Global Energy Technology Strategy

ADDRESSING CLIMATE CHANGE

PHASE 2 FINDINGS FROM AN INTERNATIONAL
PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

GTSP

Global Energy Technology
Strategy Program

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JA Edmonds, MA Wise, JJ Dooley, SH Kim,
SJ Smith, PJ Runci, LE Clarke, EL Malone, GM Stokes

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TO THE READER

This report is the capstone to nine years of research in two phases of the Global Energy Technology Strategy Program (GTSP). That research was conducted at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of that work began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

Jae Edmonds
May 2007

Executive Summary

Global climate change is one of the most complex environmental, energy, economic, and political issues confronting the international community. Its time and geographic scales are unprecedented in their scope, touching every human activity that involves energy or land and requiring a strategy that stretches a century or more into the future. The actions needed to manage the risks of climate change require long-term commitments to severely limit net emissions of greenhouse gases to the atmosphere by developing and deploying new ways of producing and using energy across the world.

Human activities release greenhouse and other gases to the atmosphere at a rate that raises concerns about human-induced climate change. Greenhouse gases include carbon dioxide (CO_2), which accounts for most of the projected human influence on climate, and such gases as methane, nitrous oxide, sulfur hexafluoride, and several fluorinated gases. Other emissions such as aerosols (e.g., sulfur dioxide) also affect the Earth's climate system.

The total concentration of CO_2 and other greenhouse gases in the atmosphere at any given time is much more important in determining climate than are emissions in any single year. Limiting the risk of human impact on the climate system therefore requires that atmospheric concentrations be stabilized (see Figure ES-1).

Recognizing this fact, the United States and 188 other countries have ratified the 1992 United Nations Framework Convention on Climate Change (UNFCCC), and it has entered into force under international law. The ultimate objective of this treaty as articulated in Article 2 is to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

The UNFCCC process has not yet specified a particular target concentration. The preindustrial CO_2 concentration was approximately 280 parts per million (ppm); in 2004 the level had risen to 377 ppm. In order to stabilize concentrations of CO_2 at any level between 450 and 750 parts per million, very large reductions of worldwide emissions (compared to emissions that might be anticipated if present trends continue) would be required during the course of this century (see Figure ES-1).

THE CHALLENGE OF STABILIZING CO_2 CONCENTRATIONS

Stabilizing the **concentration** of CO_2, the most important greenhouse gas, is fundamentally different from stabilizing CO_2 **emissions**. Because emissions accumulate in the atmosphere, emissions of greenhouse gases can affect the atmosphere for hundreds of years. Some of the CO_2 emitted during the earliest days of the Industrial Revolution is still in the atmosphere, and today's emissions will cast a shadow a thousand years into the future.

The long-lived nature of greenhouse gases—and in particular CO_2—lies at the heart of the crucial difference between stabilizing annual emissions levels and stabilizing atmospheric concentrations. Stabilizing emissions at today's levels would cause the concentration of CO_2 to continue to rise. Stabilizing global annual emissions levels is not sufficient to stabilize atmospheric concentrations.

The goal of stabilizing CO_2 atmospheric concentrations has profound implications for the nature, scale and timing of needed changes in the global energy system. Stabilizing concentrations implies:

- Global net CO_2 emissions to the atmosphere must peak and then decline year after year until, eventually, they are virtually zero.

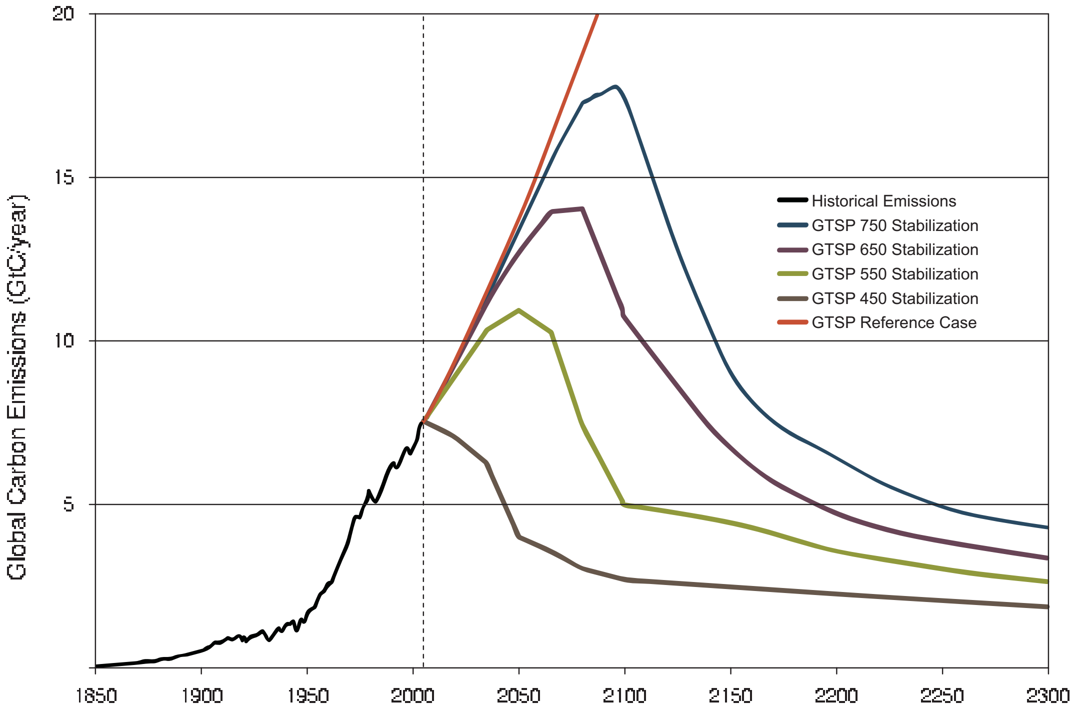


Figure ES-1. GTSP-generated global CO_2 emissions paths: historical emissions to 2005, a reference case (i.e., with no emissions-control policies), and four alternative paths that illustrate how emissions must eventually decline in order to stabilize CO_2 concentrations.

- Every ton of emissions released to the atmosphere counts against a budget of total allowable emissions, regardless of sector or region of origin. Over time, this global CO_2 emissions budget is drawn down and the remaining allowable emissions become scarcer and therefore more valuable. Thus, the price of carbon begins relatively low and will rise steadily with time.
- The key reason to develop and deploy advanced energy technologies is to control the cost of stabilizing greenhouse gas concentrations.
- The technical challenge, to invent and globally deploy energy systems that progressively release less CO_2, is unprecedented. The century-scale challenge implies that better technologies will be continuously needed in the near, middle, and long terms if costs are to be controlled.

RESPONDING TO THE CHALLENGE OF CLIMATE CHANGE

Addressing the challenge of climate change requires responses in at least four different domains:

- Improved scientific understanding
- Adaptation to climate change
- Emissions mitigation
- Development and implementation of a global energy technology strategy.

The focus of GTSP research is on energy technology. The development of a global energy technology strategy is an important component of a larger, more complete strategy and can help societies control the cost of addressing the climate challenge.

