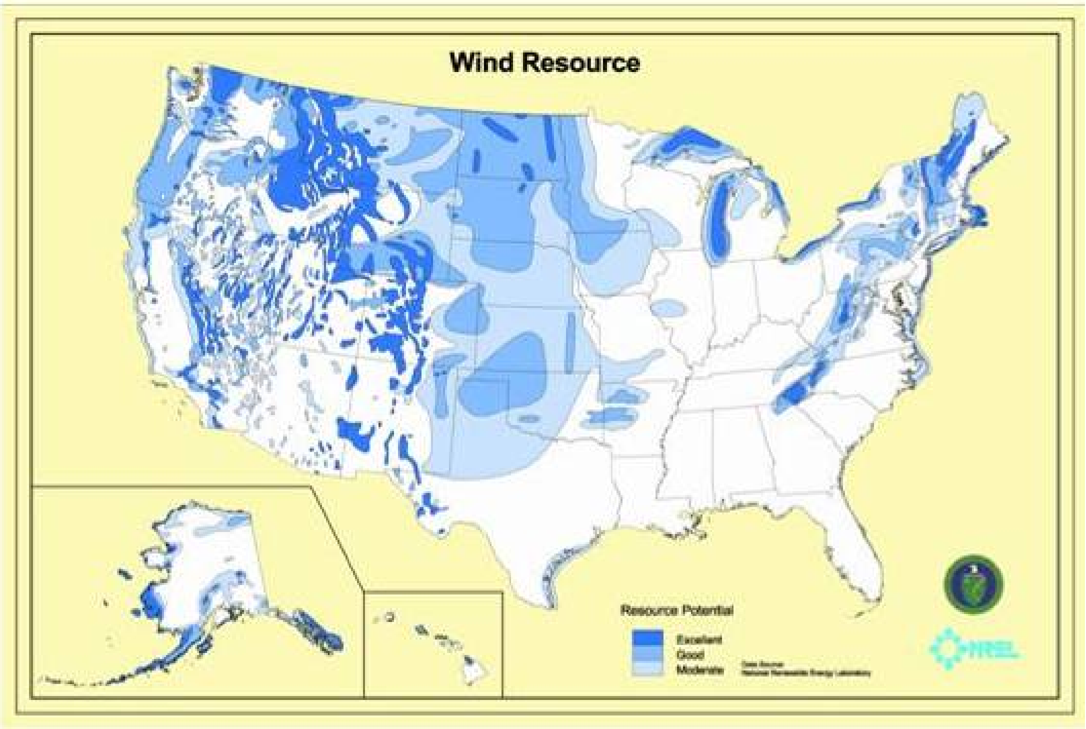


Figure 5-8. U.S. Onshore Wind Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

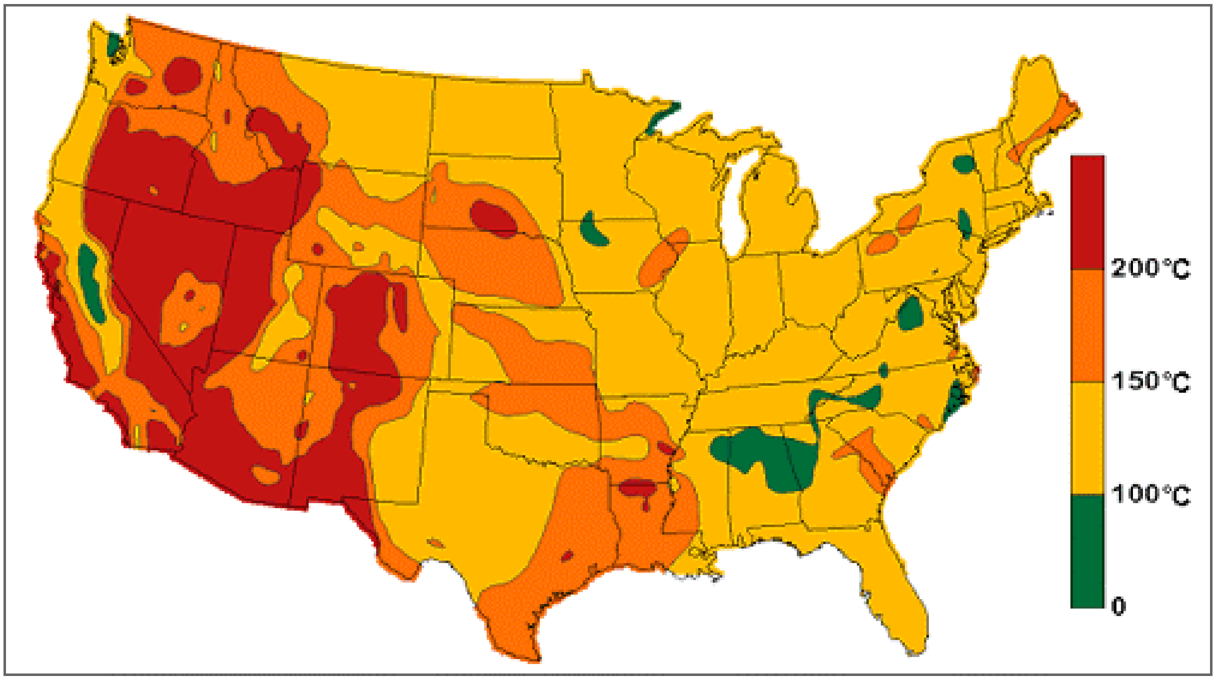


Figure 5-9. U.S. Geothermal Resources
(*Source:* DOE Office of Energy Efficiency and Renewable Energy)

5.3.1 Potential Role of Technology

Renewable energy technologies are generally modular and can be used to help meet the energy needs of a stand-alone application or building, an industrial plant or community, or the larger needs of a national electrical grid or fuel network. Renewable energy technologies can also be used in various combinations—including hybrids with fossil-fuel based energy sources and with advanced storage systems—to improve renewable resource availability. Because of this flexibility, technologies and standards to safely and reliably interconnect individual renewable electric technologies, individual loads or buildings, and the electric grid are very important.

In addition, the diversity of renewable energy sources offers a broad array of technology choices that can reduce CO_2 emissions. The generation of electricity from solar, wind, geothermal, or hydropower sources contributes no CO_2 or other GHGs directly to the atmosphere. Increasing the contribution of renewables to the Nation's energy portfolio will directly lower GHG intensity (GHGs emitted per unit of economic activity) in proportion to the amount of carbon-emitting energy sources displaced.

Analogous to crude oil, biomass can be converted to heat, electrical power, fuels, hydrogen, chemicals, and intermediates. Biomass refers to both biomass residues (agricultural wastes such as corn stover and rice hulls, forest residues, pulp and paper wastes, animal wastes, etc.) and to fast-growing "energy crops," chosen specifically for their efficiency in being converted to electricity, fuels, etc. The CO_2 consumed when the biomass is grown essentially offsets the CO_2 released during combustion or processing. Biomass systems actually represent a net sink for GHG emissions when biomass residues are used, because this avoids methane emissions that result from landfilling unused biomass (see Figures 5-10 and 5-11). Biorefineries of the future could produce value-added chemicals and materials together with fuels and/or power from nonconventional, lower-cost feedstocks (such as agricultural and forest residues and specially grown crops) with no net CO_2 emissions.

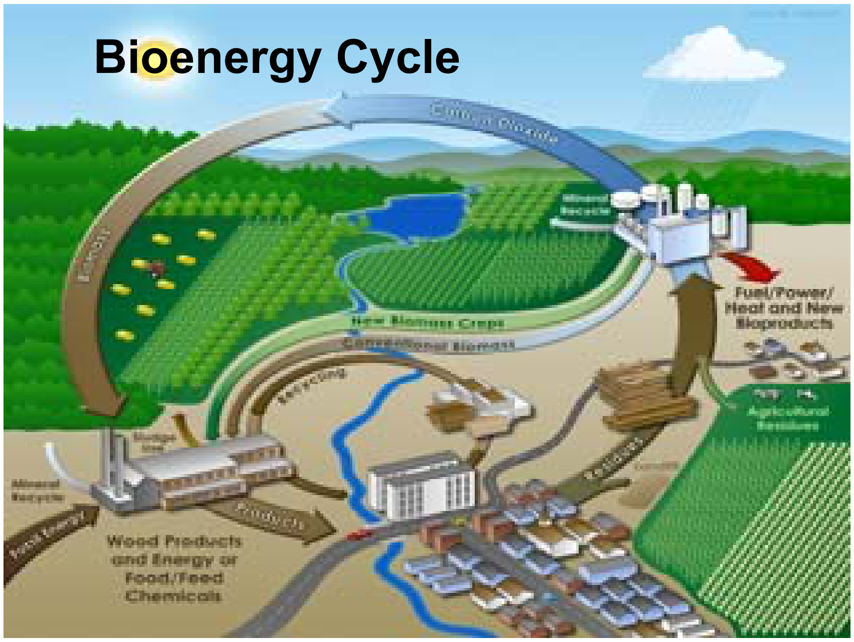


Figure 5-10. Bioenergy Cycle
(*Source:* Oak Ridge National Laboratory internal document)

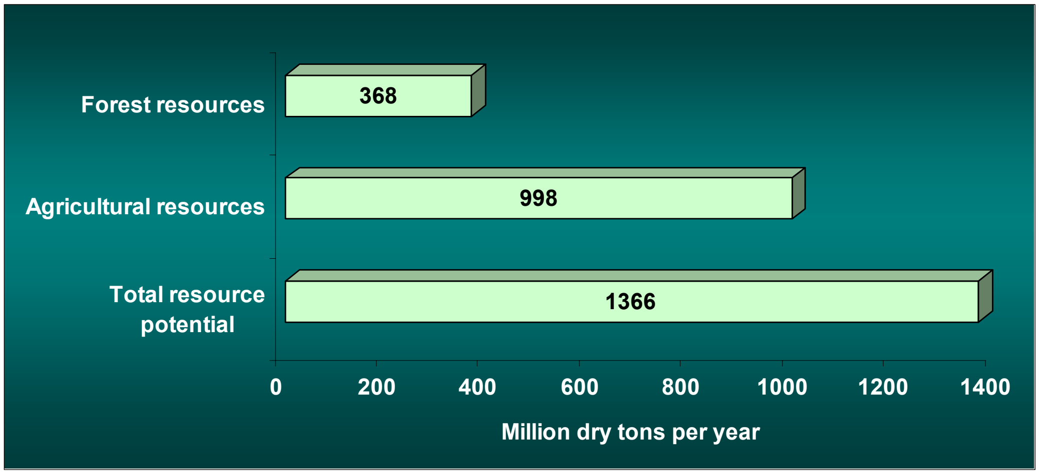


Figure 5-11. Biomass as Feedstock for a Bioenergy and Bioproducts Industry
(*Source:* Oak Ridge National Laboratory http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf)

5.3.2 Technology Strategy

Given the diversity of the stages of development of the technologies, impacts on different economic sectors, and geographic dispersion of renewable energy sources, it is likely that a portfolio of renewable energy technologies—not just one—will contribute to lowering CO_2 emissions. The composition of this portfolio will change as R&D continues and markets change. Appropriately balancing investments in developing this portfolio will be important to maximizing the effect of renewable energy technologies on GHG emissions in the future.

Transitioning from today's reliance on fossil fuels to a global energy portfolio that includes significant renewable energy sources will require continued improvements in cost and performance of renewable technologies. This transition would also require shifts in the energy infrastructure to allow a more diverse mix of technologies to be delivered efficiently to consumers in forms they can readily use.

In general, as performance continues to improve and costs continue to decline, improved new generations of technologies will replace today's renewable technologies. Combinations of renewable and conventional technologies and systems—and, therefore, integration and interconnection issues—will grow in importance.

The transition from today's energy mix to a state of GHG stabilization can be projected as an interweaving of individual renewable energy technologies with other energy technologies, as well as market developments through the upcoming decades. Today, grid-connected wind energy, geothermal, solar energy, and biopower systems are well established. Demand for these systems is growing in some parts of the world. Solar hot-water technologies are reasonably established, although improvements continue. Markets are growing for small, high-value or remote applications of solar photovoltaics; wind energy; biomass-based CHP; certain types of hydropower; and integrated systems that usually include natural gas or diesel generators. Other technologies and applications today are in various stages of research, development, and demonstration. Possible near-, mid-, and long-term scenarios for renewable energy are as follows:

In the near term, as system costs continue to decrease, the penetration of off-grid systems could continue to increase rapidly, including integration of renewable systems such as photovoltaics into buildings. As interconnection issues are resolved, the number of grid-connected renewable systems could increase quite rapidly, meeting local energy needs such as uninterruptible power, community power, or peak shaving. Wind energy may expand most rapidly among grid-connected applications, with solar expanding as system costs are reduced, and geothermal expanding as research reduces costs and extends access to resources. Environment-friendly hydropower systems could be developed. The use of utility-scale wind technology is likely to continue to expand onshore and is targeted to become competitive in select offshore locations between 5 and 50 nautical miles from shore and in water depths 30 meters or less. Small wind turbines are on the verge of operating cost-effectively in most of the rural areas of the United States, and more than 15 million homes have the potential to generate electricity with small wind turbines.[3] With a further maturing of the market, costs will be lowered to compete directly with retail rates for homeowners, farmers, small businesses, and community-based projects.

The biomass near-term strategy includes increasing the production of corn-based ethanol (already produced at nearly 4 billion gallons) by making the process more efficient. This will be demonstrated by increasing the quantity of ethanol through residual starch conversion, and conversion of fiber already collected and present at the operating facilities. The inclusion of biochemicals as byproducts will serve to secure the economics, making this a more sustainable industry. Demonstrations of biorefinery concepts could begin in the near term, producing one or more products (bioethanol, bioproducts, electricity, CHP, etc.) from one plant using local waste and residues as the feedstock. Biodiesel use may continue to grow, replacing fossil-fuel-derived diesel fuel.

In the midterm, offshore wind energy could begin to expand significantly. Technology development may focus on turbine-support structures suitable for deeper water depths, and reducing turbine system and balance of plant costs to offset increased distance from shore, decreased accessibility, and more stringent environmental conditions. Onshore use of wind turbines is also likely to expand for large and small turbines as the costs for these systems continue to decrease. Small turbines may be used to harness wind to provide pumping for farm irrigation, help alleviate water-availability problems, and provide a viable source of clean and renewable hydrogen production.[4] Reductions in cost could encourage penetration by solar technologies into large-scale markets, first in distributed markets such as commercial buildings and communities, and later in utility-scale systems. Solar-cooling systems could become cost-effective in new construction. The first geothermal plants using engineered geothermal systems technology could come online, greatly extending access to geothermal resources. Hydropower may benefit from full acceptance of new turbines and operational improvements that enhance environmental performance, lowering barriers to new development. Biorefineries could begin using both waste products and energy crops as primary feedstocks. Bioethanol and biodiesel could make substantial market penetration, beginning to lower U.S. dependence on imported petroleum.

In the long term, hydrogen from solar, wind, and possibly geothermal energy could be the backbone of the economy, powering vehicles and stationary fuel cells. Solar technologies could also be providing electricity and heat for commercial buildings, industrial plants, and entire communities in major sections

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[3] U.S. Small Wind Turbine Industry Roadmap, NREL Report No. BK-500-31958; DOE/GO-102002-1598, 2002 http://www.nrel.gov/docs/gen/fy02/31958.pdf.

[4] National Academy of Science, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs http://www4.nationalacademies.org/news.nsf/isbn/0309091632?OpenDocument.

of the country, and most residential and commercial buildings could generate their own energy on-site. Wind energy could be the lowest-cost option for electricity generation in favorable wind areas for grid power, and offshore systems could become prevalent in many countries by achieving a commercially viable cost by using floating platforms technologies. Geothermal systems could be a major source of base-load electricity for large regions. Biorefineries could be providing a wide range of cost-effective products as rural areas embrace the economic advantages of widespread demand for energy crops. Vehicle fuels could be powered by a combination of hydrogen fuel cells, with some bioethanol and biodiesel in significant markets.

5.3.3 Current Portfolio

The current Federal portfolio of renewable energy supply technologies encompasses 11areas, described below:

- **Wind Energy**. Generating electricity from wind energy focuses on using aerodynamically designed blades to drive generators that produce electric power in proportion to wind speed. Utility-scale turbines can be several megawatts and produce energy at between 4-6¢/kWh depending on the wind resource. Smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and stand-alone power applications, producing energy between 13-19¢/kWh. Research activities include wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, control systems, design and testing of new onshore and offshore prototypes, component and system testing, power systems integration, and standards development.

  Research program goals in this area vary by application. For distributed wind turbines under 100 kw, the goal is to achieve a power production cost of 10-15¢/kWh in Class 3 winds by 2007. For larger systems greater than 100 kw, the goal is to achieve a power production cost of 3¢/kWh for onshore at sites with average wind speeds of 13 mph (wind Class 4), and 5¢/kWh at offshore sites with average wind speeds of 13 mph (wind Class 4) by 2012. See Section 2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-231.pdf

- **Solar Photovoltaic Power**. Generating electricity from solar energy focuses on using semiconductor devices to convert sunlight directly to electricity. A variety of semiconductor materials can be used, varying in conversion efficiency and cost. Today's commercial modules are 13 percent to 18 percent efficient, and grid-tied photovoltaic (PV) systems generate electricity for about 17-22¢/kWh. Efficiencies of experimental cells range from 12 percent to 19 percent for low-cost thin-film amorphous and polycrystalline materials, and 25 percent to 37 percent for higher-cost III-V multijunction cells. Research activities, conducted with strong partnerships between the Federal laboratories and the private sector, include the fundamental understanding and optimization of photovoltaic materials, process, and devices; module validation and testing; process research to lower costs and scale up production; and technical issues with inverters and batteries. The photovoltaics industry is growing rapidly, with 1,200 MW produced worldwide in 2004.

  Research program goals in this area focus on scaling up laboratory-sized PV cells to much larger sizes suitable for product markets; validation of new module technologies for outdoors use to achieve 30-year outdoor warrantable lifetimes; and addressing of substantial technical issues associated with high-yield, first-time, and large-scale (greater than 100 MW/yr) manufacturing for advanced technologies. The long-term cost goal for electricity from PV cells for residential PV applications is

$0.06/kWh, compared to costs ranging from $0.18 to $0.23/kWh in 2004. The interim cost goal is to reduce the 30-year user cost for PV electric energy to a range of $0.14 to $0.19/kWh by 2010. See Section 2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-232.pdf

- **Solar Heating and Lighting**. Solar heating and lighting technologies being developed for buildings applications include solar water heating and hybrid solar lighting. The near-term solar water heating research goal is to use polymer materials and manufacturing enhancements to reduce the cost of solar water heating systems to 4.5¢/kWh from their current cost of 8¢/kWh. Near-term solar lighting research goals are to demonstrate the second generation of the lighting system, coupled with an enhanced control system, and determine the market potential of the technology. See Section 2.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-233.pdf

- **Concentrating Solar Power**. Concentrating solar power (CSP) technology involves concentrating solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is then used to produce electricity. Parabolic trough systems (1-100 MWe) that can generate electricity for a power cost of 12 to 14¢/kWh have been demonstrated commercially. Large-scale systems employing power towers (30-200 MWe) have been demonstrated. Prototype dish/Stirling engine systems (2 kWe-10 MWe) are operating in several states.

The program goals in this area are focused on CSP. The long-term goal is to achieve a power cost of between $0.035/kWh and $0.062/kWh, compared to the cost of between $0.12-$0.14/kWh in 2004. The interim goal is to reduce the cost of large-scale CSP power plants in the U.S. Southwest, where solar conditions are most favorable, to $0.09-$0.11/kWh by 2010.. See Section 2.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-234.pdf

- **Biochemical Conversion of Biomass**. Biochemical technology can be used to convert the cellulose and hemicellulose polymers in biomass (agricultural crops and residues, wood residues, trees and forest residues, grasses, and municipal waste) to their building blocks, such as sugars and glycerides. Using either acid hydrolysis (well-established) or enzymatic hydrolysis (being developed), sugars can then be converted to liquid fuels, such as ethanol, chemical intermediates and other products, such as lactic acid and hydrogen. Glycerides can be converted to a bio-based alternative for diesel fuel and other products. Producing multiple products from biomass feedstocks in a biorefinery could ultimately resemble today's oil refinery.

  Program goals in this area focus on the research and design of biorefinery processes that convert biomass feedstocks into valuable bio-based chemicals and fuels. By 2010, the goal is to finalize a process flow diagram with material and energy balances for an integrated biorefinery with the potential for three bio-based chemicals or materials. By 2012, the goal is to complete a system-level demonstration with corn kernels' fiber and recalcitrant starch aiming at 5 percent to 20 percent increase in ethanol yield from ethanol plants. Also by 2012, the goal is to reduce the estimated cost for producing a mixed, dilute sugar stream suitable for fermentation to ethanol to $0.10/lb, compared to the cost of $0.15/lb in 2003. If successful, this cost goal would correspond to $1.75 per gallon of ethanol, assuming a cost of $45 per dry ton of corn stover. See Section 2.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-235.pdf

- **Thermochemical Conversion of Biomass.** Thermochemical technology uses heat to convert biomass into a wide variety of products. Pyrolysis or gasification of biomass produces an oil-rich vapor or synthesis gas, which can be used to generate heat, electricity, liquid fuels, and chemicals. Combustion of biomass (or combinations of biomass and coal) generates steam for electricity production and/or space, water, or process heat, occurring today in the wood products industry and biomass power plants. Analogous to an oil refinery, a biorefinery can use one or more of these methods to convert a variety of biomass feedstocks into multiple products. See Section 2.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-236.pdf

- **Biomass Residues**. Biomass residues include agricultural residues, wood residues, trees and forest residues, animal wastes, pulp, and paper waste. These must be harvested, stored, and transported on a large scale to be used in a biorefinery. Research activities include improving and adapting the existing harvest collection, densification, storage, transportation, and information technologies to bioenergy supply systems—and developing robust machines for multiple applications.

  The long-term research program goal in this area is to develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications by 2020. Interim goals toward this end include, by 2006, measurable cost reductions in corn-stover supply systems with modifications of current technology. By 2007, the goal is to develop whole-crop harvest systems for supplying biorefineries of multiple products and, by 2010, enhancements to the whole-crop harvest systems that include fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices. By 2015, the goal is to develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation. See Section 2.3.7 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-237.pdf

- **Energy Crops**. Energy crops are fast-growing, often genetically improved trees and grasses grown under sustainable conditions to provide feedstocks that can be converted to heat, electricity, fuels such as ethanol, and chemicals and intermediates. Research activities include genetic improvement, pest and disease management, and harvest equipment development to maximize yields and sustainability.

  The overall research goal of this program is to advance the concept of energy crops contributing strongly to meet biomass power and biofuels production goals by 2020. Interim goals include, by 2006, to develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year and accompanying cost-effective, energy-efficient, environmentally sound harvest methods. By 2010, the goal is to identify genes that control growth and characteristics important to conversion processes in few model energy crops and achieve low-cost, "no-touch" harvest/ processing/transport of biomass to process facility. By 2020, the goal is to increase yield of useful biomass per acre by a factor of 2 or more compared with year 2000 yields. See Section 2.3.8 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-238.pdf

- **Photoconversion**. Photoconversion processes use solar photons to drive a variety of quantum conversion processes other than solid-state photovoltaics. These processes can produce electrical power or fuels, materials, and chemicals directly from simple renewable substrates such as water, carbon dioxide, and nitrogen. Photoconversion processes that mimic nature (termed "bio-inspired") can also convert CO_2 into liquid and gaseous fuels. Most of these technologies are at early stages of research where technical feasibility must be demonstrated, but a few (such as dye-sensitized solar cells) are at the developmental level.

The research program in this area is still in an exploratory stage. In the near term, research will focus on applications related to electrical power and high-value fuels and chemicals, where commercial potential may be expected during the next 5 to 10 years. If successful, larger-scale applications of photoconversion technologies may follow in the period from 2010 to 2015, with materials and fuels production beginning in the period 2015 to 2020, and commodity chemicals production in the period from 2020 to 2030. See Section 2.3.9 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-239.pdf

- **Advanced Hydropower**. The goal of advanced hydropower technology is to maximize the use of water for generation of electricity, while eliminating harmful environmental side effects. Representative technologies include new turbine designs that improve survivability of fish passing through the power plant and increase dissolved oxygen in downstream discharges, new assessment methods to optimize operation of reservoir system, and advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

  The research program goals in this area include, by 2006, the completion of testing of hydroelectric turbine technology capable of reducing the rate of fish mortality to 2 percent, which would equal or better other methods of fish passage (e.g., spillways or fishways). Also in the near term, the goal is to complete the development of the Advanced Hydro Turbine Technology in support of maintaining hydroelectric-generation capacity due for relicensing between 2010 and 2020. See Section 2.3.10 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2310.pdf

- **Geothermal Energy**. Geothermal sources of energy include hot rock masses, highly pressured hot fluids, hot hydrothermal systems, and shallow warm groundwater. Exploration techniques locate resources to drill; well fields and distribution systems allow the hot fluids to move to the point of use; and utilization systems apply the heat directly or convert it to electricity. Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications. The U.S.-installed capacity for geothermal electrical generation is currently about 2 gigawatts; but, with improved technology, the U.S. geothermal resource could be capable of producing up to 100 gigawatts of electricity at an estimated cost of less than 5¢/kWh.

  The research program goals in this area focus on reducing the cost of geothermal energy. For "flash" power systems, the goal is to reduce the levelized cost of power generated by conventional (hydrothermal) geothermal resources from 6.1 cents per kWh in 2000 to 4.3 cents per kWh by 2010. For "binary" power systems, the goal is to reduce this cost from 8.7 cents per kWh in 2000, to 6.1 cents per kWh by 2010. See Section 2.3.11 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-2311.pdf

5.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Wind Energy**. Research challenges include developing wind technology that will be economically competitive at low-wind-speed sites without a production tax credit, developing offshore wind technology to take advantage of the immense wind resources in U.S. coastal areas and the Great Lakes, and exploring the role of wind turbines in emerging applications such as electrolytic hydrogen production, water purification, and irrigation.

- **Solar Photovoltaic Power**. Research would be required to lower the cost of solar electricity further. This can occur through developing "third-generation" materials such as quantum dots and nanostructures for ultra-high efficiencies or lower-cost organic or polymer materials; solving complex integrated processing problems to lower the cost of large-scale production of thin-film polycrystalline devices; optimizing cells and optical systems using concentrated sunlight; and improving the reliability and lowering the cost of inverters and batteries.

- **Solar Buildings**. Future research could include reducing cost and improving reliability of components and systems, optimizing energy efficiency and renewable energy combinations, integrating solar technologies into building designs, and incorporating solar technologies into building codes and standards.

- **Concentrating Solar Power**. Future challenges requiring RD&D include reducing cost and improving reliability; demonstrating Stirling engine performance in the field; and developing technology to produce hydrogen from concentrated sunlight and water.

- **Biochemical Conversion of Biomass**. Research is required to gain a better understanding of genomes, proteins, and their functions; the enzymes used for hydrolyzing pretreated biomass into fermentable sugars; the micro-organisms used in fermentation; and new tools of discovery such as bio-informatics, high-throughput screening of biodiversity, directed enzyme development and evolution, and gene shuffling. Research must focus on improving the cost, yield, and equipment reliability for harvesting, collecting, and transporting biomass; pretreating biomass before conversion; lowering the cost of the genetically engineered cellulose enzymes needed to hydrolyze biomass; developing and improving fermentation organisms; and developing integrated processing applicable to a large, continuous-production commercial facility.

- **Thermochemical Conversion of Biomass**. Research is needed to improve the production, preparation, and handling of biomass; improve the operational reliability of thermochemical biorefineries; remove contaminants from synthesis gas and develop cost-competitive catalysts and processes for converting synthesis gases to chemicals, fuels, or electricity. All the processes in the entire conversion system must be integrated to maximize efficiency and reduce costs.

- **Biomass Residues**. Research challenges include developing sustainable agriculture and forest-management systems that provide biomass residues; developing cost-effective drying, densification, and transportation techniques to create more standard feedstock from various residues; developing whole-crop harvest and fractionation systems; and developing methods for pretreatment of residues at harvest locations.

- **Energy Crops**. Future crop research needs include identifying genes that control growth and characteristics important to conversion processes, developing gene maps, understanding functional genomics in model crops, and applying advanced management systems and enhanced cultural practices to optimize sustainable energy crop production.

- **Photoconversion**. Photoconversion research requires developing the fundamental scientific understanding of photolytic processes through multidisciplinary approaches involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials science, catalysts, and catalytic cycles.

- **Geothermal Energy**. Future research needs include developing improved methodologies for predicting reservoir performance and lifetime; finding and characterizing underground fracture permeability; developing low-cost innovative drilling technologies; reducing the cost and improving the efficiency of conversion systems; and developing engineered geothermal systems that will allow the use of geothermal areas that are deeper, less permeable, or drier than those currently considered as reserves.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.4 Nuclear Fission

Currently, there are 440 nuclear power plants operating in 31 nations that generate 17 percent of the world's electricity (see Figure 5-1) and provide nearly 7 percent of total world energy (see Figure 5-2). Because they emit no GHGs, today's nuclear power plants avoid the CO_2 emissions associated with combustion of coal or other fossil fuels.

During the past 30 years, operators of U.S. nuclear power plants have steadily improved economic performance through reduced costs for maintenance and operations and improved power plant availability, while operating reliably and safely. In addition, science and technology for the safe storage and ultimate disposal of nuclear waste have been advanced. Waste from nuclear energy must be isolated from the environment. High-level nuclear wastes from fission reactors (used fuel assemblies) are stored in contained, reinforced concrete steel-lined pools or in robust dry casks at limited-access reactor sites, until a deep geologic repository is ready to accept and isolate the spent fuel from the environment. Used nuclear fuel contains a substantial quantity of fissionable materials, and advanced technologies may be able to recover energy from this spent fuel and reduce required repository space and the radiotoxicity of the disposed waste.

While the current application of nuclear energy is the production of electricity, other applications are possible, such as cogeneration of process heat, the generation of hydrogen from water or from methane (with carbon capture or integration with other materials production or manufacturing), and desalination.

5.4.1 Potential Role of Technology

The currently operating 103 U.S. nuclear-reactor units are saving as much as 600 million metric tons of carbon dioxide emissions every year. Through the summer of 2005, 33 of these units have received approval to extend their operating licenses for an additional 20 years; 16 others have applications under review. All of the remaining units most likely will follow suit. Such carbon dioxide emission mitigation can be increased if new nuclear capacity were to be brought online.

To the extent the financial risks of new nuclear construction can be addressed and with improvement from new technologies in the longer term, the nuclear option can continue to be an important, growing part of a GHG-emissions-free energy portfolio. Design and demonstration efforts on near-term advanced reactor concepts—in combination with Federal financial risk mitigation tools—will enable power companies to build and operate new reactors that are economical and competitive with other generation technologies, supporting energy security and diversity of supply.

Evolutionary light-water reactors of standardized design (having received U.S. Nuclear Regulatory Commission design certification and having been constructed on schedule in Japan and South Korea) are demonstrated and available now for construction in the United States. Other newer designs should be reviewed and certified over the next several years, making them also available. However, more advanced nuclear energy systems for the longer term have the potential to offer significant advances in the areas of sustainability, proliferation resistance and physical protection, safety, and economics. These advanced nuclear energy systems—described as Generation IV reactors—could replace or add to existing light-water reactor capacity.

5.4.2 Technology Strategy

U.S. leadership is essential to the expansion of nuclear capacity in markets other than Asia and Eastern Europe (see Figure 5-12), through deployment of advanced nuclear power plants in the relatively near term. The untested Federal regulatory and licensing processes for the siting, construction, and operation of new nuclear plants must be demonstrated. In addition, other major obstacles must be addressed, including the initial high capital costs of the first few plants and the business risks resulting from both the costs and the regulatory uncertainty.

In the longer term, advanced nuclear energy systems could serve a vital role in both diversifying the Nation's energy supply and reducing GHG emissions. By successfully addressing the fundamental research and development issues of system concepts that excel in safety, sustainability, cost-effectiveness, and proliferation resistance, the systems could attract future private-sector sponsorship and ultimate commercialization by the private sector. Advanced nuclear fission-reactor systems aim to extract the full energy potential of the spent nuclear fuel from current fission reactors, while reducing or eliminating the potential for proliferation of nuclear materials and technologies, and reducing both the radiotoxicity and total amount of waste produced.

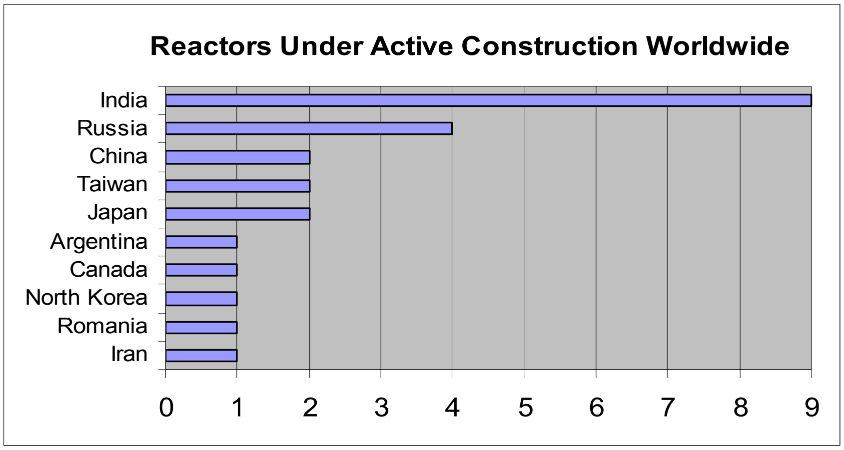

Figure 5-12. Nuclear Reactors Under Construction
(*Source:* World Nuclear Association http://www.world-nuclear.org/info/printable_information_papers/reactorsprint.htm)

A key objective of nuclear energy research and development is to enhance the basic technology; and, through advanced civilian technology research, chart the way toward the next leap in technology. From these efforts, and those of industry and overseas partners, nuclear energy may continue to fulfill its promise as a safe, advanced, inexpensive, and emission-free approach to providing reliable energy throughout the world.

5.4.3 Current Portfolio

The current Federal portfolio focuses on three areas:

- Research on **Nuclear Power Plant Technologies for Near-Term Deployment** is focused on advanced fission reactor designs that are currently available or could be made available with limited additional work to complete design development and deployment in the 2010 time frame.

  A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010, issued in October 2001 (DOE 2001), advises DOE on actions and resource requirements needed to put the country on a path to bringing new nuclear power plants online by 2010. The primary purposes of the roadmap are to identify the generic and design-specific prerequisites to near-term deployment, to identify those designs that best promise to meet the needs of the marketplace, and to propose recommended actions that would support deployment. These include, but are not limited to, actions to achieve economic competitiveness and timely regulatory approvals.

  The Nuclear Power 2010 Program is a joint government/industry cost-shared effort. The program is designed to pave the way for an industry decision to order at least one new nuclear power plant by the end of the decade. Activities under this program support cost-shared demonstration of the Early Site Permit (ESP) and combined Construction and Operating License (COL) processes to reduce licensing uncertainties and minimize the attendant financial risks to the licensee. In addition, the program includes technology research and development to finalize and license a standardized advanced reactor design, which U.S. power-generation companies will find to be more competitive in the deregulated electricity market. The economics and business case for building new nuclear power plants has been evaluated as part of the Nuclear Power 2010 program to identify the necessary financial conditions under which power-generation companies would add new nuclear capacity.

The research program goals in this area are focused on successfully demonstrating the untested regulatory processes for Early Site Permit (ESP) and combined Construction and Operating License (COL) processes, and on the regulatory acceptance (certification) and completion of first-of-a-kind engineering and design. Specific goals include an industry decision to order a new nuclear power plant by 2008 and deployment of one or more new nuclear power plants in the 2010 time frame. See Section 2.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-242.pdf

- Research under the **Generation IV Nuclear Energy Systems Initiative** will lead to advanced nuclear energy systems that offer significant advances in the areas of sustainability, proliferation-resistance and physical protection, safety, and economics. These newer nuclear energy systems will replace or add to existing light-water reactor capacity and should be available between 2020 and 2030. To develop these advanced reactor systems, DOE manages the Generation IV Nuclear Energy Systems Initiative.

Development of next-generation nuclear energy systems is being pursued by the Generation IV International Forum (GIF), a group of 10 leading nuclear nations (Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States) plus the European Atomic Energy Community (Euratom). The GIF has selected six promising technologies as candidates for advanced nuclear energy systems concepts. The Generation IV (Gen IV) Nuclear Energy Systems Initiative addresses the fundamental research and development issues necessary to establish the viability of next-generation nuclear energy system concepts. By successfully addressing the fundamental research and development issues of system concepts that excel in safety, sustainability, cost-effectiveness, and proliferation resistance, the systems are highly likely to attract future private-sector sponsorship and ultimate commercialization by the private sector.

The primary focus of these Gen IV systems will be to generate electricity in a safe, economic, and secure manner; other possible benefits include the production of hydrogen, desalinated water, and process heat (see Figure 5-13). The GIF and the DOE's Nuclear Energy Research Advisory Committee (NERAC) issued a report on its two-year effort to develop a technology roadmap for future nuclear energy systems (GIF-NERAC 2002). The technology roadmap defines and plans the necessary R&D to support the advanced nuclear energy systems known as Generation IV. The DOE also prepared a report to the U.S. Congress regarding how it intends to carry out the results of the Generation IV Roadmap (DOE-NE 2003a).

Goals for next-generation fission energy systems (Generation IV) research are focused on the design of reactors and fuel cycles that are safer, more economically competitive, more resistant to proliferation, produce less waste, and make better use of the energy content in uranium, in accord with the abovementioned reports and roadmaps. See Section 2.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-241.pdf

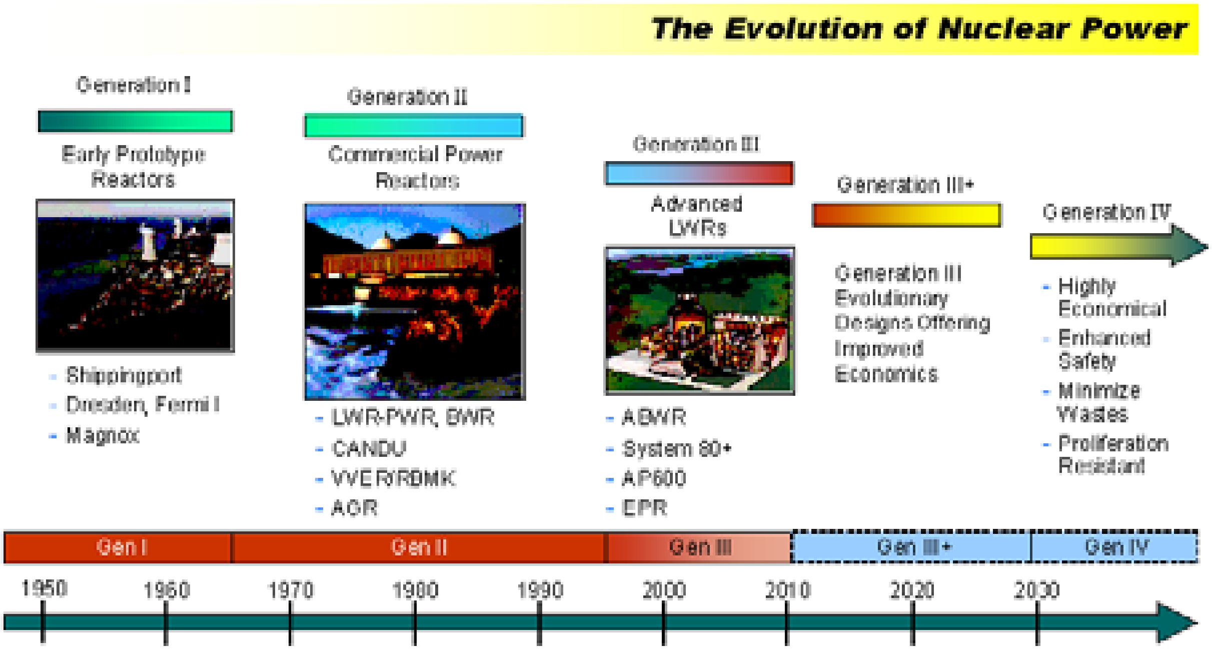

Figure 5-13. Future Nuclear Power Concepts

(*Source:* DOE, Office of Nuclear Energy, Science and Technology internal document)

- **The Advanced Fuel Cycle Initiative (AFCI),** under the leadership of DOE, is focused on developing advanced fuel-cycle technologies, which include spent fuel treatment, advanced fuels, and transmutation technologies, for application to current operating commercial reactors and next-generation reactors; and to inform a recommendation by the Secretary of Energy in the 2007-2010 time frame on the need for a second geologic repository.