ENERGY TECHNOLOGIES ARE ESSENTIAL

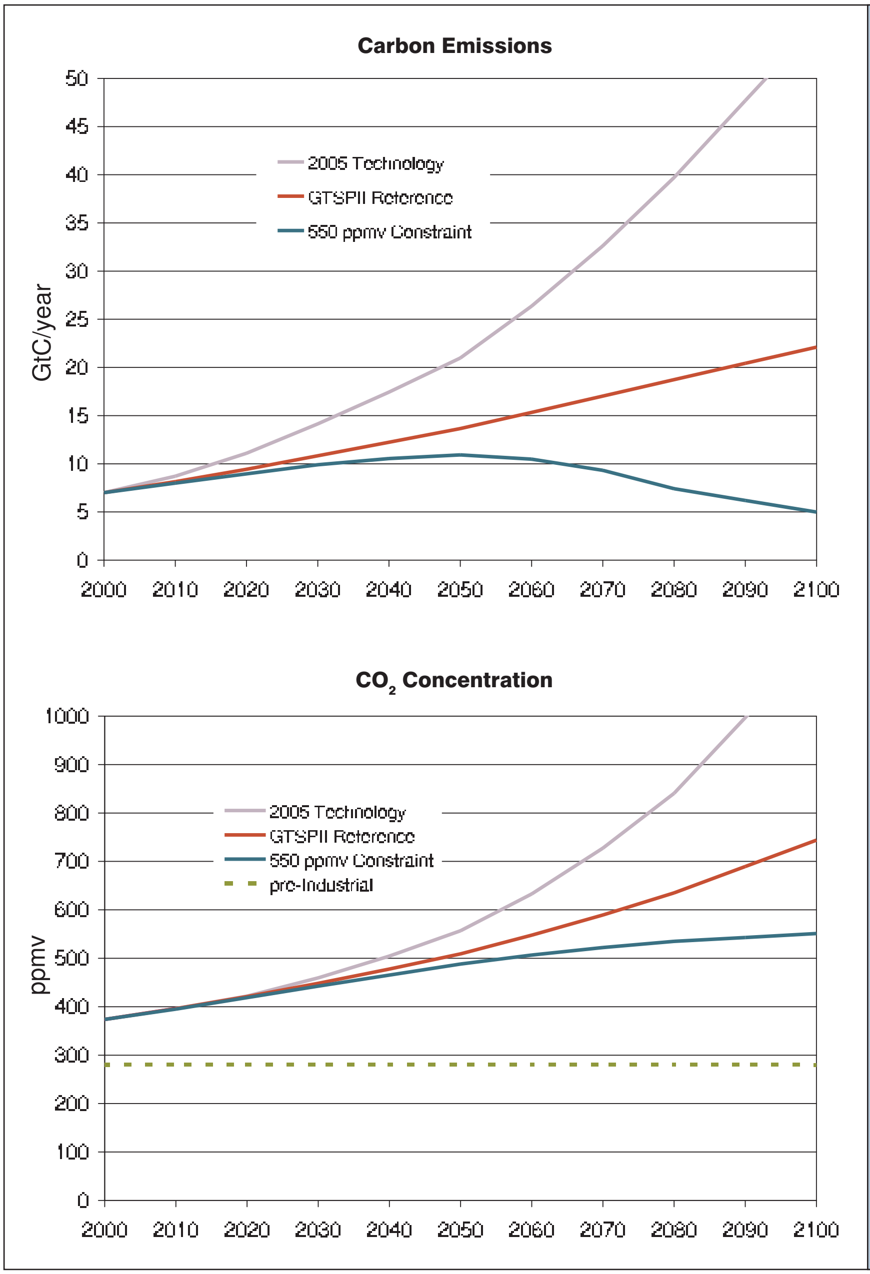
Energy and the technologies used to convert it into a myriad of goods and services are central to the global economy, to standards of living throughout the world—and to the climate issue. The large-scale, widespread use of energy technologies has been and continues to be a primary contributor to increases in greenhouse gas concentrations, mostly through CO_2 emissions from burning fossil fuels such as coal, gas, and oil.

Expected increases in world population, together with the desire for economic development, will lead to growing demand for the products and services that the energy system provides. The current global energy system is dominated by fossil fuels, and there are enormous quantities of fossil fuels still underground, more than enough to power the global economy for the remainder of this century and perhaps well beyond. How these fossil fuels and other energy sources are used will determine the future human influence on the global climate and whether there will be a rapid increase in greenhouse gas concentrations during this century. Managing the risks of climate change will require a profound, systematic, and global transformation in the production and consumption of energy.

ENERGY TECHNOLOGY STRATEGY

Fundamental changes in the world's expanding energy system are required to stabilize concentrations of greenhouse gases in the atmosphere. Incremental improvements in technology will help, but will not by themselves lead to stabilization. Figure ES-2 shows projected CO_2 emissions and concentrations if the world continues to use today's technologies (top curves), if changes are made without accounting for climate change (middle curves, the Reference Scenario), and if more transformative changes are implemented to address climate change (lowest curves).

Reference scenarios that describe potential future emissions absent measures to limit cumulative CO_2 emissions already assume dramatic improvements in energy technology. But these technology developments should not be taken for granted. If assumed improvements are not realized in vehicle fuel economy and performance, in industrial processes, in buildings



◀ **Figure ES-2.** The future without technology change (highest curves), with technology change that does not take climate change into account (middle curves), and with technology change aimed at climate stabilization (lowest curves).

energy use, and in the development and deployment of renewable and other non-emitting technologies across the globe, then greenhouse gas emissions will be even larger than predicted.

On the other hand, improvements in familiar technologies beyond those assumed in reference cases, combined with the development and deployment of new technology options, as shown in Figure ES-3, could dramatically reduce the costs of achieving the UNFCCC goal.

A technology strategy is therefore an essential complement to national and international policies aimed at limiting greenhouse gas emissions and enhancing adaptation to climate change. A technology strategy will provide value by reducing costs over a wide range of possible futures—an essential role, given the uncertainties in the science, policies, technologies, and energy resources.

GTSP has identified and analyzed six energy technology systems whose large-scale global deployment could have a profound impact on the cost of addressing climate change and therefore make it easier for society to take on the challenge of addressing climate change while simultaneously meeting a myriad of other societal needs. These advanced energy technologies are:

- CO_2 capture and storage (CCS)
- Biotechnology and biomass
- Hydrogen systems
- Nuclear energy
- Wind and solar energy
- End-use energy technologies.

In addition, the development and deployment of technologies to address emissions of non-CO_2 greenhouse gases can have important implications for global, national, and regional energy systems and for the rate and ultimate extent of the development and adoption of these six advanced energy technologies.