The AFCI program will develop technologies to address intermediate and long-term issues associated with spent nuclear fuel. The intermediate-term issues are the reduction of the volume and heat generation of material requiring geologic disposal. The program will develop proliferation-resistant processes and fuels for application to current light-water reactor systems and Generation IV reactor systems to enable the energy value of these materials to be recovered, while destroying significant quantities of plutonium. This work provides the opportunity to optimize use of the Nation's first repository and reduce the technical need for an additional repository. The longer-term issues to be addressed by the AFCI program are the development of fuel-cycle technologies to destroy minor actinides, which would greatly reduce the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of Gen IV fast reactor fuel-cycle technologies and possibly accelerator-driven systems (DOE-NE 2003b).

Goals for advanced nuclear fuel-cycle research focus on proving design principles of spent-fuel treatment and transmutation technologies, demonstrating the fuel and separation technologies for waste transmutation, and deploying Generation IV advanced fast spectrum reactors that can transmute nuclear waste. See Section 2.4.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-243.pdf

5.4.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Provide for development and demonstration of advanced technologies to reduce construction time for new nuclear power plants and to minimize schedule uncertainties and associated costs for construction

- Support operational safety, proliferation-resistant, fuel-cycle concepts; minimization of wastes; and economy of both capital, and operation and maintenance (O&M).

Additional R&D work that could be undertaken for near-term deployment options relate to advanced light-water and gas reactors, including fuel development, characterization, manufacture, testing, and regulatory acceptance; power conversion-system design and testing, including resolution of uncertainties regarding materials, reliability, and maintainability; and fission reactor internal design and verification.

Of the other challenges that must be addressed to enable a future expansion in the use of nuclear energy in the United States and worldwide, none is more important—nor more difficult—than that of dealing effectively with spent nuclear fuel. Compared to other industrial waste, the spent nuclear fuel generated during the production of electricity is relatively small in quantity. However, it is highly radioactive for many thousands of years, and its disposal requires resolution of many political, societal, technical, and regulatory issues. While these issues are being addressed in the license application for the Yucca Mountain repository in Nevada, several countries worldwide have pursued advanced technologies that could treat and transmute spent nuclear fuel from nuclear power plants. These technologies have the potential to dramatically reduce the quantity and toxicity of waste requiring geologic disposal. During the past four years, the United States has joined this international effort and found considerable merit in this area of joint advanced research.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.5 Fusion Energy

Fusion energy holds the possibility of an almost inexhaustible supply of zero-GHG electricity. Fusion is the power source of the sun and the stars. Lighter elements are "fused" together in the core of the sun, producing heavier elements and prodigious amounts of energy. On Earth, fusion energy has been demonstrated in the laboratory at powers of 5 to 15 million watts, with pulse lengths in the range of 1 to 5 seconds. The goal is for fusion power to eventually be produced at much larger scales.

Fusion power generation offers a number of advantageous features. The basic sources of fusion fuel, deuterium and tritium, are actually heavy forms of hydrogen. Deuterium is abundantly available because it occurs naturally in water; and tritium can be derived from lithium, a light metal found in the earth's crust. Tritium is radioactive, but the quantities in use at any given time are quite modest and can be safely handled. There are no chemical pollutants or carbon dioxide emissions from the fusion process. With appropriate advances in materials, the radioactivity of the fusion byproducts would be relatively short-lived, thereby obviating the need for extensive waste management measures.

From a safety perspective, the fusion process poses little radiation risk to anyone outside the facility. Also, since only a small quantity of fuel is in the fusion system at any given time, there is no risk of a critical accident or meltdown, and little after-heat to be managed in the event of an accident. The potential usefulness of fusion systems is great, but many scientific and technical challenges remain.

5.5.1 Potential Role of Technology

Fusion energy is an attractive option to consider for long-term sustainable energy generation. It would be particularly suited for base-load electricity supply, but could also be used for hydrogen production. With the growth of world population expected to occur in cities and megacities, concentrated energy sources that can be located near population centers (such as fusion energy) may be particularly attractive. In addition, the fusion process does not produce GHGs and has well-attested and attractive inherent safety and environmental characteristics that could help gain public acceptance.

Energy scenarios imposing reasonable constraints on nonsustainable energy sources show that fusion energy could contribute significantly to large-scale electricity production during the second half of the 21st century. Also, the cost of fusion electricity could be comparable to other environmentally friendly sources of electricity generation.

Making fusion energy a part of the future energy solution is among the most ambitious scientific and engineering challenges of our era. The following are some of the major scientific questions that need to be answered:

- Can burning plasma that shares the characteristic intensity and power of the sun be successfully produced and sustained?

- To what extent can models be used to simulate and predict the behavior of the burning, self-sustained fuel required for fusion applications?

- How can new materials that can survive the fusion environment (which are needed for fusion power to be commercially viable) be developed?

Answering these questions requires understanding and control of complex and dynamic phenomena occurring across a broad range of temporal and spatial scales. The experiments required for a commercially viable fusion power technology constitute a complex scientific and engineering enterprise that must be sustained over several decades.

5.5.2 Technology Strategy

Given the substantial scientific and technological uncertainties that now exist, the U.S. Government will continue to employ a portfolio strategy that explores a variety of magnetic confinement approaches and leads to the most promising commercial fusion concept. Advanced computational modeling will be central to testing the agreement between theory and experiment, simulating experiments that cannot be readily investigated in the laboratory, and exploring innovative designs for fusion plants. To ensure the highest possible scientific return, the DOE's Fusion Energy Sciences program will extensively engage with and leverage other DOE programs and international programs in areas such as magnetic confinement physics, materials science, ion beam physics, and high energy density physics. Large-scale experimental facilities will likely be necessary, and the rewards, risks, and costs of these major facilities will need to be shared through international collaborations. The target physics aspect of inertial fusion is being conducted now through the National Nuclear Security Administration's (NNSA) stockpile stewardship program. The overall Fusion Energy Sciences effort will be organized around a set of four broad goals.

Fusion Energy Sciences Goal #1: Demonstrate with burning plasmas the scientific and technological feasibility of fusion energy. The goal is to demonstrate a sustained, self-heated fusion plasma, in which the plasma is maintained at fusion temperatures by the reaction products, a critical step to practical fusion power. The strategy includes the following area of emphasis:

- Participate in the international magnetic fusion experiment, ITER (Latin for "the way") project, with the European Union, Japan, Russia, China, South Korea, and perhaps others, as partners.

Fusion Energy Sciences Goal #2: Develop a fundamental understanding of plasma behavior sufficient to provide a reliable predictive capability for fusion energy systems. Basic research is required in turbulence and transport, nonlinear behavior and overall stability of confined plasmas, interactions of waves and particles in plasmas, the physics occurring at the wall-plasma interface, and the physics of intense ion beam plasmas and high energy density plasmas. The strategy includes the following areas of emphasis:

- Conduct fusion science research through individual-investigator and research-team experimental, computational, and theoretical investigations

- Advance the state-of-the-art computational modeling and simulation of plasma behavior in partnership with the Advanced Scientific Computing Research program in DOE's Office of Science

- Support basic plasma science, partly with the National Science Foundation, connecting both experiments and theory with related disciplines such as astrophysics.

Fusion Energy Sciences Goal #3: Determine the most promising approaches and configurations to confining hot plasmas for practical fusion energy systems. The strategy includes experiments and advanced simulation and modeling; innovative magnetic confinement configurations, such as the National Spherical Torus Experiment (NSTX); and a planned compact stellarator experiment, the National Compact Stellarator Experiment (NCSX) at Princeton Plasma Physics Laboratory (PPPL); as well as smaller experiments at multiple sites.

Fusion Energy Sciences Goal #4: Develop the new materials, components, and technologies necessary to make fusion energy a reality. The environment created in a fusion reactor poses great challenges to materials and components. Materials must be able to withstand high fluxes of high-energy neutrons and endure high temperatures and high thermal gradients, with minimal degradation. The strategy includes the following areas of emphasis:

- Design materials at the molecular scale to create new materials that possess the necessary high-performance properties, leveraging investments in fusion energy research with investments in basic materials research

- Explore “liquid first-wall” materials to ameliorate first-wall requirements for advanced fusion energy concepts.

5.5.3 Current Portfolio

The current Fusion Energy Sciences (FES) program, within DOE’s Office of Science, is a program of fundamental research into the nature of fusion plasmas and the means for confining plasma to yield energy. This includes: (1) exploring basic issues in plasma science; (2) developing the scientific basis and computational tools to predict the behavior of magnetically confined plasmas; (3) using the advances in tokamak[5] research to enable the initiation of the burning plasma physics phase of the FES program; (4) exploring innovative confinement options that offer the potential of more attractive fusion energy sources in the long term; (5) developing the cutting-edge technologies that enable fusion facilities to achieve their scientific goals; and (6) advancing the science base for innovative materials to establish the economic feasibility and environmental quality of fusion energy.

The overall effort requires operation of a set of unique and diversified experimental facilities, ranging from smaller-scale university programs to several large national facilities that require extensive collaboration. These facilities provide scientists with the means to test and extend theoretical understanding and computer models, leading ultimately to an improved predictive capability for fusion science.

The two major tokamak experiments, DIII-D at General Atomics and the Alcator C-Mod at MIT, are extensively equipped with sophisticated diagnostics that allow for very detailed measurements in time and spatial dimensions as they continuously push the frontiers of tokamak plasma confinement. They each involve an array of national and international collaborators on the scientific programs.

Similarly, the NSTX at PPPL is also a well-diagnosed and highly collaborative experiment on an innovative confinement approach that seems likely to lead to improved understanding of toroidal[6] confinement systems.

An additional innovative concept, the National Compact Stellarator Experiment, is currently being fabricated at PPPL with first operation scheduled for 2009. This machine is a product of new computational capabilities that have optimized the 3-dimensional toroidal magnetic geometry for improved confinement and stability in a compact form.

In addition to these major experiments, there are a larger number of smaller magnetic confinement experiments with more specialized missions. These are generally at universities and provide an opportunity for student training.

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[5] Tokamak (Acronym created from the Russian words, “TOroidalnaya KAmera ee MAgnitnaya Katushka,” or “Toroidal Chamber and Magnetic Coil”): The tokamak is the most common research machine for magnetic confinement fusion today.

[6] Toroidal: in the shape of a torus, or doughnut. Toroidal is a general term that refers to toruses as opposed to other geometries (e.g., tokamaks and stellarators are examples of toroidal devices).

A modest-scale high energy density physics program is also underway, with an emphasis on using heavy ion drivers to explore plasma/beam dynamics and warm dense matter with potential applications to future inertial energy systems. This program also explores innovative approaches to improving inertial fusion energy such as the fast-ignition experiments. In addition, the FES program benefits from existing experimental programs conducted elsewhere for NNSA's stockpile stewardship program and the Department of Defense (DoD). Both the "Z" experiment at Sandia National Laboratories and the OMEGA experiment at the University of Rochester, for example, offer opportunities for improving understanding of high energy density physics.

Theory and computing are key parts of the present program, as they provide the intellectual framework for the overall approach to fusion energy, as well as the computer codes, which attempt to systematically rationalize the understanding of fusion plasmas. See Section 2.5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-251.pdf

5.5.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

Burning plasmas represents the next major science and technology frontier for fusion research. In the major international effort mentioned above (ITER), the United States, Europe, Japan, China, Russia, and the Republic of Korea are negotiating an agreement to construct a magnetic fusion burning plasma science and engineering test facility. The ITER international magnetic fusion experiment is a key part of the U.S. strategy to investigate the underlying science for magnetic confinement fusion energy (see Figure 5-14). Additional investments in fusion materials, components, and technologies for MFE are contingent upon favorable results from ITER.

Prior to the anticipated operation of ITER around 2014, experiments on a wide range of plasma-confinement systems worldwide will continue physics research in preparation for ITER operations. These experiments will include detailed simulations of ITER behavior as well as innovative new ways of operating fusion systems to optimize efficiency. Because of the sophisticated measurement techniques employed on modern fusion experiments, detailed data are already available to validate computer models.[7] Work will also continue on

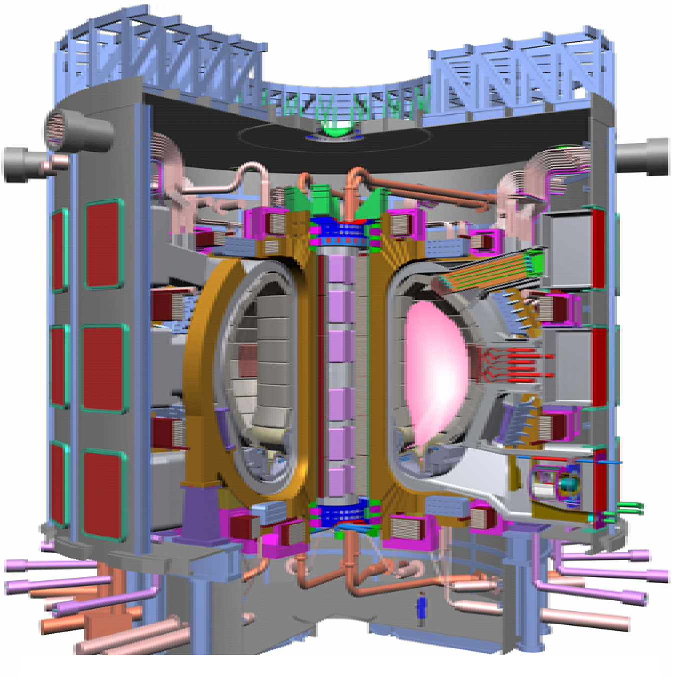

Figure 5-13. ITER Schematic
Source: http://www.iter.org/

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[7] For additional information about ITER, see http://www.iter.org/.

confinement configuration optimization that would allow better understanding or improve the confinement approach for future power systems.

In other efforts, the United States is proceeding with high energy density physics, the science base for inertial fusion, through the development of NNSA's National Ignition Facility (NIF) and other fusion energy work, including driver, target fabrication, and chamber technologies. The drivers include lasers and pulsed power-driven z-pinches in the NNSA program and heavy ion accelerators. Efforts to explore the understanding and predictability of high energy density plasma physics, including the ramifications for energy-producing applications, are also underway.[8] However, any additional investment in the inertial fusion energy approach awaits successful demonstration of ignition and gain in the NIF.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

5.6 Conclusions

Among the many thrusts for addressing climate change with the aid of technology, improved energy efficiency, CO_2 capture and sequestration, and reduced emissions of non-CO_2 GHGs, soot, and aerosols are all important, if not essential, to goal attainment. Large quantities of energy supplied by low or near-net-zero emissions technology, however, form the core of any long-term technology component of the overall strategy. Just meeting the expected growth in world energy demand over the span of the 21st century will likely be challenging enough. Meeting such demand, while simultaneously reducing emissions and maintaining economic prosperity, will be doubly challenging. Advanced technology as outlined in this chapter on energy supply can facilitate progress in that direction.

5.7 References

Energy Information Administration (EIA). 2005. *Annual Energy Outlook 2005*, DOE/EIA-0383(2005). Washington, DC: U.S. Department of Energy.

Generation IV International Forum (GIF) and the U.S. Department of Energy's Nuclear Energy Research Advisory Committee (NERAC). 2002. *A Technology Roadmap for Generation IV Nuclear Energy Systems*. GIF-002-01, December. http://nuclear.gov/geniv/Generation_IV_Roadmap_1-31-03.pdf

International Energy Agency (IEA). 2004. *Key World Energy Statistics 2004*. http://library.iea.org/dbtw-wpd/Textbase/nppdf/free/2004/keyworld2004.pdf

National Research Council (NRC), National Academy of Engineering (NAE). 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, DC: The National Academies Press. http://www.nap.edu/books/0309091632/html/

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[8] For additional information about U.S. fusion energy research, see http://www.ofes.fusion.doe.gov/.

U.S. Climate Change Technology Program (CCTP). 2003. *Technology Options for the Near and Long Term*. DOE/PI-0002. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 2005. *Hydrogen Fuel Cells and infrastructure Technologies Multi-Year Research, Development and Demonstration Plan*, *2003-2010*. Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

U.S. Department of Energy (DOE). 2004. *Hydrogen Posture Plan, an Integrated Research, Development, and Demonstration Plan*. Washington, DC: U.S. Department of Energy. http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_posture_plan.pdf

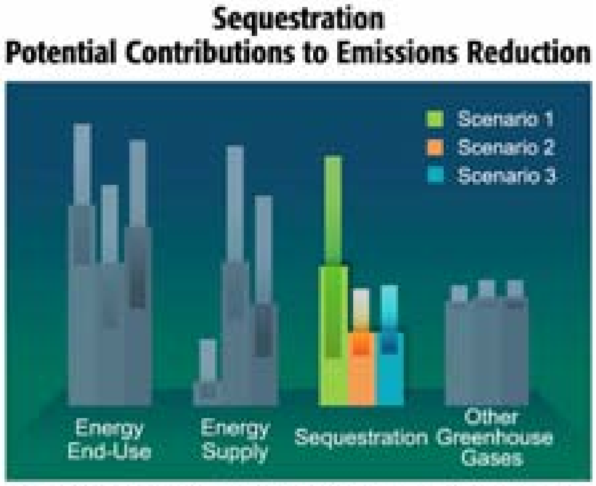
U.S. Department of Energy (DOE), Office of Nuclear Energy Science and Technology (NE). 2001. *A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010*. Washington, DC: U.S. Department of Energy. http://nuclear.gov/nerac/ntdroadmapvolume1.pdf and http://nuclear.gov/nerac/NTDRoadmapVolII.PDF

U.S. Department of Energy, (DOE), Office of Nuclear Energy Science and Technology (NE). 2003a. *The U.S. Generation IV Implementation Strategy.* Washington, DC: U.S. Department of Energy. http://nuclear.gov/reports/Gen-IV_Implementation_Plan_9-9-03.pdf

U.S. Department of Energy, (DOE), Office of Nuclear Energy Science and Technology (NE). 2003b. Report to Congress on Advanced Fuel Cycle Initiative: the Future Path for Advanced Spent Fuel Treatment and Transmutation Research. Washington, DC: U.S. Department of Energy. http://nuclear.gov/reports/AFCI_CongRpt2003.pdf

6 Capturing and Sequestering Carbon Dioxide

Technologies and improved management systems for carbon capture, storage, and sequestration can help to reduce carbon dioxide (CO_2) emissions and growth in atmospheric CO_2 concentrations. The main focus areas for research and development (R&D) related to carbon cycle management include (1) the capture of CO_2 emissions from large point sources, such as power plants, oil refineries, and industrial processes, and its storage in geologic formations or other storage media; (2) enhanced carbon uptake and storage by terrestrial biotic systems—terrestrial sequestration; and (3) improved understanding of the potential for ocean storage and sequestration methodologies.[1]


Sequestration Potential Contributions to Emissions Reduction

Potential contributions of Carbon Capture and Sequestration to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

If current world energy production and consumption patterns persist into the foreseeable future, fossil fuels will remain the mainstay of global energy production well into the 21st century. The Energy Information Administration (EIA) projects that by 2025 about 88 percent of global energy demand will be met by fossil fuels, because fossil fuels will likely continue to yield competitive advantages relative to other alternatives (EIA 2004a). In the United States, the use of fossil fuels in the electric power industry accounted for 39 percent of total energy-related CO_2 emissions in 2003, and this share is expected to slightly increase to 41 percent in 2025. In 2025, coal is projected to account for 50 percent of U.S. electricity generation and for an estimated 81 percent of electricity-generated CO_2 emissions. Natural gas is projected to account for 24 percent of electricity generation and about 15 percent of electricity-related CO_2 emissions in 2025 (EIA 2005).

Many scenarios of the future project that world coal markets will continue to grow steadily over the course of the 21^{st} century, in the absence of CO_2 emissions restrictions. While increased energy efficiency, and use of renewable and nuclear energy afford good opportunities for reducing CO_2 emissions, fossil fuel reserves are abundant and economical, making their continued use an attractive option. In various advanced technology scenarios where CO_2 capture and storage technology were assumed to become a cost-competitive technology strategy, fossil-based energy continued to supply a large portion of total electricity consumed into the future (e.g., various studies estimated a 55-70 percent share), even under high carbon management requirements.

Human activities related to land conversion and agricultural practices have also contributed to the buildup of carbon dioxide to the atmosphere. During the past 150 years, land use and land-use changes were responsible for one-third of all human emissions of carbon dioxide (IPCC 2000). Over the next 100 years, global land-use change and deforestation are likely to account for at least 10 percent of overall human-caused CO_2 emissions. The dominant drivers of current and past land-use-related emissions of

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[1] In this Plan, the three approaches are collectively referred to as “capturing and sequestering carbon dioxide” or “capturing and sequestering carbon.”

CO_2 are the conversion of forest and grassland to crop and pastureland and the depletion of soil carbon through agricultural and other land-management practices (IPCC 2000). Past CO_2 emissions from land-use activities are potentially reversible, and improved land-management practices can actually restore depleted carbon stocks. Therefore, there are potentially large opportunities to increase terrestrial carbon sequestration.

The potential storage and sequestration capacity for CO_2 in various "sinks" is quite large. Some estimates indicate that about 83 to 131 gigatons of carbon (GtC) could be sequestered in forests and agricultural soils by 2050 (IPCC 2001b), while others estimate geologic storage capacities within a broad range of 300 to 3,200 GtC (IEA 1994a, 1994b, 2000). The ocean represents the largest potential sink for anthropogenic CO_2. The potential storage capacity of the ocean is largely unknown, although some researchers estimate that it might hold thousands of GtC or greater (Herzog 2001, Smith and Sandwell 1997, Hoffert et al. 2002).

There are potential ancillary benefits associated with carbon capture, storage, and sequestration. Many land-management practices that sequester carbon can improve water quality, reduce soil erosion, and benefit wildlife. The injection of CO_2 into geologic structures can be beneficially used to enhance recovery of oil from depleted oil reservoirs and the recovery of methane from unmineable coal seams.

Carbon capture, storage, and sequestration technologies have become a high priority R&D focus under CCTP because they hold the potential to reduce CO_2 emissions from point sources, as well as from the atmosphere, and to enable continued use of coal and other fossil fuels well into the future. Near-term R&D opportunities include optimizing carbon sequestration and management technologies and practices in terrestrial systems, and accelerating the development of technologies for capturing and geologically storing CO_2 for enhanced oil recovery. Longer-term R&D opportunities include further development of other types of geologic storage and terrestrial sequestration options, as well as furthering the understanding of both the role oceans might play in storing carbon and the potential unintended consequences of using the oceans for carbon sequestration.

The remaining sections in this chapter summarize the current and future research activities and challenges associated with developing carbon sequestration technology. In each section, the description of the current R&D activities includes a hyperlink to the CCTP report, *Technology Options in the Near and Long Term* (CCTP 2003).

6.1 Carbon Capture

Point source carbon dioxide emissions from power plants vary depending on the combustion fuel, technology, and operational use. Concentrating and capturing CO_2 from flue gas is a technological challenge. Flue gas from conventional coal-fired power plants contains 10 to 12 percent of CO_2 by volume, and flue gas from integrated gasification combined cycle (IGCC) plants contains between 5 and 15 percent CO_2. For a combined cycle gas turbine system, the CO_2 concentration is about 3 percent. The CO_2 in flue gases must be concentrated to greater than 90 percent for most storage, conversion, or reuse applications. Thus, R&D programs are targeted at capture systems that can produce a concentrated and pressurized stream of CO_2 at relatively low cost.

6.1.1 Potential Role of Technology

Large CO_2 point sources, such as power plants, oil refineries, and other industrial facilities are considered the most viable sites for carbon capture. The current technology for CO_2 capture uses a class of chemical absorbents called amines that remove CO_2 from the gas stream and produce byproduct food-grade CO_2 often used in carbonated soft drinks and other foods. However, the current absorbent process is costly and energy intensive, increasing the cost of a coal-fired plant by 50 to 80 percent (Davison et al. 2001) and energy reductions on the order of 30 percent of the net power generation rate (DOE 1999). Thus, several R&D opportunities are being pursued to reduce CO_2 capture costs and lessen the energy reductions in power generation, or the "net energy penalty."

6.1.2 Technology Strategy

Realizing the possibilities for point source CO_2 capture requires a research portfolio that covers a wide range of technology areas, including post-combustion capture, oxy-fuel combustion, and pre-combustion decarbonization. R&D investments in technologies that use pure oxygen during combustion, pre-combustion de-carbonization technologies, regenerable sorbents, advanced membranes, and hydrate formation can potentially reduce costs, as well as the net energy penalty. After component performance evaluations are completed, the next short-term step would be to conduct pilot scale and slip stream (i.e., diversion of a small stream from the total emissions of an existing plant) level testing of the most promising capture technologies. Larger or full-scale tests might be appropriate within the next few decades to demonstrate and have a suite of capture technologies available for deployment. Fully integrated capture and storage demonstration systems would help to enable commercial deployment to mitigate the financial and technical performance risks associated with any new technology that must maintain a high availability, such as required by the power generation sector.

6.1.3 Current Portfolio

The metrics and goals for CO_2 capture research are focused on reducing the cost and energy penalty, because analysis shows that CO_2 capture drives the cost of sequestration systems. Similarly, the goals and metrics for carbon storage and measurement and monitoring are focused on permanence and safety. All three research areas work toward the overarching program goal of 90 percent CO_2 capture, with 99 percent storage permanence at less than 20% increase in the cost of energy services by 2007, and less than 10 percent by 2012.

Across the current Federal portfolio, agency activities are focused on a wide range of technical issues. See Section 3.1.1 (CCTP 2005):
http://www.climatetechnology.gov/library/2005/tech-options/tor2005-311.pdf

New technologies to reduce the capital and energy penalty costs for post-combustion capture are currently under development and include regenerable sorbents, advanced membranes, and novel concepts such as forming CO_2 hydrates to facilitate capture. One such novel concept, the hydrate process, could be especially attractive for advanced coal conversion systems like the IGCC.

A challenge for post-combustion capture is the large amount of gas that must be processed per unit of CO_2 captured. This is especially true for combustion turbines where the concentration of CO_2 in the flue gas can be as low as 3 percent. One area of research is developing gas/liquid contactors where CO_2 gas is chemically absorbed into a liquid, and the resulting mixture is then separated.

Oxygen-fired combustion is also being researched to determine if CO_2 can be recovered in the combustion process. In oxygen-fired combustion, oxygen and recycled flue gas, instead of air, are used in combustion of petroleum coke, coal, or biomass fuels. Current R&D investments are also being made in low-cost oxygen separation technologies, such as oxygen transport membranes.

For new construction or re-powering of existing coal-fired power plants, several technology options can provide a pure stream of CO_2 at relatively low incremental cost. These processes are referred to as pre-combustion decarbonization, which results in concentrated streams of hydrogen and CO_2. In gasification, the hydrocarbon is partially oxidized, causing it to break up into hydrogen (H_2), carbon monoxide (CO), and CO_2, and possibly some methane and other light hydrocarbons. The CO can be reacted with water to form H_2 and CO_2, and the CO_2 and H_2 can be separated. The H_2 can be used in a combustion turbine or fuel cell, and the CO_2 can be stored.

A number of collaborative efforts are currently underway that will contribute to this strategy. Regional Carbon Sequestration Partnerships have been organized within the United States, and include networks of state agencies, universities, and private companies focused on determining suitable approaches for capturing and storing CO_2. Four Canadian Provinces are also participating. The Partnerships are developing a framework to identify, validate, and potentially test the carbon capture and storage technologies best suited for each geographic region and its point sources. During Phase II, beginning in 2005, the Partnerships will pursue technologies for small-scale sequestration validation testing.

The DOE Carbon Sequestration Program is participating in collaborations with international partners in developing new capture and sequestration technologies. Among these are a cooperative agreement with Canada (Weyburn Project – Box 6-1) and the Sleipner North Sea Project (Box 6-2).

Box 6-1

WEYBURN II CO_2 STORAGE PROJECT

DOE is participating in this commercial-scale project that is using CO_2 for enhanced oil recovery. CO_2 is being supplied to the oil field in southern Saskatchewan, Canada, via a 320 kilometer pipeline from a North Dakota coal gasification facility. The goal is to determine the performance and undertake a thorough risk assessment of CO_2 storage in conjunction with its use in enhanced oil recovery. The project will include extensive above and below ground CO_2 monitoring.

Box 6-2

Sleipner North Sea Project

Roughly one million metric tons per year of vented CO_2 from a natural gas platform in the North Sea is being captured and injected into the Utsira saline aquifer formation. The Sleipner Project was spearheaded by Statoil and began operation in 1996. DOE is providing research funding for measurement, verification and transport modeling activities to compliment and enhance the injection experiment.
(DOE/NETL 2004)

The Carbon Sequestration Leadership Forum (CSLF – Box 6.3) is an international collaborative effort to focus international attention on the development of carbon capture and storage technologies.

Box 6-3
Carbon Sequestration Leadership Forum (CSLF)

Established by the State Department and DOE in February 2003, the CSLF coordinates data gathering, R&D and joint projects to advance the development and deployment of geologic carbon sequestration technologies worldwide. The CSLF is a particularly attractive mechanism for achieving international cooperation for larger field tests. See http://fossil.energy.gov/programs/sequestration/cslf

6.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Reduce the costs for sorbents, reducing regeneration energy requirements, and increasing sorbent life.

- Increase understanding of the CO_2 purity requirements to ensure that CO_2 transportation and storage operations are not compromised. Regarding CO_2 transportation, small quantities of SO_2 can lead to two-phase flow and pipeline pressure loss. The presence of water and other minute contaminants might promote acid formation and lead to pipeline and wellbore integrity problems. The history of transporting CO_2 in pipelines that contain substantial amounts of SO_x and NO_x is limited. These components can also impact the integrity of reservoir cap rock.

- Develop pre-and post-combustion CO_2 capture technologies that reduce the economic impacts of contaminants in a gas stream. For example, the corrosive nature of some of the contaminants can complicate CO_2 separation processes. Too much nitrogen in the CO_2 can significantly increase the cost of compression prior to geologic storage.

- Develop pre- and post-combustion CO_2 capture technologies that enable storage of criteria pollutants (SO_x, NO_x, H_2S) with the CO_2. In this area, the criteria pollutants are not separated from the CO_2 stream, but rather stored along with the CO_2.

- Continue to improve the cost-effectiveness of CO_2 separation membranes. Performance is improved by more cost-effective designs and materials with increased selectivity to CO_2 (increased CO_2 concentration per single membrane pass), increased throughput (increased flow rate per single membrane pass), and improved chemical stability (a measure of how well the membrane resists chemical reaction with its environment).

- Continue to lower the costs of oxygen used by coal-fueled power plants with separation technologies such as oxygen transport membranes. Success in this area is important to reducing the costs of oxy-combustion technologies (e.g., circulating fluidized bed designs), as well as gasification technologies.

- Develop an integrated modeling framework for evaluating alternative carbon capture technologies for existing and advanced electric power plants.

- Pursue innovative, potentially high-payoff concepts in areas such as advanced materials, and chemical and biological processes. Examples include ionic compound CO_2 solvents, novel microporous metal organic frameworks (MOFs) suitable for CO_2 separation and metabolic engineering to create strains of microbes that feed off CO_2 and produce useful chemical byproducts.

- Continue system integration and advancements of classical MEA-based systems for near-term carbon dioxide availability.

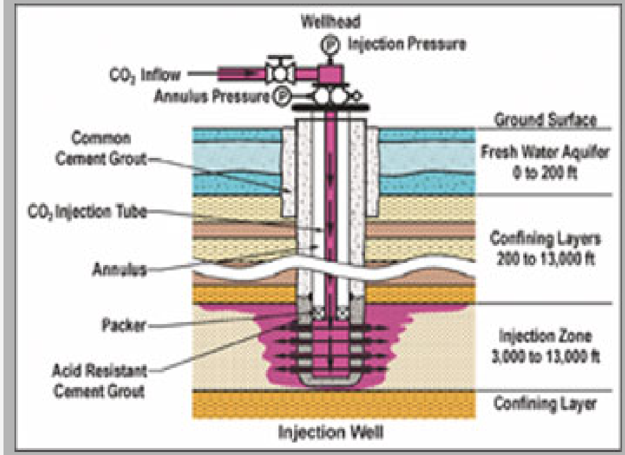
The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.2 Geologic Storage

Different types of geologic formations can store CO_2, including depleted oil reservoirs, depleted gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. Such formations have provided natural storage for crude oil, natural gas, brine, and CO_2 over millions of years. Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. Many power plants and other large point sources of CO_2 emissions are located near geologic formations that are amenable to CO_2 storage. For example, DOE, along with private and public sector partners, is conducting research on the suitability of geologic formations at the Mountaineer Plant in West Virginia (Box 6-4).

Box 6-4

Carbon Sequestration Research at American Electric Power's Mountaineer Plant



American Electric Power's Mountaineer Plant in New Haven, West Virginia, is the site for a carbon sequestration research project funded by the U.S. Department of Energy and a consortium of public and private sector participants. The research will determine whether the geology near the Mountaineer Plant is suitable for injection of CO_2, where it can be absorbed and stored. If the site proves to be geologically sound for storage, the data collected during the study will be used to inform simulations, risk assessment and permit applications, and to design the monitoring plans for future applications.

The study is part of a $4.2 million carbon sequestration research project led by Battelle Memorial Institute (in Columbus, Ohio). The project is managed by DOE's National Energy Technology Laboratory.

6.2.1 Potential Role of Technology

Geologic formations offer an attractive option for carbon storage. The formations are found throughout the United States, and there is extensive knowledge about many of them from the experience of exploration and operation of oil and gas production. Opportunities exist in the near term to combine CO_2 storage with enhanced oil recovery (EOR) and enhanced coal-bed methane (ECBM) recovery using injected CO_2. In 2000, 34 million tons of CO_2, roughly equivalent to annual emissions from 6 million cars, were injected as part of EOR activities in the United States.

Coal-bed methane has been one of the fastest growing sources of domestic natural gas supply. Pilot projects have demonstrated the value of CO_2 ECBM recovery as a way to increase production of this resource.

In the long term, CO_2 storage in saline and depleted gas formations is being explored. One project is currently in commercial operation, where one million tons of CO_2 per year are being injected in a saline formation at the Sleipner natural gas production field in the North Sea (see Box 6-2). The Frio Brine Pilot experiment near Houston, Texas, is the first U.S. field test to investigate the ability of saline formations to store greenhouse gases (GHGs). In October 2004, 1,600 tons of carbon dioxide was injected into a mile-deep well. Extensive methods were used to characterize the formation and monitor the movement of the carbon dioxide. The site is representative of a very large volume of the subsurface from coastal Alabama to Mexico and will provide experience useful in planning carbon dioxide storage in high-permeability sediments worldwide.

The overall estimated capacity of geologic formations appears to be large enough to store decades to centuries worth of carbon emissions, although the CO_2 storage potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. For example, characteristics of reservoir integrity, volume, porosity, permeability, and pressure vary widely even within the same reservoir, making it difficult to establish a reservoir's storage potential with certainty. Assessments of storage capacity could help to better understand the potential of geologic formations for CO_2 storage.

6.2.2 Technology Strategy

Potential CO_2 sources and sinks vary widely across the United States, and the challenge is to understand the economic, health, safety, and environmental implications of potential large-scale geologic storage projects. The geologic storage program was initiated in 1997 and initially focused on smaller projects. However, field testing is necessary to verify the results of smaller-scale R&D, and the program is taking on larger projects, as knowledge grows and opportunities and funding become available.

In the near-term, activities will focus on addressing important carbon storage-related issues consistent with the *Carbon Sequestration Technology Roadmap and Program Plan* (DOE 2005). Among these activities are developing an understanding of the behavior of CO_2 when stored in geologic formations. Long-term activities will be needed in the areas of understanding and reducing potential health, safety, environmental, and economic risks associated with geologic sequestration.

Regional domestic partnerships and international cooperation are viewed as key to deploying carbon storage technologies. Field validation activities are needed to test the large-scale viability of point-source capture and storage systems and demonstrate to interested parties the potential of these systems.

6.2.3 Current Portfolio

The goal of geologic storage R&D portfolio is to develop domestic CO_2 underground storage repositories capable of accepting around a billion tons of CO_2 per year. Toward this goal, there is a need to demonstrate that CO_2 storage underground is safe and environmentally acceptable, and an acceptable GHG mitigation approach. Another need is to demonstrate an effective business model for CO_2 enhanced oil recovery and enhanced coalbed methane, where significantly more CO_2 is stored for the long term than under current practices.

The Federal portfolio for geologic storage activities includes several major thrusts designed to move technologies from early R&D to deployment. See Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf

Core RD&D focuses on understanding the behavior of CO_2 when stored in geologic formations. For example, studies are being conducted to determine the extent to which CO_2 moves within the geologic formation, and what physical and chemical changes occur to the formation when CO_2 is injected. This information is needed to ensure that CO_2 storage will not impair the geologic integrity of an underground formation and that CO_2 storage is secure and environmentally acceptable. There are three major research thrusts:

- **Knowledge Base and Technology for CO_2 Storage Reservoirs**. These activities seek to increase the knowledge base and technology options. The petroleum industry has built significant experience over the past few decades on how to inject carbon dioxide into oil reservoirs for EOR. Many of the issues related to injection technologies and gas compression have already been solved. Because oil and gas reservoirs have been able to store gases and other hydrocarbons for geologically significant periods of time (hundreds of thousands to millions of years), they likely have caprocks that will be good seals for CO_2 as well. Furthermore, CO_2 can potentially enhance oil and gas production, which can help mitigate carbon storage costs. However, because the petroleum industry understandably has been focused on resource recovery and not on CO_2 storage, it has not developed procedures to maximize the amount of CO_2 that is stored or to track the CO_2 once it is has been injected to ensure that it remains in the ground. In addition, most well-developed oil fields, by definition, contain many wells that have pierced the caprock for the field, creating potential leakage pathways for CO_2. Research is currently underway to develop technologies to locate abandoned wells, to track the movement of CO_2 in the ground, and to ensure long-term storage, as well as to optimize costs, assess performance, and reduce uncertainties in capacity estimates.

  Another attractive option is carbon storage in deep, unmineable coal seams. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable byproduct and decreasing the overall storage cost. One potential barrier is the tendency of coal to swell in volume when adsorbing CO_2. This can cause a sharp drop in permeability, thereby impeding the flow of CO_2 and the recovery of methane. Laboratory, modeling and field studies are currently being implemented and proposed to gain a better understanding of the processes behind coal swelling and determine if it will be a significant barrier to sequestration in coal seams.

  Another option is the use of large saline formations for CO_2 storage, a relatively new concept. About two-thirds of the United States is underlain by deep saline formations that have significant sequestration potential. Since the water in the saline formations is typically not suitable for irrigation or consumption, many opportunities exist for CO_2 to be injected without adverse impacts. The storage capacity of saline formations is enhanced because of the ability of CO_2 to dissolve in the aqueous phase. But, there are uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine, and minerals in the surrounding strata, especially with respect to reaction kinetics. For example, saline formations contain minerals that could react with injected CO_2 to form solid carbonates, which would eliminate potential migration out of the reservoir. On the negative side, the carbonates could plug the formation in the immediate vicinity of the injection well. Researchers are looking into multiphase behavior of CO_2 in saline aquifers and the volume, fate, and transport of the stored CO_2. New technologies and techniques are being developed to reduce cost and inefficiency due to leaks and to better define the geology of the saline aquifers. A recent review article addresses the technological challenges of sequestering carbon dioxide in saline formations and coal seams (White et al. 2003). For more information, see Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf

- **Measurement and Monitoring**. These activities are described more fully in Chapter 8. An important R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues, but also can help ensure that geologic storage of CO_2 is safe. Long-term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic storage of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and borehole seismic monitoring; and electromagnetic/geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection.