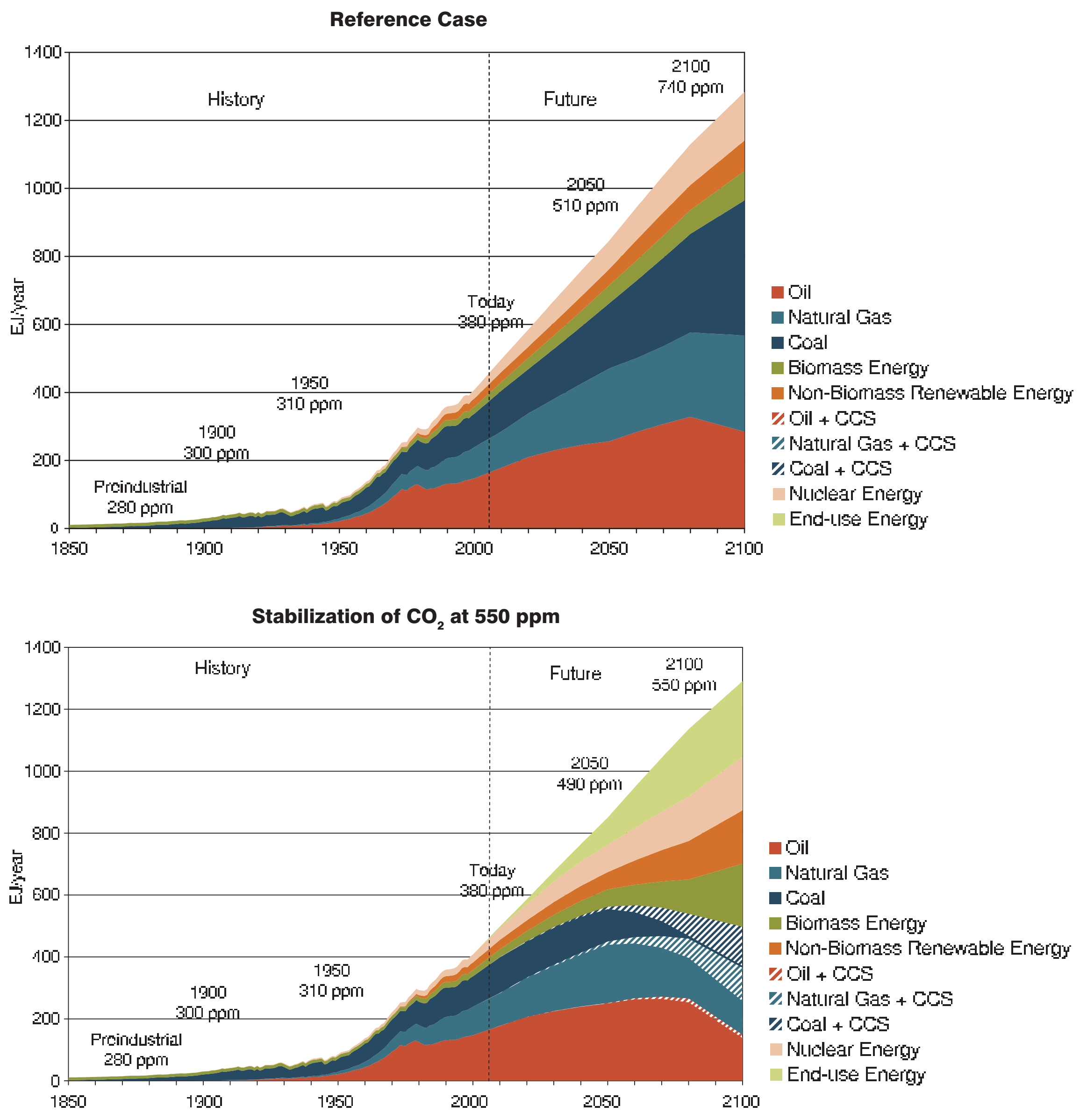
The six technology systems neither exhaust the possible range of technologies in the future global energy system, nor are they mutually exclusive. Instead, some of these technologies reinforce and enhance each other, yielding larger and more cost-effective emissions reductions when deployed in tandem.

None of these six technology systems is a "silver bullet"—that is, none alone can stabilize greenhouse gas concentrations without cost—but together they have the potential to significantly reduce the cost of stabilizing greenhouse gas concentrations.

Each technology system is in a different state of development and deployment. Each is characterized by different challenges and will require different tools to enable dramatic expansion in a climate-constrained world.

Some technologies will play transitional roles or serve niche markets in certain regions of the world, while other regions might utilize these same technologies intensively. Yet, despite all that is uncertain about the precise timing, location, and ultimate extent of deployment of these six advanced energy technologies, research conducted under the GTSP validates that these technologies are potential core elements of a robust solution set, even across widely different potential futures.

In the sections that follow, we briefly summarize insights from the GTSP about the present state of each of these six technology systems, their potential to participate in the future global energy system, and the R&D and deployment challenges they face. We then present a set of research findings that have emerged from the GTSP and a brief glance at the future of GTSP.



▲ **Figure ES-3.** Technologies that produce energy will be radically different if climate change is addressed. The Reference Case is dominated by fossil-fueled technologies (shown in the upper chart as projected without climate constraints). The lower climate-stabilization chart shows that coal, oil, and gas use depends to a great extent on whether CO_2 capture and storage technologies can be employed. Also, improvements in energy efficiency (shown on the charts as “end-use energy”) become much more important.

Key Advanced Energy Technologies

The GTSP Phase 2 Analyses

CARBON DIOXIDE CAPTURE AND STORAGE (*See Chapter 3*)

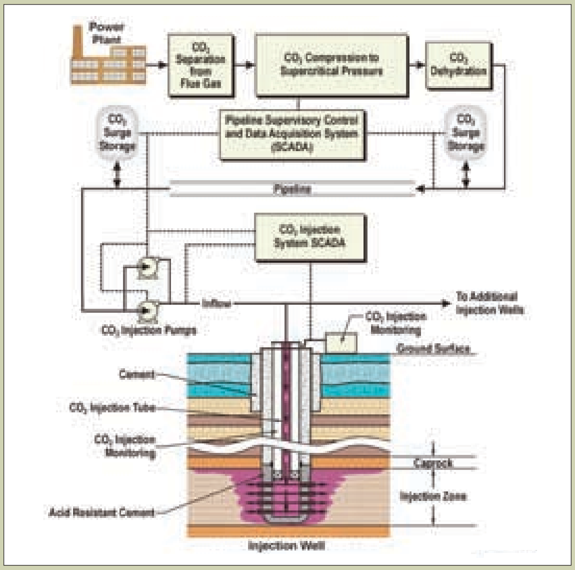
In a greenhouse-gas-constrained world, carbon dioxide capture and storage (CCS) technologies offer the potential for continuing to use the Earth's resources of fossil fuels while preventing their CO_2 emissions from being released to the atmosphere.

CCS technologies could be widely deployed in many regions of the world as part of a global commitment to reduce greenhouse gas emissions. Such large-scale deployment under such a commitment could greatly lower the cost of emissions reductions. There is potential geological capacity to store more than 11,000 billion tonnes of carbon dioxide globally—far more than what will be needed over the course of this century.