- **Health, Safety, and Environmental Risk Assessment**. Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. In some cases, geologic storage sites may exist near populated areas. Although CO_2 is not toxic or flammable, it can cause suffocation if present at high concentrations. Therefore, the mechanism for potential leaks must be better understood. The assessment of risks includes identifying potential subsurface leakage modes, the likelihood of an actual leak, leak rate over time, and the long-term implications for safe carbon storage. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis.

Two activities cited in Section cited in Section 6.1.3 will continue to play an important role in encouraging the deployment of technologies developed under the core RD&D program. The Regional Partnerships Program[2] is building a nationwide network of Federal, State, and private sector partnerships to determine the most suitable technologies, regulations, and infrastructure for future point source carbon capture, storage, and geologic sequestration in different areas of the country. The Carbon Sequestration Leadership Forum is facilitating the development and worldwide deployment of technologies for separation, capture, transportation, and long-term storage of CO_2.

In addition, the FutureGen project (Box 6-5) is expected to be the world's first coal-fueled prototype power plant that will incorporate geological storage. It will provide a way to demonstrate some of the key technologies developed with Federal support, and demonstrate to the public and regulators the viability of large-scale carbon storage.

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[2] For more information on the Regional Partnerships Program, see http://fossil.energy.gov/programs/sequestration/partnerships.

6.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Defining the factors that determine the optimum conditions for sequestration in geological formations, such as depleting oil and gas reservoirs, saline formations, and coal seams, as well as unconventional hydrocarbon bearing formations.
- Developing the ability to predict and optimize CO_2 storage capacity and resource recovery.
- Developing the ability to track the fate and transport of injected CO_2 in different formations. This includes applying surface and near-surface monitoring techniques such as surface CO_2 flux detectors, injecting tracers in soil-gas, and measuring changes in shallow aquifer chemistry for CO_2 leakage.
- Developing models to simulate the migration of CO_2 throughout the subsurface and the effects of injection on the integrity of caprock structures.
- Understanding geochemical reactions (see Box 6-6) and harnessing them to enhance containment.
- Developing injection practices that preserve cap integrity, and practices to mitigate leakage to the atmosphere.
- Developing an understanding of CO_2 reactions and movement in shales and other unconventional hydrocarbon-bearing formations that will permit the economic recovery of these hydrocarbons.
- Taking advantage of geologic differences in various regions by developing cost-effective systems to integrate energy conversion with carbon capture, geologic storage, and subsurface conversion of CO_2 into benign materials or useful byproducts (e.g., through biogeochemical processes that can create methane or carbonates).
- Developing improved methods and data for estimating the overall costs of geologic sequestration, including capture, compression, and transportation.

Box 6-5

Future Gen

FutureGen is a public-private initiative to build the world's first integrated carbon capture/storage and hydrogen production power plant. When in operation, the prototype will be the cleanest fossil fuel power plant in the world. The plant will be a "living prototype" with future technological innovations incorporated into the design as they develop. An industrial consortium representing the U.S. coal and power industry will work closely with DOE to implement this project. Other countries have been invited to participate via the Carbon Sequestration Leadership Forum. See: http://www.netl.doe.gov/coalpower/sequestration/futureGen/main.html

- Economics of geologic sequestration.

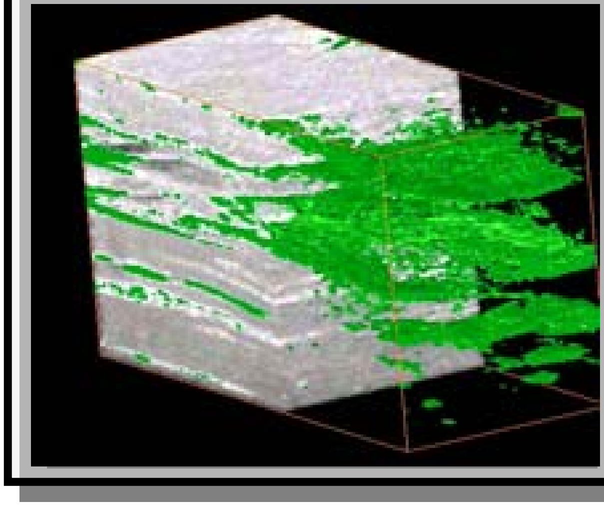
Pursuit of breakthrough concepts may be important for reaching long-term program goals. Breakthrough concepts R&D is pursuing revolutionary and transformational approaches with potential for low cost, permanence and large global capacity. For example, some of the lowest cost estimates for capture/sequestration options are for systems where flue gas components from coal-fueled plants are not scrubbed but rather stored in geologic formations with CO_2. This eliminates the need for costly flue gas cleanup systems, but the potential effects of this option are unknown. Technological innovations could come from concepts associated with areas not normally related to traditional energy R&D fields.

In the long term, CO_2 capture can be integrated with geologic storage and/or conversion. Many CO_2 conversion reactions are attractive, but too slow for economic chemical processes. Use of impurities in captured CO_2 (e.g., SO_x and NO_x) or additives could possibly enhance geologic storage and provide an opportunity to combine CO_2 emissions reduction with criteria pollutant emissions reduction.

Box 6-6

CO_2-Coal Interactions

Understanding the interactions between carbon dioxide and coal is one challenge that must be met before large-scale sequestration in coal seams will occur. Coal appears to swell in the presence of CO_2 under pressures found in deep unmineable coal seams. Laboratory studies and field trials are underway to determine how coal swelling occurs and whether CO_2 injectivity can be held high enough in the presence of swelling.



Field tests will be needed to verify R&D results. It is anticipated that many of these tests will eventually be carried out through the Regional Partnerships Program based on analysis of CO_2 sources and sinks by participants to determine the highest benefit projects.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.3 Terrestrial Sequestration

Terrestrial sequestration can play a significant role in addressing the increase of CO_2 in the atmosphere. A wide range of technologies and practices, including tree planting, forest management, and conservation tillage practices are available to increase the sequestration of carbon in plants and soils. Terrestrial sequestration activities can provide a positive force for improving landscape-level land management and provide significant additional benefits to society, such as improvements in wildlife and fisheries habitat, enhanced soil productivity, reduction in soil erosion, and improved water quality. Terrestrial sequestration represents a set of technically and commercially viable technologies that have the capability to reduce the rate of CO_2 increase in the atmosphere. Given the size and productivity of the U.S. land base, terrestrial sequestration has distinct economic and environmental advantages. Globally, the potential for terrestrial sequestration is also significant, due in part to low-cost opportunities to reduce ongoing emissions from current land-use practices and land conversion and to enhance carbon stocks via afforestation, forest restoration, and improved forest and agricultural management.

Terrestrial sequestration technologies refer broadly to equipment, processes, decision tools, management systems and practices, and techniques that can enhance carbon stocks in soils, biomass, and wood products, while reducing CO_2 concentrations in the atmosphere. Extensions of terrestrial sequestration can use sustainably generated biomass to displace fossil fuels. Examples of terrestrial sequestration technologies include conservation tillage, conservation set-asides, cover crops, buffer strips, biomass energy crops, active forest management, active wildlife habitat management, low-impact harvesting, precision use of advanced information technologies, genetically improved stock, wood products life-cycle management, and advanced bioproducts.

6.3.1 Potential Role of Technology

Increasing terrestrial carbon stocks is attractive because it can potentially offset a major fraction of emissions, and serve as a bridge over an interim period, allowing for development of other low-CO_2 or CO_2-free technologies. Carbon stock management technologies and practices that enhance soil and forest carbon sinks need to be maintained once the carbon stock reaches higher levels. Although the benefits can be temporarily reversed by fire, plowing of cropland soils, and other disturbances, the potential improvements in carbon stocks are of such magnitude that they can play a significant overall role in addressing the increase in atmospheric CO_2 emissions from the United States and globally throughout the 21st century.

Other opportunities described in this section can provide benefits essentially indefinitely. For example, changes in crop management practices can reduce annual emissions of trace GHGs; sustainable biomass energy systems can displace fossil fuels and provide indefinite net CO_2 emissions reductions; and enhanced forest management and conversion to durable wood products provide a mechanism to allow forests to continually sequester carbon.

Estimates of the global potential for terrestrial sequestration activities remain uncertain. Such estimates are generally of the technical potential (i.e., the biophysical potential of managed ecosystems to sequester carbon), and disregard market and policy considerations. The IPCC (IPCC 2001c) estimates such technical potential of biological mitigation options (i.e., forest, agricultural, and other land-management activities) to be on the order of 100 GtC cumulative by 2050, at costs ranging from about \$0.1 to about \$20/t carbon in tropical countries, and from \$20/t carbon to \$100/t in non-tropical countries. Technical potential estimates for the United States range widely, depending on assumptions about biophysical sequestration rates per hectare, the land area available for different activities, and other factors. Widely cited estimates of U.S. technical potential for carbon sequestration include about 55-164 teragrams of carbon (TgC) per year for potential sequestration on croplands (Lal et al. 1998); 29-110 TgC per year on grazing lands (Follett et al. 2001); 210 TgC per year on forest land (Joyce and Birdsey 2000); and 91-152 TgC per year on dedicated bioenergy croplands (Tuskan and Walsh 2001). In addition, dedicated bioenergy crops would substitute for fossil fuels, leading to an estimated 450 Tg C reduction of CO_2 emissions (Tuskan and Walsh 2001). These estimates generally represent technical potential that does not reflect barriers to implementation, competition across land uses and sectors, or landowner response to public policies and economic incentives. A recent study of cropland (Eve et al. 2002) indicates a potential of about 66 TgC per year on croplands, toward the lower end of the Lal et al. (1998) range.

With regard to bioenergy, a recent DOE/USDA analysis estimates that U.S. forest and agricultural lands could sustainably supply up to 1,300 Tg of biomass/year for bioenergy, similar to the findings of Tuskan and Walsh, but without major shifts in land use or food or fiber production (Perlack et al. 2005). Such a quantity of biomass could displace over 30 percent of current U.S. petroleum consumption.

6.3.2 Technology Strategy

Realizing the opportunities to sequester carbon in terrestrial systems will require managing resources in new ways that integrate crosscutting technologies and practices. A balanced portfolio is needed that supports basic science, technological development, emerging technology demonstrations, innovative partnerships with the private sector, and techniques and metrics for measuring success.

An array of actual and potential technologies can be found in the short, mid, and long terms. In the short term, some technologies and practices being routinely used can be expanded to increase carbon sequestration. In addition, improvements to many current systems are needed to enable them to enhance above- and below-ground carbon stocks, and manage wood products pools. In the mid to long term, research can focus on options that take advantage of entirely new technologies and practices.

In the near- and long-term, the R&D portfolio needs include:

- Design, develop and demonstrate carbon management strategies consistent with economic and environmental goals for terrestrial ecosystems.
- Improve the understanding of the relationship of carbon management and ecosystem good and services.
- Determine how terrestrial systems' capacities can be manipulated to enhance carbon sequestration in time and space.
- Analyze the relationship between natural resource and agricultural policy, and terrestrial sequestration technologies and identifying ways to maximize synergies and avoid potential conflicts between the two.
- Evaluate existing and new market-based adoption and diffusion strategies for terrestrial sequestration technologies.
- Optimize management practices and techniques, accounting for all GHGs and their effects.
- Improve methods of measuring changes in carbon pools and verifying sequestration rates.
- Develop and analyze incentives for implementation.

6.3.3 Current Portfolio

Much of the research currently underway that could have applications for increasing terrestrial carbon sequestration is being undertaken for multiple reasons, often unrelated to climate change. Significant investments are being made in developing sustainable natural resource management systems that provide economic and environmental benefits. In particular, advances have been made in increasing forest productivity, effective and environmentally sound uses of crop fertilizers, enhancing soil quality, and in producing biomass feedstocks (see Figure 6-1).

Figure 6-1. Terrestrial Sequestration: Short Rotation Woody Crops, Soil, and Wood Products

Across the current Federal portfolio of terrestrial sequestration-related RD&D, multi-agency activities are focused on a wide range of issues, including the following:

- Cropland management and precision agriculture that can increase the amount of carbon stored in agricultural soils by increasing plant biomass inputs or reducing the rate of loss of soil organic matter to the atmosphere. The goals of this activity are to quantify the carbon sequestration potential of agricultural practices for various climates and soils; develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of agricultural practices; and develop decision support tools for farmers, other land managers, and policy makers to inform agricultural policy decisions of the relative costs and benefits of different cropland management approaches, both in terms of carbon sequestration and production. See Section 3.2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3211.pdf

- Conversion of marginal croplands to other less-intensive land uses to conserve reserves and buffer areas. The goals of this activity are to quantify the carbon sequestration potential of cropland conservation programs for various climates and soils; develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of cropland conservation practices; and develop decision support tools for farmers, other land managers, and policy makers to inform cropland conservation policies and the relative costs and benefits of different cropland conservation approaches, both in terms of carbon sequestration and production. See Section 3.2.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3212.pdf

- Evaluation of advanced forest and wood products management that may offer significant carbon sequestration opportunities. The goals and milestones of this activity are to increase energy efficiency of forest operations; develop and apply models to better understand the economics of achieving certain GHG mitigation goals through improved forest management; sensors/monitors and information management systems; advanced fertilizers, technologies, and application strategies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs; integrated management strategies and systems to increase nutrient and water use efficiency, increase CO_2 uptake and sequestration and reduce emissions.; and wood product management and substitution strategies. The milestones are to have initial systems models and prototype operation on major plantation types in place by 2007. Also, to deploy first-generation integrated system models and technology by 2010. See Section 3.2.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3213.pdf

- Grazing management to increase amount of carbon in soils. The goals of this activity are to construct quantitative models that describe site-specific interactions among grazing systems, vegetation, soil and climate, and the effects on greenhouse gas dynamics; and to develop decision support tools to inform the relative costs and benefits of different grassland management scenarios for carbon sequestration and other conservation benefits. See Section 3.2.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3214.pdf

- Restoration of degraded rangelands using low-cost, reliable technologies. The goals of this activity are to develop low-cost, reliable technologies for the restoration of vegetation on degraded arid and semi-arid rangelands; improve decision support for the application of low-cost technologies, such as fire, to control invasive species and to reduce greenhouse gas emissions from mesic rangelands; and to develop seed production technology to produce low-cost seeds for reestablishing desired rangeland species. Currently costs are high and seed supply is limited for many cultivars. See Section 3.2.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3215.pdf

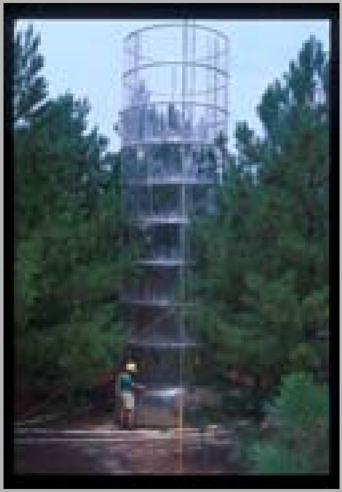
- Wetland restoration and management for carbon sequestration and GHG offsets. The goals of this activity are to evaluate various management practices on restored wetlands; delineate and quantify carbon stocks in U.S. wetlands by region and type; develop and demonstrate integrated management strategies for wetland carbon sequestration; and identify wetland areas most likely to be impacted by climate change and prioritize areas for protection. See Section 3.2.1.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3216.pdf

- Reclamation of mined lands using grassland, cropland, and forest restoration practices. The goals of this activity are to quantify carbon sequestration on reclaimed mined lands and evaluate the extent to which various management practices on reclaimed mined lands enhance carbon sequestration (i.e., measure the effects of organic and inorganic residues, grazing, plant biodiversity. See Section 3.2.1.7 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3217.pdf

- Use of biotechnology for modifying the chemical composition of plants and microorganisms to enhance carbon sequestration (see Box 6.7). The goals of this activity are to identify the traits needed in plants and microorganisms to increase soil carbon sequestration capacity; determine the feasibility of using biotechnology to modify the traits of plants and microorganisms that can affect soil carbon sequestration; develop systems for monitoring non-target environmental affects associated with plant modifications; develop methods to incorporate genetically modified plant and microorganisms into cropland and conservation reserve and buffers systems. See Section 3.2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3221.pdf

Box 6-7

Physiological Mechanisms of Growth, Response and Adaptation in Forest Trees



Enhancing the natural capacity of terrestrial ecosystems to store carbon is a viable strategy for stabilizing rising CO_2 concentrations in the atmosphere. However, gains in improving the sequestration potential of croplands, grasslands, and forest lands could be enhanced by major scientific advancements in understanding the processes that control the initial uptake, ultimate chemical forms, and subsequent carbon transfer in plants and soils.

Research carried out by the U.S. Department of Agriculture and the U.S. Department of Energy is underway to determine the mechanisms that control the quantity and quality of carbon allocated to stems, branches, leaves, and roots of trees as a means of understanding the biological processes that underlie carbon sequestration in trees and soils; understanding controlling genetic mechanisms; and selecting, testing, and demonstrating useful genotypes. Research is focused on several species, including hybrid poplar, willow, and loblolly pine. The studies are designed to determine the interaction of physiological and biogeochemical processes and water and nutrient management on carbon fixation, allocation, storage, and dynamics in forest systems. Field and laboratory studies are being used to quantify and understand carbon dynamics, both above and below ground. Forest researchers hope that these and similar studies will provide the scientific foundation for managing forest systems to enhance carbon sequestration, and improve environmental quality and productivity.

- Terrestrial sensors, measurements, and modeling. The goals of this activity are to develop a new generation of sensors, probes, and other instruments to measure soil carbon, GHGs flux in situ across a wide variety of agricultural ecosystems. See Section 3.2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3231.pdf

- Measuring, monitoring, and verification for forests. The goals of this activity are to develop technologies remote sensing data collection and analysis, in situ instrumentation and monitoring systems, and other measuring and monitoring technologies. See Section 3.2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3232.pdf

6.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Quantifying the carbon sequestration potential for management practices and techniques across all major land uses, including cropland, forests, grasslands, rangelands, and wetlands; across cultivation and management systems; and across regions.

- Designing, developing, and testing management systems to increase carbon sequestration, maintain storage, and minimize net GHG emissions while meeting economic (i.e., forest and agricultural production) and environmental goals.

- Developing bioenergy and additional durable uses of bio-based products and improve management of residues and wood products.

- Improving biomass supply technologies (harvesting, handling, onsite separation and processing, transportation) to reduce costs and impacts; and enhance techniques that improve yields, transport, and efficiency of conversion to fuels.

- Exploring the use of trees and other vegetative cover in urban environments to both sequester carbon and reduce the urban heat island effect.

- Evaluating terrestrial carbon stock vulnerabilities and stability.

- Improving the understanding of the implications of potential sequestration options on the emissions of other GHGs through comprehensive accounting of all GHG emissions and sinks as land-based carbon sequestration technologies are implemented.

- Improving the performance of technologies and practices to provide additional benefits, including improvements in wildlife habitat; water and air quality; and soil characteristics such as stability, water infiltration and retention, and nutrient retention.

- Enhancing sequestration potential through the use of advanced technologies, including biotechnology techniques to enhance seed stock qualities, precision water and nutrient application, land management using geographic information system and other tools, and alternative tillage and harvest techniques.

- Developing novel alternative technologies such as high-lignin trees for combustion and low-lignin trees to reduce paper processing costs and improved digestibility of fodder and forage.

- Researching biotechnology (genomics, genetics, proteomics), and in managing biological and ecological processes affecting carbon allocation, storage, and system capacity that may aid in managing carbon. Improved understanding of the functional genomics of high-potential biomass crops can increase yields and provide a more effective basis for increasing the conversion efficiency of biomass of fuels, chemicals, and other bioproducts.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.4 Ocean Sequestration

Because of the large CO_2 storage capacity of the ocean, increasing the carbon uptake and storage of carbon in the oceans has generated some interest. To understand the role the ocean could play, several issues must be addressed, including the *capacity* of the ocean to sequester CO_2, its *effectiveness* at reducing atmospheric CO_2 levels, the *depth and form* (liquid) for introduction of the CO_2 stream, and the *potential for adverse environmental consequences*. Ocean storage has not yet been deployed or thoroughly tested, but there have been small-scale field experiments and 25 years of theoretical, laboratory, and modeling studies of intentional ocean storage of CO_2. Nevertheless, little is known about the potential environmental consequences to ocean ecosystems and natural biogeochemical cycles.

Two strategies are typically considered for ocean carbon sequestration: (1) direct injection of a relatively pure stream of CO_2 into the ocean interior, and (2) iron fertilization to enhance the ocean's natural biological pump. It is generally thought that direct injection of CO_2 would be technically feasible and effectively isolate CO_2 from the atmosphere for at least several centuries, and the primary concerns relate to possible adverse environmental effects. In contrast, the technical feasibility and effectiveness of ocean fertilization remain open to question; furthermore, whereas direct injection approaches seek to minimize ecosystem impacts, ocean fertilization depends upon our ability to manipulate ecosystem function over large areas of the ocean.

Various observations indicate that the oceans take up (net) about 2 GtC/year or about one-third of the global emissions, and ultimately, over the period of centuries, oceans may take up about 70 percent of global fossil carbon emissions as carbon is transported across the ocean thermocline and mixed with deep ocean waters (IPCC 2001a). Ocean carbon sequestration strategies seek to increase the deep ocean inventory of CO_2. Intentional ocean storage of CO_2 could slow the increase of CO_2 in the atmosphere. After some time, injected CO_2 would be distributed widely in the oceans.

The volume of the ocean is very large relative to the size of fossil-fuel resources; thus, ocean carbon storage is not limited by physical capacity. The two factors that have the greatest potential to limit the available capacity of the ocean are (i) the goal for long-term equilibrium atmospheric CO_2 concentration and (ii) adverse environmental consequences. All CO_2 placed in the ocean will eventually interact with the atmosphere, adding some part of that CO_2 to the atmospheric burden. For example, injection of about 8000 Gt CO_2 to the deep ocean will eventually produce atmospheric CO_2 concentrations of about 750 ppm, even in the absence of additional CO_2 release to the atmosphere. It has been shown in experiments that high concentrations of CO_2 can harm marine organisms, but the effects of long-term exposure to relatively small additions of CO_2 are unknown.

6.4.1 Potential Role of Technology

Ocean sequestration offers the potential to reduce the level of CO_2 concentrations in the atmosphere. Under the direct injection approach, CO_2 would be captured from large point sources, e.g., fossil-fired power plants, industrial processes, etc., and then pressurized and injected at depths of 2,000 to

3,000 meters below surface, where it would be expected to remain for centuries. However, it has yet to be tested or deployed in a continuous mode at industrial concentrations.

Fertilization of the oceans with iron, a nutrient required by phytoplankton, is a strategy being considered to enhance the draw-down of CO_2 from the atmosphere and to accelerate the biological carbon pump. Iron fertilization is intended to promote carbon fixation by phytoplankton (primary production) leading to the sinking of some of this carbon to the deep ocean, where some of it will be oxidized back into carbon dioxide. Thus ocean fertilization will directly affect surface ocean ecosystems and expose deep-sea ecosystems to long-term, but relatively small, increases in CO_2 concentrations. Direct injection is likely to produce acute effects in the local region of injection, whereas fertilization would produce ecosystem shifts over large areas of the surface ocean.

6.4.2 Technology Strategy

To adequately assess the potential of ocean-based options as mitigation strategies, the potential adverse impacts on the ocean biosphere and the potential effectiveness must be evaluated and specific R&D criteria need to be addressed. A research portfolio is required that seeks to determine, via experimentation and computer simulations, the potential for storing anthropogenic CO_2 in the world's oceans while minimizing negative environmental consequences.

A variety of studies based on models and ocean observations indicate that the isolation of carbon from the atmosphere generally increases with the depth of injection (or oxidation of organic carbon). In the near term, the key research questions related to direct injection involve evaluating the impact of added CO_2 and/or nutrients on marine ecosystems and the biogeochemical cycles to which they contribute. This is being investigated through both observations and modeling of marine organisms and ecosystems, as is now being funded by DOE and the National Science Foundation (NSF), among others. In the long-term, the most important R&D activities need to focus on improving an understanding of the effects of elevated concentrations of CO_2 on marine organisms and ecosystems.

Near-term research needs related to iron fertilization are associated with understanding the magnitude of carbon export down through the water column and the effects of growth of harmful phytoplankton or diatom species. In the long-term, more emphasis is needed on understanding the effectiveness and environmental and ecological consequences of this approach.

6.4.3 Current Portfolio

Ongoing research activities target ocean carbon sequestration using direct injection and iron fertilization. These activities are summarized below:

- **Direct Injection**. Currently, the technology exists for the direct injection of CO_2. Previous laboratory experiments concentrated on establishing an understanding of the processes that occur when CO_2 comes into contact with high pressure seawater. As a result, a much better understanding of the influence of CO_2 hydrates (or clathrates) on the dissolution processes exists. Additional research conducted by DOE's Oak Ridge National Laboratory simulated a negatively buoyant clathrate. In addition, the Monterey Bay Aquarium Research Institute demonstrated that CO_2 clathrates ("solids" in which gas molecules are held in place) tended to be negatively buoyant at depths below 3,000 meters. This property of clathrates would presumably reduce the potential ecological impact of CO_2 on the shallow layers of the ocean, where most marine life occurs. It would also increase the length of time that CO_2 injected would remain in the ocean, thus enhancing the effectiveness of CO_2 sequestration by injection. The goal of this R&D activity is to demonstrate that CO_2 direct injection is safe and environmentally acceptable. See Section 3.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-331.pdf

- **Iron fertilization**. Fundamental research related to iron fertilization is targeting the magnitude of carbon export down through the water column and the effects on the growth of harmful phytoplankton or diatom species. The goal of this R&D activity is to determine if iron-induced phytoplankton blooms result in the vertical flux (transport) of carbon from the surface waters (export production) to the deep waters. See Section 3.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-332.pdf

  The Southern Ocean Iron Fertilization Experiment (SOFeX), funded by NSF and DOE, occurred in January-February 2002. These demonstrations aimed to determine the magnitude of export production—that is, how much carbon is transported to the deeper ocean after iron fertilization. The small increase in flux to the deep ocean suggests that iron fertilization would have to be done over a large area of the ocean and sustained for extended periods of time in order to meaningfully reduce the concentration of atmospheric CO_2. NSF has also funded small-scale experiments in the equatorial Pacific Ocean. The mechanics of producing an iron-enriched experimental patch and following it over time was developed in experiments (IronEx I and II) in the equatorial Pacific (Martin et al. 1994; Coale et al. 1996, 1998) and more recently in the Southern Ocean Iron Enrichment Experiment (Boyd et al. 2000).

6.4.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Direct Injection**. The most important R&D need related to direct injection involves improving our understanding of the long-term effects of elevated concentration of CO_2 on marine organisms and ecosystems. This would likely require both *in situ* and laboratory experiments combined with a program of process modeling aimed at a predictive capability for both biological and physico-chemical parameters.

- **Iron Fertilization**. There are a multitude of R&D opportunities regarding the effectiveness and environmental consequences of ocean fertilization. The most pressing question is whether iron enrichment increases the downward transport of carbon from the surface waters to the deep sea. This would help for predicting whether fertilization is an effective carbon sequestration mechanism. Other important questions need to be explored: What are the long-term ecological consequences of iron enrichment on surface water community structure, and on mid-water and benthic processes? How can carbon export best be verified?

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.5 Conclusions

The development of the technical, economic, and environmental feasibility and acceptability of CO_2 sequestration strategies has important implications for meeting the needs for food, fiber, and energy while minimizing GHG emissions. As the current energy infrastructure evolves around fossil fuels, the viability of sequestration could provide many options for a future of near-net-zero GHG emissions. Carbon sequestration has the potential to reduce the cost of stabilizing GHG concentrations in the atmosphere, conceivably at lower costs than other alternatives, if successful, and further support domestic and global economic growth.

If carbon sequestration proves technically and economically viable, fossil fuels can continue to play an important role as a primary energy supply. The ability to cost-effectively and safely separate and sequester carbon could have potentially profound implications for the dynamics of food, fiber, and energy production. The current energy infrastructure is designed around fossil fuels, and the viability of carbon capture and sequestration preserves a number of options for an energy future. Although an energy infrastructure later in this century presumably will be different from that of today, without the options that capture and sequestration provide, infrastructure changes must occur sooner and much more dramatically than would otherwise be the case. A more gradual transition that continues the use of fossil fuels, particularly coal, could avoid potentially disruptive consequences that might occur if a rapid change to non-fossil energy sources is required.

6.6 References

Boyd, P.W., A.J. Watson, C.S. Law, E.R. Abraham, T. Trull, R. Murdoch, D.C.E. Bakker, A.R. Bowie, K.O. Buessler, H. Chang, M.A. Charette, P. Croot, K. Downing, R.D. Frew, M. Gall, M. Hadfield, J.A. Hall, M. Harvey, G. Jameson, J. La Roche, M.I. Liddicoat, R. Ling, M. Maldonado, R.M. McKay, S.D. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S.M. Turner, A. Waite, and J. Zeldis. 2000. A mesoscale phytoplankton bloom in the polar southern ocean stimulated by iron fertilization. *Nature* 407:695-702.

CCTP (See U.S. Climate Change Technology Program)

Coale K.H., K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S. Tanner, F.P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W.P. Cochran, M.R. Landry, J. Constantinou, R. Rollwagen, A. Trasvina, and R. Kudela. 1996. A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383:495-501.

Coale, K.H., K.S. Johnson, S.E. Fitzwater, S.P.G. Blain, T.P. Stanton, and T.L. Coley. 1998. IronEx-I, an in situ iron-enrichment experiment: experimental design, implementation and results. *Deep-Sea Research, Part II: Topical Studies in Oceanography* 45:6 919-945.

Davison, J., P. Freund, and A. Smith. 2001. *Putting carbon back into the ground.* Technical Report. Paris: International Energy Agency (IEA) Greenhouse Gas R&D Programme. http://www.ieagreen.org.uk/putcback.pdf

DOE (See U.S. Department of Energy)

Energy Information Administration (EIA). 2004. *International energy outlook 2004.* Washington, D.C: U.S. Department of Energy. http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2004).pdf

Energy Information Administration (EIA). 2005. *Annual energy outlook 2005.* Washington, DC: U.S. Department of Energy. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2005).pdf

Eve, M.D., M. Sperow, K. Paustian, and R. Follett. 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. *Environmental Pollution* 116: 431-438.

Follett R.F., J.M. Kimble, and R. Lal. 2001. *The potential of US grazing lands to sequester carbon and mitigate the greenhouse effect*. New York: Lewis Publishers.

Herzog H. 2001. What future for carbon capture and sequestration? *Environmental Science and Technology* 35(7):148A-153A.

Hoffert, et al. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298:981-7.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land use, land-use change, and forestry*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001a. Chapter 3: the carbon cycle and atmospheric carbon dioxide. In *Climate change 2001: Working Group I: the scientific basis*. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg1/095.htm

Intergovernmental Panel on Climate Change (IPCC). 2001b. *Summary for policymakers to climate change 2001: synthesis report of the IPCC third assessment report.* Cambridge, UK: Cambridge University Press. http://www.ipcc.ch/pub/un/syreng/spm.pdf

Intergovernmental Panel on Climate Change (IPCC). 2001c. Chapter 4: technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineering. In *Climate change 2001: mitigation: contribution of working group iii to the third assessment report.* Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/155.htm

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 1994a. *Carbon dioxide utilisation.* Cheltenham, UK.

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 1994b. *Carbon dioxide disposal from power stations.* Cheltenham, UK.

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 2000. *Barriers to overcome in implementation of* CO_2 *capture and storage*. Report PH3/22. Cheltenham, UK.

Joyce, L.A., and R. Birdsey, eds. 2000. *The impact of climate change on American's forests: a technical document supporting the 2000 USDA Forest Service RPA assessment*, 133. Gen. Tech. Rep. RMRS-GTR-59. Fort Collins, Colorado: U.S. Department of Agriculture. http://www.fs.fed.us/rm/pubs/rmrs_gtr059.pdf

Lal et al. 1998. *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Ann Arbor Press.

Martin, J.H., K.H. Coale, K.S. Johnson, S.E. Fitzwater, R.M. Gordon, and 39 others. 1994. Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean." *Nature* 371.

Perlack, R.D., L.L. Wright, A. Turhollow, R.L. Graham, B. Stokes, and D. Erbach. 2005. *Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply*. ORNL/TM-2005/66. Oak Ridge, TN: Oak Ridge National Laboratory. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

Post, W.M., C. Izaurralde, J.D. Jastrow, B.A. McCarl, J.E. Amonette, V.L. Bailey, P.M. Jardine, T.O. West, and J. Zhou. 2004. "Enhancement of carbon sequestration in US soils." *Bioscience* 54:895-908.

Smith, W.H.F., and D.T. Sandwell. 1997. "Global seafloor topography from satellite altimetry and ship depth soundings." *Science* 277:1957-62.

Tuskan, G.A., and M.E. Walsh. 2001. "Short-rotation woody crop systems, atmospheric carbon dioxide and carbon management: a U.S. case study." *The Forestry Chronicle* 77:259-264.

U.S. Climate Change Technology Program (CCTP). 2003. *Technology options for the near and long term*. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm
Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 1999. *Carbon sequestration research and development*. DOE/SC/FE-1. Washington, DC: U.S. Department of Energy. http://fossil.energy.gov/programs/sequestration/publications/1999_rdreport/index.html

U.S. Department of Energy (DOE). 2005. *Carbon sequestration technology roadmap and program plan 2005*. Washington, DC: Office of Fossil Energy. http://fossil.energy.gov/programs/sequestration/publications/programplans/2005/sequestration_roadmap_2005.pdf

U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL). 2004. A sea floor gravity survey of the Sleipner Field to monitor CO_2 migration. *Project Facts.* http://www.netl.doe.gov/publications/factsheets/project/Proj247.pdf

White, C.M., B.R. Strazisar, E.J. Granite, J.S. Hoffman, and H.W. Pennline. 2003. "Separation and capture of CO_2 from large stationary sources and sequestration in geological formations—coalbeds and deep saline aquifers." *Journal of Air & Waste Management* 53:645-715.

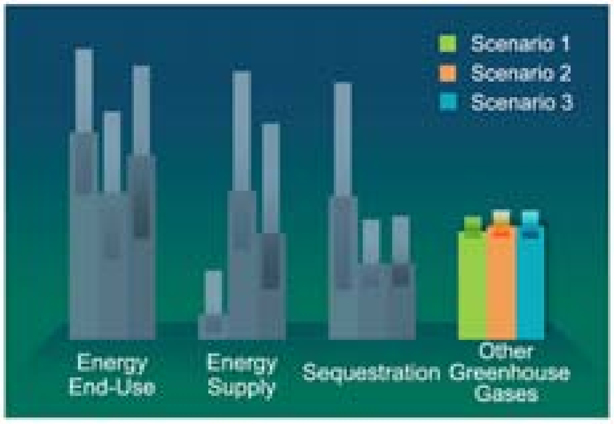
7 Reducing Emissions of Non-CO_2 Greenhouse Gases

Several gases other than carbon dioxide (CO_2) are known to have greenhouse gas (GHG) warming effects. When concentrated in the Earth's atmosphere, these non-CO_2 GHGs can contribute to climate change. The more significant of these are methane (CH_4) from natural gas production, transportation and distribution systems, biodegradation of waste in landfills, coal mining, and agricultural production; nitrous oxide (N_2O) from industrial and agricultural activities; and certain fluorine-containing substances, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from industrial sources (see Box 7-1).

The Intergovernmental Panel on Climate Change's (IPCC's) *Third Assessment Report* (IPCC 2001) states that "well-mixed" non-CO_2 gases, including methane, nitrous oxide, chlorofluorocarbons, and other gases with high global warming potentials (GWPs) may be responsible for as much as 40 percent of the estimated increase in radiative climate forcing between the years 1750 and 2000.[1] In addition, emissions of black carbon (soot), organic carbon and other aerosols, as well as tropospheric ozone and ozone precursors, have important effects on the Earth's overall energy balance.

Developing technologies for commercial readiness that can reduce emissions of these non-CO_2 GHGs is an important component of a comprehensive strategy to address concerns about climate change. A recent modeling study (Placet et al. 2004) showed that there is a considerable amount of uncertainty about future rate of growth of non-CO_2 emissions, but most models project that emissions will increase over time in the absence

Other Greenhouse Gases
Potential Contributions to Emissions Reduction



Potential contributions of Other Greenhouse Gases to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

Box 7-1
What are the "Other" Greenhouse Gases?

The term "non-CO_2 greenhouse gases" covers a broad category of gases and aerosols, but usually refers to methane, nitrous oxide, and the high global warming potential (GWP) gases hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Tropospheric ozone, tropospheric ozone precursors, and black carbon (soot) also have important climatic effects. Of these, only ozone is a greenhouse gas. Chlorofluorocarbons (CFCs) and other related chemicals contribute to both global warming and stratospheric ozone depletion. Because these chemicals are already being phased out under the Montreal Protocol, they are not addressed in this plan. To streamline terminology for purposes of readability, and unless otherwise noted, the term "non-CO_2 greenhouse gases" includes methane, nitrous oxide, high-GWP gases, tropospheric ozone, tropospheric ozone precursors, and black and organic carbon aerosols.

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[1] The radiative forcing due to increases in the well-mixed greenhouse gases between the years 1750 and 2000 is estimated to be 2.43 Wm^{-2}: 1.46 Wm^{-2} from CO_2; 0.48 Wm^{-2} from CH_4; 0.34 Wm^{-2} from the halocarbons (CFC and HCFC); and 0.15 Wm^{-2} from N_2O.

of constraints (see Chapter 3). One set of scenarios that included a wide range of advanced technologies[2] for reducing emissions of non-CO_2 gases showed that emissions could potentially be reduced by a range of 125-160 gigatons (Gt) of carbon-equivalent emissions (cumulatively) over a 100-year horizon.

In the context of global warming, emissions of the non-CO_2 GHGs are usually converted to a common and roughly comparable measure of the "equivalent CO_2 emissions." This conversion is performed based on physical emissions, weighted by each gas' global warming potential (GWP). The GWP is the relative ability of a gas to trap heat in the atmosphere over a given timeframe, compared to the CO_2 reference gas (per unit weight). GWP values allow for a comparison of the impacts of emissions and reductions of different gases, although they typically have an uncertainty of ±35 percent (EPA 2005). The choice of time frame is significant and can change relative GWPs by orders of magnitude. All non-CO_2 gases are compared to CO_2, which has a GWP of one. The GWPs of other GHGs, using a 100-year time horizon, range from 23 for methane to 22,200 for SF_6, as shown in Box 7-2.

Box 7-2

Global Warming Potentials of Selected Greenhouse Gases (100-Year Time Horizon)

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296
Hydrofluorcarbons:	
HFC-23	12000
HFC-125	3400
HFC-134a	1300
HFC-143a	4300
HFC-152a	120
HFC-227ea	3500
HFC-236fa	9400
HFC-43-10mee	1500
Fully Fluorinated Species:	
CF_4	5700
C_2F_6	11900
C_4F_{10}	8600
C_6F_{14}	9000
SF_6	22200

(*Source*: IPCC 2001)

Non-CO_2 gases have different GWPs due to differences in atmospheric lifetimes and effectiveness in trapping heat. Methane and some HFCs have relatively short atmospheric lifetimes as compared to other non-CO_2 gases. Thus, emissions reductions among these gases manifest themselves as lower atmospheric concentrations in a matter of a few decades. PFCs and SF_6, in contrast, can remain in the atmosphere for thousands of years. Emissions of these GHGs essentially become permanent additions to the Earth's atmosphere, with concomitant increases in the atmosphere's ability to capture and retain radiant heat. Finally, tropospheric ozone and black carbon aerosols (soot) are very short-lived in the atmosphere (i.e., remaining airborne for a period of days to weeks) and therefore do not become well-mixed in the atmosphere. Primarily for this reason, GWP metrics have not been assigned to these gases and aerosols, but they are nonetheless recognized as significant contributors to climate change.

There is a strong record of successful collaboration between industry and government to reduce emissions of non-CO_2 gases, and these partnerships provide a solid foundation from which to pursue additional technological developments and more substantial future emission reductions. Some highlights of the current activities include:

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[2] The technologies discussed in this chapter were included in this set of scenarios.

- Industry and the U.S. Environmental Protection Agency (EPA) have developed nine successful public/private partnerships to reduce emissions of methane and high-GWP gases.[3] These programs have led to substantial emission reductions; with U.S. methane emissions in 2003 10 percent below 1990 levels and emissions of many sources of high-GWP gases also declining (EPA 2005). They also provide excellent forums for transferring technical information in an efficient and cost-effective manner. The partnership programs host or participate in annual technical conferences with the respective industries. Public-private partnerships help facilitate effective use of the technologies that are or will soon become available.

- The Federal government is currently addressing agricultural sources of methane and nitrous oxide through a combination of voluntary partnerships and research, development, and demonstration (RD&D) efforts. Cooperative efforts between government and the agriculture industry are needed to evaluate and develop technologies for lowering N_2O emissions from soils and methane emissions from livestock enteric fermentation.

- The U.S. Department of Energy (DOE) and EPA have teamed to co-fund the development of the first ventilation air methane (VAM) project in the United States utilizing a thermal flow reversal reactor to oxidize mine ventilation air, which contains low concentrations of methane. The process generates thermal energy that can have many uses. EPA is also working cooperatively with Natural Resources Canada (NRCan) to deploy a similar technology developed by NRCan's CANMET Energy Technology Centre (CETC).

- An international network of those involved in research on non-CO_2 GHGs has been formed by the International Energy Agency (IEA) Greenhouse Gas R&D Programme, EPA, and the European Commission Directorate General Environment. The experts involved in this network cover emissions, abatement options, and systems modeling for policy advice. The network provides an international forum for identification of needed research, as well as creating opportunities for international deployment of non-CO_2 emission reduction technologies.

- An international analytical effort has been undertaken by the Stanford Energy Modeling Forum (EMF) to better characterize the role of non-CO_2 mitigation in addressing climate change.[4] This multi-year effort has led to the development of data on the cost and performance of currently available and near-to-market technologies to reduce non-CO_2 emissions. In addition, the nineteen international modeling teams participating in the project have incorporated data on non-CO_2 gases into their economic and integrated assessment models and are improving the capabilities needed to analyze comprehensive climate strategies focusing on both CO_2 and non-CO_2 options.

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[3] The Landfill Methane Outreach Program, Natural Gas STAR Program, AgSTAR Program, Coalbed Methane Outreach Program, SF_6 Emission Reduction Partnership for Electric Power Systems, Voluntary Aluminum Industrial Partnership, SF_6 Emission Reduction Partnership for the Magnesium Industry, PFC Reduction/Climate Partnership with the Semiconductor Industry, and HCFC-22 Partnership Program.

[4] Results from this study, EMF 21, are to be published in a special issue of the *Energy Journal* in 2005. See http://www.stanford.edu/group/EMF/research/index.htm.

- Established in November 2004, the Methane to Markets Partnership (Box 7-3) is a new global initiative to advance international cooperation on the recovery and use of methane as a valuable clean energy source. The partnership will increase energy security, enhance economic growth, improve air quality, improve industrial safety, and reduce GHG emissions throughout the world. Methane to Markets has the potential to reduce net methane emissions by up to 50 million metric tons of carbon equivalent annually by 2015 and continue at that level or higher in the future.

Box 7-3

Methane to Markets

The United States is collaborating with 14 countries (Argentina, Australia, Brazil, China, Colombia, India, Italy, Japan, Mexico, Nigeria, Russia, South Korea, Ukraine, and the United Kingdom) and members of the private sector, financial institutions, and other governmental and non-governmental organizations to undertake activities to capture and use methane at landfills, coal mines, and oil and gas systems.

The United States is committing up to $53 million over the next five years to facilitate the development and implementation of methane projects in developing countries and countries with economies in transition. EPA plays a lead role in the partnership and coordinates efforts with several other departments, including the Departments of State and Energy, the U.S. Trade and Development Agency and the U.S. Agency for International Development. See http://www.methanetomarkets.org.

These partnerships and others that are discussed in this chapter demonstrate the potential for significant near-term emission reductions from currently available technologies. In addition, longer-term analyses have identified the potential for current and future technologies to lead to even more significant emission reductions. Historically, non-CO_2 gases were either not included or were treated in a cursory manner in climate change modeling and scenario studies. This situation is changing, however, and many modelers are incorporating the non-CO_2 gases into their models and are developing the capability to assess the role of the non-CO_2 gases in addressing climate change. Studies published to date indicate that substantial mitigation of future increases in radiative forcing could be achieved by reducing emissions of these other GHGs. It is possible that such reductions could contribute as much as one-half of the abatement levels needed to stay within a total radiative forcing gain that would be consistent with commonly discussed stabilization ranges of CO_2 concentrations.[5]

Achieving significant reductions in the emissions of the non-CO_2 gases is possible, taking into account the current achievements in reducing emissions as well as the results of detailed analyses of the technical and economic potential to reduce emissions from particular sources and sectors. Based on the information presented in this chapter, it is possible to achieve CH_4 emissions reductions of 40 to 60 percent by 2050, and 45 to 70 percent by 2100. Emissions of N_2O can be reduced by 25 to 30 percent by 2050, and 50 percent by 2100 (DeAngelo, 2005, Delhotal, 2005). In addition, it is possible to reduce emissions of high-GWP gases by 60 to 80 percent by 2050, and 55 to 75 percent by 2100 (Schaefer, 2005).

There are a number of potentially fruitful areas for technologies to mitigate growth in emissions of non-CO_2 GHGs, and strong promise that over time emissions could be reduced substantially. The strategy for addressing non-CO_2 GHGs has two key elements. First, it focuses on the key emission sources of these GHGs and identifies specific mitigation options and research needs by gas, sector, and source. Given the diversity of emission sources, a generalized technology approach is not practical. Second, the strategy

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[5] US Climate Change Science Program, Prospectus for Synthesis and Assessment Product 2.1. http://www.climatescience.gov/Library/sap/default.htm

emphasizes both the expedited development and deployment of near-term and close-to-market technologies and expanded R&D into longer-term opportunities leading to large-scale emission reductions. By stressing both near- and long-term options, the strategy offers maximum climate protection in the near term and a roadmap to achieve dramatic gains in later years.

The discussion of the key emission sources of other GHGs is organized around five broad categories—or "target areas"—listed in Table 7-1. Following the table, each target area is discussed in subsequent technology sections. Each of these technology sections includes a sub-section describing the current portfolio. The technology descriptions include a link to the CCTP *Technology Options for the Near and Long Term* (CCTP 2003).

Table 7-1. Target Areas for Reducing Emissions of Non-CO_2 GHGs (2000 Emissions in Tg CO_2 Equivalent)[6]

Target Area	U.S. Emissions	% of Total U.S. Non-CO_2	Global Emissions	% of Global Non-CO_2
CH_4 Emissions from Energy and Waste	371	34	2836	31
CH_4 and N_2O Emissions from Agriculture	444	41	5428	60
Emissions of High Global Warming Potential (GWP) Gases	139	13	368	4
N_2O Emissions from Combustion and Industrial Sources	98	9	390	4
Emissions of Tropospheric Ozone Precursors and Black Carbon	N/A*			
* Emissions estimates exist but they cannot be converted into CO_2 equivalent units.				

Sources: EPA 2005, 2004

7.1 Methane Emissions from Energy and Waste

In 2000, methane emissions from the energy and waste sectors accounted for 31 percent of global non-CO_2 GHG emissions (Table 7-2), and nearly 50 percent of global methane emissions. The major emission sources in these sectors include coal mining, natural gas and oil systems, landfills, and wastewater treatment. As Table 7-2 shows, among the energy and waste-related methane emission sources, oil and gas systems, and landfills are the largest emission sources, accounting for 9 and 11 percent, respectively, of global non-CO_2 emissions.

The energy and waste sectors present some of the most promising and cost-effective near-term reduction opportunities. Reducing methane emissions, the primary component of natural gas, can be cost-effective in many cases due to the market value of the recovered gas. Efforts in the United States to voluntarily encourage these economically attractive opportunities have already been successful by focusing on the deployment of available, cost-effective technologies. As Table 7-3 shows, emissions from the key sources in the United States have declined in absolute terms by about 16 percent since 1990, equal to about 65 teragrams of carbon dioxide equivalent (Tg CO_2 equivalent).

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[6] For this chapter, the GWP-weighted emissions of methane (estimated at 21) are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2 equivalent). To convert the emission estimates included in this chapter to gigatonnes of carbon (GtC) multiply the emissions estimate by .000272. For example, 200 Tg CO_2 equivalent X (.000272) = .054 GtC.

Table 7-2. U.S. and Global Methane (CH_4) Emissions from Energy and Waste (2000 Emissions in Tg CO_2 Equivalent)

Source	U.S. Emissions	% of Total U.S. Non-CO_2 GHG Emissions	Global Emissions	% of Global Non-CO_2 GHG Emissions
Landfills	130.7	12	814	9
Coal Mining	56.2	5	439	5
Natural Gas and Oil Systems	149.7	14	1013	11
Wastewater Treatment	34	3	569	6
Total	371	34	2836	31

Sources: EPA 2005, 2004.

Table 7-3. Change in U.S. Methane (CH_4) Emissions from Energy and Waste (1990 and 2000 Emissions in Tg CO_2 Equivalent)

Source	1990 Emissions	2000 Emissions	% Change
Landfills	172	130.7	- 24
Coal Mining	82	56.2	- 32
Natural Gas & Oil	148	149.7	+1
Total	402	337	- 16

Source: EPA 2005.

Despite this success, significant opportunities remain for further emission reductions through the expanded deployment of currently available technologies and the development of promising new technologies. These longer-term technologies could lead to substantial additional methane reductions in the future. The remainder of this section discusses these technical opportunities for the three major emission sources in this category: landfills, oil and gas systems, and coal mines.

7.1.1 Landfills

Methane emissions from landfills result from the decomposition of organic material (yard waste, food waste, etc.) by bacteria in an anaerobic environment. Emission levels are affected by site-specific factors such as waste composition, moisture, and landfill size. Landfills are the second largest anthropogenic methane emission source in the United States, releasing an estimated 131 Tg CO_2 equivalent to the atmosphere in 2003 (EPA 2005). Globally, landfills are also a significant emission source, accounting for an estimated 814 Tg CO_2 equivalent in 2000 or almost 10 percent of global non-CO_2 emissions (Table 7-2). The majority of emissions currently come from developed countries where sanitary landfills facilitate the anaerobic decomposition of waste. Emissions from developing countries, however, are expected to increase as solid waste will be increasingly diverted to managed landfills as a means of improving overall waste management. By 2020, three regions are projected to account for more than 10 percent of global methane emissions from landfills: Africa (16%), Latin America (13%) and Southeast Asia (12%) (EPA 2004).

7.1.1.1 Potential Role of Technology

The principal approach to reduce methane emissions from landfills involves the collection and combustion (through use for energy or flaring) of landfill gas (LFG). LFG utilization technologies can be divided into two main categories: electricity generation and direct gas use. About 75 percent of the projects in the United States involve electricity generation, using reciprocating engines or combustion turbines. Direct use technologies account for about 25 percent of total projects, but their implementation has grown in recent years. Some of these technologies use landfill gas directly as a medium-Btu fuel, while others require the gas to be upgraded and delivered to a natural gas pipeline.

7.1.1.2 Technology Strategy

Additional CH_4 emission reductions at landfills can be achieved through RD&D efforts focused on improvements in LFG collection efficiency, gas utilization technologies, and alternatives to existing solid waste management practices. In the near term, RD&D efforts focused on improving collection efficiency and demonstrating promising emerging gas use technologies can yield significant benefits. These approaches could increase emission reductions from the waste currently contained in landfills, which will emit CH_4 for 30 or more years. Longer-term reductions will result from research on advanced utilization technologies and development of solid waste management alternatives, such as bioreactor landfills.

7.1.1.3 Current Portfolio

The current Federal portfolio focuses on three areas:

- Research and development (R&D) of anaerobic and aerobic bioreactor landfills that more quickly stabilize the readily decomposable organic constituents of the waste stream through enhanced microbiological processes. The goal is to have three to five commercial full-scale anaerobic and aerobic bioreactor landfill demonstration units operational by the close of 2006 plus increased market penetration 2007-2012. An additional goal is to further evaluate environmental and public-health impacts, and design and operational issues. See Section 4.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-411.pdf

- R&D of emerging technologies that facilitate the conversion of LFG to readily usable forms, such as compressed natural gas/liquefied natural gas, and methanol/ethanol. Near-term goals to convert landfill gas to alternative uses include verifying performance of LNG conversion technology application on landfill gas and converted vehicle performance; development of additional commercially available LNG vehicles (e.g., solid waste collection trucks); and development of distribution/fueling infrastructure. Mid-term goals target research on cost-effective separation technology applications for pipeline quality gas production and to evaluate and demonstrate technologies for producing commercial carbon dioxide. See Section 4.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-412.pdf

7.1.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

Future applied research efforts, for example, could focus additional efforts on improving landfill gas collection efficiencies, and developing additional economical gas utilization technologies and long-term alternatives to current solid waste disposal practices. Development and deployment of near-term technologies to recover landfill gas from current waste disposal sites could reduce emissions by 50 percent (Delhotal, 2005). Over the long term, however, emissions could theoretically be eliminated through the commercialization and deployment of advanced waste processing and treatment systems. These systems would include technologies that remove all organic waste (paper, yard debris, food, etc.) from the solid waste stream, facilitate the aerobic decomposition of organics through mechanical biological treatment, and enable the rapid and controlled anaerobic decomposition of organics along with enhanced methane gas recovery.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.1.2 Coal Mines

Coal mines are a significant methane emission source in the United States and worldwide, accounting for about 10 percent of total anthropogenic methane emissions (EPA 2004). Methane trapped in coal deposits and in the surrounding strata is released during normal mining operations in both underground and surface mines. In addition, handling of the coal after mining (e.g., through storage, processing, and transportation) results in methane emissions. Underground mines are the largest source of coal mine methane (CMM) emissions.

Emissions of CMM in the United States in 2000 were 56 Tg CO_2 equivalent and are projected to increase to 70 Tg CO_2 equivalent by 2010 (EPA 2005). Worldwide emissions of methane from the coal industry are estimated to be 432 Tg CO_2 equivalent and are expected to rise to 495 Tg CO_2 equivalent by the year 2010 as coal production increases (EPA 2004). Globally, the major coal producing countries and regions of China; India; the United States; the Confederation of Independent States; Australia; Central, Eastern, and Western Europe; the United Kingdom; and Southern Africa account for almost all CMM emissions.

Underground mines present the greatest opportunities for reducing emissions; however, emission reductions are also possible at surface mines. Emissions from both underground and surface mines vary depending on the technology used to mine the coal, the rate of coal production, the technologies employed to remove the methane from the mines, and the local geological conditions.

7.1.2.1 Potential Role of Technology

Upstream and downstream technologies are integral to reducing methane emissions from coal mines. The most important upstream technological contributions are in the recovery of methane from mine degasification operations and in the oxidation of low-concentration methane in mine ventilation air. Degasification systems are used to remove methane from the coal seams to provide for a safe working environment. These systems generally consist of boreholes drilled into the coal seams and adjacent strata, with in-mine and surface gathering systems used to extract and collect methane. CMM can be recovered in advance of mining or after mining has occurred and may consist of surface wells, in-mine boreholes, or some combination of the two.

From a technical viewpoint, the most appropriate drainage technology is dependent on the surface topography, subsurface geology, reservoir characteristics, mine layout, and mine operations. Degasification technologies are used around the world and are commonplace in most the aforementioned countries. Surface gob wells are used to extract methane after mining has occurred and in-mine horizontal boreholes are standard at many gassy mines. However, advanced degasification employing long-hole in-mine directional drilling has only been successful in a limited number of countries, including the United States, Australia, China, Japan, United Kingdom, Germany, and Mexico, and is currently being tested in Ukraine. Only the United States and Australia have had success with pre-mine drainage using surface wells. Although gas drainage is practiced primarily at underground mines, drainage is also occurring at surface mines in some countries, including the United States, Australia, and Kazakhstan. Horizontal boreholes can be drilled into the coal seam ahead of mining and the methane extracted.

In a number of countries, commercially applied technologies have led to large reductions in CMM emissions through use of the captured methane. These technologies have included the use of CMM as fuel for power generation (primarily internal combustion engines), injection into the natural gas pipeline system and local gas distribution networks, boiler fuel for use at the mine, local heating needs, thermal drying of coal, vehicle fuel, and as a manufacturing feedstock (e.g., methanol, carbon black, and dimethyl ether production). Technology advances in gas processing over the past decade have also resulted in projects to upgrade the quality of CMM and liquefy the gas, which in turn provide more end-use options and improve access to markets.

Although considerable effort is still directed at improving methane drainage recovery efficiencies and broadening the application of end-use technologies, attention is also focused on the capture and use of coal mine ventilation air methane (VAM). Mine ventilation air generally contains less than 1 percent methane in accordance with regulatory standards. The low concentration greatly limits possible uses of the methane. However, VAM is the largest source of underground methane emissions, and presents a significant opportunity to further mitigate GHG emissions from coal mines if capture and use technologies can be successfully applied. Worldwide VAM emissions in 2000 were 238 Tg CO_2 equivalent and are expected to increase to 282 Tg CO_2 equivalent by 2010 and 308 Tg CO_2 equivalent by 2020. Emissions of VAM in the United States in 2000 were about 37 Tg CO_2 equivalent and are anticipated to rise slightly to 40 Tg CO_2 equivalent by 2010 and remain steady thereafter (EPA 2003a).

7.1.2.2 Technology Strategy

RD&D efforts aimed at emerging methane reduction technologies for coal mines could target VAM and advanced coalbed methane drilling techniques. The development of technologies to use VAM will enable overall emission reductions at underground mines to reach 90 percent, as compared to the current technical recovery limit of 30 to 50 percent (EPA 1999). The most promising approach for recovering VAM emissions is through commercialization of technologies that convert the low-concentration (typically under 1 percent) methane directly into heat using thermal or catalytic flow reversal reaction processes. The heat can then be employed for power production or other heating. Demonstration projects in Australia, Canada, and the UK have shown that these technologies can be technically viable. The world's first commercial unit is expected to be operative in Australia in the fourth quarter of 2005, generating enough thermal energy to supply a 6-MW steam turbine. Future efforts will need to focus on continued testing and commercial deployment of VAM combined with market development support to ensure that it is seen by industry as an energy resource, rather than being vented to the atmosphere.

The other potentially important approach to reduce emissions is the development of advanced drilling technologies. Over the 1990s, advances in steerable motors and stimulation techniques have increased the ability to recover a higher percentage of the total methane in coal seams. This methane, much of which is high quality, may then find a viable market. The most promising technologies include in-mine and surface directional drilling systems, which may enable fewer wells to produce more gas, and advanced stimulation techniques, such as nitrogen injection, that increase the recovery efficiency of surface wells. There is also considerable interest in CO_2 injection; however, this is currently not an option for mine degasification. Injecting the CO_2 into the coal seam renders the coal seams unmineable due to the hazard of releasing too much CO_2 into the mine workings. While it is difficult to characterize the potential for enhanced gas drainage, these technologies have been shown to obtain drainage efficiencies of 70 to 90 percent (EPA 1999). Future RD&D activities will need to focus on the continued testing and commercial deployment of directional drilling and use of other gases in coalbed methane recovery. In addition, market development support will be needed to ensure that increased drained emissions are put to productive use, rather than vented to the atmosphere.

7.1.2.3 Current Portfolio

The current Federal portfolio focuses on two areas:

- Research on advances in coal mine ventilation air systems is focused on use of VAM in flow reversal reactors, lean fuel turbines, as combustion air in small scale reciprocating engines or large-scale mine-mouth power plants, as co-combustion medium with waste coal, and use of concentrators to increase methane concentration. The goal of coal mine ventilation air systems RDD&D program is market penetration by 2005-2010, ultimately leading by the end of the program to the majority of ventilation air methane emissions mitigated. See Section 4.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-414.pdf

- Research on advances in coal mine methane recovery systems is focused on improving mine drainage system technology through improved directional drilling technologies, in-mine hydraulic fracturing techniques, development of nitrogen and inert gas injection techniques and improved drilling technologies. See Section 4.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-415.pdf

7.1.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- RD&D efforts focused on achieving full commercialization and deployment of VAM and advanced coalbed methane drilling techniques. These technologies alone could reduce emissions from underground mining operations by 90 percent (EPA 2003a).

- RD&D efforts focused on developing new, fully automated mining systems that eliminate methane emissions. Since underground mining represents about 83 percent of U.S. coal mine methane emissions, this would represent the potential for a 75 percent reduction in overall U.S. methane emissions from this source.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.1.3 Natural Gas and Petroleum Systems

Methane emissions from the oil and gas industry accounted for approximately 11 percent of global non-CO_2 emissions in 2000 (EPA 2004). Russia and the United States accounted for over 30 percent of global methane emissions from oil and gas systems. Emissions occur throughout the production, processing, transmission, and distribution systems and are generally process related. Normal operations, routine maintenance, and system upsets are the primary contributors. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment. Over 90 percent of methane emissions from oil and gas systems, however, are associated with natural gas rather than oil-related operations (EPA 2005, 2004).

As demand for oil and gas increases, global methane emissions are projected to increase by more than 72 percent between 1990 and 2020 (EPA 2004). In many developed countries, however, there is increasing concern about the contribution of oil and gas facilities to deteriorating local air quality, particularly emissions of non-methane volatile organic compounds (NMVOC). Measures designed to mitigate NMVOC emissions, such as efforts to reduce leaks and venting, have the ancillary benefit of reducing methane emissions. In addition, as economies in many Eastern European countries undergo restructuring, efforts are underway to modernize gas and oil facilities. For example, Germany expects to reduce emissions from the former East German system through upgrades and maintenance. Russia also plans to focus on opportunities to reduce emissions from its oil and gas system as part of modernization.

7.1.3.1 Potential Role of Technology

Reducing methane emissions from the petroleum and natural gas industries necessitates both procedural and technology improvements. Methane emission reduction strategies generally fall into one of three categories: (1) technologies or equipment upgrades that reduce or eliminate equipment venting or fugitive emissions, (2) improvements in management practices and operational procedures, or (3) enhanced management practices that take advantage of improved technology. Each of these technologies and management practices requires a change from business as usual in terms of how the daily operations are scheduled and conducted. To date, over 90 emission reduction opportunities have been identified by corporate partners in EPA's Natural Gas STAR Program. In many cases, these actions are cost-effective and have wide applicability across industry sectors.

7.1.3.2 Technology Strategy

Despite the current availability of cost-effective methane emission reduction opportunities in the natural gas and petroleum industry, research, development, demonstration, and deployment (RDD&D) efforts could have an important impact on future methane emissions. Both in the near and long terms, RDD&D efforts could focus on increasing market penetration of current emission reduction technologies, improving leak detection and measurement technologies, and developing advanced end-use technologies.

- *Current Emission Reduction Technologies* – Perhaps the greatest environmental benefits would be associated with an enhanced demonstration and deployment effort focused on currently available emission reduction technologies. In 2000, deployment of these technologies in the United States reduced emissions by 15 Tg CO_2 equivalent, approximately 12 percent of total industry emissions (EPA 2005). An enhanced effort would encourage additional technology penetration and emissions reductions.

- *Leak Detection and Measurement* – Additional benefits could be realized through improvements in and deployment of leak detection and measurement technologies. While potential industry-wide emission reductions are difficult to quantify, improved identification and quantification of methane losses and leaks would promote mitigation activities. These new technologies will allow for quick, relatively inexpensive detection of leaks that are cost-effective to repair. Some of the emerging leak detection and measurement technologies include the High-Flow^{TM} Sampler and hand-held optimal imaging cameras that can visualize methane leaks (i.e., Image Multi-Spectral Sensor [IMSS] camera).

- *Advancing End-Use Technologies* – Research aimed at advancing fuel cell and microturbine technologies could reduce emissions at remote well sites by enabling remote power generation at these locations. For example, power generated from the lower-quality gas can be used to support instrument air systems and eliminate the need for gas-driven pneumatic devices and pumps.

7.1.3.3 Current Portfolio

The current Federal R&D portfolio primarily focuses on leak detection measurement and monitoring technologies for natural gas systems. Advanced leak detection and measurement technologies enable quick and cost-effective detection and quantification of fugitive methane leaks. Natural gas systems RDD&D goals related to measurement and monitoring technologies are focused on completing of the development and deployment of advanced measurement technologies like the Hi-Flow^{TM} and on advancing the development of imaging technology for methane leak measurement and facilitate demonstration and deployment. See Section 4.1.6 (CCTP 2005):
http://www.climatetechnology.gov/library/2005/tech-options/tor2005-416.pdf

7.1.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- RDD&D to further facilitate emission reduction with more accurate and cost-effective leak detection and measurement equipment, which could be effective in reducing fugitive and vented emissions from gas production, processing, transmission, and distribution operations.

- Long-term R&D efforts to identify additional opportunities. In particular, these efforts could target the leading emission sources, such as reciprocating compressors and wellhead venting.

- Long-term R&D efforts to explore revolutionary equipment designs. This might focus on "smart equipment," such as smart pipes or seals, that could alert operators to leaks or self-repairing pipelines made of material that can regenerate and automatically seal leaks. Development of additional technologies could enable emission reductions of 50 percent by mid-century.

Future RDD&D efforts could have an important impact on methane emissions, both in the near and long terms. Enhanced leak-detection and measurement efforts can yield significant methane emission reductions. Demonstration of improved technologies has indicated that emissions at compressor stations and gas-processing plants can be reduced cost effectively by as much as 80 to 90 percent. More importantly, an enhanced demonstration and deployment effort focused on currently available emission reduction technologies would encourage additional technology penetration. In the United States alone, this effort could reduce emissions by an estimated 37 Tg CO_2 equivalent in 2010.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.2 Methane and Nitrous Oxide Emissions from Agriculture

Over 40 percent of total U.S. non-CO_2 GHGs come from methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture (EPA 2005). Globally, agricultural sources of methane and nitrous oxide contribute an estimated 5,428 Tg CO_2 equivalent, nearly 60 percent of global non-CO_2 emissions (EPA 2004). These emissions result from natural biological processes inherent to crop and livestock production and cannot be realistically eliminated, although they can be reduced. For example, emissions of N-oxides can likely be decreased by 15 to 35 percent through programs that improve crop nitrogen use efficiency, through plant fertilizer technology, precision agriculture, and plant genetics. Table 7-4 shows N_2O and methane emissions from agricultural sources (Tg CO_2 equivalent).

Key research efforts have focused on the largest agriculture GHG emission sources:

- Nitrous oxide emissions from agricultural soil management.

- Methane and nitrous oxide emissions from manure management.

- Methane emissions from livestock enteric fermentation.

Table 7-4. U.S. and Global CH_4 and N_2O Emissions from Agriculture (2000 Emissions in Tg CO_2 Equivalent)

Source	U.S. Emissions	% of Total U.S. Non-CO_2 GHG Emissions	Global Emissions	% of Global Non-CO_2 GHG Emissions
N_2O Emissions from Agriculture	282	26	2875	32
Enteric Methane Emissions	116	11	1712	19
Methane Emissions from Manure	38	3	199	2
Methane Emissions from Rice Production	8	<1	643	7
Total	443	40	5429	60

Sources: EPA 2005, 2004.

7.2.1 Advanced Agricultural Systems for Nitrous Oxide Emissions Reductions

Low efficiency of nitrogen use in agriculture is primarily caused by large nitrogen losses due to leaching and gaseous emissions (ammonia, nitrous oxide, nitric oxide, and nitrogen). In general, N_2O emissions from mineral and organic nitrogen can be decreased by nutrient and water management practices that optimize a crop's natural ability to compete with processes that result in plant available nitrogen being lost from the soil-plant system.

7.2.1.1 Potential Role of Technology

Key technologies in the area of nutrient management can be applicable to N_2O mitigation. They focus on the following areas:

- *Precision agriculture* – targeted application of fertilizers, water and pesticides.
- *Cropping system models* – tools to assist farmer management decisions.
- *Control release fertilizers and pesticides* – delivery of nutrients and chemicals to match crop demand and timing of pest infestation.
- *Soil microbial processes* – use of biological and chemical methods, such as liming, to manipulate microbial processes to increase efficiency of nutrient uptake, suppress N_2O emissions, and reduce leaching.
- *Agricultural best management practices* – limiting N-gas emissions, soil erosion, and leaching.
- *Soil conservation practices* – utilizing buffers and conservation reserves.
- *Livestock manure utilization* – development of mechanisms to more effectively use livestock manure in crop production.
- *Plant breeding* – to increase nutrient use efficiency and decrease demand for pesticides.

7.2.1.2 Technology Strategy

Technologies and practices that increase the overall nitrogen efficiency while maintaining crop yields represent viable options to decrease N_2O emissions. Focused RDD&D efforts are needed in a number of areas to develop new technologies and expanded deployment of commercially available technologies and management practices:

- Further development of precision agriculture technologies to meet the fertilizer and energy reduction goals could lead to increased adoption of these technologies and improved performance.
- "Smart materials" for prescription release of nutrients and chemicals for major crops currently require modest breakthroughs in materials technology to reach fruition.
- Soil microbial processes could also be manipulated to increase N-use efficiency; however, further development is needed to insure full efficacy and avoid the introduction of environmental risks.
- First-generation integrated system models, technology, and supporting education and extension infrastructure need to be implemented, and research on using these techniques to improve management expanded.
- Genetically designed major crop plants could utilize fertilizer more efficiently.
- Increased extension efforts are needed to fully utilize best management practices.
- Basic research on process controls and field monitoring programs are needed to ensure that theoretical understanding exists as technology evolves and that changes in management practices to mitigate GHG emissions actually function as theorized.
- Accurate measurement technologies and protocols are needed for assessment and verification.

7.2.1.3 Current Portfolio

Although many mitigation options for N_2O emissions can be readily identified, their implementation has not been carried out on a large scale. Other than programs to limit nitrogen losses, programs that directly address the issue of N_2O emissions from agricultural soil management are very limited. The current Federal portfolio focuses on N_2O emissions from agricultural soil management; precision agriculture; understanding and manipulation of soil microbial processes; expert system management; and the development of inexpensive, robust measurement and monitoring technologies. Research for reductions in N_2O emissions focus on improved production efficiencies and reduced energy consumption by developing and deploying precision agriculture technologies, sensors/monitors and information-management systems, and smart materials for prescription release utilized in major crops. An additional goal is to improve fertilizer efficiency and reduce nitrogen inputs by developing advanced fertilizers and technologies, methods of manipulating soil microbial processes, and genetically designed major crop plants. See Section 4.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-421.pdf

7.2.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Precision agriculture in general requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time characterization of crop water need; real-time crop yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and massive data/information management systems.

- Improved understanding of specific soil microbial processes is required to support development of methods for manipulation of these processes and to identify how manipulation impacts GHG emissions.

- To continue to improve systems management, models that represent an accurate understanding of plant physiology must be coupled with soil process models, including decomposition, nutrient cycling, gaseous diffusion, water flow, and storage on a mass balance basis, to understand how ecosystems respond to environmental and management change.

Other options could include improved utilization of the nitrogen in manure on croplands/pasturelands to offset use of synthetic nitrogen and decrease the quantity of nitrogen excreted from livestock by better matching the intake of nitrogen (e.g., protein) with the actual dietary requirements of the animals. A large portion of the N_2O emissions from soils comes from livestock waste directly deposited on pastures, and this has significant mitigation potential both in the United States and globally.

Wide-scale implementation of these technologies and improved management systems in the United States could lead to reductions in nitrous oxide emissions from agriculture of 15 to 35 percent. In some developing countries, where greater inefficiencies are identified and where potential use of nitrogen is likely to increase greatly in the future as the demand for more crop and pasture production increases, the potential is even greater.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.2.2 Methane and Nitrous Oxide Emissions from Livestock and Poultry Manure Management

Globally, nitrous oxide and methane emissions from livestock and poultry manure management totaled approximately 400 Tg CO_2 equivalent in 2000 (EPA 2004). Livestock and poultry manure has the potential to produce significant quantities of CH_4 and N_2O, depending on the waste management practices. When manure is stored or treated in systems that promote anaerobic conditions, such as lagoons and tanks, the decomposition of the biodegradable fraction of the waste tends to produce CH_4. When manure is handled as a solid, such as in stacks or deposits on pastures, the biodegradable fraction tends to decompose aerobically, greatly reducing CH_4 emissions; however, this practice increases emissions of N_2O, which have a greater global warming potential. Practices are needed that minimize both GHGs simultaneously.

7.2.2.1 Potential Role of Technology

Methane reduction and other environmental benefits can be achieved by utilizing a variety of technologies and processes. Aeration processes, such as aerobic digestion, auto-heated aerobic digestion, and composting, remove and stabilize some pollutant constituents from the waste stream. These technologies facilitate the aerobic decomposition of waste and prevent methane emissions. Anaerobic digestion systems, in contrast, encourage methane generation, and the collection and transfer of manure-generated off-gases to energy-producing combustion devices (such as engine generators, boilers, or odor control flares). Solids separation processes remove some pollutant constituents from the waste stream through gravity, mechanical, or chemical methods. These processes create a second waste stream that must be managed using techniques different from those already in use to manage liquids or slurries. Separation processes offer the opportunity to stabilize solids aerobically, i.e., to control odor and vermin propagation.

7.2.2.2 Technology Strategy

Methane collection from anaerobic digestion systems plays an important role in reducing emissions from livestock manure management. In addition, these systems can provide additional odor-control and energy benefits by collecting and producing electricity from the combustion of methane-using devices, such as engine generators and boilers. Although the use of commercial farm-scale anaerobic digesters has increased over the past five years due to private sector activities, significant opportunity remains. Currently there are only 12 companies that provide proven commercial-scale anaerobic digestion systems and gas utilization options for farm applications in the United States. As of 2003, an estimated 40 anaerobic digester systems, which produce about 1 million kWh/year, were in use at commercial swine and dairy farms in the United States (EPA 2003b).

Expanded technology research and extension efforts could include commercial-scale demonstration projects and evaluation of emerging technologies to determine their effectiveness in reducing emissions, overall environmental benefits, and cost-effectiveness. For example, a number of emerging anaerobic digester systems adopted from the sewage industry are currently under evaluation for farm-scale applications. In addition, it is important to encourage research on odor and nitrogen emission control and ensure that it is coordinated with research on CH_4 production and emission technology development.

7.2.2.3 Current Portfolio

Methane reduction and other environmental benefits can be achieved by utilizing a variety of technologies and processes including aeration processes to remove and stabilize some pollutant constituents from the waste stream; anaerobic digestion systems that collect and transfer manure-generated off-gases to energy producing combustion devises (such as engine generators, boilers or odor control flares); and solids separation processes to remove some pollutant constituents from the waste stream. The goals of this R&D activity are to reduce costs and improve biological efficiencies of methane and N_2O emissions by developing new types of digesters; developing separation processes for solid and liquid fractions; and on developing, applying, and evaluating process performance of aeration systems for manure waste streams. The current Federal portfolio focuses these technologies. See Section 4.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-422.pdf

7.2.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Reduction of carbon in the lagoons by solids separation.
- Shifts from anaerobic lagoons to solid waste management systems.
- Aeration of lagoon waste systems.
- Development of centralized anaerobic digestion systems for multiple farm operations.
- Improved separation processes that remove solids from liquids for improved waste management and stabilization.
- Development of new types of digestors with reduced costs and improved biological efficiencies.
- Development of aeration processes and pollution control methods for manure waste streams.

Expanded extension efforts to the livestock, agricultural, energy, and regulatory communities in a number of key livestock producing states (for example, by expanding the activities currently conducted through the AgSTAR Program[7]), could lead to additional emissions reductions in the United States. In addition, research that utilizes new technological developments in analytical instrumentation and molecular biology related to a commercial farm's operational ability would be useful. If such activities were undertaken globally, the emission reductions could be substantial.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.2.3 Methane Emissions from Livestock Enteric Fermentation

Methane emissions from enteric fermentation are the second largest global agricultural GHG source, contributing an estimated 1712 Tg CO_2 of emissions in 2000 (EPA 2004). Methane emissions occur through microbial fermentation in the digestive system of livestock. The amount of CH_4 emitted depends primarily on the animal's digestive system, and the amount and type of feed. Ruminant livestock such as dairy cattle, beef cattle, and buffalo emit the most CH_4 per animal, while non-ruminant livestock such as

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[7] For additional information on the AgSTAR Program, see http://www.epa.gov/agstar/.

swine, horses, and mules emit less. Because CH_4 emissions represent an economic loss to the farmer—where feed is converted to CH_4 rather than to product output—viable mitigation options can entail efficiency improvements to reduce CH_4 emissions per unit of beef or milk.

7.2.3.1 Potential Role of Technology

Reductions in this energy loss can be achieved through increased nutritional efficiency. The goal of much livestock nutrition research has been to enhance production efficiency in order to indirectly reduce CH_4 per unit of product through breed improvements, increased feeding efficiency through diet management, and strategic feed selection. Without reductions in national herds, however, this approach will not result in net decreases of enteric methane, as methane per animal may actually increase. Historic and near-term projected trends show both a decreasing herd size and reduced CH_4 emissions on a per unit product basis.

7.2.3.2 Technology Strategy

Technologies that would likely reduce CH_4 emissions in addition to enhancing production efficiency include precision nutrition; and improvements in grazing management, feed efficiency, and livestock production efficiency. Research includes but is not limited to investigating between-animal differences to determine if traits for reduced methane production can be inherited, and dietary manipulation of grains, oils, and fats that reduce methane production. Key technologies include the following:

- Precision nutrition can minimize excess nutrients, particularly nitrogen, while meeting the nutritional needs of the ruminal microflora and those of the animal for growth, milk production, and digestion.

- Improved grazing management can increase forage yield and digestibility.

- Using ionophores to improve feed efficiency can inhibit the formation of CH_4 by rumen bacteria.

- Improving livestock production efficiency with natural or synthetic hormone feed additives or implants to increase milk production and growth efficiency and reduce feed requirements.

7.2.3.3 Current Portfolio

The current Federal research portfolio focuses on improved feed and forage management and treatment practices to increase the digestibility and reduce residence digestion time in the rumen, best-management practices for increased animal reproduction efficiency, and use of growth promotants and other agents to improve animal efficiency. Enteric emissions reduction goals focus on improved forage and feedstuffs production efficiencies and increase digestibility and include genetically design forages, manipulating ruminal microbial processes to sequester hydrogen making it unavailable to methanogens, and genetically design bacteria that can compete with natural microbes. See Section 4.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-423.pdf

7.2.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Genetic engineering of plants to enhance digestibility of feeds, reduce fertilizer requirements, and provide appropriate nutrients to enhance beneficial microbial competitiveness.
- Development of livestock with increased productivity and dietary energy use efficiency that can be productive in various environments and use reduced feed resources.
- Improved understanding of specific rumen microbial processes to support development of methods for making desirable engineered microbes competitive with natural rumen microbes.
- Development of models that represent accurate understanding of animal nutrient needs.
- Development of vaccinations that can reduce methane production in the rumen.

It is estimated that an increase in production efficiency of approximately 25 percent could be realized if maximum implementation were to occur. A large potential exists as well in developing countries, where the livestock population is expected to increase significantly over the next few decades and where production efficiency is currently low (i.e., high methane per unit product).

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.2.4 Methane Emissions from Rice Fields

Another significant source of global anthropogenic methane is rice production. Rice is the dietary staple of a large proportion of the world's population. It is generally grown in flooded paddy fields, where methane is generated by the anaerobic decomposition of organic matter in the soil. Traditional wet cultivation emits an estimated 642 Tg CO_2 equivalent of methane (EPA 2004). Emissions from this source have leveled off in the past two decades.

Although water management, fertilizer selection, cultivar selection, and nutrient management are potential options for limiting CH_4 emissions from rice fields, further R&D is needed to determine their cost-effectiveness and feasibility. Currently, there is no research ongoing in this area.

A number of opportunities for future research exist in this area, some of which include plant genetics, water management, and nutrient management. In general, the greatest challenges for mitigating CH_4 emissions from rice fields arise from uncertainties in effecting changes in cultivation management, which affects rice yields; and developing feasible management practices that reduce CH_4 emissions without increasing nitrogen losses and reducing yields. In addition, reduction of methane emissions could be difficult to implement because, in many cases, the necessary actions could involve significant changes in agricultural practices (e.g., shifting to different water management regimes). In principle, application of known techniques could reduce methane emissions by 30 to 40 percent by the year 2020. Achieving these large emission reductions would, however, require finding suitable incentives and delivery mechanisms to induce changes in current practices.