Most of the components for complete CCS systems exist; however, they are too small and inefficient to work at the scales necessary to address climate change, and current knowledge and experience with complete end-to-end CCS systems is very limited.

Also, geologic CO_2 storage reservoirs are not distributed evenly throughout the world. Nations like Australia, Canada, and the United States have abundant supply, which will allow them to maintain a more balanced energy portfolio even in a greenhouse-gas-constrained world.

CCS technologies will be most economical when deployed with new advanced coal-fired baseload electric power plants. Therefore, an important criterion for siting baseload plants is nearby storage capacity for 50 or more years of CO_2 emissions.



CCS technologies are also potentially a key means to cost-effectively reduce emissions from many other industrial processes, such as cement manufacturing, oil refining, steel production, chemicals processing and hydrogen production. Currently, 60 percent of all anthropogenic CO_2 emissions come from stationary CO_2 point sources that could adopt CCS.

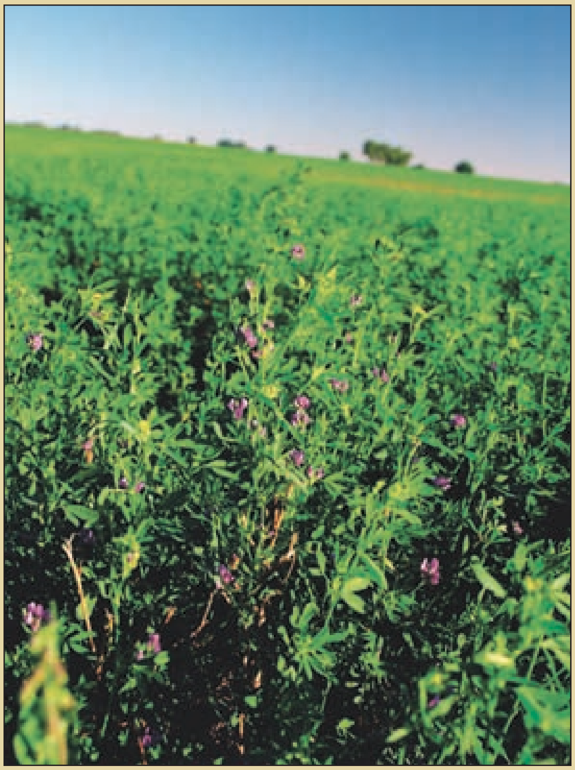
R&D and Deployment Challenges

- Continually improve CO_2 capture technologies and tune them to a wide array of industrial sectors.
- Survey global candidate CO_2 reservoirs, especially in rapidly industrializing countries such as China and India.
- Develop a more advanced and broader set of measuring, monitoring, and verification technologies for stored CO_2.
- Obtain more experience with end-to-end CCS systems in real-world conditions and increase technical, infrastructural, and institutional understanding of the factors needed to bring about large-scale deployment of CCS systems.

BIOTECHNOLOGY AND BIOMASS (*See Chapter 4*)

Since mankind's earliest days, bioenergy has been a component—and until the Industrial Age the dominant component—of the global energy system. Currently, approximately 10 percent of the world's primary energy comes from biomass. In some places, modern commercial biomass energy technology has been deployed extensively. For example, Brazil is the world's largest producer of ethanol, and more than half of that nation's automobiles can run on 100 percent ethanol or petroleum-based fuels.

In a future greenhouse-gas-constrained world, the large-scale use of bioenergy is likely to be significant in the transport, industrial, and electric power sectors of the economy. As carbon prices rise, the use of bioenergy will tend to shift to higher value-added uses so as to serve markets where there are few or significantly more expensive abatement options. For example, bioenergy will move from electricity production toward steam generation for industry and low-carbon fuels for the transportation sector. Over the course of this century, the nature of bioenergy will also likely go through significant changes, transitioning from the use of agricultural waste and excess crops to the purposeful growing of energy crops such as switchgrass to the application of advanced genetic engineering techniques.



To avoid a large inadvertent release of carbon to the atmosphere if land is cleared to grow bioenergy crops, the carbon locked up in soils and standing biomass must be valued at the same rate as the prevailing carbon price. The imposition of such a constraint could have potentially huge consequences for farming and for land use in general.

R&D and Deployment Challenges

- Develop less costly and less energy-intensive processes for converting biomass into liquid and gaseous fuels.
- Continue progress in agricultural productivity for food crops so that land can be freed up for growing energy crops.
- Explore coupling biomass production with carbon dioxide capture and storage technologies, which could be a paradigm-shifting technology system that actually removes CO_2 that has already been emitted to the atmosphere.
- Improve understanding of the potential for competition between agricultural and bioenergy uses for land, and explore possible ways to alleviate adverse consequences.

HYDROGEN AS AN ENERGY CARRIER (*See Chapter 5)*

Hydrogen is appealing in the context of climate change because it is a portable energy carrier that does not emit any CO_2 as it is consumed. Hydrogen is also appealing in terms of conventional pollutants since water vapor is the only byproduct of its use.

Because hydrogen is portable, it could be used to serve transportation energy demands—automobiles, trucks, and other commercial carriers—which now rely almost completely on fossil fuel-based liquids that do emit CO_2. The promise of hydrogen is that it could provide a non-emitting fuel to compete with these fossil fuel-based liquids. In addition, hydrogen could displace direct fossil fuel use in buildings and industry.

However, a greenhouse-gas-emissions constraint will not create widespread use of hydrogen. Rather, its expanded use will depend on the overall efficiency and relative cost of the entire system of hydrogen production, transport, storage, and end-use. The extent to which hydrogen makes substantial contributions to addressing climate change will depend on the CO_2 emissions associated with hydrogen production as well as on hydrogen's cost competitiveness with other low- or non-emitting energy systems.

Hydrogen use in stationary applications may be as important as its use in transport. And, if it were to develop first, the infrastructure supporting stationary applications might provide the foundation for later expansion to a more distributed set of hydrogen distribution points for transportation.

R&D and Deployment Challenges

- Develop and use hydrogen production methods that do not create or release CO_2 to the atmosphere. Carbon dioxide capture and storage enabled fossil fuel, biomass and nuclear thermal hydrogen production technologies could all play important roles in this regard.
- Improve the cost and performance of future hydrogen storage and end-use technologies.

NUCLEAR ENERGY
(*See Chapter 6*)

Nuclear energy emits no CO_2 in operations and is already a significant component of the global energy system. In 2006, existing nuclear power stations accounted for approximately 16 percent of global electric power generation, 20 percent of United States electric power generation, 40 percent in South Korea, and more than 75 percent in France.

Nuclear power generation technology continues to evolve. Third-generation nuclear reactors have lower costs of power generation, improved safety characteristics, and better waste and proliferation management features than previous reactor designs. This third generation of nuclear reactors is economically competitive at present electricity prices and is beginning to be deployed around the world.

While most nuclear power plants are currently in industrialized countries, rapidly growing demand for electric power in countries such as China, India, and South Africa imply rapidly growing potential for deployment of nuclear power.