The public is invited to comment on future research directions that could potentially have a significant impact in this area. No assurance can be provided that any suggested concept would meet the criteria for a priority investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options over the long-term

7.3 Emissions of High Global-Warming Potential Gases

In 2000, high-GWP gases represented 13 percent of total U.S. non-CO_2 GHG emissions and 4 percent of global non-CO_2 emissions (Table 7-5). There are two different types of emission sources in this category, and each has different R&D priorities. As discussed below, emissions of high-GWP gases used as substitutes for ozone-depleting substances (ODSs) that are being phased out under the Montreal Protocol are currently increasing. High-GWP gases are also used or emitted by several other industries, and in many cases these emissions can be readily managed or eliminated. Table 7-5 shows emissions of substitutes for ODSs and high-GWP gases (Tg CO_2 equivalent).

Table 7-5. U.S. and Global Emissions of High-GWP Gases (2000 Emissions in Tg CO_2 Equivalent)

Source	U.S. Emissions	% of Total U.S. Non-CO_2 GHG Emissions	Global Emissions	% of Global Non-CO_2 GHG Emissions
Substitutes for Ozone-Depleting Substances	75	7	126	1
Industrial Use of High-GWP Gases	64	6	242	3
Total	139	13	368	4

Sources: EPA 2005, EPA 2004

7.3.1 Substitutes for Ozone Depleting Substances

Emissions of high-GWP gases used as substitutes for ODSs are a growing emission source in the United States and globally. These high-GWP gases are being used as replacements for chemicals (like CFCs) that deplete the stratospheric ozone layer (see Box 7-2). ODSs, which are also GHGs, are being phased out under the Montreal Protocol and, thus, are not counted in national inventories. To address ozone depletion, the refrigeration, air conditioning, fire suppression, foam blowing, solvent cleaning, and other industries are in the midst of the ODS phaseout.

7.3.1.1 Potential Role of Technology

For many industries, the ODS phaseout is accomplished by switching to alternative chemicals. For most industries, the most popular and highest performing alternatives are chemicals like HFCs, which do not deplete the ozone layer but are potent GHGs. At the same time, the phaseout is providing industries with an opportunity to improve processes and practices related to chemical use, management, and disposal in ways that reduce the emissions of HFCs and PFCs, where those chemicals are used as alternatives. As the ODS phaseout continues, opportunities exist to find better life-cycle climate performance (LCCP) alternatives and/or continue reducing emissions.

7.3.1.2 Technology Strategy

To reduce emissions of GHGs used as ODS substitutes, focus might be given to the following: (1) finding alternative gases with lower or no GWP to perform, safely and efficiently, the same function currently served by the HFCs and PFCs; (2) exploring technologies that can reduce the use of these chemicals and/or the rate at which they are emitted; and (3) supporting responsible handling practices and principles that reduce unintended and unnecessary emissions.

7.3.1.3 Current Portfolio

The Federal R&D portfolio is focused on the two largest sources of hydrofluorocarbon emissions. These emissions arise from the supermarket refrigeration and motor vehicle air conditioning sectors.

Motor Vehicle Air Conditioning: Hydrofluorocarbon Emissions – The motor vehicle industry phased out the use of CFC-12 (with a GWP of about 10,000) in new car air conditioners between 1992 and 1994, and since then has used exclusively HFC-134a (with a GWP of 1300). R&D is underway to commercialize even lower-GWP refrigerants, mainly CO_2 (GWP=1) and HFC-152a (GWP=120). Due to the high-pressure and toxic effects of CO_2, and the flammability of HFC-152a, additional safety engineering and risk mitigation technologies are being developed. Furthermore, research and testing are needed to maintain or improve the energy efficiency (and hence gas usage and CO_2 emissions) of the new air conditioners. In the United States, direct refrigerant GWP emissions can be reduced by more than 95 percent and indirect fuel use emissions reduced by 30 percent or more, for a total reduction of total vehicle fuel emissions (in vehicles with air conditioning) by up to 2 percent.

- *Supermarket Refrigeration: Hydrofluorocarbon Emissions* – Supermarkets are phasing out the use of ozone-depleting refrigerants and substituting HFCs, which are potent GHGs. Technologies under development include distributed refrigeration, which reduces the need for excessive refrigerant piping (and hence emissions), and secondary-loop refrigeration, which segregates refrigerant-containing equipment to a separate, centralized location while using a benign fluid to transfer heat from the food display cases. The RDD&D goals for reducing HFC emissions from supermarket refrigeration include improving costs and energy-use performance of these new technologies and educating store designers and builders regarding new technologies and how these technologies can be integrated into new or retrofitted stores at a net savings. See Section 4.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-436.pdf

7.3.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Continuation of the responsible-use practices developed to control emissions of ODSs has had and will continue to have a substantial effect on HFC and PFC emissions. Research indicates that approximately 80 percent of the previous use of ODSs has been replaced through conservation methods and use of non-fluorocarbon technologies. Continued emphasis on this success is needed, for example, by using equipment and technologies to reduce emissions during service and maintenance.

- Long-term research could focus on technologies that hold the most potential for reducing or eliminating total GHG emissions, including associated energy production emissions, and are practical for their applications. Key areas for consideration over the long term are the investigation of new technologies and processes to replace current uses of ODSs and avoid or reduce emissions of high-GWP gases.

A focused RD&D program to develop and deploy safe, high-performing, cost-effective climate protection technologies could result in U.S. emission reductions of 50 percent or more by 2020. However, due to the long lifetimes of many of the products that use these gases, efforts need to be taken in the near term to realize the stock turnover necessary to achieve these reductions in a cost-effective manner.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.3.2 Industrial Use of High-GWP Gases

High-GWP synthetic gases are generally used in applications where they are critical to highly complex manufacturing processes and provide safety and system reliability, such as in semiconductor manufacturing, electric power transmission and distribution, and magnesium production and casting. High-GWP gases are also emitted as byproducts from the manufacture of refrigerants (HCFC-22) and from the production of primary aluminum.

7.3.2.1 Potential Role of Technology

Incremental improvements to current technology have been made through the initiation of voluntary public-private industry partnerships. EPA’s partnerships with industries, including the U.S. primary aluminum producers, HCFC-22 manufacturing, electric utility industry, magnesium producers, and semiconductor industry, are identifying new technologies and process improvements that not only reduce emissions of high-GWP gases but also improve production efficiency, thereby saving money. With continued support, production technologies are expected to further improve, allowing these industrial sectors to cost effectively reduce and possibly eliminate emissions of high-GWP gases.

7.3.2.2 Technology Strategy

High-GWP gas-emitting industries are implementing an RDD&D strategy focused on pollution prevention. The industries have established long-term goals of reducing and in some cases eliminating high-GWP emissions and are pursuing these goals by investigating and implementing source reduction, alternative process chemicals, high-GWP gas capture and reuse, and abatement.

While the U.S. sources of high-GWP emissions are well defined, they are also very diverse, and thus a customized approach for each industry is required. New and enhanced R&D will accelerate and expand options to stabilize and reduce emissions. Opportunities exist for both near- and long-term RD&D on technologies including alternative chemicals for plasma etching for semiconductors and magnesium melt protection, as well as continued demonstration of advanced plasma abatement devices for the semiconductor industry.

7.3.2.3 Current Portfolio

The current Federal portfolio for reducing industrial emissions of high-GWP gases focuses on five areas:

- *Research on the Semiconductor Industry: Abatement Technologies* – Abatement of high-GWP gases from the exhaust gas stream in semiconductor processing facilities may be achieved by two mechanisms: (1) thermal destruction and (2) plasma destruction. The RDD&D goals for the thermal-destruction mechanism target lowering high GWP emissions from waste streams by more than 99%, while minimizing (1) NO_x emissions to levels at or below emissions standards, (2) water use and burdens on industrial wastewater-treatment systems, (3) fabrication floor space, (4) unscheduled outages and (5) maintenance costs. Plasma-destruction mechanism goals focus on the application of plasma technology to develop a cost-effective POU abatement device that lowers exhaust stream concentrations of high GWP gases by two to three orders of magnitude from etchers and plasma-enhanced chemical vapor deposition chambers; and transforms those gases into molecules that can be readily removed from air emissions using known scrubbing technologies. See Section 4.3.1 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-431.pdf

- *Research on the Semiconductor Industry: Substitutes for High-GWP Gases* – One method of reducing high-GWP gas emissions from the semiconductor industry is to use an alternative chemical or production process. Identifying and replacing high-GWP gases with more environmentally friendly substitutes for chemical vapor deposition clean and dielectric etch processes is a preferred option when viewed from the perspective of EPA's pollution prevention framework. The goal of reducing high GWP gases in the semiconductor industry is to identify the chemical and physical mechanisms that govern chemical vapor deposition chamber cleaning and etching with perfluorocarbons and non-perfluorocarbons as well as govern process performance so that emissions of high GWP gases may be significantly reduced without either adversely affecting process productivity or increasing health and safety hazards. See Section 4.3.2 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-432.pdf

- *Semiconductors and Magnesium: Recovery and Recycle* – Three recovery-and-recycle technologies are being investigated and evaluated: membrane separation, cryogenic capture, and pressure swing absorption. The goal in this area is to develop and demonstrate a cost-effective, universally applicable recovery-and-recycle technology (all fabrication facilities and all high GWP gases) that can yield "virgin"-grade high GWP gases for semiconductor fabrication or magnesium plant reuse or sufficiently pure high GWP gases for further use or purification elsewhere. See Section 4.3.3 (CCTP 2005):
  http://www.climatetechnology.gov/library/2005/tech-options/tor2005-433.pdf

- *Aluminum Industry: Perfluorocarbon Emissions* – Current efforts to reduce perfluorocarbon emissions from primary aluminum production focus on using more efficient smelting processes to reduce the frequency and duration of anode effects, which create the PFC. Another concept, now in the R&D phase, involves replacing the carbon anode with an inert anode. Doing so would completely eliminate process-related perfluorocarbon emissions. The goal to reduce perfluorocarbon emissions in the aluminum industry is to develop a commercially viable inert anode technology design by 2005, with commercialization expected by 2010-2015. If successful, the nonconsumable, inert anode technology would have clear advantages over conventional carbon anode technology, including energy efficiency increases, operating cost reductions, elimination of perfluorocarbon emissions, and productivity gains. See Section 4.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-434.pdf

- *Research for Electric Power Systems and Magnesium: Substitutes for SF_6* – The challenge is to identify substitutes to SF_6 with low or no global-warming potential that satisfy the magnesium industry's melt protection requirements and meet the electric power industry's high-voltage insulating needs. See Section 4.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-435.pdf

7.3.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Environmentally friendly alternative cover gases for magnesium melt protection.

- Improved process controls and computer based operator-training tools to further reduce PFC emissions from aluminum smelting.

- New electric power transmission equipment that does not require SF_6 insulation.

Long-term research might focus on technologies that hold the most potential for reducing or eliminating total GHG emissions, including associated energy production emissions, and are practical for their applications. Many of these research efforts may prove to be high risk due to unknown commercial viability, and thus are unlikely to be pursued by the industry without significant government funding.

Long-term R&D focused on eliminating high-GWP emissions could include research and demonstration of inert anode technology for primary aluminum smelting and high-voltage power transmission equipment that does not require SF_6 insulation. These types of innovative technologies would eliminate emissions of high-GWP gases from these sources but presently face significant barriers to commercialization.

EPA's successful public-private industry partnerships provide excellent forums for transferring technical information in an efficient and cost-effective manner. The partnership programs host or participate in annual technical conferences with the respective industries. Public-private partnerships help facilitate effective use of the technologies that are and will soon become available. Examples of successful research partnerships to reduce high-GWP gas emissions include Semiconductor Manufacturing, Electric Power Systems, Magnesium, Aluminum, HCFC-22 Production, Retail Food (Supermarket) Refrigeration, and Motor Vehicle Air Conditioning.

Several near-term opportunities exist to reduce emissions. A focused RD&D program to develop safe, high-performing, cost-effective climate protection technologies could result in emission reductions of 40 percent or more over the near term and a dramatic reduction and, in some cases, elimination of emissions by key industries within a few decades.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.4 Nitrous Oxide Emissions from Combustion and Industrial Sources

Stationary and mobile source combustion and the production of various industrial acids account for about 8 percent of non-CO_2 emissions in the United States and 4 percent globally (EPA 2005, 2004). U.S. emissions of N_2O associated with industrial acid production declined significantly after 1996 due to voluntary industry action and could remain relatively stable. Although generally not accounted for in N_2O emission inventories, significant emissions of nitrogen oxides (NO_x) from combustion sources are chemically transformed in the atmosphere and are eventually deposited as nitrogen compounds which subsequently result in emissions of N_2O in a manner similar to emissions from fertilizer application. In 2000, the U.S. N_2O emissions from combustion and industry accounted for nearly 10 percent of total non-CO_2 GHG emissions, with the combustion sources accounting for over 70 percent of these (EPA 2005). Table 7-6 shows N_2O emissions from combustion and industrial sources. R&D priorities differ between N_2O combustion and industrial sources. The priorities for reducing N_2O emissions for each of the sources are discussed below.

Table 7-6. U.S. and Global N_2O Emissions from Combustion and Industrial Sources (2000 Emissions in Tg CO_2 Equivalent)

Source	U.S. Emissions	% of Total U.S. Non-CO_2 GHG Emissions	Global Emissions	% of Global Non-CO_2 GHG Emissions
Combustion	68	6	230	2
Industrial Sources	26	2	160	2
Total	93	9	390	4

Sources: EPA 2005, 2004.

7.4.1 Combustion

Combustion of fossil fuels by mobile and stationary sources is the largest non-agricultural contributor to N_2O emissions. Nitrous oxide can be formed under certain conditions during the combustion process and during treatment of exhaust or stack gases by catalytic converters. Since N_2O emissions do not contribute significantly to ozone formation or other public health problems, N_2O has not been regulated as an air pollutant and has historically not been a focus of emission control research.

7.4.1.1 Potential Role of Technology

A better understanding is needed of how and when N_2O forms and how N_2O emissions can best be prevented and reduced. For both stationary and mobile combustion sources, N_2O emissions appear to vary greatly with different technologies and under different operating conditions, and the phenomena involved are poorly understood. For stationary sources, catalytic NO_x reduction technologies can reduce N_2O emissions. Other NO_x control technologies either have no impact or can increase N_2O.

7.4.1.2 Technology Strategy

A key to identifying the most promising approaches and technologies for reducing N_2O emissions is understanding how N_2O is formed during combustion and under what circumstances catalytic technologies contribute to N_2O emissions. The main research thrust in the near term is to improve scientific understanding of these basic questions.

7.4.1.3 Current Portfolio

The current Federal research portfolio on N_2O emissions from combustion is focused on better understanding the formation and magnitude of N_2O emissions from fuel combustion and catalytic-converter operation; evaluating the climate-forcing potential of atmospheric nitrogen deposition, especially from combustion; and developing emission models to assess the potential climate benefits from changes in emissions from nitrogen oxide. The goal in this area is to determine linkages of NO_x emissions from transportation combustion and catylitic-converter operation to climate-change impacts due to nitrogen deposition and develop enhanced modeling capabilities. See Section 4.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-442.pdf

In addition, Federal research on advanced engine/combustion technologies and alternative fuel vehicles will contribute to a reduction in N_2O emissions. Research in these areas is described in the Transportation section of Chapter 4 (Reducing Emissions from Energy End-Use and Infrastructure).

7.4.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

For example, limited but recent additional collection of N_2O test data have provided statistically reliable N_2O emissions estimates for most gasoline-powered passenger cars and light duty trucks. It will be important to develop vehicle- and engine-testing programs to generate N_2O emissions data for a variety of vehicles and engines equipped with a range of current and advanced emission-control technologies and operated over a range of real-world operating conditions, particularly for diesel engines. In addition, future research could determine the effect of catalyst formulation including noble metal loadings and compositions for alternative catalysts that result in less N_2O formation. Finally, an intensified research effort is needed to assess the role of airborne nitrogen compounds emitted from combustion sources and deposited onto the ground to soil-generated N_2O emissions.

The development of new combustion technologies and catalyst formulations that reduce or eliminate N_2O emissions will require new Federal efforts to facilitate joint public-private RD&D activities that can effectively address the reduction of N_2O emissions from combustion and industrial sources. This could include research that would form the basis for identification of new technologies in the future. Some areas for near-term study are outlined below:

- Characterizing N_2O from diesel and advanced technology engines through collaborative research between the EPA National Vehicle and Fuels Emission Laboratory (NVFEL), state air agencies and manufacturers of vehicles/engines. This research may include a variety of vehicles and engines equipped with a range of current and advanced emission control technologies and operated over a range of real-world operating conditions.

- Characterizing N_2O from heavy-duty diesel vehicles that meet future (2007/2010) emission standards. Research is now being started in this area. As these vehicles will most likely use catalytic after treatment, they may be an additional source of N_2O that previously had not existed. Research on how to minimize these emissions is also needed. Emissions of N_2O from combustion sources could be significantly reduced with improved catalyst technologies and other advances.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.4.2 Industrial Sources

Nitric acid is an inorganic compound used primarily to make synthetic commercial fertilizer. As a raw material, it also is used for the production of adipic acid and explosives, for metal etching, and in the processing of ferrous metals. Facilities making adipic acid used to be high emitters of nitrous oxide, but now that adipic acid plants in the United States have implemented N_2O abatement technologies, nitric acid production is the largest industrial source of N_2O emissions.

7.4.2.1 Potential Role of Technology

The nitric acid industry currently controls NO_x emissions using both non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. NSCR is very effective at controlling N_2O while SCR can actually increase N_2O emissions. NSCR units, however, are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. A catalyst to reduce N_2O emissions from SCR plant is being developed in the Netherlands, and a manufacturer of nitric acid is testing a catalyst for use in the ammonia burners in nitric acid plants. Both research groups claim to be capable of reducing N_2O emissions by up to 90 percent and their technology can be easily installed on existing plants. These technologies could be available for commercial application by 2010. Another manufacturer has developed an integrated destruction process; however, this process is only considered suitable for use on new plants because of the high capital costs and long operational down times needed to retrofit existing plants.

7.4.2.2 Technology Strategy

Additional research is needed to develop new catalysts that reduce N_2O with greater efficiency, and to improve NSCR technology to make it a preferable alternative to selective catalytic reduction and other control options.

7.4.2.3 Current Portfolio

The current Federal portfolio focuses on developing catalysts that reduce N_2O to elemental nitrogen with greater efficiency and promoting the use of NSCR over other NO_x control options such as SCR and extended absorption. The goal in this area is to focus on development of catalysts that reduce N_2O to elemental nitrogen with greater efficiency and to promote the use of nonselective catalytic reduction over other NO_x control options such as selective catalytic reduction and extended absorption. See Section 4.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-441.pdf

7.4.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

For example, the use of a catalyst that can reduce a higher percentage of N_2O emissions might be a promising avenue for future research. Current technology is primarily implemented to reduce NO_x emissions, not as an N_2O emission-reduction technology. In the longer term, in order to achieve further reductions in N_2O emissions from nitric acid production, an advanced NSCR technology that is not energy intensive will likely need to be developed and implemented at most nitric acid production facilities.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.5 Emissions of Tropospheric Ozone Precursors and Black Carbon

Understanding of the role of black carbon (BC) and tropospheric ozone in climate change is still evolving. Large uncertainties remain with regard to emission levels, atmospheric concentrations, net climatic effects, and mitigation potential. Research to date indicates, however, that these substances influence the global radiation budget, particularly at regional scales. Complicating our understanding is that BC, which tends to have a warming effect, is co-emitted with organic carbon (OC), which tends to have a cooling effect on climate, much like sulfate aerosols.

Mitigation options for BC and tropospheric ozone can already be identified in various sectors. However, for particular emission sources it is often difficult to precisely quantify the emission implications of different mitigation scenarios for these substances, and even more difficult to quantify the climatic implications of such scenarios. Activities to reduce tropospheric ozone precursors and BC will have large public health and local air quality benefits, in addition to their role in mitigating climate change. In fact, it is expected that even in the absence of climate-change-driven mitigation actions, reductions in tropospheric ozone and black carbon will be achieved as local and regional air quality concerns are addressed, in the United States and many other countries.

7.5.1 Potential Roles of Technology

Ozone and particulate matter (PM), of which BC is a component, have been key targets of air pollution control efforts in the United States for many years. National, State, and local regulations have aimed at reducing the significant human health and environmental impacts from high levels of tropospheric ozone and particulate matter. Emission control programs directed toward reducing ozone have focused on the primary precursors that contribute to formation of 1-hour peak ozone concentrations in and near urban centers—i.e., emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOC).

Programs aimed at reducing PM have led to significant advances in emission control technologies in the transportation, power generation, and industrial sectors, which have and will continue to reduce emissions of BC in the United States. Power plants and other large combustion sources use control technologies such as high-efficiency electrostatic precipitators, fabric filters, and scrubbers to reduce particulate matter, including BC. Regulatory efforts for other stationary sources have addressed biomass burning and include new source performance standards for residential wood heaters and limits on open and agricultural burning.

7.5.2 Technology Strategy

The approach to address the most significant sources of tropospheric ozone precursors and BC involve the following abatement technology areas:

- **Transportation control technologies**. PM emissions smaller than 2.5 microns (PM 2.5) from on- and off-road diesel vehicles (the largest source of BC emissions in the United States) are being targeted by stricter vehicle emission standards, where per-vehicle PM emissions are expected to be reduced by 90 percent over the next decade. Total national mobile source PM 2.5 emissions are expected, by 2020, to decline by 53 percent compared to 1996 levels and by 24 percent compared to projected 2020 baseline levels.

- **Temperature reduction in cities.** Heat islands form as cities replace natural vegetation with pavement for roads, buildings, and other structures. There are several measures available to reduce the urban heat island effect that can decrease ambient air temperatures, energy use for cooling purposes, GHG emissions, and the chemical formation of smog (ozone and precursors). (See Urban Heat Island Technologies in the Buildings subsection of Chapter 4.)

- **Biomass burning**. Important sources of BC aerosols in the United States include combustion of not only fossil fuels but also biomass. Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning. However, open biomass burning emits greater amounts of OC relative to BC, meaning that, from a strictly climate-carbonaceous aerosol perspective, reducing these emissions could lead to net warming.

7.5.3 Current Portfolio

The current Federal portfolio focuses on the representative technologies listed below. Transportation goals are focused on developing cost-effective NO_x and PM black carbon engine and vehicle controls, especially for diesel engines, hybrid-diesel, and gasoline drive trains for medium- and heavy-duty vehicles. Goals for temperature reduction in cities are focused on understand and quantifing the impacts that heat island reduction measures have on local meteorology, energy use, GHG emissions, and air quality. Basic research goals are focused on better understanding of the joint role of BC and OC in climate change, including establishing linkages between air pollution and climate change by enhancing modeling capabilities; designing integrated emissions control strategies to benefit climate, regional and local air quality simultaneously. See Section 4.5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-451.pdf

- Transportation control technologies include advanced tailpipe NO_x controls (including NO_x adsorbers), particulate matter filters (traps) for diesel engines (including catalyzed traps capable of passive regeneration), and hybrid and fuel cell vehicles.

- Representative technologies for *temperature reduction in cities* include:
  - Strategically planted shade trees.
  - Reflective roofs: There are over 200 EnergySTAR^{TM} roof products, including coatings and single-ply materials, tiles, shingles and membranes. Energy savings with reflective roofs range as high as 32 percent during periods of peak electricity demand (and average 15 percent for the summer season).
  - Reflective paving materials: There are several reflective pavement applications being developed, including new pavement and resurfacing applications, asphalt, concrete and other material types.

- Alternatives to *biomass burning* include prescribed burning programs (which are directed at minimizing wildfires), and regulation or banning of open burning (such as in land clearing).

7.5.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

For example, basic research is needed to both better understand the role of black and organic carbon and tropospheric ozone precursors in climate change, and to achieve emission reductions in the near and long terms. Much of this research is a focus of the Administration's Climate Change Science Program. Some of the areas where basic research is needed include the following:

- The study of the roles of tropospheric ozone and BC and OC in global warming has begun only relatively recently. While there are strong indications that these pollutants are important actors in climate change, much more research is needed to address the complex optical, chemical, and meteorological factors involved. For BC, this new research would be aimed at establishing more clearly how these pollutants affect solar radiation and cloud formation. For BC and tropospheric ozone, new research could focus on how atmospheric concentrations vary with geography, time, and the presence of other compounds in the atmosphere.

- Greater understanding of the use of different definitions of and measurement protocols for BC (and its differentiation from elemental carbon and organic carbon), and the implications of such differences for climate assessments, is also needed. Much of this work is underway.

- Advanced, real-time measurement techniques for fine particulate matter and carbonaceous soot are needed. It is difficult to measure the composition, number, volume, and mass densities of nanometer-size particles at combustion sources and in the atmosphere.

- Quantification of the synergies and potential tradeoffs among GHGs, BC, OC, tropospheric ozone, and other criteria air pollutants for different mitigation options, whether these options are targeted for climate, air quality, or both issues.

- Regarding BC emissions from open biomass burning, potential mitigation options include wildfire suppression and altering prescribed burning practices. However, it remains difficult to quantify emission reduction benefits due to large uncertainties in the time dynamics of wildfires and uncertainties in emissions factors resulting from different kinds of fires. Furthermore, the climate benefits are difficult to quantify because greater amounts of OC relative to BC are emitted from biomass burning. Further research into this area could support practices that reduce both BC and OC emissions for health and regional haze concerns, while at the same time understanding the net climatic effects. This type of effort could also enhance carbon sequestration on forestlands.

- A thorough study of life-cycle GHG and particulate matter emissions is needed to resolve questions of the overall climate impacts of vehicle emissions (including CO_2 and organic carbon particles) of vehicles operating on gasoline as compared to diesel fuel (taking into account the future schedule of diesel vehicle PM standards).

- Jet fuel additives could be found that minimize emission of carbonaceous particles (i.e., black carbon/soot) from aircraft engines during take-off, landing, and cruising.

- Computational models of soot formation are needed to enable inexpensive design of combustion devices and their optimum operational conditions.

R&D of alternative, non-carbon based fuels in the longer term could lead to significant reductions in emissions of tropospheric ozone precursors and BC. Additional longer-term R&D needs include the following:

- Efforts to develop technologies to reduce NO_x emissions from on-road heavy-duty diesel engines are moving beyond engine-based technologies to exhaust after-treatment technologies.
- For both NO_x and particulate control technologies for diesel engines, designs capable of being retrofitted onto engines in the existing fleet could significantly accelerate the heath and climate benefits of these technologies by reducing the time that is otherwise required for engines to be retired and replaced by new models.

Improved understanding is necessary to translate these measures into quantifiable reductions in ozone precursors, BC, OC, and the associated climate effects.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

7.6 Conclusions

New and improved technologies are required, if emissions of non-CO_2 GHGs are to be reduced effectively across a wide variety of emission sources and at lower costs. If successfully developed through R&D and adopted, such technologies could contribute significantly to the goal of mitigating future increases in radiative climate forcing, in both the near term and long terms. Methane emissions reductions of as much as 60 percent could be achieved by 2050 by focusing on additional methane capture, recovery and utilization, particularly from natural gas systems and landfills (DeAngelo, 2005, Delhotal, 2005). Methane emissions reductions of almost 70 percent may be possible by 2100, if longer-term research opportunities, particularly in the agriculture sector, are pursued.

It is estimated that emissions of nitrous oxide could be reduced by as much as 30 percent in 2050 and 50 percent in 2100 through long-term R&D on improved catalysts to reduce N_2O emissions from combustion and precision agriculture technologies to address N_2O emissions from agricultural soils. (DeAngelo, 2005, Delhotal, 2005). For high-GWP gases, it is estimated that significant near-term reductions are possible by targeted deployment of existing technologies, and emission reductions of 75 percent could be realized in 2050 and 2100 through longer-term R&D aimed at the development of chemical substitutes. (Schaefer, 2005)

7.7 References

DeAngelo, B., F. de la Chesnaye, R. Beach, A. Sommer, and B. Murray, 2005. Methane and Nitrous Oxide Mitigation in Agriculture. Energy Journal (forthcoming).

Delhotal, K. Casey, F. C. de la Chesnaye, A. Gardiner, J. Bates, and A. Sankovski, 2005. Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry. Energy Journal (forthcoming).

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001: the scientific basis.* Cambridge, UK: Cambridge University Press.

Placet, M., K.K. Humphreys, and N.M. Mahasenan. 2004. *Climate change technology scenarios: energy, emissions and economic implications*. Richland, WA: Pacific Northwest National Laboratory. http://www.pnl.gov/energy/climatetechnology.stm

Schaefer, D., D. Godwin, and J. Harnish, 2005. Estimating Future Emissions and Potential Reductions of HFCs, PFCs, and SF6. Energy Journal (forthcoming).

U.S. Climate Change Technology Program (CCTP). 2003. *Technology options for the near and long term.* DOE/PI-0002. Washington, DC: U.S. Department of Energy.
http://www.climatetechnology.gov/library/2003/tech-options/index.htm
Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Environmental Protection Agency (EPA). 1999. *U.S. methane emissions 1990 – 2020: inventories, projections, and opportunities for reductions.* #430-R-99-013. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/methane/reports/methaneintro.pdf

U.S. Environmental Protection Agency (EPA). 2003a. *Assessment of the worldwide market potential for oxidizing coal mine ventilation air*. #430-R-03-002. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/coalbed/pdf/ventilation_air_methane.pdf

U.S. Environmental Protection Agency (EPA). 2003b. Current status of farm-scale digesters. *AgSTAR Digest*. #430-F-02-028. Washington, DC: U.S. Environmental Protection Agency.
http://www.epa.gov/agstar/pdf/handbook/appendixa.pdf

U.S. Environmental Protection Agency (EPA). 2004. *Global emissions of non-*CO_2 *greenhouse gases, 1990 – 2020*. Washington, DC: Environmental Protection Agency.

U.S. Environmental Protection Agency (EPA). 2005. *Inventory of U.S. greenhouse gas emissions and sinks: 1990 – 2003*. #430-R-05-003. Washington, DC: U.S. Environmental Protection Agency.
http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR69V4ZS/$File/05_complete_report.pdf

8 Enhancing Capabilities to Measure and Monitor Greenhouse Gases

The sources of greenhouse gas (GHG) emissions are varied and complex, as are the potential mitigation strategies afforded by advanced climate change technologies, such as those presented in the previous chapters. Measurement and monitoring systems will be needed to complement these technologies in order to assess their efficacy and sustainability and guide future enhancements. Contributing measurement and monitoring systems cover a wide array of GHG sensors, measurement platforms, monitoring and inventorying systems, and associated analytical tools, including databases, models and inference methods. Development and application of such systems can provide accurate characterizations of advanced technologies, enable increased understanding of performance, guide further research, reduce costs, and improve effectiveness. Research and development (R&D) on these systems is required to increase their capabilities and facilitate and accelerate their adoption.

Observations using measurement and monitoring technologies can be used to establish informational baselines necessary for analytical comparisons, and to measure carbon storage and GHG fluxes across a range of scales, from individual locations to large geographic regions. If such baselines are established, the effectiveness of implemented GHG-reduction technologies can be assessed against a background of prior or existing conditions and other natural indicators. Many of the measurement and monitoring technologies and the systems they can enable benefit from the ongoing R&D under the aegis of the Climate Change Science Program (CCSP), and from other Earth observation activities that are underway. All such measurement and monitoring systems could be improved through further development as outlined below, and constitute an important component of a comprehensive Climate Change Technology Program (CCTP) R&D portfolio.

On February 16, 2005, 55 countries endorsed a 10-year plan to develop and implement the Global Earth Observation System of Systems (GEOSS) for the purpose of achieving comprehensive, coordinated, and sustained observations of the Earth system. The U.S. contribution to GEOSS is the Integrated Earth Observation System (IEOS). IEOS will meet U.S. needs for high-quality, global, sustained information on the state of the Earth as a basis for policy and decision making in every sector of society. A strategic plan for IEOS[1] was developed by the United States Group on Earth Observation (USGEO), a Subcommittee reporting to the National Science and Technology Council's Committee on Environment and Natural Resources and released in April 2005. Both the GEOSS and the IEOS are focused around societal benefits, including climate variability and change, weather forecasting, energy resources, water resources, land resources, and ocean resources - all of which are relevant to the Climate Change Science and Technology Program.

8.1 Potential Role of Technology

Measurement and monitoring systems are important to addressing uncertainties associated with cycling of GHGs through the land, atmosphere, and oceans, as well as in measuring and monitoring GHG-related performance of various advanced climate change technologies. These systems offer the potential to:

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[1] Accessible at http://iwgeo.ssc.nasa.gov

- Characterize inventories, concentrations, and cross-boundary fluxes of carbon dioxide (CO_2) and other greenhouse compounds, including the size and variability of the fluxes.

- Characterize the efficacy and durability of particular mitigation technologies or other actions, and verify and validate claims for results.

- Measure (directly or indirectly through proxy measurements) anthropogenic changes in sources and sinks of GHGs and relate them to causes, to better understand the role of various technologies and strategies for mitigation.

- Identify opportunities and plans for guiding research investments in GHG measurement and monitoring methods, technologies, and strategies.

- Explore relationships among changes in GHG emissions, fluxes and inventories due to changes in surrounding environments.

- Optimize the efficiency, reliability, and quality of measurement and monitoring that maximizes support for understanding and decision making while minimizing the transaction costs of mitigation activities.

Ideally, an integrated observation system strategy would be employed to measure and monitor the sources and sinks of all gases that have an impact on climate change, using the most cost-effective mix of techniques ranging from local *in situ* sensors to global remote sensing satellites. This would involve technologies aimed at a spectrum of applications, including CO_2 from energy-related activities (such as end-use, infrastructure, energy supply, and CO_2 capture and storage) and GHGs other than CO_2 (including methane, nitrous oxide, fluorocarbons, ozone, and other GHG-related substances, such as black carbon aerosol). An integrating system architecture serves as a guide for many of the step-by-step development activities required in these areas. It could establish a framework for R&D that places measurement and monitoring technologies in context with the Integrated Earth Observation System (IEOS) and other CCTP technologies (see Figure 8-1).

Such a framework facilitates coordinated progress over time toward effective solutions and common interfaces of the gathered data and assessment systems. An integrating architecture would function within the context of and in coordination with other federal programs (e.g., CCSP and the U.S. Group on Earth Observations) and international programs (e.g., the World Meteorological Organization and the Intergovernmental Panel on Climate Change) that provide or use complementary measurement and monitoring capabilities across a hierarchy of temporal and spatial scales. It could, therefore, take advantage of the synergy between observations to measure and monitor GHG mitigation strategies and the research observation systems for the CCSP, as well as the operational observations systems for weather forecasting, as described more fully in the CCTP report, *Technology Options for the Near and Long Term* (DOE CCTP 2003).

In the near term, opportunities for advancing GHG measuring and monitoring systems present themselves as integral elements of the CCTP R&D programs and initiatives. Efforts must focus on the significant emission sources and sinks and on measurement and monitoring of carbon sequestration and storage.

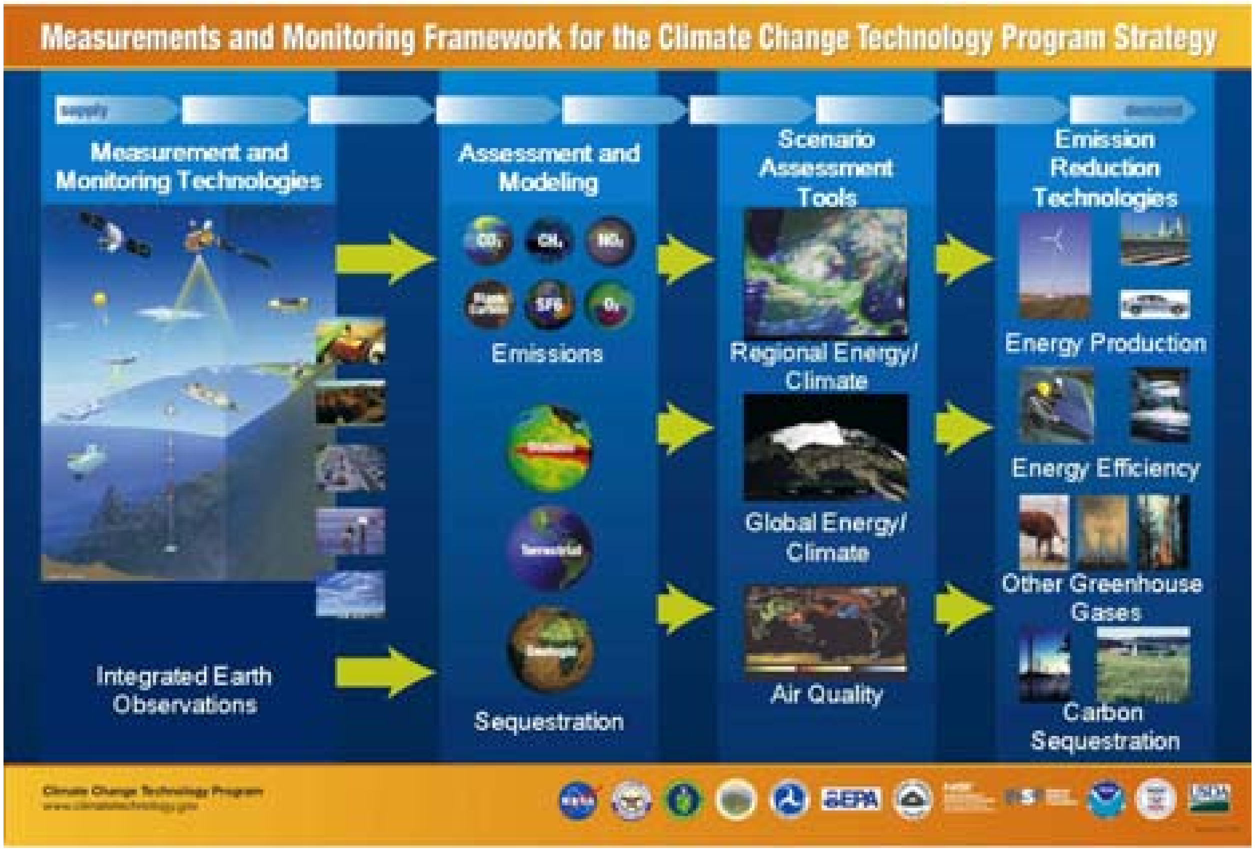

Figure 8-1. Measurement and Monitoring Technologies for Assessing the Efficacy, Durability, and Environmental Effects of Emission Reduction and Stabilization Technologies

Technology can be developed to address knowledge gaps in GHG emissions and to improve inventories. In some cases it is not necessary or cost-effective to measure emissions directly. In such cases, emissions can be measured indirectly by measuring other parameters as proxies, such as feedstock, fuel, or energy flows (referred to as "parametric" or "accounting-based" estimates); or by measuring changes in carbon stocks. Under CCTP, there is a benefit to undertaking research to test, validate, quantify uncertainties, and certify such uses of proxy measurements.

The long-term approach is to evaluate data needs and pursue the development of an integrated and overarching system architecture that focuses on the most critical and supplementary data needs. Common databases would provide measurements for models that could estimate additions and removals of various GHG inventories, forecast the long-term fates of various GHGs, and integrate results into relevant decision support tools and global-scale monitoring systems. This approach would include protocols for calibrated and interoperable (easily exchanged) data products, emissions accounting methods development, and coordination of basic science research in collaboration with CCSP. Tools would be validated by experimentation to benchmark protocols (to quantify the improvements that the tools provide), so that they would be recognized and accepted by the community-of-practice for emissions-related processes.

The measurement and monitoring technologies that are emphasized in the following sections are based on their capacity to address one or more of the following criteria:

- Measurement and monitoring technology that support the successful implementation and validation of a technological option that mitigates a substantial quantity of GHG emissions, on the order of a gigaton of carbon equivalent or more over the course of a decade from the United States.

- Measurement and monitoring technology capacity to reduce a key uncertainty associated with a mitigation option.