The supply of uranium, which is the principal feedstock for nuclear power, is not likely to be a limiting factor on the future deployment of nuclear power. The potentially significant expansion of nuclear power will require the use of lower quality and more expensive grades of uranium in the long term, but this will have only a modest impact on the cost of electricity from nuclear power.

Sufficient uranium is likely to be available to support an expansion of nuclear energy without reprocessing well into the second half of the century. If uranium should prove to be in short supply, then reactors capable of breeding nuclear fuels, along with recycling of used fuels, could continue to support the global expansion of nuclear energy.

R&D and Deployment Challenges

- Establish the economic viability of next-generation nuclear energy systems.
- Demonstrate the feasibility of high-level waste disposal in geologic repositories.
- Develop recycling and fuel processing technologies and advanced reactor designs that enable a long-term transition from the once-through to a closed nuclear fuel cycle.
- Develop nuclear capacity to generate hydrogen for use in transportation and other end-use sectors.
- Create innovative international policies for trade in nuclear technology and fuel that allow for global expansion of nuclear energy for electric power generation while addressing proliferation concerns.

WIND AND SOLAR POWER
(See Chapter 7)

Wind and solar power are renewable resources characterized by large potential, no direct emissions of pollutant or greenhouse gases, and the capability of sustainable energy production indefinitely. With or without a climate policy, the contribution of wind and solar power technologies will continue to increase. Their role would become even more important under greenhouse gas emissions constraints.

Wind power in favorable locations is already cost-competitive with other technologies. Solar technologies have not penetrated the market to a great extent. Thermal central station solar electric plants are currently the most cost-effective solar electric technology, although these fascilities are only practical in fairly cloud-free regions. Photovoltaic (PV) and direct heating systems are more versatile and require much less land, but PV systems are also more expensive.

R&D and Deployment Challenges

- Reduce the capital costs of solar photovoltaic and concentrating thermal technologies to be more competitive with conventional sources.
- Improve grid management systems to incorporate the intermittency of wind and solar energy.
- Reduce costs of large-scale energy storage so that wind and solar resources can be fully utilized when they are not available but their electricity is needed or most valued.
- Continue to develop and refine wind turbines that are optimized to work in environments that are offshore or have low wind speeds.
- Reduce the cost of transmission from remote sites with large wind and solar potential to electric load centers.

END-USE ENERGY TECHNOLOGIES (*See Chapter 8*)

End-use technologies consume energy from sources such as electricity, natural gas, and gasoline to provide a multitude of services for businesses and individuals, such as cooling, heating, and lighting homes; transporting people and freight; and heating and powering a range of industrial processes. This diversity necessitates a portfolio perspective when considering the role of end-use technologies in climate change mitigation.

End-use energy technology improvements contribute to emissions mitigation both directly and indirectly whether or not a climate constraint exists. Efficiency gains in end-use technologies are leveraged, reducing the demand for energy, but also reducing energy losses in converting primary fuels to electricity and delivered fuels. The continued development and deployment of more efficient end-use technologies also helps to conserve natural resources, reduce the impact of energy production on the environment (air quality, other pollution), and enhance energy security.

The importance of increased electrification in response to a CO_2 policy is one of the key findings of our research on end-use energy. The development of improved, more cost-effective end-use energy technologies that use electricity can reduce emissions through both efficiency improvements and the use of electricity from low-carbon emission sources.

R&D and Deployment Challenges

Buildings Sector

- Make substantial efficiency gains in specific end-uses such as solid state lighting and heat-pump-based technologies for space conditioning, but also through integrated building design.

- Develop smart appliances that could also help stabilize the grid, increase reliability, and perhaps expand the deployment of non-dispatchable renewable energy.

Transportation Sector

- Realize the substantial potential for efficiency gains in light-duty vehicles, with further opportunities for shifting to low-emission technologies such as electricity, hydrogen, and biofuels.

- Improve battery technologies to benefit all electric-based vehicles, whether fuel-cell, hybrid, or plug-in hybrid.

Industrial Sector

- Re-engineer industrial processes to require less energy services, such as the use of membrane technologies for chemical separation processes that would use much less heat and steam.

- Explore burning commercial biomass as a non-fossil option where processes still require high temperatures for steam or heat.

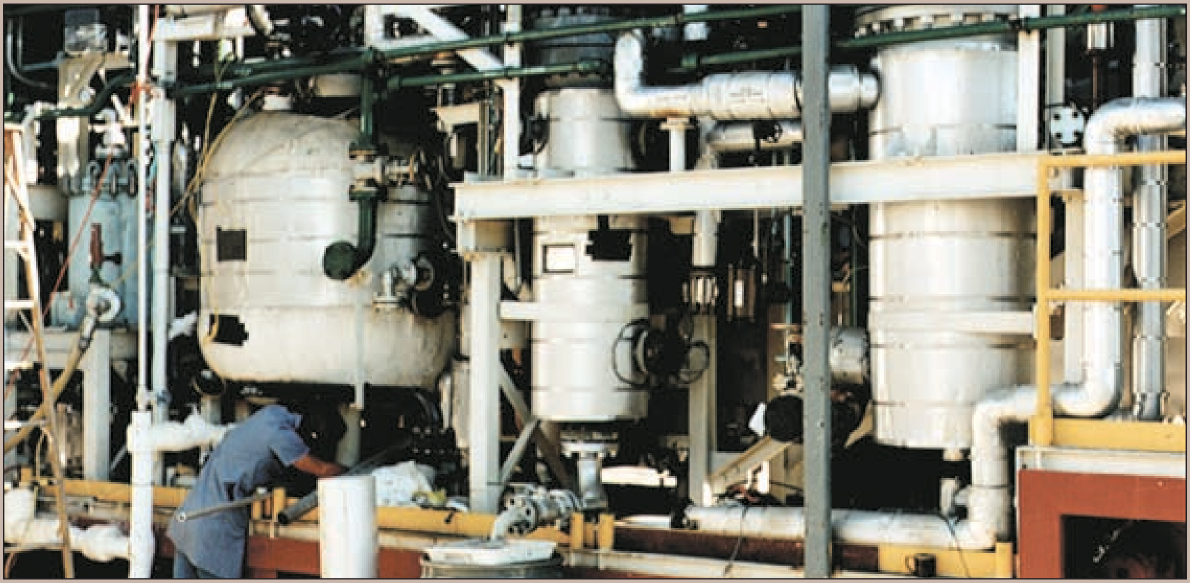
NON-CO_2 GREENHOUSE GASES (*See Chapter 9*)

People contribute to climate change chiefly through emissions of CO_2. However, other greenhouse gases are important components. After CO_2, methane is the second most important greenhouse gas. Tropospheric ozone is also a significant greenhouse gas as well as an air pollutant, the levels of which are regulated in many countries. Nitrous oxide is a long-lived greenhouse gas, the largest source of which is agricultural activities. Fluorinated gases are used in a variety of industrial processes and as working fluids in refrigeration systems.

The effect of aerosol particles on the climate is still very uncertain. The uncertainty in aerosol forcing is one of the largest contributors to the uncertainty in the climate response to increasing greenhouse gases.