- Measurement and monitoring technology sufficiently differentiated from, or adequately integrated with, comparable research efforts in the CCSP, IEOS, or other operational Earth observation systems.

- Measurement and monitoring technology helping to assure that a proposed advanced climate change technology does not threaten either human health or the environment.

8.2 Energy Production and Efficiency Technologies

Measurement and monitoring systems provide the capability to evaluate the efficacy of efforts in reducing GHG emissions through the use of (1) low-emission fossil-based power systems; (2) potentially GHG-neutral energy supply technologies, such as biomass energy systems (see Chapter 6) and other renewable energy technologies, including geothermal energy; and (3) technologies to more efficiently carry and/or transmit energy to the point of use. In this section, the measurement and monitoring R&D portfolio for energy production and efficiency technologies is presented. Each of these technology sections includes a sub-section describing the current portfolio. The technology descriptions include a link to an updated version of the CCTP report, *Technology Options for the Near and Long Term*. The full report is available at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

8.2.1 Technology Strategy

Measurement and monitoring technologies can enhance and provide direct and indirect emissions measurements at point and mobile sources of GHG emissions. Point sources can range from electric generation plants to industrial facilities, while mobile sources typically refer to vehicles. Table 8.1 summarizes the nature of point and mobile sources and the potential roles for measurement and monitoring technologies, which are broadly applicable across the range of emission sources and scales. The technology strategy emphasizes the potential role of measurement and monitoring technologies in applications across a range of scales, from the individual vehicle to the larger power plant or industrial facility, as well as the balance between those measurement and monitoring technologies needed in both the near and long terms. In the near term, the strategy focuses on technologies that measure multiple gases across spatial dimensions. In the long term, the strategy focuses on development of a system of systems for remote, continuous, and global measurement and monitoring that facilitates emissions accounting from the local to the global level.

Table 8-1. Proposed R&D Portfolio for Measurement and Monitoring of Energy Production and Use Technologies

GHG Emission Source	Nature of Emissions and Scale	R&D Portfolio of Measurement and Monitoring Technology
Power Generation	Large point sources	Component and system-level technologies to enable and demonstrate direct measurements, continuous emission monitoring, on-board diagnostics, remote sensing, data transmission and archiving, inventory-based reporting, and decision support systems.
Industrial Facility	Many different processes, but mostly point sources	As above.
Transportation	Many mobile sources and widely distributed	As above.

8.2.2 Current Portfolio

R&D programs for measurement and monitoring technologies spanning the federal complex are focused on a number of areas including:

- High-temperature sensors for NO_x and ozone, ammonia and other gas emissions, with application in caustic industrial environments (e.g., steel mills, pulp and paper industries)
- Fast-response mass spectrometers, and field deployable isotope analysis systems
- Continuous emissions monitors (CEMs) for measuring multiple gases at point sources (linked with energy use statistics at a facility)
- Light Detection and Ranging (LIDAR) for remote monitoring of truck and aviation emissions.

The overall goals are to develop sensors and data transmission systems that allow quantification of emission reductions resulting from energy efficiency improvements. For more details on the current R&D activities, see (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/index.htm

8.2.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Improvements in performance, longevity, autonomy, spatial resolution of measurements, and data transmission of CEMs with the ability to measure multiple gases.

- More thorough process knowledge and life-cycle analysis for the estimation of changes in emission factors as a function of time and process.

- Satellite-based sensors for direct measurement of CO_2 and other gases or indicators, tracers, and isotopic ratios.

- Low-cost, multiple wireless micro sensor networks to monitor migration, uptake, and distribution patterns of CO_2 and other GHGs in soil and forests.

- Data protocols and analytical methods for producing and archiving specific types of data to enable interoperability and long-term maintenance of data records, data production models, and emission coefficients that are used in estimating emissions.

- Direct measurements to replace proxies and estimates when these measurements are more cost-effective in order to optimize emissions from sources and improve understanding of the processes behind the formation of GHGs.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.3 CO_2 Capture and Sequestration

As discussed in Chapter 6, capture, storage, and sequestration of CO_2 can be accomplished by various approaches, including capture from point sources, accompanied by geologic or oceanic storage, and terrestrial sequestration. Advanced technologies can make significant contributions to measuring and monitoring GHG emissions that are captured, stored, and sequestered.

Innovations to assess the integrity of geologic structure, leakage from reservoirs, and accounting of sequestered GHGs are useful. Also useful are integrated carbon sequestration measurements of different components (e.g., geologic, oceanic, and terrestrial) across a range of scales and time, from the point of use at the present time to regional or larger scales over the future to provide a consistent net accounting of GHG inventories, emissions, and sinks. Advanced measurement and monitoring technologies can provide histories of CO_2 concentration profiles near the sites of sequestration and track the potential release of CO_2 into the atmosphere. Different measurement and monitoring strategies associated with the three alternative storage and sequestration approaches are described in the sections that follow.

8.3.1 Geologic Sequestration

Measurement and monitoring technologies are useful to assess the performance and efficacy of geologic storage systems. They will be critically important in assessing the integrity of geologic structures, transportation, and pipeline systems, the potential of leakage of sequestered GHGs in geologic structures, and in fully accounting for GHG emissions.

8.3.1.1 Technology Strategy

Realizing the possibilities of these technologies employs a research portfolio that embraces a combination of measurement and monitoring technologies that focuses on separation and capture, transportation, and geologic storage. In the near term, technologies can be improved to measure efficacy of separation and capture, and the integrity of geologic formations for long-term storage. Within the constraints of available resources, a balanced portfolio addresses the objectives shown in Table 8-2.

Table 8-2. Proposed R&D Portfolio for Measurement and Monitoring Systems for Geologic Sequestration

System Concepts	R&D Portfolio
Separation and Capture	• Monitors for CO_2 emissions using process knowledge • Sensors to monitor fugitive emissions around facilities
Transportation	• Leak detection systems from pipelines and other transportation • Pressure transducers • Remote detectors • Gaseous tracers enabling remote leakage detection
Geologic Storage	• Detectors for surface leakage • Indicators of leakage based on natural and induced tracers • Seismic/electromagnetic/electrical resistivity/pressure monitoring networks

8.3.1.2 Current Portfolio

Recent progress has been made in developing measurement and monitoring technologies for geologic carbon sequestration. There are many technologies for monitoring and measuring that exist today. However they may need to be modified to meet the requirements of CO_2 storage. The goal is to develop the ability to assess the continuing integrity of subsurface reservoirs using integrated system of sensors, indicators, and models; improve leak detection from separation and capture pipeline systems; apply remote sensors to fugitive emissions from reservoirs and capture facilities; improve, develop, and implement tracer addition and monitoring programs; evaluate microbial mechanisms for monitoring and mitigating diffuse GHG leakage from geologic formations; and more. For more information on the current R&D activities, see Section 5.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-53.pdf

Both surface and subsurface measurement systems for CO_2 leak detection and reservoir integrity estimates have been employed at sites currently storing CO_2. Large measurement and monitoring efforts have taken place at Weyburn, Alberta, and at Sleipner in the North Sea. Within the measurement systems employed at these sites, seismic imaging using temporal analyses of 3-dimensional (3D) seismic structures (called 4D seismic analyses) have been commonly employed to characterize the reservoir, determine changes in reservoir structure and integrity, and to determine locations of CO_2 that have been pumped downhole. At the Sleipner site, for example, efforts to quantify the CO_2 have been undertaken through 4D seismic research. Other methods of subsurface reservoir analyses are cross-well seismic tomography, passive and active doublet analyses, microseismic analyses, and electromagenetic analyses.

Leak detection of CO_2 from storage reservoirs has been performed in the subsurface and surface regions. Within the subsurface, groundwater chemistry, precipitation of calcite, and subsurface CO_2 concentration measurements have been used to detect small gas emissions from reservoirs. At the ground surface, CO_2 flux changes, isotopes of CO_2 and other tracers, and vegetation changes have been monitored to detect surface leaks of CO_2 and identify the source.

Specific examples include four ongoing experiments: (1) Seismic methods are being used at the Sleipner test site to map the location of CO_2 storage. (2) Models, geophysical methods, and tracer indicators are being developed through the GEO-SEQ project (see Box 8-1). (3) Detection of CO_2 emissions from natural reservoirs has been investigated by researchers at the Colorado School of Mines, University of Utah, and the Utah Geological Survey, including isotopic discrimination of biogenic CO_2 from magmatic, oceanographic, atmospheric, and natural gas sources. (4) Fundamental research on high-resolution seismic and electromagnetic imaging and on geochemical reactivity of high partial-pressure CO_2 fluids is being conducted.

Box 8-1

Geological Sequestration of Carbon Dioxide (GEO-SEQ) is a comprehensive program examining a range of issues that include cost optimization, monitoring, modeling, and capacity estimation, associated with CO_2 sequestration in geological formations. The GEO-SEQ Project is a public-private applied R&D partnership, formed with the goal of developing the technology and information needed to enable safe and cost-effective geologic sequestration by the year 2015. The effort, supported by DOE and involving several of its national laboratories, as well as universities and industry, conducts applied research and development to reduce the cost and potential risk of sequestration, as well as to decrease the time to implementation. See DOE-NETL (2004).

8.3.1.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Tying the experimental research to the process models for geological storage systems, where fate and transport of the stored CO_2 are measured and verified with models. This contributes to verification of CO_2 storage in geologic structures in both the near and long terms.

- The ability to assess the continuing integrity of subsurface reservoirs using an integrated system of sensors, indicators, and models. The heterogeneity of leakage pathways and probable changes over time make detection and quantification difficult.

- Indicators such as seismic, electromagnetic imaging, and tracers are needed for quantitative determination of CO_2 stored and specific locations of where the CO_2 is located underground.

- Improvements in leak detection from separation and capture and pipeline systems. Low leakage rates occurring at spatially separated locations make full detection difficult.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.3.2 Terrestrial Sequestration

Sequestering carbon in terrestrial ecosystems (forests, pastures, grasslands, croplands, etc.) increases the total amount of carbon retained in biomass, soils, and wood products. Methods used to measure and monitor terrestrial sequestration of carbon should address both the capture and retention of carbon in both above- and below-ground components of ecosystems. Determining measures of the desired levels of net sequestration will depend on evaluation of GHG emissions as a function of management practices and naturally occurring environmental factors (Post et al. 2004).

8.3.2.1 Technology Strategy

Measurement and monitoring systems employ an R&D portfolio that provides for integrated, hierarchical systems of ground-based and remote sensing technologies of different system components over a range of scales. A system's utility is based on its applicability to a wide range of potential activities and a very diverse land base, an accuracy that satisfies reporting requirements of the 1605(b) voluntary reporting system (EIA 2004), and a cost of deployment such that measurement and monitoring does not outweigh the value of the sequestered carbon. A balanced portfolio should address (1) remote sensing and related technology for land cover and land cover change analysis, biomass and net productivity measurements, vegetation structure, etc.; (2) low-cost portable, rapid analysis systems for *in situ* soil carbon measurements; (3) flux measurement systems; (4) advanced biometrics from carbon inventories; (5) carbon and nutrient sink/source tracing and movement, including using isotope markers; and (6) analysis systems that relate management practices (e.g., life-cycle wood products, changes in agriculture rotations, energy use in ecosystem management, and others) to net changes in emissions and sinks over time (e.g., changes in agriculture rotations, energy use in ecosystem management, and others).

8.3.2.2 Current Portfolio

Current research activities associated with terrestrial sequestration are found across a number of federal agencies. The goals of the current activities are to provide an integrated hierarchical system of ground-based and remote sensing for carbon pools and CO_2 and other GHG flux measurements; reduce uncertainty on regional-to-country scale inventories of carbon stocks; develop low-cost, portable, rapid analysis systems for in situ soil carbon measurements; and develop standard estimates that relate to management practices to net changes in emissions/sinks over time.

For a detailed discussion on technologies and current research activities, see Section 5.4 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-54.pdf, Section 3.2.3.1 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3231.pdf, and Section 3.2.3.2 http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3232.pdf (CCTP 2005).

The current portfolio includes the following:

- EPA, with assistance from the U.S. Department of Agriculture's (USDA's) Forest Service, prepares national inventories of emissions and sequestration from managed lands. These inventories capture changes in the characteristics and activities related to land uses, and are subject to ongoing improvements and verification procedures.

- The USDA Forest Service Forest Inventory and Analysis Program and the Natural Resources Conservation Service's National Resources Inventory provide baseline information to assess the management, structure, and condition of U.S. forests, croplands, pastures, and grasslands. This information is then converted to State, regional, and national carbon inventories. Hierarchical, integrated monitoring systems are being designed in pilot studies such as the Delaware River Basin interagency research initiative.

- Prototype soil carbon analysis systems have been developed and are undergoing preliminary field testing.

- Methods are being developed for the use of Synthetic Aperture Radar in estimating forest bole volume at landscape scale.

- Satellite and low-altitude remote sensing systems have been developed that can quantify agricultural land features at spatial resolution of approximately 0.5 square meters and measure indicators of the carbon sequestration capacity of land use.

- Prototype versions of web-based tools are being developed for estimating carbon budgets for regions.

- Multidisciplinary studies are providing increased accuracy of carbon sequestration estimates related to land management and full accounting of land/atmosphere carbon exchange.

- The Agriflux and AmeriFlux programs (see Boxes 8-2 and 8-3) are being implemented to improve the understanding of carbon pools and fluxes in large-scale, long-term monitoring areas. The flux measurements provide quantitative data for calibrating/validating remote sensing and other estimates of carbon sequestration. Approaches for scaling these results to regional estimates are under development (DOE-ORNL 2003).

Box 8-2

Agriflux

The Agriflux network is being developed by the USDA to measure the effects of environmental conditions and agricultural management decisions on carbon exchange between the land and the atmosphere. The network now comprises more than 125 sites in North and South America. Studies will identify crop management practices to optimize crop yield, crop quality, and carbon sequestration and other environmental conditions. Research will lead to new ways for prediction and early detection of drought in agricultural systems based on weekly and monthly climate forecasts.

Box 8-3

AmeriFlux

Flux towers such as the one pictured above are taking long-term measurements of CO_2 and water vapor fluxes in over 250 sites throughout the world, including the United States. Data gathered from these measurement sites are important to understand interactions between the atmospheric and terrestrial systems. The network (http://public.ornl.gov/ameriflux/) is part of an international scientific program of flux measurement networks (e.g., FLUXNET-Canada, CarboEurope, and AsiaFlux) that seeks to better understand the role of the terrestrial biosphere carbon cycle. See http://www.fluxnet.ornl.gov/fluxnet/index.cfm for a global listing of flux towers.

- Other aerospace research activities focusing on imaging and remote sensing methods include LIDAR and RADAR, used for 3D imaging of forest structure for the estimation of carbon content in standing forests.

- Isotopes are being used to assess sequestration potentials by monitoring fluxes and pools of carbon in natural ecosystems.

- Increased accuracy of carbon sequestration estimates is being accomplished for use in land management and full carbon accounting procedures.

- Ongoing tillage and land conservation practices offer test beds for ground-based and remote sensing methods, as well as verification of rules of thumb for emission factors.

- Many of the DOE National Laboratories are conducting R&D on *in situ* and remote sensing technologies and laser-based diagnostics, supported by a variety of federal agencies. These diagnostics include microbial indicators, Laser Induced Breakdown Spectroscopy (LIBS), LIDAR, Fourier Transform Infrared (FTIR) Spectroscopy, and a variety of satellite Earth observation programs (see Box 8-4).

Box 8-4

Diagnostic Technologies

Laser Induced Breakdown Spectroscopy (LIBS) is a robust chemical analysis technique that has found application in a range of areas where rapid, remote and semi-quantitative analysis of chemical composition is needed. The technique in its essential form is quite simple. Light is used to ionize a small portion of the analyte and the spectral emission (characteristic of the electronic energy levels) from the species in the resulting plasma is collected to determine the chemical constituents. Most often the light comes from a laser since high photon fluxes can be obtained readily with this type of light source. By focusing the light from the laser to a small spot, highly localized chemical analysis can be performed.

LIght Detection and Ranging (LIDAR) uses the same principle as RADAR. The LIDAR instrument transmits light out to a target. The transmitted light interacts with and is changed by the target. Some of this light is reflected/ scattered back to the instrument where it is analyzed. The change in the properties of the light enables some property of the target to be determined. The time for the light to travel out to the target and back to the LIDAR is used to determine the distance to the target.

Fourier Transform Infrared Spectroscopy (FTIR) technology has the capability to measure more than 100 of the 189 Hazardous Air Pollutants (HAPs) listed in Title III of the Clean Air Act Amendments of 1990. FTIR has the capability of measuring multiple compounds simultaneously, thus providing an advantage over current measurement methods which measure only one or several HAPs. FTIR can provide a distinct cost advantage since it can be used to replace several traditional methods.

8.3.2.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Further development of imaging and volume measurement sensors for land use/land cover and biomass estimates.

- Development of low-cost, practical methods to measure net carbon gain by ecosystems, and life cycle analysis of wood products, at multiple scales of agriculture and forest carbon sequestration.

- Isotope markers to identify and distinguish between natural and human sources and determine movement of GHGs in geological, terrestrial, and oceanic systems.

- Identification of new measurement technology needs that support novel sequestration concepts such as enhanced mechanisms for CO_2 capture from free air, new sequestration products from genome sequencing, and modification of natural biogeochemical processes.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.3.3 Oceanic Sequestration

Sequestering carbon in oceans generally refers to two techniques: direct injection of CO_2 to the deep ocean waters and fertilization of surface waters with nutrients. For direct injection, CO_2 streams are separated, captured, and transported using processes similar to those for geologic sequestration, and injected below the main oceanic thermocline (depths of greater than 1,000 to 1,500 meters). Fertilization of the oceans with iron, a nutrient required by phytoplankton, is a potential strategy to accelerate the ocean's biological carbon pump and thereby enhance the draw-down of CO_2 from the atmosphere. For a description of oceanic sequestration approaches, see Section 6.4 in Chapter 6.

Measuring and monitoring technologies associated with CO_2 injection are directed towards the performance of the quantities of CO_2 injected and dispersion of the concentrated CO_2 plume. Measurement and monitoring technologies associated with ocean fertilization are focused on the quantity of carbon exported deeper in the water column and the stability and endurance of the carbon sink. Carbon sequestration in oceans can be enhanced significantly, but this has yet to be demonstrated, and the environmental impact of such an approach has not been fully evaluated.

8.3.3.1 Technology Strategy

These technologies could be advanced through R&D in direct measurement and model analysis, as well as indirect indicators that can be used across spatial scales for obtaining process information and for ocean-wide observations. In the near term, possible advances include: (1) measurement of comprehensive trace gas parameters (total CO_2, total alkalinity, partial pressure of CO_2, and pH) to monitor the CO_2 concentration in seawater; (2) development of indirect indicators of fertilization effectiveness using remote sensing technology; and (3) development of CO_2 sensors that "track" the dissolved CO_2 plume from injection locations. In the long term, advances could include a system that monitors CO_2 in the oceans, temporally and spatially, using integrated measurement and monitoring concepts, satellite-based sensors, and other analysis systems that can avoid costly ship time.

8.3.3.2 Current Portfolio

The goal of the current research in support of measurement and monitoring technologies associated with ocean sequestration is to develop integrated concepts that include direct measurement, model analysis, and indirect indicators that can be used across scales; data transmission and analysis systems that avoid costly shipping time; quantitative satellite-based sensors; and development of plume dispersion models for direct injection of CO_2. Research activities in support of measurement and monitoring technologies associated with ocean sequestration have been underway for several years. See Section 5.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-55.pdf

For example, for more than 13 years, DOE and the National Oceanic and Atmospheric Administration (NOAA) sponsored the ocean carbon dioxide survey during the World Ocean Circulation Experiment, monitoring the carbon concentration in the Indian, Pacific, and Atlantic Oceans from oceanographic ships (Box 8-5).

Another R&D effort underway is to develop low-cost discrete measurement sensors that can be used in conjunction with the conductivity, temperature, depth, and oxygen sensors to measure the ocean profile on oceanographic stations.

Box 8-5

World Ocean Circulation Experiment

The **World Ocean Circulation Experiment (WOCE)** was a component of the World Climate Research Program (WCRP) designed to investigate the ocean's role in decadal climate change. NSF, NASA, NOAA, the Office of Naval Research (ONR), and DOE supported U.S. participation in WOCE. Scientists from more than 30 countries collaborated during the WOCE field program to sample the ocean on a global scale with the aim of describing its large-scale circulation patterns, its effect on gas storage, and how it interacts with the atmosphere. As the data are collected and archived, they are being used to construct improved models of ocean circulation and the combined ocean-atmosphere system that should improve global climate forecasts.

In 2004, as its final activity, the WOCE program published a series of four atlases, concentrating respectively on the hydrograph of the Pacific, Indian, Atlantic, and Southern Oceans. The Southern Ocean is given a separate volume because of the importance of the circumpolar flow on the transport of heat, freshwater, and dissolved components. The volumes each have three main components: full-depth sections, horizontal maps of properties on density surfaces and depth levels, and property-property plots. The vertical sections feature potential temperature, salinity, potential density, neutral density, oxygen, nitrate, phosphate, silicate, CFC-11, 3He, tritium, 14C, 13C, total alkalinity and total carbon dioxide, against depth along the WOCE Hydrographic Program one-time lines.

8.3.3.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Measurement of injected CO_2, and the tracking and dispersion of the concentrated CO_2 plume.
- Monitoring of the plume or pool to verify trajectory and lack of contact with the mixed layer.
- Monitoring of the local fauna for adverse effects of enhanced acidity or alkalinity and/or pH changes.

With iron fertilization, it is not well understood whether the excess production stimulated by iron fertilization is exported out of the mixed layer, and on what time scale it remains out of contact with the atmosphere. To better understand this, the following R&D investments in measurement technologies would help:

- Measurement of the amount of CO_2 drawn down per unit of fertilization effort.

- Characterization of the fate and transport of organic carbon exported deeper in the water column and its longevity from using fertilization technologies, including the spatial and temporal CO_2 concentration histories.

- Technologies that can provide accurate monitoring of local CO_2 concentrations and pH. Monitoring of fauna most likely will involve sampling bacterial populations using advanced biological techniques, but may also include macrofauna as appropriate.

- In addition to the specific measurements noted above, it will also be necessary to conduct ocean circulation studies and modeling support selection of injection and fertilization site and estimating storage timescale. As in deep ocean injection, the impact of fertilization on the ocean's biota and chemistry can be monitored carefully to determine the behavior and possible impacts (e.g., pH changes, fish behavior) to deep ocean systems, including the effects of nutrient fluxes on plankton biogeochemistry.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.4 Other Greenhouse Gases

As discussed in Chapter 7, a wide variety of substances other than CO_2 contribute to the atmospheric burden of GHGs. Other GHGs include methane, nitrous oxide, chlorofluorocarbons, perfluorocarbons, sulfur hexaflourine (SF_6), hydrofluorocarbons (HFCs), tropospheric ozone precursors, and black carbon aerosols. These gases are emitted from both point sources (industrial plants) and diffuse sources (open pit coal mines, landfills, rice paddies, and others), and offer unique challenges for measurement and monitoring emissions due to their spatial and temporal variations. A robust R&D program should consider direct measurements of emissions and reporting methods and will become part of a larger integrated system. Moreover, the program should consider the needs for measurement and monitoring both for point sources, and for the extensive and important diffuse sources, such as those associated with agriculture.

8.4.1 Technology Strategy

Advanced technologies can make important contributions to direct and indirect measurement and monitoring approaches for point and diffused sources of emissions. Realizing the contributions of these technologies employ an R&D portfolio that combines a number of areas.

In the near term, technical improvements to measurement equipment and sampling procedures can improve extended period sampling capabilities that would allow better spatial and temporal resolution of emissions estimates. Software development that allows further integration of measurement data with emission modeling processes can lead to improved estimates. In addition, instruments to measure from stand-off distances (tower measurements), and airborne and space-borne sensors to address regional, continental, and global reductions of GHG emissions can be developed.

In the long term, development of inexpensive CEMs, satellite-based sensors, and improved accounting estimates of emissions offer promise. Integrating modeling techniques, including inverse modeling procedures that integrate bottom-up and top-down emissions data, regional or global data are also desirable to identify data gaps or confirm source levels. To facilitate the delivery of cost-effective solutions, the strategy will couple academic and national laboratory R&D to benchmarking and transfer to industry for production and deployment.

8.4.2 Current Portfolio

There is a wide range of ongoing R&D programs in the area of measurement and monitoring of emissions of other GHGs. The goals of these programs are to develop an integrated system that meshes observations (and estimations) from point sources, diffuse sources, regional sources, and national scales; inexpensive and easily deployed sensors for a variety of applications, such as stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other GHG emissions from transportation vehicles; accurate "rules-of-thumb" (reporting/accounting rules) for practices that reduce emissions or increase sinks; a high-resolution system that captures process-level details of sources and sinks (e.g. CO_2 or CO_2, isotopes) and a methodology to scale it up reliably; and data archiving and analysis system-to-integration observations and reporting information. A detailed review of these R&D activities can be found in Section 5.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-56.pdf

The following is a summary of some of these programs:

- Annual national inventories prepared by EPA rely on both indirect modeling techniques and direct measurement data. These inventories capture changes in the characteristics and activities related to each source, and are subject to ongoing improvements and verification procedures. The indirect modeling procedures developed for these inventories are particularly important to capture emissions from diffuse area sources where individual measurements are not practical.

- Through the Advanced Global Atmospheric Gases Experiment (AGAGE) Network and other university-led measurement programs, NASA Earth science research includes measuring global distributions and temporal behavior of biogenic and anthropogenic gases important for both stratospheric ozone and climate. These include CFCs, HCFCs, HFCs, halons, nitrous oxide, methane, hydrogen, and carbon monoxide. Measurements made at the sites in the NASA-sponsored AGAGE network, along with sites in cooperative international programs, are used in international assessments for updating global ozone depletion and climate forcing estimates and in NASA's triennial report to the Congress and the EPA on atmospheric abundances of chlorine and bromine chemicals.

- NOAA monitors the global atmospheric concentration of methane, nitrous oxide, chlorofluorocarbons (CFCs), HFCs, halons and SF_6, in addition to CO_2, through its network of observatories and global cooperative programs. Through these measurements the global climate forcing by GHGs is updated annually.

- There are generally well-established measurement procedures for energy and industrial point sources, as well as for diffuse sources that are involved with voluntary programs of reduction (e.g., natural gas, coal mines) or are subject to monitoring through regulatory programs for other gases (e.g., landfills). There is ongoing integration of these direct measurement results with indirect modeling procedures as part of the national inventory process.

- Recent activities for sources such as agricultural soils, livestock, and manure waste focus on advanced modeling of emissions with verification and validation by direct measurements. Improvements to sampling and measurement techniques are a current priority for these sources.

- A number of measurement technologies have evolved to address the diffuse nature of many of the non-CO_2 sources. These include advanced chamber techniques for *in situ* sensors, FTIR, tracer gas, micrometeorological methods, and leak detection systems. The results of these measurements are being used to verify and feed back to emission factor development.

- Black carbon and tropospheric ozone precursor emissions are an emerging area of importance. Although there is long history of monitoring particulate matter and ozone precursor emissions for criteria pollutant inventories, investigations into the particular sources, speciated forms, and fate of these gases and aerosols that are most applicable to climate forcing potential have become a priority research area.

- EPA is conducting analysis and research to improve GHG inventories and emissions estimation methods, implementing formalized quality control/quality assurance procedures and uncertainty estimation. This concentrated effort will improve all emission estimates for all source categories by identifying areas where to target improved or expanded measurement and monitoring efforts.

8.4.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Further development of measurement, monitoring, and sampling techniques for agricultural sources, particularly in the area of nitrous oxide (N_2O) from agricultural soils and methane (CH_4) and N_2O from manure waste. These techniques would address the temporal and spatial variation that is inherent to these emission sources.

- Development of high quality and current emission factors for black carbon, and, to some extent, tropospheric ozone precursors where there is limited measurement data available.

- CEMs that can measure multiple gases are well developed, but improvements in performance, longevity, autonomy, spatial resolution of measurements, and data transmission would improve measurement of multiple gases. CEMs have particular application to the industrial and point sources; however, applying CEM technology to more diffuse sources is also an area for further research.

- Modeling activities that increase the accuracy of spatial and temporal estimates of CH_4 and N_2O from area-type sources such as wetlands, wastewater treatment plants, livestock, and agricultural soils. These are sources that are typically too numerous to measure and monitor on an individual basis, but can be addressed through indirect modeling techniques to account for global, national, and regional emissions. More sophisticated modeling practices could improve the accuracy of the estimates, particularly in terms of greater representation of changing conditions of operation.

- The National Aeronautic and Space Administration (NASA) Earth system science research program is developing space-based technologies for long-term monitoring of the global distribution and transport of black carbon aerosols and other aerosol types (see Box 8-6).

Box 8-6

Concepts for Global CO_2 and Black Carbon Measurements

As part of its scientific research mission supporting the Climate Change Science Program, NASA conducts R&D of aerospace science and technology that is relevant to CCTP measurement and monitoring needs. Several new measurement concepts have been developed by NASA. The Orbiting Carbon Observatory (OCO) concept involves space-based observations of atmospheric carbon dioxide (CO_2) and generates the knowledge needed.

An Aerosol Polarimetery Sensor (APS) is being designed to provide improvements in monitoring of black carbon aerosols compared to the legacy satellite instruments that only measure the intensity of reflected sunlight.

Studies indicate that multi-angle spectro-polarimetric imager (MSPI) and a high spectral resolution LIDAR (HSRL) would have the capacity to provide column average estimates of aerosol optical depth, particle size distribution, single scattering albedo, size-resolved real refractive index, and particle shape to distinguish natural and anthropogenic aerosols and improve projections of future atmospheric CO_2.

- In addition to measuring CO_2, the NASA Orbiting Carbon Observatory (OCO) will serve as a proof of concept for the measurements needed to derive surface sources and sinks of other GHGs, including CH_4, on regional scales. This measurement approach will have applications to future spaceborne measurements of GHGs. Planned collaborations with international partners—e.g., the Japan Aerospace Exploration Agency's GOSAT mission—will lead to a more complete suite of global GHG observations.

- Sophisticated modeling procedures that can fingerprint large-scale measurements to unique sources could help integrate continental and global measurements with regional and local emissions data.

- Collaborative research between EPA's National Vehicle and Fuels Emission Laboratory (NVFEL), manufacturers of vehicles/engines, emission control technology, and analytical equipment manufacturers on developing N_2O measurement techniques for emerging gasoline and diesel engines and their emission control systems. Measurement technology applies to both laboratory and field measurement.

Science questions driving future development of technologies for climate change measurement and monitoring include:

- What effects do anthropogenic activities have on aerosol radiative forcing, at accuracies sufficient to establish climate sensitivity, i.e., < 1 W/m^2?

- What are the separate impacts of anthropogenic and natural processes, including urban activities, fuel-use changes, emission controls, forest fires, and volcanoes, on trends in particulate pollution near the surface?
- What connections are there between cloud properties and aerosol amount and type?

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.5 Integrated Measurement and Monitoring System Architecture

The integrated system architecture established the context of a systems approach to delivering the information needed to plan, implement, and assess GHG reduction actions (see Figure 8-2). This architecture provides a framework for assessing measurement and monitoring technology developments in the context of their contribution to observation systems that support integrated system solutions for GHG reduction actions and helps in identifying more cost-effective solutions. It enables the benchmarking of planned improvements against current capabilities.

An integrated measurement and monitoring capability has the ability to integrate across spatial and temporal scales and at many levels, ranging from carbon measurements in soils to emissions from vehicles, from large point sources to diffused area sources, from landfills to geographic regions. This capability is graphically depicted in Figure 8-3. The integrated system builds on existing and planned observing and monitoring technologies of the CCSP and includes new technologies emerging from the CCTP R&D portfolio.

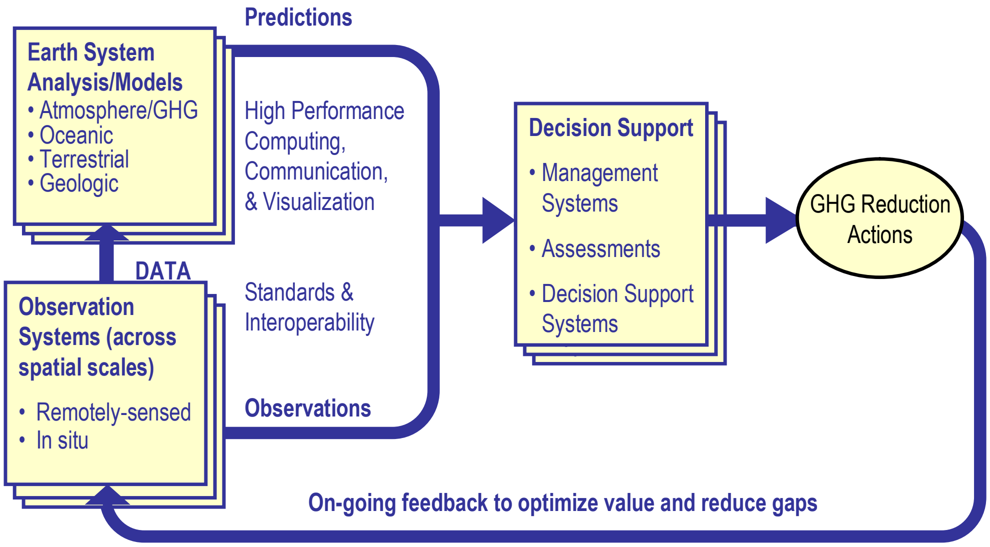

Figure 8-2. Integrating System Architectural Linking Measurement and Monitoring Observation Systems to Greenhouse Gas Reduction Actions

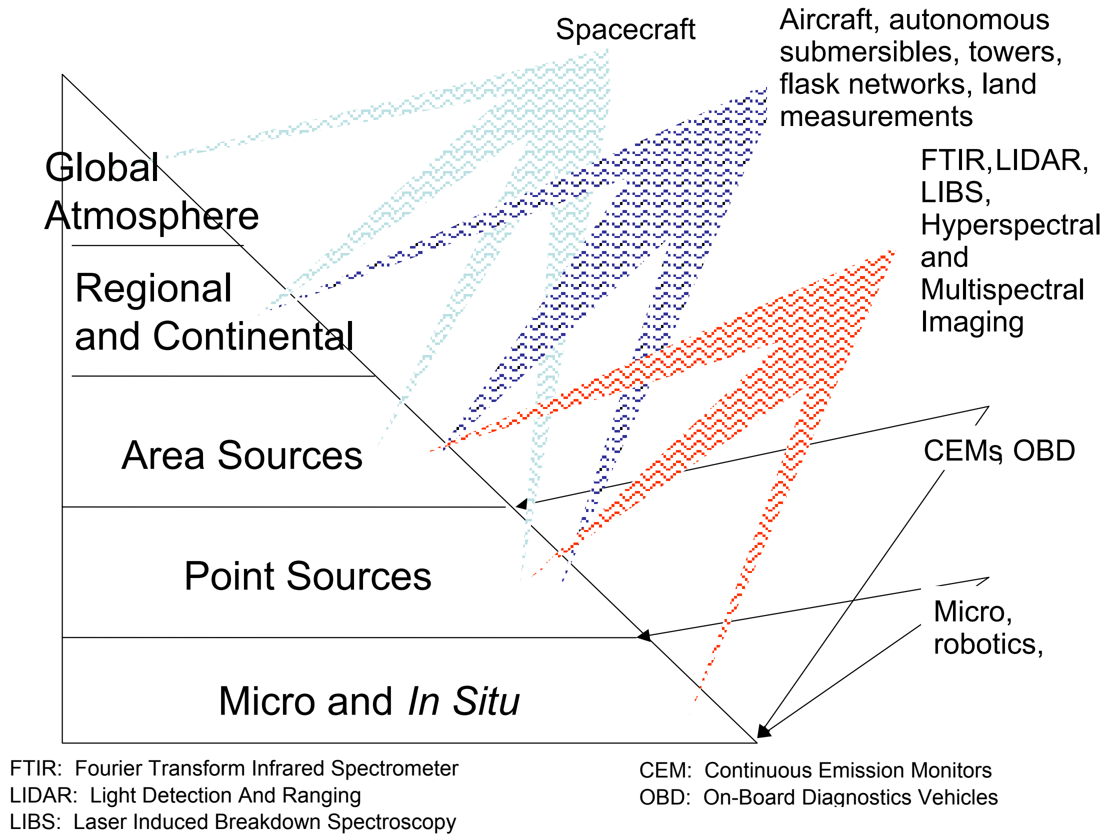

Figure 8-3. Hierarchical Layers of Spatial Observation Technologies and Capabilities

Advanced measurement and monitoring technologies offer the potential to collect and merge global and regional data from sensors deployed on satellite and aircraft platforms with other data from ground networks, point-source sensors, and other *in-situ* configurations. Wireless microsensor networks can be used to gather relevant data and send to compact, high-performance computing central ground stations that merge other data from aircraft and satellite platforms for analysis and decision making. An integrated system provides the benefits of compatibility, efficiency, and reliability while minimizing the total cost of measurement and monitoring.

8.5.1 Technology Strategy

The strategy for developing an integrated system is to focus on the most important measurement needs and apply the integrated concept design to ongoing technology opportunities as they arise. The near term focuses on development of observation systems at various scales. The longer term focuses on merging these spatial systems into an integrated approach employing IEOS. IEOS will enable and facilitate sharing, integration, and application of global, regional, and local data from satellites, ocean buoys, weather stations, and other surface and airborne Earth observing instruments (IEOS 2005). Although IEOS serves multiple purposes, one outcome will be the strengthening of U.S. capabilities to measure and monitor GHG emissions and fluxes.

8.5.2 Current Portfolio

The current Federal R&D portfolio has been targeted at a number of developments, with the goal to develop an integrated system that meshes observations (and estimations) from point sources (e.g., power plant or geologic storage site), diffuse sources (e.g., from commercial and agricultural systems), regional sources (e.g., city/county), and national scales so that checks and balances up and down these scales can be accomplished. The system should be able to attribute emissions/sinks to both national level activities and individual/corporate activities and provide verification for reporting activities. The system must be inexpensive and easily deployed sensors for a variety of applications (stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other GHG emissions from transportation vehicles. In addition, the integrated system should have data archiving and analysis capability for system-to-integration observations and reporting information.

For a detailed analysis of the current research, see Section 5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-51.pdf

Some examples of the current R&D activities include

- **Global**. R&D programs enabled by NASA’s Earth Observation System research satellites, NOAA’s operational weather and climate satellites, and NOAA’s distributed ground networks (including the Mauna Loa observatory) support improved understanding and measurements and monitoring capabilities relevant to CCSP and CCTP. The transition of NASA’s research to NOAA operational use (referred to as “Research & Operations”) enhances program planning and budget execution capabilities for the U.S. Earth Observation System.

- **Continental**. Recent research has tried to determine the net emissions for the North American continent using different approaches: inversion analysis based on CO_2 monitoring equipment as currently arrayed, remote sensing coupled with ecosystem modeling, and compilation of land inventory information. European researchers have embarked on a similar track by combining meteorological transport models with time-dependent emission inventories provided by member states of the European Union.

- **Regional**. Advanced technology, such as satellites, is being developed to monitor and/or verify a country’s anthropogenic and natural emissions. NOAA is building an atmospheric carbon monitoring system under the CCSP using small aircraft and tall communications towers that will be capable of determining emissions and uptake on a 1000-km scale (Box 8-7).

Box 8-7
NOAA Regional Carbon Monitoring

As part of the Climate Change Science Program (CCSP) and the North American Carbon Program (NACP), NOAA is building a Carbon Cycle Atmospheric Observing System mainly across the United States in order to reduce the uncertainty in the North American carbon sink. To measure carbon fluxes on a 1000-km scale over land, vertical profiling is necessary. From about 24 sites, small aircraft will, on a weekly basis, carry automatic flask sampling systems. These systems will collect 12 samples for analysis of carbon gases and isotopic carbon ratios at predetermined altitudes from the surface to about 8 km. In conjunction, tall communications towers (~ 500 m) will sample carbon and other GHGs continuously from about 12 U.S. sites. This technique will be capable of determining regional carbon sources and sinks and may have applications in the Climate Change Technology Program (CCTP) for monitoring the effectiveness of, for example, sequestration activities.

- **Local (micro or individual)**. A number of techniques are currently used to directly or indirectly estimate emissions from individual sites and/or source sectors, such as mass balance techniques, eddy covariance methods (i.e., AmeriFlux sites, source identification using isotope signatures), application of emissions factors derived from experimentation, forestry survey methods, and CEMs in the utility sector.

8.5.3 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

From diverse sources, including technical workshops, R&D program reviews, scientific advisory panels, and expert inputs, a number of such ideas have been brought to CCTP's attention. One idea is to develop a system that merges data from across the spectrum of measurement and monitoring systems, with information from one layer helping to calibrate, constrain, and verify information in other layers. Data fusion and integration technologies enable the integration of information from numerous sources, such as satellite observations, real-time surface indicators, and reported emissions inventories. Data integration could be advanced through innovative technology capacity in the area of data handling and processing, and through the development of innovative sensors, platforms, and computational models and systems; and their integration into decision support resources. Cross-verification of these data elements is based on coordination with national and international standards-setting bodies to develop protocols for interoperability of datasets. Data systems allow for integrating and comparing data among hierarchical layers of the system and for application of the measurement and monitoring technologies. Some measurements are averaged or processed to reflect the variability in emissions rates or volumes, as well as spatial and temporal variability.

Another idea is to develop and use platforms for all spatial scales and measurement layers, for example, from new types of global sensors on satellite platforms and from new airborne platforms (e.g., remotely operated or autonomous) facilitated by IEOS. GHG emission sources and geologic sequestration would be supported by development of portable platforms for sensors and autonomous units that measure, analyze, and report emissions, while ocean sequestration would be supported by development and deployment of autonomous submersible systems with appropriate sensors and reporting capabilities.

A final concept is to develop decision support tools to incorporate the data and information created from the measurement and monitoring systems (e.g., change in emissions, regional or continental information, fate of sequestered gases), along with model sensitivities and model predictions generated by CCSP activities into interactive tools for decision makers. These tools would provide the basis for "what-if" scenario assessments of alternative emission reductions technologies (e.g., sequestration, emission control, differential technology implementation time schedules in key countries of the developing world).

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

8.6 Conclusions

Meeting the GHG measuring and monitoring challenge is possible with a thoughtful system design that includes near- and long-term advances in measurement and monitoring technologies. Near-term opportunities for R&D include, but are not limited to: (1) incorporating transportation measurement and monitoring sensors into the onboard diagnostic and control systems of production vehicles; (2) preparing geologic sequestration measurement and monitoring technologies for deployment with planned demonstration projects; (3) exploiting observations and measurements from current and planned Earth observing systems to measure atmospheric concentrations and profiles of GHGs from planned satellites; (4) undertaking designs and deploying the foundation components for a national, multi-tiered monitoring system with optimized measuring, monitoring, and verification systems; (5) deploying sounding instruments, biological and chemical markers (either isotopic or fluorescence), and ocean sensors on a global basis to monitor changes in ocean chemistry; (6) maintaining *in situ* observing systems to characterize local-scale dynamics of the carbon cycle under changing climatic conditions; and (7) maintaining *in situ* observing systems to monitor the effectiveness and stability of CO_2 sequestration activities.

Through sustained investments, the United States can: (1) enhance its ability to model emissions based on a dynamic combination of human activity patterns, source procedures, energy sources, and chemical processing; (2) develop process-based models that reproduce the atmospheric physical and chemical processes (including transport and transformation pathways) that lead to the observed vertical profiles of GHG concentrations due to surface emissions; (3) determine to what degree natural exchanges with the surface affect the net national emissions of GHGs; (4) develop a combination of space-borne, airborne (including satellite, aircraft, and unmanned aerial vehicles), and surface-based scanning and remote sensing technologies to produce 3D, real-time mapping of atmospheric GHG concentrations; (5) develop specific technologies for sensing of global methane “surface” emissions with resolution of 10 km; (6) develop remote sensing methods to determine spatially resolved vertical GHG profiles rather than column averaged profiles; and (7) develop space-borne and airborne monitoring for soil moisture at resolutions suitable for measurement and monitoring activities.

With continuing progress in GHG measuring and monitoring systems, field data can guide and inform policy decisions and research plans for the development and deployment of advanced climate change technologies. The technology components of future strategies to reduce, avoid, capture or sequester CO_2 and other GHG emissions, can be better supported, enabled and evaluated.

8.7 References

Energy Information Administration (EIA). 2004. *Voluntary reporting of greenhouse gases 2002*. DOE/EIA-0608(2002). Washington, DC: Energy Information Administration. January. http://www.eia.doe.gov/oiaf/1605/vrrpt/. For additional information on reporting requirements, see: EIA 1994. *General guidelines for the voluntary reporting of greenhouse gases under Section 1605(b) of the Energy Act Policy of 1992*. Washington, DC: Energy Information Administration. http://www.eia.doe.gov/oiaf/1605/1605b.html

Integrated Earth Observation System (IEOS). 2005. Strategic Plan for the U.S. Integrated Earth Observation System. http://ostp.gov/html/EOCStrategic_Plan.pdf

Post, W.M., R.C. Izaurralde, J.D. Jastrow, B.A. McCarl, J.E. Amonette, V.L. Bailey, P.M. Jardine, T.O. West, and J. Zhou. 2004. Enhancement of carbon sequestration in US soils. *Bioscience* 54:895-908.

U.S. Climate Change Technology Program (CCTP). 2003. *Technology options for the near and long term.* DOE/PI-0002. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL). 2004. Geological sequestration of CO2: the GEO-SEQ project. http:/www.netl.doe.gov/publications/factsheets/project/Proj287.pdf

U.S. Department of Energy (DOE), Oak Ridge National Laboratory (ORNL). 2003. Ameriflux. http://public.ornl.gov/ameriflux/

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9 Bolster Basic Science Contributions to Technology Development

The challenge of encouraging and sustaining economic growth, while simultaneously reducing GHG emissions, calls for the development of an array of new and advanced technologies. Such an undertaking depends on and can be assisted significantly by new scientific knowledge arising from basic research. Chapters 4 though 8 of this *Plan* present a number of technology research and development (R&D) activities believed to be important to technological progress and attainment of Climate Change Technology Program (CCTP) strategic goals. Each technology area appearing in these chapters is associated with a technology strategy for development, replete with highlighted activities, links to ongoing R&D programs, and the identification of promising areas for future research.

All of these technology development activities could potentially benefit from basic research in underlying scientific and technical disciplines. Fundamental discoveries can reveal new properties and phenomena that can be applied to development of new energy technologies and other important systems. These can include, but are not limited to, breakthroughs in understanding of biological functions, properties and phenomena of nano-materials and structures, computing architectures and methods, plasma sciences, environmental sciences, and many more that are currently on the horizon.

Of CCTP's seven core approaches to be followed in pursuit of its six strategic goals, one of the most important for advancing R&D is to strengthen basic research in Federal research facilities and in universities. A strong and creative basic research program can nurture this strengthening. It can also give rise to knowledge and technical insights necessary to enable technical progress throughout CCTP's portfolio of applied R&D, explore novel approaches to new challenges, and bolster the underlying knowledge base for new discoveries.

In considering the roles for basic research and related organizational planning in advancing climate change technology development, opportunities for contributions may be characterized as follows:

- **Fundamental Research**: Fundamental research is basic research that provides the underlying foundation of scientific knowledge and understanding necessary for carrying out more applied activities of research and problem solving. It is the systematic study of properties and natural behavior that can lead to greater knowledge and understanding of the fundamental aspects of phenomena, properties, and observable facts, but without prior specification toward applications to design or develop specific processes or products. It includes scientific study and experimentation in the physical, biological, and environmental sciences and many interdisciplinary areas, such as computational sciences. Although not directly related to CCTP, it is the source of much of underlying knowledge that will enable future progress in CCTP.

- **Strategic Research**: Strategic research is basic research that is inspired by technical challenges in the applied R&D programs. This is research that could lead to fundamental discoveries (e.g., new properties, phenomena, or materials) or scientific understanding that could be applied to solving specific problems or technical barriers impeding progress in technology development in energy supply and end-use, carbon capture, storage and sequestration, non-CO_2 GHGs, and monitoring and measurement. This "strategic" research applies knowledge gained from more fundamental science research to the more practical problems associated with technology R&D.

- **Exploratory Research**: Exploratory research is basic research undertaken in the pursuit of novel or emergent concepts, not elsewhere covered, that are often too risky or multi-disciplinary for a particular R&D program to support. Many such novel approaches are pursued within existing R&D programs, but sometimes new concepts do not fit neatly within the constructs of the existing mission-specific programs. Therefore, not all of the research on innovative concepts for climate-related technology is, or should be, aligned directly with an existing Federal R&D mission-related program. This *Plan* calls for new breakthroughs in technology development that could dramatically change the way energy is produced, transformed, and used in the global economy. Exploratory research of innovative and novel concepts, not elsewhere covered, is one way to uncover such "breakthrough technology", strengthen the community, and broaden the R&D portfolio.

- **Integrated Planning**: Effective integration of fundamental research, strategic research, exploratory research and applied technology development presents challenges to and opportunities for both the basic research and applied research communities. These challenges and opportunities can be effectively addressed through innovative and integrative planning processes that place emphasis on communication, cooperation and collaboration among the many associated communities. CCTP strongly encourages and plans to build on the successful models and best practices in this area.

This chapter discusses the potential research contributions to climate-related technology development of each of the above categories. Section 9.1, *Fundamental Research*, describes the basic science that provides the underlying scientific knowledge needed to underpin other research. Section 9.2, *Strategic Research in Support of Technology R&D Programs,* describes the basic science underway or planned that explores the key technical challenges associated with the five strategic goals discussed in Chapters 4 through 8. Section 9.3, *Exploratory Research on Innovative Concepts and Enabling Technologies*, addresses the basic research of novel concepts and others areas that are important to the climate change technology development agenda, but not elsewhere covered. Finally, CCTP recognizes that clarifying and communicating research needs of the applied technology R&D programs will help the basic science programs plan and focus future efforts in key areas of need. Therefore, Section 9.4, *Toward Enhanced Integration in R&D Planning Processes,* describes an approach to better integrating basic research with the applied programs related to climate change technology.

9.1 Fundamental Research

At the outset of the 21st century, science appears to be on the threshold of many new and promising discoveries across a variety of fields. In addition, the rapidly developing global infrastructure for computing, communications, and information is expected to accelerate scientific processes through computational modeling and simulation and reduce the time and cost of bringing new discoveries to the marketplace. These potential discoveries and infrastructure developments portend a rapid advancing of capabilities to further the development of CCTP technologies. Fundamental research in the following areas is representative of the opportunities afforded and serves as a reminder of the importance of sustained leadership and continued support of the pursuit of fundamental scientific knowledge.

9.1.1 Physical Sciences

Many of the advances in lowering energy intensity have come from developments in the materials and chemical sciences, such as new magnetic materials; high strength, lightweight alloys and composites; novel electronic materials; and new catalysts, with a host of energy technology applications. Two remarkable explorations—observing and manipulating matter at the molecular scale, and understanding the behavior of large assemblies of interacting components—may accelerate the development of more efficient, affordable, and cleaner energy technologies. Nanoscale science research—the study of matter at the atomic scale—will enable structures, composed of just a few atoms and molecules, to be engineered into useful devices for desired characteristics such as super-lightweight and ultra-strong materials. Underpinning these basic research explorations are the powerful tools of science, including a suite of specialized nanoscience centers and the current generation synchrotron x-ray and neutron scattering sources, terascale computers, higher resolution electron microscopes, and other atomic probes. Fundamental research in the physical sciences includes research in material sciences, chemical sciences and geosciences, all of which are described in more detail below.

- *Materials sciences* research helps in the development of energy generation, conversion, transmission, and use. Research currently being conducted by the U.S. Department of Energy (DOE) and relevant to climate-related technology involves fundamental research for the development of advanced materials for use in fuel cells, exploration of corrosion and high-temperature effects on materials with potential crosscutting impacts in both energy generation and energy use technologies, investigations of radiation-induced effects relevant to nuclear fission and fusion technologies, fundamental research in condensed matter physics and ceramics that might lead to high-temperature superconductors and solid-state materials, electro-chemistry research leading to better energy storage devices, chemical and metal hydrides research related to hydrogen storage, and nanoscale materials science (see Figure 9-1) and technology that offer the promise of designing materials and devices at the atomic and molecular level.

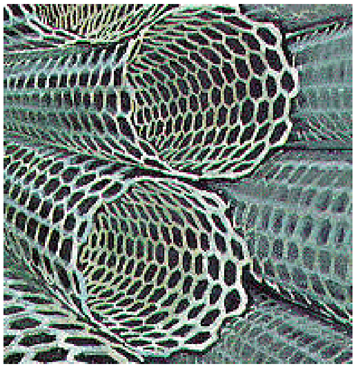

Figure 9-1. Carbon Nanostructure

- *Chemical sciences* research provides the fundamental understanding of the interactions of atoms, molecules, and ions with photons and electrons; the making and breaking of chemical bonds in gas phase, in solutions, at interfaces, and on surfaces; and the energy transfer processes within and between molecules. The fundamental understanding resulting from this research—an understanding of the chemistries associated with combustion, catalysis, photochemical energy conversion, electrical energy storage, electrochemical interfaces, and molecular specific separation from complex mixtures—could result in reductions in carbon dioxide emissions. Advances in chemical sciences will enable the development of hydrogen as an energy carrier; new alternative fuels; low-cost, highly active, durable cathodes for low-temperature fuel cells; separations and capture of CO_2; and catalysts for new industrial and energy processes.

- *Geosciences* research supports mineral-fluid interactions; rock, fluid, and fracture physical properties; and new methods and techniques for geosciences imaging from the atomic scale to the kilometer scale. The activity contributes to the solution of problems in multiple DOE mission areas, including development of the scientific basis for evaluating methods for sequestration of CO_2 in subsurface regions; for the discovery of new fossil resources, such as oil and gas, and methane hydrates; and for techniques to locate geothermal resources, to map and model geothermal reservoirs, and to predict heat flows and reservoir dynamics.

9.1.2 Biological Sciences

The revolution in genomics research has the potential to provide entirely new ways of producing forms of energy, sequestering carbon, and generating materials that require less energy to produce. It includes research to investigate the underlying biological processes of plants and microorganisms, potentially leading to new processes and products for energy applications, thereby enabling the harnessing of natural processes for GHG mitigation. Research includes:

- *Genomic research on microbes* focusing on their ability to harvest, store, and manipulate energy in almost any form to carry out life's functions. Current genomic research is focused on sequencing microbes that either aid in carbon sequestration or produce fuels.

- *Genomic research on plants*—for example, on the genome of Poplar, a common tree species—is characterizing key biochemical functions that could improve the ability of these trees to sequester carbon or produce biofuels.

- Research on *biological catalytic reactions* aims to improve the understanding of reactions in photoconversion processes and advanced techniques for screening and discovering new catalysts.

- Research related to *engineered plants and soil microorganisms* can provide a basis for use and renewal of marginal lands for bio-based energy feedstocks, incorporating stress-resistant plants and microbes, and developing advanced bioengineering approaches to capturing and retaining nitrogen and other essential plant nutrients.

- *Biotechnology* has the potential to provide the basis for direct conversion of sunlight into hydrogen. Work in this field can accelerate an understanding of fundamental aspects of microbial production systems, including thermophilic, algal, and fermentative approaches.

- New *bio-based industrial processes* can be developed, involving combining biological functionality with nano-engineered structures to achieve new functionalities and phenomena. Incorporating biological molecular machines (such as elements of photosynthetic chromophores) into nanostructures has the potential to achieve the selectivity and efficacy of biological processes with the high intensity and throughput of engineered processes.

- Research on key *biotechnology platforms* includes designs for bio-refineries to produce bio-fuels, bio-power, and commercial chemical products derived from biomass rather than fossil fuels; fuel cells powered by bio-based fuels or bio-generated hydrogen; engineered systems to support processes such as direct photo-conversion utilizing bio-based processes of water, CO_2, and nitrogen to produce useful fuels; and small modular bio-power systems for incorporation of biological processes.

9.1.3 Environmental Sciences

Research in the environmental sciences is undergoing a revolution with the development and application of new tools for measuring and monitoring environmental processes both *in situ* and remotely at scales never before possible. These new tools will provide data on the functioning of ecological systems, including the provision of goods and services such as sequestering carbon and how they are affected by environmental factors. Genomics research is and will continue to contribute to the advances in environmental sciences by providing understanding of the fundamental processes, structures, and mechanisms of complex living systems, including ecological systems. Examples of such fundamental research include the following:

Figure 9-2. Free-Air CO_2 Enrichment (FACE) Facility

- *Carbon sequestration research* could identify how efforts to increase terrestrial carbon sequestration might influence other environmental processes, such as nutrient cycling, the emissions of other GHGs, and local, regional, and global climate through impacts on heat balances and albedo (Figure 9.2).

- In *biological and ecological processes* there is a need to understand, quantify, predict, and manage biological and ecological processes affecting carbon allocation, storage, and capacity in terrestrial systems.

- Understanding the *ocean biological pump* is important for identifying the biogeochemical mechanisms of conversion and transport of carbon between the atmosphere and surface waters, and between the surface waters and the deep ocean, as well as to identify key processes for carbon cycling in marine sediments and how those processes are coupled to the water column.

- Research can be focused on the development of sensors that allow *measuring and monitoring* of environmental carbon flows. Computational models can be developed that can simulate and predict carbon flows resulting from, for example, specific carbon management policy actions and that provide a consistent picture of the effectiveness of efforts to reduce anthropogenic emissions.

- Research can be conducted on *indoor air quality* and its interrelationship with other buildings-related environmental factors, so as to understand the possible ramifications of increasing the energy efficiency of buildings.

9.1.4 Advanced Scientific Computation

Computational science is increasingly central to progress at the frontiers of almost every scientific discipline. The science of the future demands advances beyond the current computational capabilities. Accordingly, new advanced models, tools, and computing platforms to dramatically increase the effective computational capability available for scientific discovery in such areas as fusion, nanoscience, climate and environmental science, biology, and complex systems are necessary. With advances in computation, its role will become even more central to a broad range of future discoveries and subsequent innovations in climate change technologies. Examples of areas in which exploratory modeling and simulation research are being employed to assist in the development of advanced energy systems include the following:

- Modeling and simulation of advanced fusion energy systems to support ITER and the National Ignition Facility (NIF)

- Modeling of combustion for advanced diesel engines and other combustion systems; modeling of heat transfer in thermoelectric power systems

- Modeling and simulation of nanoscale systems (the computational effort required to simulate nanoscale systems far exceeds any computational efforts in materials and molecular science to date)
- Improved models of photovoltaics and other materials
- Improved models of the aerodynamics of wind turbines and other fluid dynamics processes
- Computer-assisted simulations of proposed advanced components and energy systems
- Predictive modeling of physical systems.

9.1.5 Fusion Energy Sciences

The majority of fusion energy sciences research is aligned, generally, with the goal of providing the knowledge base for an environmentally and economically attractive energy source (summarized in Section 9.2.2); the remainder of the basic research is fundamental in nature. This research includes general plasma sciences, the study of ionized gases as the underpinning scientific discipline for fusion research, through university-based experimental research, theory, plasma astrophysics, and plasma processing and other applications. See also Section 5.5.

9.2 Strategic Research

Scientific research enables both current and new generations of technologies that are needed to address the problem of GHG emissions. The outcomes expected from scientific research are time-variant:

- In the **near-term**, a significant role of research is to overcome bottlenecks and barriers that presently limit or constrain the development and application of technologies that are progressing toward commercial status. Some of the barriers include a lack of suitable materials, the need for information on key processes, and the need for new instrumentation and methods. Research will contribute to studying the feasibility of new technologies, solving key materials and process issues, developing new instrumentation and methods, and reducing costs. For example, science-based analyses will help to assess the viability of carbon storage and sequestration over the next decade; to better understand the interactions between engineered systems and natural systems (e.g., in systems involving biotechnology); and to solve materials and chemistry problems in advanced energy systems, such as hydrogen production and fuel cells.

- In the **mid-term**, science will take nascent ideas and develop them to the point they can enter the technology cycle. For example, innovations achieved through the support of science programs may result in new nanomaterials and devices for energy transformation, the ability to capture bioenzymes in biomimetic membranes for various energy applications, advances in plasma science for the development of fusion energy, and identification of new materials and efficient processes for hydrogen production, storage, and conversion.

- In the **long-term**, the current wave of research "at the frontier" may open up entirely new fields involving genomics and the molecular basis of life, computational simulations, advanced analytical and synthetic technologies, and novel applications of nanoscience and nanotechnology. It is hard to predict discoveries that will open entirely new ways of making, transforming, and using energy, or dramatically alter industrial processes.

Much of the research needed to address the complex challenges of climate change technology development requires cross-cutting strategic research approaches. These are discussed in the sections that follow, organized by the CCTP strategic goals (Chapters 4-8):

- Reduce Emissions from Energy End-Use and Infrastructure
- Reduce Emissions from Energy Supply
- Capture and Sequester Carbon Dioxide
- Reduce Emissions of Non-CO_2 Greenhouse Gases
- Enhance Capabilities to Measure and Monitor Greenhouse Gases.

9.2.1 Research Supporting Emissions Reductions from Energy End-Use and Infrastructure

There is a broad array of research that underpins emissions reductions from energy end-use and infrastructure, spanning the areas of transportation, buildings, industry, and electric grid and infrastructure. These areas of research include, but are not limited to, the following:

Transportation

Research on reducing vehicle weight while maintaining strength and safety includes *materials science* that improves efficiency, economy, environmental acceptability, and safety in transportation. Foci are ceramics and other durable high-temperature, wear-resistant materials and coatings, strong and lightweight alloys, polymers, and composite materials for structural components. *Joining and welding science* will enable the application of advanced materials.

The *nanosciences* can potentially contribute to many aspects of energy efficient vehicles, engines, and engine processes. Research can build on basic research in materials, chemistry, and computation to develop fundamentally new types of materials with specific desired properties, including innovative applications such as highly conductive nanofluids for lubrication and cooling.

Advanced fuel cell concepts and materials, including *membrane research* and *fuel cell stack materials* will improved the efficiency of fuel cells along with their performance, durability, and cost.

Electrochemistry research may lead to innovations in onboard energy storage.

For conventional and novel sources of power in mobile applications, *thermoelectric materials* and *energy conversion* cycles can be developed and made more efficient.

Research on intelligent transportation systems can include *complex systems science* for sustainable transportation; and *computational science* and *improved mathematical algorithms and models* for improved traffic handling/management and for science, design, and performance simulation.

For both combustion and other transportation energy sources, research on the *energetics of chemical reactions* and the interactions of *fluid dynamics and chemistry* may significantly improve or transform the efficiency of energy-producing reactions. The design and development of efficient, clean burning designs can be accomplished more quickly and with a higher probability of success if *combustion models* are improved.

Buildings

In improving energy efficiency in the building envelope, *corrosion science* can contribute to more durable materials and coatings for external applications. The *joining and welding sciences* will support fabrication and construction of energy-efficient envelopes. *Materials science* will have a broad range of impacts, from building insulation to transparent films for energy-efficient windows to new classes of lightweight structural materials.

Building equipment will become more energy efficient through research in *plasma science* for arc lighting and *semiconductor alloys* for solid-state lighting, as well as *light-emitting polymers*. More efficient heating and cooling systems will be possible because of *combustion, materials, and engineering research* and fundamentally new approaches to heating and cooling will result from research into *thermoacoustics and thermoelectrics*. Breakthroughs in *magnetism* will enable more efficient motors.

Research in whole building integration will include the science behind *smart transistors* for energy-saving sensors and electronic devices, new and improved self-powered smart windows through research in *constricted-plasma source thin film applications, electrochromics* and *dye-sensitized solar cells*, as well as *multilayer thin film materials* and *deposition processes* to control the interior environment, and smart filters for water systems based on *tailored pore sizes* and *pore chemistry*.

Industry

A broad range of *materials research* (Figure 9-3) will lead to increased energy efficiency in industrial processes; areas of study include ion implantation, thin films, fullerenes, ceramics, alloys, composites, quasicrystals, welding and joining; foundations for nanomechanics and nano-to-micro assembly.

Solid-state physics and related sciences will support advanced, energy-efficient computer chip concepts and manufacturing.

Exotic sensors and controls and *superconducting quantum interference devices (SQUIDS)* will provide feedback to systems and reduce energy use as situations change.

Research into the *magneto-caloric effect* will lead to new, energy-efficient forms of industrial refrigeration.

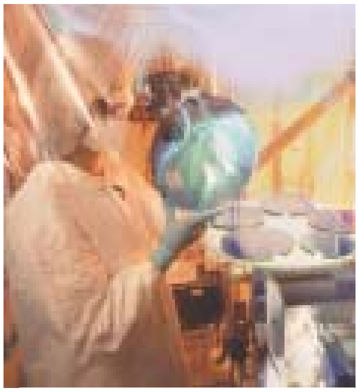

Figure 9-3. Use of Synchrotron Radiation for Materials Research

Electric Grid and Infrastructure

Materials that improve the transmission and storage of electricity will achieve highly improved energy efficiency. *Solid-state physics* and *materials science* will enable high-performance semiconductors and high-temperature superconductors. Other materials include *highly conductive high-strength nanowires; superlattices*; high-strength, lightweight *composites* and *corrosion-resistant materials; metallic glasses* for vastly improved transformers. *Silicon carbides* and *thin-film diamond switching* **devices** will improve performance and energy efficiency of power electronics and controls.

Electrochemistry research, including electrolytes, electrode materials, thin films, electrolytes, and interfaces, will improve commercial batteries.

Superconductivity research will make possible innovative storage devices.

Computational science and *computer/network science* will improve real-time control of the utility transmission infrastructure and, thus, its energy efficiency.

9.2.2 Research Supporting Emissions Reductions from Energy Supply

Strategic research underpinning emissions reductions from energy supply targets low-emissions fossil-based power, hydrogen, renewable energy and fuels, nuclear fission, and nuclear fusion. Research in these areas includes the following:

Low-Emissions Fossil-Based Power

Since high temperatures result in lower-emissions combustion, *materials research* can contribute improved and new materials for high temperature, pressure, and corrosive environments.

Research in *sensors* and sensor materials will lead to improved monitoring and control of processes in fossil fuel combustion.

Computational sciences will advance simulation and design, especially for improved models and codes for fluid dynamics, turbulence, and heat transfer modeling.

Catalysis research will find efficient pathways for use of fossil fuels, including a catalyst for petroleum refining and chemical manufacturing and catalysis of carbon-hydrogen bonds

Hydrogen

Research will focus on understanding the atomic and molecular processes that occur at the interface of hydrogen with materials in order to develop new materials suitable for use in a hydrogen economy. New materials are needed for membranes, catalysts, and fuel cell assemblies that perform at much higher levels, at much lower cost, and with much longer lifetimes.

In the hydrogen production area, a key focus is on *catalysts* and better understanding *mechanisms* for hydrogen production. In addition, biological enzyme catalysis, nanoassemblies and bio-inspired materials and processes are areas of basic research related to hydrogen production from biomass. Solar photelectochemisty and photocatalysis research may lead to breakthroughs in solar production of hydrogen, And, thermodynamic modeling, novel materials research and membranes and caalyst research may support nuclear hydrogen production.

Hydrogen storage is a major challenge. Basic science research related to storage includes the study of *hydrogen storage-hydrides, nanofibers, and nanotubes.* For instance, research on complex metal hydrides and chemical hydrides may support on-board recharging of fuel cell vehicles.

In the fuel cells area, *electrochemical energy conversion mechanisms* and *materials research* are important. In addition, there are identified needs for higher temperatuve memranes and tailored nnanostructures that basic science research could support.

Renewable Energy and Fuels

Biochemistry, bioenergetics, genomics, and *biomimetics* will lead to new forms of biofuels and capabilities for microbial conversion of feedstocks to fuels. This includes research on strategies for cellulose treatment, sugar transport, metabolism, regulation, and microbial systems design to develop microbes that can break down different types of complex biomass to sugars and ferment those sugars to ethanol or other fuels in a single microbe rather than the current two-step approach that uses enzyme cocktails for sugar production and yeast for fermentation. The research may lead to scientific breakthroughs in the design of a single microbe for making ethanol from cellulose. Similarly, basic research in *photochemistry* and *photocatalysis* will provide foundations for future, alternative processes for light-energy conversion, thin-film, and nanosciences research for photovoltaics, biofuels, and capabilities for microbial conversion. *Nanoscale hybrid assemblies* will enable the photo-induced generation of fuels and chemicals. *Plant genomic research* and function studies will make possible increased crop yields and disease resistance.

Geophysics and *hydrology* research will support a broad range of siting issues as well as hydro and geothermal power sources, e.g., mapping and monitoring geothermal reservoirs, and predicting heat flows and reservoir dynamics.

Plant biology, metabolism and *enzymatic properties* will support the development of improved biomass fuel feedstocks.

Research in *materials* and *composites* will lead to improved wind energy.

Research on key *biotechnology* platforms includes designs for biorefineries to produce biofuels, biopower, and commercial chemical products derived from biomass rather than fossil fuels.

Nuclear Fission Energy

Heavy element chemistry, advanced *actinide and fission product separations* and extraction, and *fuels research* will support better process controls in nuclear fission.

Fundamental research in *heat transfer* and *fluid flow* will lead to improve efficiency and containment.

Basic research will meet the *materials sciences* challenges of Gen IV reactor environments, with emphasis on the search for radiation-tolerant, ultra-strong, alloy and composite materials. Also research into *basic defect physics in materials*, equilibrium and radiation-modified *thermodynamics of alloys and ceramics* will improve reactor design. *Deformation and fracture studies* and analyses of *helium and hydrogen effects on materials* will contribute to safety and reliability of advanced nuclear energy systems, as will atomistic and three-dimensional *dislocation dynamics studies*, and *welding and joining science* to reduce failure rates and improve verification/certification practices.

Geophysical research will support nuclear siting.

Chemistry and corrosion research will improve design, operation, and predictability for performance.

Fusion Energy

Research in *burning plasmas* will validate the scientific and technological feasibility of fusion energy. Moreover, research aimed at a fundamental understanding of plasma behavior will provide a reliable predictive capability for fusion systems.

Studies will identify the most promising approaches and configurations for confining hot plasmas for practical fusion energy systems.

Research in materials, components, and technologies will be necessary to make fusion energy a reality.

A broad underpinning of *computational sciences* (Figure 9-4) will advance fusion research.

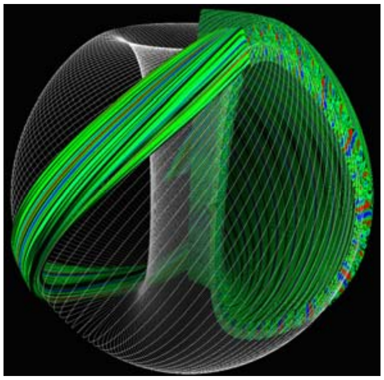

Figure 9-4. Magnetic Fusion Energy Simulation

9.2.3 Research Supporting Capture and Sequestration of Carbon Dioxide

Research on carbon capture and sequestration underpins the development of technologies and strategies for CO_2 capture and sequestration that are described in Chapter 6. Research areas include the following:

Carbon Capture and Storage in Geologic Repositories

Materials and *chemistry* research will enable separating CO_2 in stack gases, capturing it, and if needed, transforming it to another form of carbon that may be more useful.

Geophysics, *geochemistry*, and *hydrology* research of CO_2 repositories in geological formations will increase understanding of how CO_2 injected into such formations interacts with minerals and what the long-term fate of CO_2 would be after injection. This research will probe the factors that determine the residence time of carbon sequestered in soils, and ways in which the quantity and residence time of carbon sequestered in soils can be increased. Such research provides the scientific foundation for credible calculation of sequestration by terrestrial ecosystems. Environmental science research can identify how efforts to increase terrestrial carbon sequestration might influence other environmental processes, such as nutrient cycling, the emissions of other GHGs, and albedo effects on climate at all scales.

Modeling, *simulation*, and *assessment of geological repositories* are necessary to identify sites that have been or could be selected for use in sequestering CO_2 removed from industrial flue gases.

Basic *biological research* could lead to the development of technologies for enhancing the ability of trees to sequester carbon. For example, research on the genome sequence of black cottonwood, an important member of the widespread and important tree genus *Populus*, or poplar, is characterizing key biochemical functions.

Genomic research will develop traits that would enable plant species to grow and persist in environments that are of marginal quality and hence, may not be useful for purposes other than capturing carbon in plant biomass. Genomic research on microalgae and photosynthetic bacteria will develop traits that enable the organisms to efficiently capture and fix CO_2 separated from other industrial flue gases before it is released into the atmosphere.

Carbon Sequestration

Basic *biological research* could lead to the development of technologies for enhancing the biological capture of CO_2 directly from the atmosphere, including genomic research on algae and higher plants, such as *Populus*, with the objective of selecting or modifying strains to impart traits that result in, for example, increased rates of storage in relatively recalcitrant forms.

Research will discover the potential ancillary benefits and unintended consequences, and will provide the scientific foundation for quantifying and enhancing carbon sequestration in terrestrial ecosystems (in plant biomass and in soils).

Basic research on *ocean carbon sequestration* will aim to better understand the ocean biological pump and how it might be modified to enhance carbon sequestration in the ocean.

Research will explore ways of injecting CO_2 into the deep ocean, how long the injected CO_2 would remain isolated from the atmosphere, and what the potential *ecological and chemical* effects might be of injecting relatively pure streams of CO_2 into the deep ocean.

Research related to *engineered plants and soil microorganisms* can provide a basis for use and renewal of marginal lands for bio-based energy feedstocks, incorporating stress-resistant plants and microbes, and developing advanced bioengineering approaches to capturing and retaining nitrogen and other essential plant nutrients.

9.2.4 Research Supporting Emissions Reductions of Non-CO_2 Greenhouse Gases

Basic and applied research is also supported by Federal agencies to develop ways of reducing emissions of non-CO_2 GHGs. This includes research in *the physical sciences*, the *biological and environmental sciences*, and in *computational sciences*.

Work on *materials* and *chemistry* will lead to replacements for industrial processes that use non-CO_2 GHGs that have a high global warming potential.

Research on *thin films and membranes* will isolate non-CO_2 GHGs in industrial flue gases and other waste streams; *combustion research* will reduce emissions of nitrous oxide, ozone precursors, and soot; and *catalysis research* will reduce emissions of non-CO_2 GHGs.

Basic research in the *biological and environmental sciences*, including microbial processes in the rumen of farm animals, animal metabolism, and animal grazing will enable reductions in methane emissions by livestock. *Biological research* will increase understanding of soil microbes to reduce methane emissions from livestock feedlots.

9.2.5 Basic Research Supporting Enhanced Capabilities to Measure and Monitor Greenhouse Gases

There is a continuing need to develop more robust and sensitive sensors and monitoring systems to measure GHG emissions and concentrations and to understand the fate of GHGs released into the environment so that measurement and monitoring systems can be appropriately designed and sited to measure their fate. Such sensors need to be developed for making precise and accurate measurements in remote and/or hostile environments. Basic research in this area includes the following:

Various kinds of measurement for GHGs in the atmosphere are necessary. *Atmospheric physical and chemical processes* will lead to the observed vertical profiles of GHG concentrations due to surface emissions, while *remote sensing methods* will determine spatially resolved vertical GHG profiles rather than column-averaged profiles. Combined *airborne and surface-based scanning techniques* for remote sensing will yield three-dimensional, real-time mapping of atmospheric GHG concentrations. Specific technologies for *airborne remote sensing* will measure methane surface emissions at a 10-km spatial resolution.

Innovative technologies for non-invasive measurement of soil carbon will provide rapid methods for monitoring the effectiveness of carbon management approaches applied to terrestrial ecosystems and agricultural practices.

Microbial genomics research will seek to identify or develop eco-genomic sensors and sentinel organisms and communities for use in monitoring the effects of sequestering CO_2 in terrestrial soils and in the ocean.

Models will simulate and predict GHG emissions based on dynamic combinations of human activity patterns, energy technologies and energy demand, and industrial activities.

Environmental science and *computational science* can develop models that can simulate and predict carbon flows resulting from, for example, specific carbon management policy actions and that provide a consistent picture of the effectiveness of efforts to reduce GHG emissions.

9.3 Exploratory Research

Typically, the applied R&D programs, as described in Chapters 4 through 8, focus on completing well-defined research projects to meet deadlines and achieve results-oriented, specific metrics. As described in Section 9.2, strategic research has a long-term, basic research focus, yet is still oriented toward and inspired by understanding and contributing to solving problems associated with currently-supported technology development thrusts. To meet the challenges associated with the CCTP goals, there is a need to augment existing applied R&D and strategic research programs with exploratory research aimed at pursuing novel concepts, not elsewhere covered, for meeting CCTP goals. Some important generic areas for exploratory research may include, but would not be limited to:

- *Novel concepts*. Novel concepts, by definition, are “atypical” ideas and do not have funding support within the boundaries of traditional R&D organizations. They may build on scientific disciplines outside the usual disciplines in that field or attempt to apply previously-unexplored methods, and they may offer approaches that compete with the more traditional approaches already being pursued.

Yet, such concepts may lead to better ways to reduce GHG emissions, reduce GHG concentrations, or otherwise address the effects of climate change.

- *Advanced concepts*. Advanced concepts are high-risk, long-term ideas that are often too risky or unconventional for applied R&D programs to support, but are too purposeful or applied for basic research programs to support. For example, advanced concepts may be emerging in the field of biotechnology. While development of biofuels (e.g., ethanol) could be considered an accepted applied technology R&D area, advanced biotechnology concepts might include attempts to unlock the potential of the biological processes of plants and microorganisms through a combination of genomics, chemistry, biotechnology and bioengineering.

- *Integrative concepts*. Integrative concepts cut across R&D program lines and attempt to combine technologies and/or disciplines. An example might be a scheme that combines sequestration of carbon in soils with the development of a novel form of bio-energy. Integrative concepts might be difficult to coordinate across agencies or across traditional R&D program or mission areas; hence more concerted effort might be required to explore such concepts and manage research in these multi-mission areas.

- *Enabling concepts*. Enabling technologies contribute indirectly to the reduction of GHG emissions by enabling the development, deployment, and use of other important technologies that reduce GHG emissions.

- *CCTP decision-support tools*. Such tools include analytical, assessment, software, modeling, or other quantitative methods for better understanding and assessing the role of technology in long-term approaches to achieving stabilization of GHG concentrations in the atmosphere. While individual R&D programs sponsor the development of such tools, the tools thus developed are applicable mainly within their respective areas of responsibility or technologies.

Exploratory research on such areas, if not elsewhere covered among the existing Federal R&D programs, would not duplicate, but complement and potentially enrich, the existing R&D portfolio of climate-change-related strategic research and applied technology R&D. If the exploratory research revealed promising concepts, CCTP would then recommend such concepts for future support within the existing Federal R&D program areas. CCTP plans to explore agency experiences with such exploratory research programs, including those of the Defense Advanced Research Projects Agency, and encourage the pursuit of novel approaches, as appropriate, within the Federal climate change technology portfolio.

9.4 Toward Enhanced Integration in R&D Planning Processes

Effective integration of fundamental science, strategic research, exploratory research and applied technology R&D presents challenges and opportunities for any mission-oriented research campaign. These challenges and opportunities can be addressed by CCTP through enhanced integrative R&D planning processes that place emphasis on communication, cooperation and collaboration among the affected scientific and technical research communities.

Technology development programs are often hindered by incomplete knowledge and lack of innovative solutions to technical stumbling blocks. Information can be shared and potential pathways to solutions can be suggested by bringing together multi-disciplinary research expertise and applied technology developers. Increased discussion among research personnel from various complementary fields and face-to-face exploration of ideas is a good way to foster innovative ideas and create synergies. The traditional structure of research, operating mainly within the narrower confines of specific disciplinary groups, will not be sufficient.

A model integrated planning process would include:

- Systematic exploration of various technology program issues, challenges and impediments to progress
- Mechanisms to communicate technology program needs to the basic research community
- Exploration of a wide range of potential research avenues to address the identified issues, challenges and impediments
- Design of strategic research program areas to pursue the most promising avenues, including clear articulation of research goals
- Solicitations of research proposals to address the identified areas
- Funding of specific meritorious research projects, selected by a peer review process.