In all sectors of the economy and for most of these non-CO_2 greenhouse gases, analysis indicates that cost-effective mitigation options exist, e.g., in opportunities to reduce methane released in mining operations. Development and deployment of technologies that address non-CO_2 greenhouse gas emissions can be an important component in an overall technology strategy to address climate change. In fact, the potential reductions are equivalent to a cumulative reduction of CO_2 amounting to hundreds of billions of tons of carbon by the end of the 21st century.

Most non-CO_2 abatement technologies deploy relatively early in a carbon policy regime. Even larger reductions early in the policy phase could be achieved if the abatement potential of non-CO_2 abatement technologies were increased by research and development.



OVERALL FINDINGS OF THE GTSP

Fundamental insights stemming from GTSP research frame the economic and technology issues associated with climate change. These insights affirm the nature of the challenges and pathways to meet those challenges for those who make decisions about R&D and technology deployment.

1. **Stabilizing atmospheric concentrations of greenhouse gases requires fundamental transformations, especially in the energy system.**

   - Energy is central to the climate change issue. Carbon dioxide (CO_2) emissions from the production and consumption of fossil fuels are the largest contributor to human emissions of greenhouse gases.

   - If present trends continue, CO_2 emissions from energy will continue to rise, resulting in increased concentrations of greenhouse gases in the atmosphere. The influences of future population growth and economic development on the demand for energy services are likely to outstrip currently projected improvements in energy intensity and the ongoing transition to less carbon-intensive fuels.

   - Stabilization of greenhouse gas concentrations will require commitments for both limiting net global emissions of greenhouse gases and for developing and deploying a broad portfolio of advanced energy technologies across the globe.

2. **Technology development and deployment are essential both to stabilizing greenhouse gas concentrations and to controlling costs.**

   - The role of technology is to help control costs. Limiting cumulative global CO_2 emissions implies economic costs, but these can be minimized through the development and deployment of advanced technologies.

   - If non-CO_2 emissions reduction technologies are developed and deployed, the energy sector can minimize the extent of premature retirement of capital assets, which will lower the cost of stabilizing concentrations. If deployed widely, non-CO_2 emission reduction technologies could achieve the equivalent of hundreds of billions of tons of carbon emissions reductions over the course of the 21st century.

3. **A portfolio of technologies is necessary to manage the risks and costs of climate change and to respond to evolving conditions, including the challenge of ever-increasing emissions mitigation needed to stabilize greenhouse gas concentrations.**

   - No single advanced energy technology can solve the greenhouse gas problem. CO_2 capture and storage, biotechnology, hydrogen, nuclear, solar and wind, and end-use energy technologies may all have roles in addressing climate change, but none is capable of delivering all possible energy services (e.g., electricity, transportation, heat, industrial steam) across the globe and over the course of this century. The portfolio must also include technologies to reduce the emissions of non-CO_2 greenhouse gases.

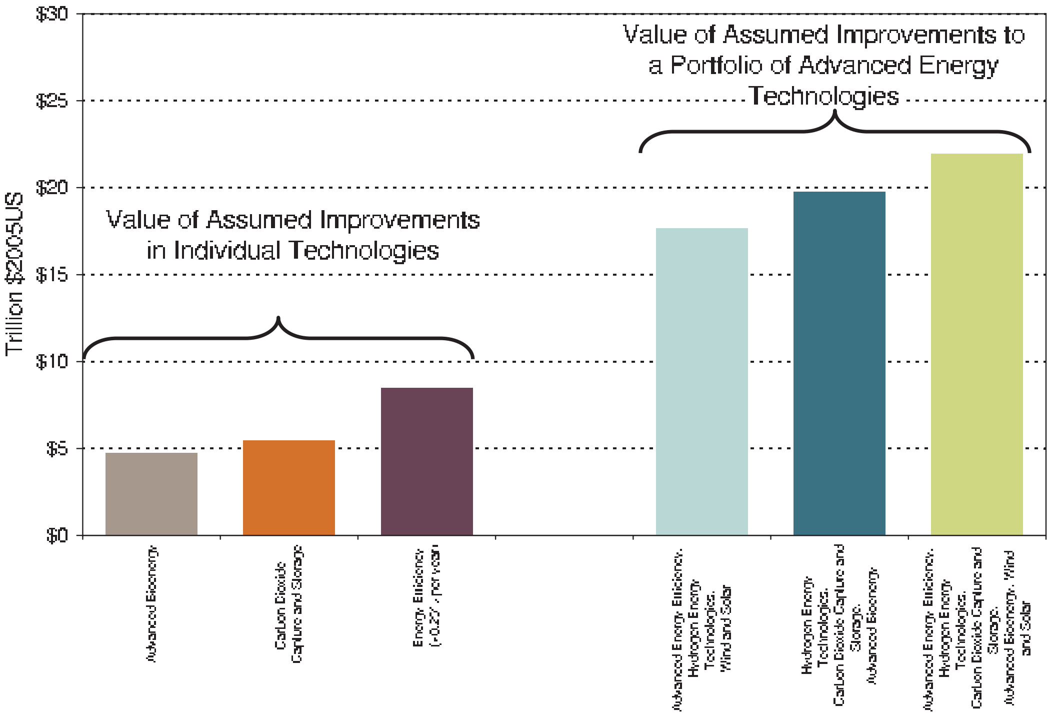
   - Investing in research, development, and implementation in multiple technology areas will provide the foundation for deployment of a broad portfolio of advanced energy technologies. The large-scale deployment and use of these advanced energy technologies has the potential to reduce the cost of stabilization by trillions of dollars. Removing any one of them from the mix will increase the cost.

- The value of this portfolio increases as technologies are added and improved. Figure ES-4 shows that each individual technology can lower the cost of climate stabilization by $4–8 trillion—but the savings are significantly higher when a portfolio approach is implemented.

4. A portfolio of advanced energy technologies also helps manage the risks and costs of climate change inherent in diverse national and regional energy systems, natural resource endowments, and rates of economic development and growth—heterogeneities that will likely persist during this century.

- Society and even individual nations and firms benefit from the development and deployment of a broad suite of energy technologies to meet the diversity of technology needs likely to be present over time and across regions.

- The mix of technologies deployed around the world varies over time and from place to place. The heterogeneous distribution of resources potentially relevant to a technology strategy (e.g., geologic storage sites for CO_2 or sunny locations for solar power) as well as regional differences in culture, institutions and economic systems imply heterogeneous technology needs that must evolve over time.



▲ **Figure ES-4.** Developing and deploying advanced energy technologies individually and in combination. The value—i.e., the reduction in cost—is substantial for each individual technology but increases when technologies are implemented in portfolios.

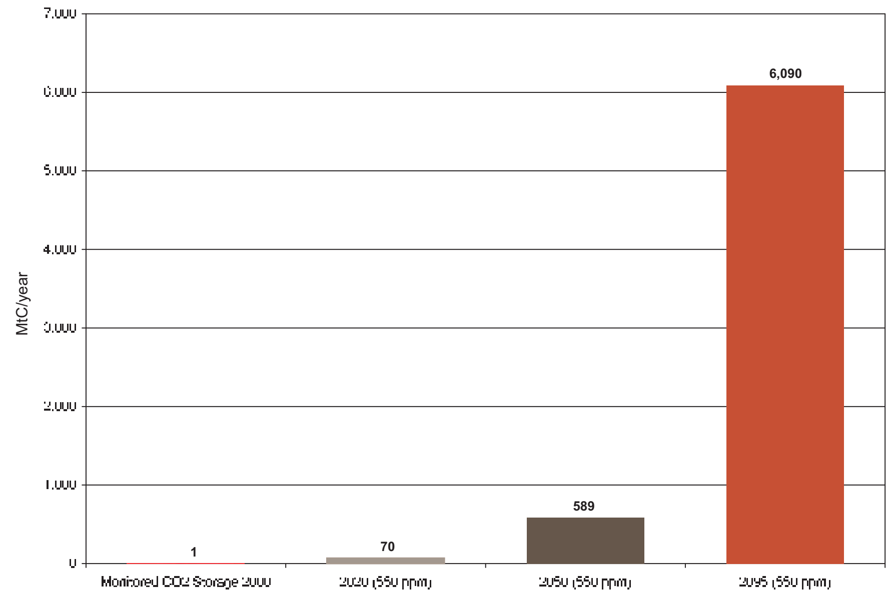
5. Realizing the potential of energy technologies and technology systems presents challenges in expanding the scale of deployment at every time and spatial scale ranging from the next few years to the entire century.

- The scale of the technology challenge implied by the goal of stabilization is daunting. For example, Figure ES-5 shows that deployment of CCS technologies was about 1 million tons of carbon in 2000; to realize its potential contribution to climate change mitigation, the amount of CCS stored would need to increase dramatically over the century—to 70 million tons per year in 2020, 600 million tons per year in 2050, and 6,000 million tons per year by 2095. The same kind of scale-up challenge exists for all key technologies and for any given stabilization goal.

- Technology deployment will vary with time and place for any given stabilization goal.

- Technology deployment depends on not only the technology's own performance, but also on the performance of other available technology options—both direct competitors and technology complements. The deployment of bioenergy crops depends not only on the productivity of the bioenergy crop itself, but also on the continued growth of food crop productivity. If food crop productivity does not increase, the demand for food could take most productive lands, leaving little for bioenergy crops. Similarly, the use of CCS with bioenergy holds the potential of large-scale energy production with negative CO_2 emissions.

- Technology choice depends on the policy environment—as do economic costs. That is, different policies (taxes, trading regimes, standards, voluntary programs, corporate policies, R&D tax credits, etc.) will result in different sets of technology choices and those choices in turn will have cost implications.



▲ **Figure ES-5.** CCS deployment over the 21st century. The projected scale of CO_2 capture and storage technologies illustrates the almost-unprecedented rapid growth needed to address climate change—more than several orders of magnitude over the amount of CO_2 captured and stored in 2000.

MEETING THE CHALLENGE: GTSP PROVIDES ESSENTIAL INSIGHTS FOR MITIGATING CLIMATE CHANGE

Although much progress has been made, economically efficient greenhouse gas emissions reductions will remain an elusive goal without a long-term global technology strategy.

The challenge is to craft policies that promote the development, demonstration, and commercial adoption of the advanced energy technologies described in this report.

- Economic efficiency requires the creation and implementation of mitigation regimes that engage the world's major emitters and that become predictably and progressively more restrictive over time (e.g., carbon permit prices that rise at a predictable rate over time). Knowing the likely trajectory of future carbon prices enables public and private-sector decision-makers to rationally plan their R&D and capital investment decisions.

- Long-term, consistent financing for technology development and demonstration is also essential. Much of the support for the early stages of this process will likely come from the public sector or other means of collective action.

Both the overall level and the allocation strategy for energy R&D are integral parts of a global energy technology strategy. After declining for almost a quarter-century, global funding for energy R&D has been stable over the past decade—but it continues to decline relative to the size of the economy (GDP).

The large-scale deployment of advanced energy technologies also requires the development of institutional and policy infrastructure.

- To be most cost-effective, institutional mechanisms should treat all carbon as having equal value, regardless of the sector of origin. Maximal economic efficiency implies that policies should treat carbon emissions from land-use change as having the same value as carbon emissions from fossil fuels.

- Varied institutional developments—from setting standards to public education—are necessary to realize the full potential of any given technology.

- Institutions will also be critical in effectively communicating, to both investors and consumers, the value of reducing CO_2 and other greenhouse gas emissions.

As the GTSP research program further evolves, it will build on its established foundations—its capacity to describe and analyze the complex interactions between energy, the economy, technology, and natural systems over century-long time scales for global, national, and regional systems; its ability to explore in depth specific technology systems and to articulate the strategic and tactical implications of their deployment; and its ability to work at geographic scales ranging from the power plant to the planet.

An important lesson for society, given the uncertainties, is this:

Act, then learn, then act again. No strategy to address climate change can anticipate all future developments. Society will need to regularly review and revise technology strategies in the light of new information in the realms of science, technology, economics, and society.

The Challenge

This chapter explains the foundations of the climate challenge. The challenge has profound implications for energy systems and for technology development, deployment, and innovation. Climate change involves time and geologic scales that humanity has never before faced, and requires strategic responses that are inherently different from responses that have served societies well in addressing local and regional environmental problems. The major points established in this chapter are:

- Humans are releasing greenhouse gases to the atmosphere through a myriad of economic, agricultural, and land-use activities. The human activities that emit greenhouse gases are pervasive and needed for societal well-being.
- Greenhouse gases contribute to climate change by trapping more of the sun's heat energy in the Earth's atmosphere.
- Carbon dioxide (CO_2) is the most important greenhouse gas emitted by human activities, and most of CO_2 emissions come from burning fossil fuels for energy. But emissions of other greenhouse gases are also an important part of the human influence on the climate.
- Mitigation of the human causes of climate change requires stabilizing concentrations of greenhouse gases in the atmosphere at levels that would prevent "dangerous" climate change. Stabilizing the concentration of CO_2 means that global emissions of CO_2 to the atmosphere from all sources must peak and begin to decline during this century. Eventually—centuries from now—net emissions of CO_2 must decline to virtually ZERO so that CO_2 concentrations can be stabilized.

1

- Even without a consensus on the appropriate stabilization level, it is clear that for any level a fundamental set of changes in the way energy is produced and consumed must occur.

- There is little reason to expect that climate change is a self-correcting problem. Historical trends in technology development and the continuing abundance of fossil fuels imply that the world will likely continue to rely on these fuels and will continue to emit the resulting CO_2 to the atmosphere, without measures that explicitly limit greenhouse gas emissions.