The first few steps in the model process described above could be accomplished using workshops and other multi-party planning mechanisms. For instance, in recognition of the growing challenges in the area of energy and related environmental concerns, the Department of Energy's Office of Basic Energy Sciences (BES) initiated a new series of workshops in 2002 focusing on identification of the underlying basic research needs related to energy technologies. The first of these workshops, in October 2002, undertook a broad assessment of basic research needs for energy technologies to ensure a reliable, economical, and environmentally sound energy supply for the future. More than 100 people from academia, industry, the national laboratories, and Federal agencies attended this workshop. A subsequent meeting in January 2003 focused on specific discussions of energy biosciences (BESAC 2003). Subsequent Office of Science activities have included a workshop on hydrogen production, storage, and use (BESAC, 2004, ANL 2004); catalysis (BESAC, 2002); solar energy utilization (DOE-SC 2005); and the roadmapping of various technology development processes, such as carbon sequestration (SC/FE 1999). CCTP will seek to encourage broader application, across all agencies, of the best practice in integrated research planning.

Based on the experiences of three workshops held by the Office of Science, Basic Energy Sciences, the following principles were identified to help guide future planning:

- *Make Merit-Based Decisions*: All decisions should be based on merit and need. Once this principle is compromised, the process degenerates quickly.
- *Share Ownership*: Long-term commitment and ownership by those in positions of authority and responsibility is a must for success.

- *Understand and Formalize Relationships*: Roles, responsibilities, rules of integration, allocation of resources, and terms of dissolution should be formalized at the start.

- *Measure Performance*: At the start, participants must agree on goals, objectives, operational elements, and methodology for measuring progress, outputs, and outcomes. (Avoid collaboration for collaboration's sake and integration for integration's sake.)

- *Ensure Commitment and Stability*: Team members must commit to work seamlessly, with the goal of a stable operation for the time necessary to achieve results.

- *Provide Flexibility*: Within general guidelines, flexibility ensures accountability and fosters innovation and experimentation. The process must allow for unanticipated results and empower people to act on their own.

- *Have a Customer Focus*: A clear understanding of who the customer is, what the customer wants, and the customer's complete involvement in all phases of the activity is critical to success.

Achieving the CCTP vision will likely require discoveries and innovations well beyond what today's science and technology can offer. Better integration of basic scientific research with applied technology development may be key to achievement of CCTP's other goals related to energy efficiency, energy supply, carbon capture and sequestration, measurement and monitoring, and reducing emissions of non-CO_2 gases. Basic science research is likely to provide the underlying knowledge foundation on which new technologies are built.

The CCTP framework aims to strengthen the basic research enterprise so that it will be better prepared to find solutions and create new opportunities. The CCTP approach includes strengthening basic research in Federal research facilities and academia by focusing efforts on key areas needed to develop insights or breakthroughs relevant to climate-related technology R&D. Another important component of basic research is training and developing the next-generation of scientists who will be needed in the future to provide continuity of such research to find solutions and create new opportunities.

9.5 References

Argonne National Laboratory (ANL). 2004. *Basic research needs for the hydrogen economy*. Argonne, IL: Argonne National Laboratory. http://www.sc.doe.gov/bes/hydrogen.pdf

Basic Energy Sciences Advisory Committee (BESAC). 2002. Basic Energy Sciences Advisory Committee Subpanel Workshop Report: Opportunities for Catalysis in the Twenty-First Century. http://www.sc.doe.gov/bes/besac/CatalysisReport.pdf

Basic Energy Sciences Advisory Committee (BESAC). 2003. *Basic research needs to assure a secure energy future*. http://www.sc.doe.gov/bes/besac/Basic_Research_Needs_To_Assure_A_Secure_Energy_Future_FEB2003.pdf

Basic Energy Sciences Advisory Committee (BESAC). 2004. Basic Research Needs for the Hydrogen Economy: A report to the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use.

Office of Science (SC) and Office of Fossil Energy (FE). 1999. *Carbon sequestration research and development*. Washington, DC: U.S. Department of Energy, Office of Science and Office of Fossil Energy. http://www.fe.doe.gov/programs/sequestration/publications/1999_rdreport/index.html

U.S. Climate Change Science Program (CCSP). 2003. *Strategic plan for the U.S. Climate Change Science Program*. http://www.climatescience.gov

U.S. Department of Energy, Office of Science (DOE-SC). 2005. *Basic research needs for solar energy utilization – report of the Basic Energy Sciences Workshop on Solar Energy Utilization*, April 18-21, 2005. http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf

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10 Conclusions and Next Steps

Under Presidential leadership, and in partnership with others, the United States is now embarked on an ambitious undertaking to develop new and advanced climate change technologies. These technologies have the potential to facilitate a global shift toward significantly lower greenhouse gas (GHG) emissions, and do so at substantially lower cost, while continuing to provide the energy-related and other services needed to spur and sustain economic growth.

The United States recognizes that making meaningful progress in such an undertaking will require a long-term commitment and international cooperation. By providing Federal leadership, through strategic direction and sustained commitment to a significant and well-guided portfolio of Federal R&D investments, CCTP seeks to strengthen the U.S. research enterprise; stimulate U.S. innovation and technology development on a broad scale, inside and outside the Federal Government; and inspire others at home and abroad to join in this effort. In this way, the United States intends to contribute to the building of a global technological capability that can achieve meaningful progress toward attainment of the world's shared commitment to the UNFCCC's ultimate objective.

Working under the auspices of the Cabinet-level Committee on Climate Change Science and Technology Integration (CCCSTI) and its Interagency Working Group on Climate Change Science and Technology (IWG), the U.S. Climate Change Technology Program (CCTP) seeks to provide strategic direction and effect coordinated implementation of the technological component of U.S. approach to climate change. CCTP, led by DOE, functions as a multi-agency planning and coordination entity, whose leadership and ongoing activities are both guided and carried out by representatives of its participating R&D agencies. CCTP's principal aim is to accelerate the advancement of technologies believed to be important to attaining its strategic goals.

CCTP's strategic goals parallel the opportunities for advanced technologies to contribute to the attainment of CCTP's mission and vision (Chapter 2). These opportunities were identified, in part, by the synthesis assessment of a number of long-term studies and analyses (Chapter 3). To the extent that agency missions and other priorities may allow, each participating CCTP agency will be guided by applicable elements of this *Strategic Plan* and align the relevant components of its R&D portfolio in ways that are consistent with and supportive of one or more of following CCTP strategic goals:

- Reduce emissions from energy end-use and infrastructure
- Reduce emissions from energy supply
- Capture, store, and sequester carbon dioxide (CO_2)
- Reduce emissions of non-CO_2 greenhouse gases
- Improve capabilities to measure and monitor GHG emissions
- Bolster basic science contributions to technology development

Consistent with principles established by the President, CCTP and its participating R&D agencies will pursue seven approaches to ensure progress toward attainment of CCTP's strategic goals: (1) strengthen climate change technology R&D; (2) strengthen basic research contributions; (3) enhance opportunities for partnerships; (4) increase international cooperation; (5) support cutting-edge technology demonstrations; (6) ensure a viable technology workforce of the future, and (7) provide supporting technology policy. To one extent or another, all approaches may be applied to each strategic goal.

Much work lies ahead. The next steps outlined at the end of this chapter indicate where CCTP's work will focus in the coming years. Much work is also underway. Core R&D programs related to climate change are being examined and strengthened. In certain research areas, the R&D portfolio has been realigned. Proposals for future technology R&D investments are now being evaluated, in part, on their ability to contribute to CCTP strategic goals. In some research areas, climate change strategic goals have provided compelling motivations for new or realigned program rationales, thus strengthening the overall CCTP R&D portfolio.

10.1 Portfolio Priorities and Current Emphasis

Emerging from this ongoing planning, coordination, and prioritization process is a CCTP R&D portfolio of activities that is reasonably well aligned with CCTP's strategic goals, but where additional refinements are expected. The CCTP portfolio is at an early stage of development, will undergo further scrutiny and evaluation, and is expected to continue to evolve as CCTP and its participating R&D agencies become more informed by analyses and technology assessments, search for key gaps and opportunities, and plan for the future.

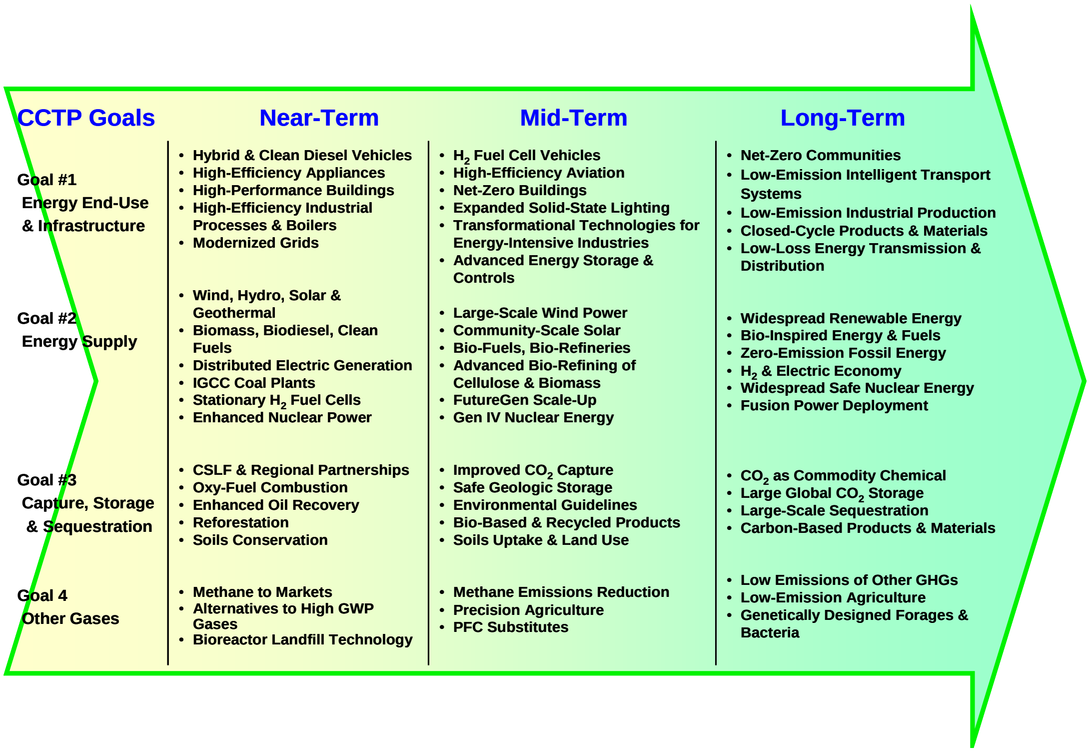
Chapters 4 through 9 of this *Strategic Plan* examine the potential role for advanced technology to address each of CCTP's six strategic goals. These chapters articulate strategies for technology development, highlight ongoing R&D activities aligned with these strategies, and identify promising directions for future research, particularly in basic research areas. Representative technologies arising from these strategies are shown graphically by CCTP strategic goal in Figure 10-1 and summarized in the sections that follow.

10.1.1 Energy End-Use

The Federal government makes a substantial investment in the development of advanced energy efficiency technologies. Owing to the readiness of many of energy-efficient technologies in the near term, this area of the CCTP research and technology development portfolio is augmented by significant expenditures on technology deployment activities.

The existing CCTP portfolio related to energy end-use reduction is diverse, supporting an array of potentially productive avenues for reduced emissions in all sectors of the economy. Some of the research efforts are directed at lowering energy consumption and emissions in residential and commercial buildings, and in industrial facilities and processes. In addition, one of the more significant thrusts is toward new transportation technologies. Analyses suggest that the transportation sector, apart from electricity generation, may have the highest growth in global CO_2 emissions over the next 25 years. The CCTP portfolio emphasizes the introduction and expanded use of low-carbon fuels and other energy carriers, such as hydrogen, as well as research initiatives directed toward advanced light and heavy vehicles, organized primarily under the FreedomCAR program and the 21st Century Truck Partnership, involving the Departments of Transportation, Energy, and Defense (DOT, DOE, and DoD). These programs include research on fuel cell vehicles that use hydrogen (in cooperation with the Hydrogen Fuels Initiative).

Another important component of this strategic area is modernizing the electricity transmission grid and its associated infrastructure, particularly because such modernization can enable the use of technology for many new and advanced supply and end-use technologies. Significant efficiency gains are possible from



CCTP Goals	Near-Term	Mid-Term	Long-Term
Goal #1 Energy End-Use & Infrastructure	• Hybrid & Clean Diesel Vehicles • High-Efficiency Appliances • High-Performance Buildings • High-Efficiency Industrial Processes & Boilers • Modernized Grids	• H_2 Fuel Cell Vehicles • High-Efficiency Aviation • Net-Zero Buildings • Expanded Solid-State Lighting • Transformational Technologies for Energy-Intensive Industries • Advanced Energy Storage & Controls	• Net-Zero Communities • Low-Emission Intelligent Transport Systems • Low-Emission Industrial Production • Closed-Cycle Products & Materials • Low-Loss Energy Transmission & Distribution
Goal #2 Energy Supply	• Wind, Hydro, Solar & Geothermal • Biomass, Biodiesel, Clean Fuels • Distributed Electric Generation • IGCC Coal Plants • Stationary H_2 Fuel Cells • Enhanced Nuclear Power	• Large-Scale Wind Power • Community-Scale Solar • Bio-Fuels, Bio-Refineries • Advanced Bio-Refining of Cellulose & Biomass • FutureGen Scale-Up • Gen IV Nuclear Energy	• Widespread Renewable Energy • Bio-Inspired Energy & Fuels • Zero-Emission Fossil Energy • H_2 & Electric Economy • Widespread Safe Nuclear Energy • Fusion Power Deployment
Goal #3 Capture, Storage & Sequestration	• CSLF & Regional Partnerships • Oxy-Fuel Combustion • Enhanced Oil Recovery • Reforestation • Soils Conservation	• Improved CO_2 Capture • Safe Geologic Storage • Environmental Guidelines • Bio-Based & Recycled Products • Soils Uptake & Land Use	• CO_2 as Commodity Chemical • Large Global CO_2 Storage • Large-Scale Sequestration • Carbon-Based Products & Materials
Goal 4 Other Gases	• Methane to Markets • Alternatives to High GWP Gases • Bioreactor Landfill Technology	• Methane Emissions Reduction • Precision Agriculture • PFC Substitutes	• Low Emissions of Other GHGs • Low-Emission Agriculture • Genetically Designed Forages & Bacteria

Figure 10-1. Roadmap for Climate Change Technology Development and Deployment for the 21st Century

(Note: Technologies shown are representations of larger suites. See Chapters 4 through 9 for more comprehensive information on technology strategies, development plans and timelines. With some overlap, "near-term" envisions significant technology adoption by 10 to 20 years from present, "mid-term" in a following period of 20-40 years, and "long-term" in a following period of 40-60 years. See also List of Acronyms and Abbreviations.)

the adoption of advanced technology and practices—such as distributed generation technologies; energy storage; sensors, controls, and communications; and power electronics, which can be applied in both developed and emerging economies. High-temperature superconductivity has the potential to revolutionize electric transmission systems. Technologies are needed that would make it possible to store energy for many hours at attractive costs to effectively make use of intermittent renewable energy technologies, thus permitting very large contributions from renewable energy to electricity supplies in the long term. More detail on these initiatives can be found in Chapter 4.

10.1.2 Energy Supply

Despite large and relatively cost-effective contributions expected in the CCTP technology strategy from energy-efficiency gains, energy supply technologies with low or net-zero GHG emissions are likely to be required under a range of advanced technology planning assumptions. Recent changes in the CCTP portfolio show increasing emphasis on low-emissions, fossil-based power and fuels; hydrogen; renewable energy and fuels; nuclear fission; and fusion energy. Details can be found in Chapter 5.

Selected highlights of key initiatives include (1) FutureGEN, aimed at demonstrating the viability of near-zero-emissions, high-efficiency, coal-based electricity generation plants with CO_2 capture and storage that have the ability to co-produce low-cost hydrogen; (2) the Hydrogen Fuel Initiative, which complements the FreedomCAR initiative and focuses on research to produce, store, and deliver hydrogen; (3) the International Partnership for the Hydrogen Economy (IPHE), which now involves 15 countries; (4) increasing emphasis on wind energy, biomass, and photovoltaics; (5) the next-generation nuclear fission energy systems (Generation IV) that offer advances in proliferation resistance, physical protection, safety, waste reduction, and economic efficiency; (6) the Nuclear Power 2010 program, designed to pave the way for an industry decision by the latter half of this decade to order at least one new nuclear power plant for deployment in the 2010-2015 timeframe; (7) the Advanced Fuel Cycle Initiative (AFCI), focused on developing advanced nuclear fuel cycle technologies; and (8) the international magnetic fusion experiment (ITER), which involves the United States, Europe, Japan, China, Russia, and the Republic of Korea.

10.1.3 Carbon Capture and Sequestration

Capture, storage, and sequestration of CO_2 may play a potentially transforming role in addressing climate concerns. In areas related to CO_2 capture, geologic storage, and oceanic sequestration, many questions regarding the technical, economic, and environmental acceptability will need to be explored and resolved. Early resolution of such issues is important, as the outcomes will have implications for investments in R&D on other technologies. Details on the research related to carbon capture, geologic storage, terrestrial sequestration, and ocean sequestration are presented in Chapter 6.

Important research activities include (1) the international Carbon Sequestration Leadership Forum (CSLF), which coordinates data gathering, R&D, and joint projects to advance the development and deployment of carbon sequestration technologies worldwide; (2) the Regional Carbon Sequestration Partnerships, which include seven regional partnerships of state agencies, universities, and private companies that form the core of a nationwide network designed to determine the best approaches for capturing and storing CO_2 for the long term; and (3) R&D programs in advanced forest and crop management systems, which are important to understanding and implementing cost-effective methods to enhance terrestrial sequestration. In addition, FutureGen (mentioned above) has elements relevant to this goal.

10.1.4 Other Greenhouse Gases

The CCTP analyses suggest that there are a number of potentially fruitful areas for technologies to mitigate growth in emissions of non-CO_2 GHGs and that such emissions-reduction contributions can be significant. The strategy for addressing non-CO_2 GHGs has two main elements. First, it focuses on the key emission sources of these GHGs and identifies specific mitigation options and research needs by gas, sector, and source. Given the diversity of emission sources, a generalized technology approach is not practical. Second, the strategy emphasizes both the expedited development and deployment of near-term and close-to-market technologies, and expanded R&D into longer-term opportunities that could lead to large-scale emission reductions, considering tradeoffs among mitigation options for carbon dioxide and other gases. By stressing both near- and long-term options, the strategy offers maximum climate protection in the early part of the 21st century and a roadmap to achieve dramatic gains in later years.

Research aimed at reducing emissions of these GHGs focuses on (1) methane emissions from energy and waste, (2) methane and nitrous oxide emissions from agriculture, (3) emissions of gases with high global warming potential, (4) nitrous oxide emissions from combustion and industrial sources, and (5) emissions of tropospheric ozone precursors and black carbon. Details are provided in Chapter 7.

10.1.5 Measurement and Monitoring

A wide assortment of GHG sensors, measurement platforms, monitoring and inventorying systems, models, and inference methods will likely be needed to meet the basic GHG emissions measurement requirements of the future. Measurement systems must be developed that can establish baselines and measure carbon storage and GHG fluxes at various scales, from individual projects to large geographic areas. Improved measurement and monitoring technologies and capabilities can also inform the state of climate science and help to identify and guide future opportunities for technology development.

Under the Applied Terrestrial Sequestration Partnership, the Department of Agriculture (USDA), DOE and the National Energy Technology Laboratory (NETL) are working to improve measuring and monitoring of GHG emissions and changes in soil carbon. For example, Laser Induced Breakdown Spectroscopy (LIBS), supported by USDA, DOE, and the National Aeronautics and Space Administration (NASA), is a breakthrough carbon measurement technology with the ability to quickly and cost-effectively measure carbon in soils. It will be key to the monitoring of terrestrial sequestration projects.

Another important project is Agriflux, a USDA-led network of 30 sites for measuring the effects of environmental conditions and agricultural management decisions on carbon exchange between the land and the atmosphere. Studies will identify crop management practices to optimize crop yield, crop quality, and carbon sequestration under carbon dioxide concentrations and other environmental conditions expected in the 21st century. A third example is AmeriFlux, a research network of 75 sites, used in collecting, synthesizing, and disseminating long-term measurements of CO_2, water, and energy exchange for a variety of terrestrial landscapes across the United States. Details are provided in Chapter 8.

The CCTP is encouraging integrative system design, with near- and long-term advances in technology. In the near term, it is possible to (1) incorporate transportation measurement and monitoring sensors into the onboard diagnostic and control systems of production vehicles; (2) prepare geologic sequestration measurement and monitoring technologies for deployment with planned demonstration projects; (3) exploit observations and measurements from current and planned Earth observing systems to measure atmospheric concentrations and profiles of GHGs from planned satellites; (4) undertake designs and deploy the foundation components for a national, multi-tiered monitoring system with optimized measuring, monitoring, and verification systems; (5) deploy sounding instruments, biological, and chemical markers (either isotopic or fluorescence), and ocean sensors on a global basis to monitor changes in ocean chemistry; (6) maintain *in situ* observing systems to characterize local-scale dynamics of the carbon cycle under changing climatic conditions; and (7) maintain *in situ* observing systems to monitor the effectiveness and stability of CO_2 sequestration activities. The Integrated Earth Observing System (IEOS) is an important part of these technology advances.

In the long term, with sustained future investments, it may be possible to (1) model emissions based on a dynamic combination of human activity patterns, emission sources, energy sources, and chemical processes; (2) develop process-based models that reproduce the atmospheric physical and chemical processes (including transport and transformation pathways) that lead to the observed vertical profiles of GHG concentrations due to surface emissions; (3) determine to what degree natural exchanges with the surface affect the net national emissions of GHGs; (4) develop a combination of space-borne, airborne (including satellite, aircraft, and unmanned aerial vehicles), and surface-based scanning and remote sensing technologies to produce three-dimensional, real-time mapping of atmospheric GHG concentrations; (5) develop specific technologies for sensing of global methane "surface" emissions with resolution of 10 km; (6) develop remote sensing methods to determine spatially resolved vertical GHG profiles rather than column averaged profiles; and (7) develop space-borne and airborne monitoring for soil moisture at resolutions suitable for measurement and monitoring activities.

10.1.6 Basic Science Support to Climate-Related Technology Development

A diverse range of energy sources, GHG emissions reduction strategies, and carbon sequestration technologies will be required to meet the climate change challenge, and similarly a broad range of basic science research is needed to enable these diverse technologies. Science is on the threshold of a variety of discoveries in biology, nanoscience, computational modeling and simulation, physical processes, and environmental sciences that offer opportunities, many yet unimagined, for innovations in both technologies and instrumentation. In addition, the rapidly developing global infrastructure for computing, communications, and information is expected to accelerate the scientific process and reduce the time and cost of bringing new discoveries to the marketplace. Such new discoveries may hold the ultimate key to GHG emissions reduction.

Workforce development and education are also integral components of any sustained and successful scientific and technological undertaking of this scope and magnitude. Basic research conducted in conjunction with CCTP goals can provide unique opportunities to strengthen and revitalize Federal investments in science, math, and engineering education, with an additional emphasis on climate change technology development. This would attract new talent to associated careers and ensure the growth of a future workforce knowledgeable and skilled in the needed technical areas.

In this area of the CCTP portfolio, three strategic thrusts are being pursued. One is to conduct basic research, that is, strategic research, in areas inspired by the technical challenges in the applied R&D programs associated with the CCTP strategic goals, described in Chapters 4 through 8. The second is to carry out, subject to the availability of funds, an exploratory research program on innovative concepts and enabling technologies, which have great potential for breakthroughs in new or unknown areas important to the climate change challenge. The third thrust is to improve and more widely implement an integrative R&D planning process that will better identify and facilitate agency pursuit of the basic science research needed by the applied climate change technology R&D programs. Recent examples of planning processes that have attempted to bolster this linkage between basic and applied R&D include workshops on carbon sequestration and hydrogen research needs.

10.2 Next Steps

The CCTP's next steps focus on two broad thrusts. First, the CCTP will continue to provide support to the Administration's leadership on climate change, namely, the Cabinet-level CCCSTI and its IWG. Support is likely to include activities such as multi-agency planning, portfolio reviews, interagency coordination, technical and other analyses, and formulation of recommendations. The CCTP will strive to provide support that will enable CCCSTI and the IWG to address issues, make informed decisions, and weigh policies and priorities on related science and technology matters to the President and the agencies.

Second, the CCTP will continue to work with and support the participating agencies in developing plans and carrying out activities needed to advance the attainment of the CCTP's vision, mission, and strategic goals. For each CCTP strategic goal, to the extent suitable for each goal, agency plans and activities will be guided by the seven core approaches.

Specific activities that follow these seven approaches are outlined below, although not all activities will be pursued at once.

Strengthen Climate Change Technology R&D

- Continue to review, realign, reprioritize, and expand, where appropriate, Federal support for climate change technology research, development, demonstration, and deployment.
- Periodically assess the adequacy of the multi-agency portfolio with respect to its ability achieve or make technical progress toward CCTP strategic goal attainment, identify gaps and opportunities, and make recommendations.
- In key technology areas, perform long-term assessments of technology potentials, including market considerations and potentially limiting factors.
- Develop improved methods, tools, and decision making processes for climate technology planning and management, and R&D planning and assessment, including tools that allow portfolio planning that addresses risk in a way that hedges that risk.

Strengthen Basic Research Contributions

- Establish or improve within each of the participating Federal R&D agencies a process for the integration with, and application of, basic research to help overcome barriers impeding technical progress on climate change technology development.
- Develop means for expanding participation in climate change technology R&D, including relevant basic research, at universities and other non-Federal research institutions.

Enhance Opportunities for Partnerships

- Review status and encourage further formation of public-private partnerships as a common mode of conducting R&D portfolio planning, program execution, and related technology demonstration, transfer, and commercialization activities.

Increase International Cooperation

- Expand international participation in key climate change technology activities; build on the many cooperative international initiatives already underway.
- Assist the Department of State and CCSP in the coordination of U.S. input and support of the IPCC's Fourth Assessment Report, Working Group III on Mitigation; the IPCC Special Report on Carbon Capture and Storage; and other relevant Special Reports, as means of stimulating international efforts to develop advanced technologies.

- Support continued efforts to negotiate and execute bilateral agreements that encourage international cooperation on climate change science and technology research. Pursue opportunities for outreach and communication to build relationships and encourage other country initiatives.

- Pursue additional means to enhance the effective use of existing international organizations, such as OECD, IEA, IPCC, Group of 8 (G8[1]), GEOSS, and others, to shape and encourage expanded R&D on climate change technology development worldwide. Witness the recent G8 Communiqué of Gleneagles, Scotland, and the assisting role envisioned for IEA.

- Develop globally integrated approaches, such as the recently established Asia-Pacific Partnership for Clean Development[2], to foster capacity building in developing countries, encourage cooperative planning and joint ventures and, enable the development, transfer and deployment of advanced climate change technology.

Support Cutting-Edge Technology Demonstrations

- As part of the agencies' regular planning and budgeting processes, consider additional cutting-edge technology demonstrations relevant to CCTP strategic goals.

Ensure a Viable Technology Workforce of the Future

- Explore the establishment of graduate fellowships for promising candidates who seek a career in climate-change-related technology research and development.

- Explore possibilities of expanding internships related to climate change technology development in Federal agencies, national and other laboratories, and other Federally Funded Research and Development Centers (FFRDCs).

- Explore possibilities for establishing CCTP-sponsored educational curricula in K-12 programs related to climate change and advanced technology options.

Provide Supporting Technology Policy

- Evaluate various technology policy options for stimulating private sector investment in CCTP-related research, development, and experimentation activities.

- Evaluate various technology policy options for stimulating private investment in advanced technology related to climate change or other GHG-related investments, and/or for accelerating the experimentation with and adoption of advanced technology to reduce GHGs.

- Evaluate various technology policy options for stimulating land-use and land management practices that promote carbon sequestration and GHG emission reductions.

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[1] The countries are, in alphabetical order, Canada, France, Germany, Italy, Japan, Russia, United Kingdom, and United States. The G8 meetings often include the European Commission.

[2] The Asia Pacific Partnership for Clean Development was announced in July 2005. Six countries are participating, namely: Australia, China, India, Japan, South Korea and the United States.

In carrying out these activities, CCTP will be advised by the CCTP Steering Group, assisted by its multi-agency CCTP Working Groups, informed by inputs from varied sources, and supported by CCTP staff and resources. Results will be conveyed to the CCCSTI via the Interagency Working Group. The CCTP also plans to issue reports on its current activities, future plans, and research progress.

10.3 Closing

This CCTP *Strategic Plan* completes an important step toward implementing the President's initiative in this area. The *Plan* provides a vision for the role of advanced technology in addressing climate change, defines a supporting mission for the multi-agency CCTP, establishes strategic direction for the Federal R&D portfolio within a framework of guiding principles, outlines the approaches to be employed in pursuing attainment of CCTP's six strategic goals, and identifies a series of next steps by which to effect progress on implementation.

As evidenced by the programs highlighted in Chapters 4 through 9, a number of important activities are underway in the Federal R&D portfolio, motivated by climate change considerations. However, much work remains to be done, both in following through on current commitments and in identifying and pursuing additional opportunities. With sustained vision and commitment, augmented by enhanced activity and cooperation from others, this technological undertaking will succeed, securing a bright energy and economic future for our Nation and ensuring a healthy planet for future generations.

10.4 References

Office of Management and Budget (OMB) 2005. *Federal climate change expenditures report to Congress*. Washington, DC: Executive Office of the President. http://www.whitehouse.gov/omb/legislative/fy06_climate_change_rpt.pdf

U.S. Department of Energy. 2003. *U.S. climate change technology program research and current activities*. DOE/PI-0001. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov

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Appendix A

Federal Research, Development, Demonstration and Deployment Investment Portfolio for Fiscal Years 2004 and 2005, with Budget Request Information for Fiscal Year 2006, U.S. Climate Change Technology Program

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Appendix A

Federal Research, Development, Demonstration and Deployment Investment Portfolio for Fiscal Years 2004 and 2005, with Budget Request Information for Fiscal Year 2006, U.S. Climate Change Technology Program

In order for the U.S. Climate Change Technology Program (CCTP) to carry out its mission, it is necessary to assess on a periodic and continuing basis the adequacy of Federal investments in the CCTP-relevant research portfolio and make recommendations. A first step in this regard is to compile an inventory, or baseline, of all the Federal research, development, demonstration and deployment (R&D) activities among the participating agencies relevant to the vision, mission and goals of the CCTP. This baseline, and subsequent years of data, can be used to identify and track trends and other changes in the portfolio.

The CCTP, OMB and other agencies agreed upon a set of classification criteria to identify R&D activities that would be included as part of the CCTP. These criteria are provided on page A-2.

The baseline information for the Federal R&D budget shown here are for Appropriations for Fiscal Years 2004 and 2005, and for the Administration's Budget Request for 2006. For each year, respectively, the participating Federal agencies submitted budget data for R&D activities that met the CCTP/OMB criteria. Table A-1 is a summary table for all participating agencies.

This baseline activity and resulting portfolio contributes to the requirement for the Office of Management and Budget (OMB) to report annually on Federal climate change expenditures. The multi-agency R&D baseline for CCTP constitutes the technology component of OMB's Federal Climate Change Expenditures Report to Congress.[1]

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[1] *Federal Climate Change Expenditures Report to Congress*, March 2005. This report is an account of Federal spending for climate change programs and activities, both domestic and international. The report is provided annually, as required by Section 559(b) of Public Law 107-115, Foreign Operations, Export Financing, and Related Programs Appropriations Act, 2002.

A.1 Climate Change Technology Program Classification Criteria

Research, development, and deployment activities[2] classified as part of the Climate Change Technology Program (CCTP) must be activities funded via discretionary accounts that are relevant to providing opportunities for:

- Current and future reductions in or avoidances of emissions of greenhouse gases,[3]
- Greenhouse gas capture and/or long-term storage, including biological uptake and storage;
- Conversion of greenhouse gases to beneficial use in ways that avoid emissions to the atmosphere;
- Monitoring and/or measurement of GHG emissions, inventories and fluxes in a variety of settings;
- Technologies that improve or displace other GHG emitting technologies, such that the result would be reduced GHG emissions compared to technologies they displace;
- Technologies that could enable or facilitate the development, deployment and use of other GHG-emissions reduction technologies;
- Technologies that alter, substitute for, or otherwise replace processes, materials, and/or feedstocks, resulting in lower net emission of GHGs;
- Technologies that mitigate the effects of climate change, enhance adaptation or resilience to climate change impacts, or potentially counterbalance the likelihood of human-induced climate change;
- Basic research activities undertaken explicitly to address a technical barrier to progress of one of the above climate change technologies, and
- Greenhouse gas emission reductions resulting from clear improvements in management practices or purchasing decisions.

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[2] In this context, “research, development, demonstration, and deployment activities” is defined as: applied research; technology development and demonstration, including prototypes, scale-ups, and full-scale plants; technical activities in support of research objectives, including instrumentation, observation and monitoring equipment and systems; research and other activities undertaken in support of technology deployment, including research on codes and standards, safety, regulation, and on understanding factors affecting commercialization and deployment; supporting basic research addressing technical barriers to progress; activities associated with program direction; and related activities such as voluntary partnerships, technical assistance/capacity building, and technology demonstration programs that directly reduce greenhouse gas emissions in the near and long term.

[3] Greenhouse gases (GHGs) are gases in the Earth’s atmosphere that vary in concentration and may contribute to long-term climate change. The most important GHG that arises from human activities is carbon dioxide (CO_2), resulting mainly from the oxidation of carbon-containing fuels, materials or feedstocks; cement manufacture; or other chemical or industrial processes. Other GHGs include methane from landfills, mining, agricultural production, and natural gas systems; nitrous oxide (N_2O) from industrial and agricultural activities; fluorine-containing halogenated substances (e.g., HFCs, PFCs); sulfur hexafluoride (SF_6); and other GHGs from industrial sources. Gases falling under the purview of the Montreal Protocol are excluded from this definition of GHGs.

A.2 Climate Change Technology Program Example Activities

Specific examples of climate change technology activities include, but are not limited to:

- Electricity production technologies and associated fuel cycles with significantly reduced, little, or no net GHG emissions;
- High-quality fuels or other high-energy density and transportable carriers of energy with significantly reduced, little, or no net GHG emissions;
- Feedstocks, resources or material inputs to economic activities, which may be produced through processes or complete resource cycles with significantly reduced, little or no net GHG emissions;
- Improved processes and infrastructure for using GHG-free fuels, power, materials and feedstocks;
- CO_2 capture, permanent storage (sometimes referred to as sequestration), and biological uptake;
- Technologies that reduce, control or eliminate emissions of non-CO_2 GHGs;
- Advances in sciences of remote sensing and other monitoring, measurement and verification technologies, including data systems and inference methods;
- Technologies that substantially reduce GHG-intensity, and therefore limit GHG emissions;
- Voluntary government/industry programs designed to directly reduce greenhouse gas emissions;
- Programs that result in energy efficiency improvements through grants or direct technical assistance.

***Note**: Programs and activities presented for consideration can include Congressionally mandated "earmarks," but earmarked activities must be relevant to one or more of the CCTP criteria, and descriptions and funding levels must be clearly called out as such in the information provided. Programs and activities funded by mandatory authorizations should not be included.*

A.3 CCTP Participating Agencies, Budgets and Requests

In the following budget table, data are provided on CCTP-related activities, per the criteria above, for Fiscal Years 2004 and 2005, and for the President's Budget Request for Fiscal Year 2006, across all CCTP participating agencies. In each FY, budget data includes activities for CCTP-related research, development and demonstration (R&D).

Table A-1
CCTP Participating Agency – FY 2004 to FY 2006 Budgets and Requests
Categorization of RDD&D Funding To Climate Change Technology
(Funding, $ Millions) (3)

Department and Account(s)	**FY 2004 Actual**	**FY 2005 Enacted**	**FY 2006 Proposed (Preliminary)**
Department of Agriculture			
Natural Resources Conservation Service – Biomass R&D (Section 9008 Farm Bill)	13.9	14.4	12.4
Natural Resources Conservation Service – Carbon Cycle	0.5	0.5	0.5
Forest Service R&D--inventories of carbon biomass	0.0	0.5	0.5
Agricultural Research Service--Bioenergy Research	2.4	2.4	2.4
Cooperative State Research, Education and Extension Service--Biofuels/Biomass research; formula funds, National Research Initiative	5.4	5.4	6.9
Forest Service--Biofuels/Biomass, Forest and Rangeland Research	0.4	2.4	2.5
Rural Business Service – Renewable Energy Program	22.8	22.8	10.0
Subtotal – USDA	**45.4**	**48.4**	**35.2**
Department of Commerce - NIST			
National Institute of Standards and Technology (NIST) Scientific and Technological Research and Services	9.8	9.5	7.4
Industrial Technical Services - Advanced Technology Program	18.1	20.2	0.0
Subtotal – DOC - NIST	**27.9**	**29.7**	**7.4**
Department of Defense			
Research, Development, Test and Evaluation, Army	15.3	50.5	43.0
Research, Development, Test and Evaluation, Navy	16.5	11.0	7.1
Research, Development, Test and Evaluation, Air Force	0.8	0.8	0.0
Research, Development, Test and Evaluation, Defense-wide	16.8	12.7	9.5
Research, Development, OSD	2.0	0.0	0.0
Subtotal – DOD	**51.5**	**75.0**	**59.6**
Department of Energy			
Energy Conservation	868.0	868.2	846.8
Energy Supply/Electricity Transmission & Distribution	73.0	103.0	84.0
Energy Supply/Nuclear	308.7	394.4	416.1
Energy Supply/Renewables	352.3	380.3	353.6
Fossil Energy R&D (Efficiency and Sequestration)	455.0	388.2	405.3
Science (Fusion, Sequestration, and Hydrogen)	332.7	370.6	398.7
Climate Change Technology Program Direction	0.0	0.0	1.0
Subtotal – DOE	**2389.6**	**2504.7**	**2505.5**

Department and Account(s)	**FY 2004 Actual**	**FY 2005 Enacted**	**FY 2006 Proposed (Preliminary)**
Department of the Interior			
US Geological Survey - Surveys, Investigations and Research - Geology Discipline, Energy Program	0.5	2.0	2.0
Subtotal – DOI	**0.5**	**2.0**	**2.0**
Department of Transportation			
Office of the Secretary for Technology - Transportation, Policy, R&D	4.0	0.8	0.0
National Highway Traffic Safety Admin	0.0	0.0	1.4
Research and Innovative Technology Admin	0.5	0.5	1.0
Subtotal – DOT	**4.5**	**1.3**	**2.4**
Environmental Protection Agency (1)			
Environmental Programs and Management	89.8	91.5	95.7
Science and Technology	20.5	17.5	17.7
Subtotal – EPA	**110.3**	**109.0**	**113.4**
National Aeronautics and Space Administration (2)			
Exploration, Science & Aeronautics	226.6	207.8	127.6
Subtotal – NASA	**226.6**	**207.8**	**127.6**
National Science Foundation			
Research and Related Activities	11.2	10.6	11.3
Subtotal – NSF	**11.2**	**10.6**	**11.3**
CCTP Total (3)	**2867.5**	**2988.5**	**2864.5**

USAID Activities Associated with CCTP (4)			
Development and Assistance	173.0	173.0	147.0
Subtotal – USAID	**173.0**	**173.0**	**147.0**
Total CCTP and Associated USAID Activities	**3040.5**	**3161.5**	**3011.5**

Notes:

(1) For EPA, FY 2005 Enacted numbers are for those of the President's FY05 request, not enacted, and that once EPA operating plans are complete, the FY05 numbers will change.

(2) For FY 2006, NASA went through a realignment within its Aeronautics Research. NASA no longer plans to pursue previously reported activities in certain vehicle systems areas.

(3) Totals may not add due to rounding. All agency data are as of March 2005.

(4) USAID activities are not included in the totals for CCTP, but are shown here for completeness, to the extent that such activities are consistent with the criteria for inclusion in CCTP, as shown below.

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