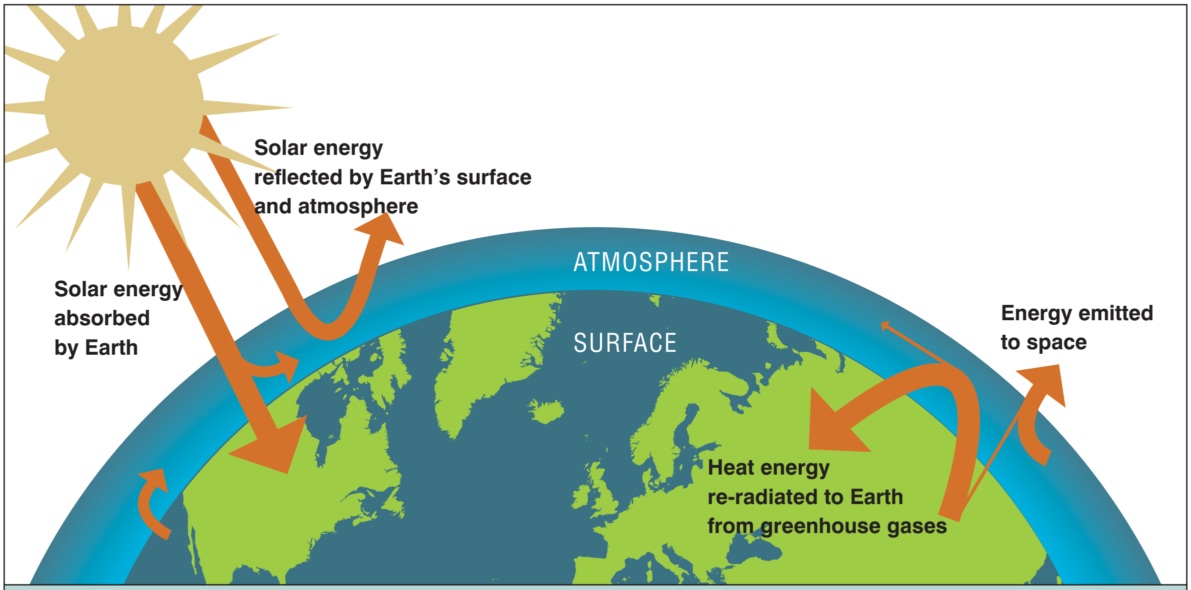
The challenge is to formulate and implement a strategy to reduce the risks of climate change—including a technology strategy for transforming global energy and industrial systems.

Since its inception in 1998, the Global Energy Technology Strategy Program has been focused on the important—and all too often overlooked—role that the development and deployment of advanced energy technologies can play in addressing climate change. To show why technology development and deployment is an essential element in a strategy to address climate change, we begin by considering the basic principles at work, starting with the greenhouse effect.

Greenhouse gases trap solar radiation (heat that would otherwise leave the Earth's atmosphere) and radiate it back to the Earth's surface, providing additional warming (see Box 1-1). The naturally occurring "greenhouse effect" makes the planet livable for humans and all other life forms—but increasing concentrations of greenhouse gases have led to concerns that human activities could warm the Earth and fundamentally change the natural processes controlling the climate. Since the middle of the 18th century and the start of the Industrial Revolution, human societies have been significantly increasing their energy use and production, changing the uses of land, manufacturing new products, and conducting other activities that result in emissions of greenhouse gases. The activities that produce these emissions are pervasive in human societies and essential to society's well-being.

GLOBAL COMMITMENT: THE FRAMEWORK CONVENTION ON CLIMATE CHANGE

Concerns about possible changes in climate induced by a rapid increase in greenhouse gases from human activities have led 189 countries to ratify the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC establishes an ultimate



Box 1-1. The Earth's climate is governed primarily by complex interactions among the sun, oceans, terrestrial biosphere and atmosphere. These interactions are all part of the greenhouse effect.

Much of the incoming solar radiation that falls on the Earth is absorbed, allowing it to warm the surface. Some is radiated back toward space as heat. Various constituents of the atmosphere—water vapor, carbon dioxide, methane, nitrous oxide, and minor trace gases—retain heat and create a natural greenhouse effect. Rather than passing through the atmosphere to space, most of that heat is absorbed by these gases in the atmosphere and redirected back to the surface where it further warms the Earth.

The heat-trapping property of these greenhouse gases is well established, as is the role of human activities in the buildup of these gases. Uncertainty remains about when and how significantly humans might be affected by the resulting intensified greenhouse effect. However, global climate change poses significant risks that people need to be prepared to manage.

objective, expressed in Article 2, to stabilize concentrations of greenhouse gases in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system." The stabilization is to be achieved "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."

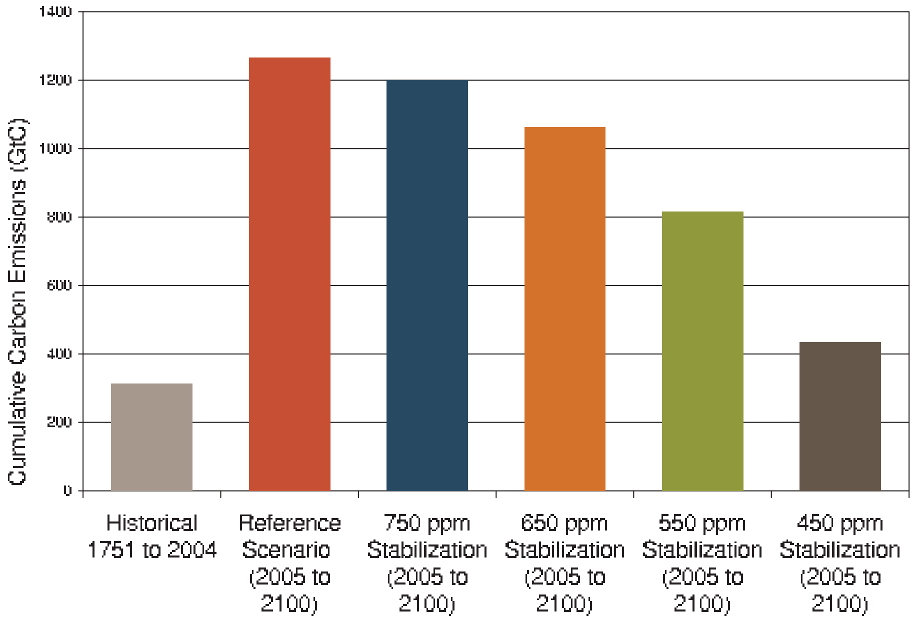
In addition, these 189 countries agreed "that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." They also agreed to adopt national policies and take corresponding measures to mitigate (moderate or lessen) climate change.

Box 1-2. STABILIZING CONCENTRATIONS—AT WHAT LEVEL?

Societies must determine what level of greenhouse gas concentrations will "prevent dangerous anthropogenic inference with the climate system." The scientific community has focused a great deal of attention and productive research on the issue of what the appropriate concentration level might be; however, the level that meets this criterion has not yet been determined. Even without a firm consensus on the appropriate stabilization level, the GTSP has shown that for any level a profound set of changes in the way energy is produced and consumed must occur.

CO_2 EMISSIONS AND CONCENTRATIONS

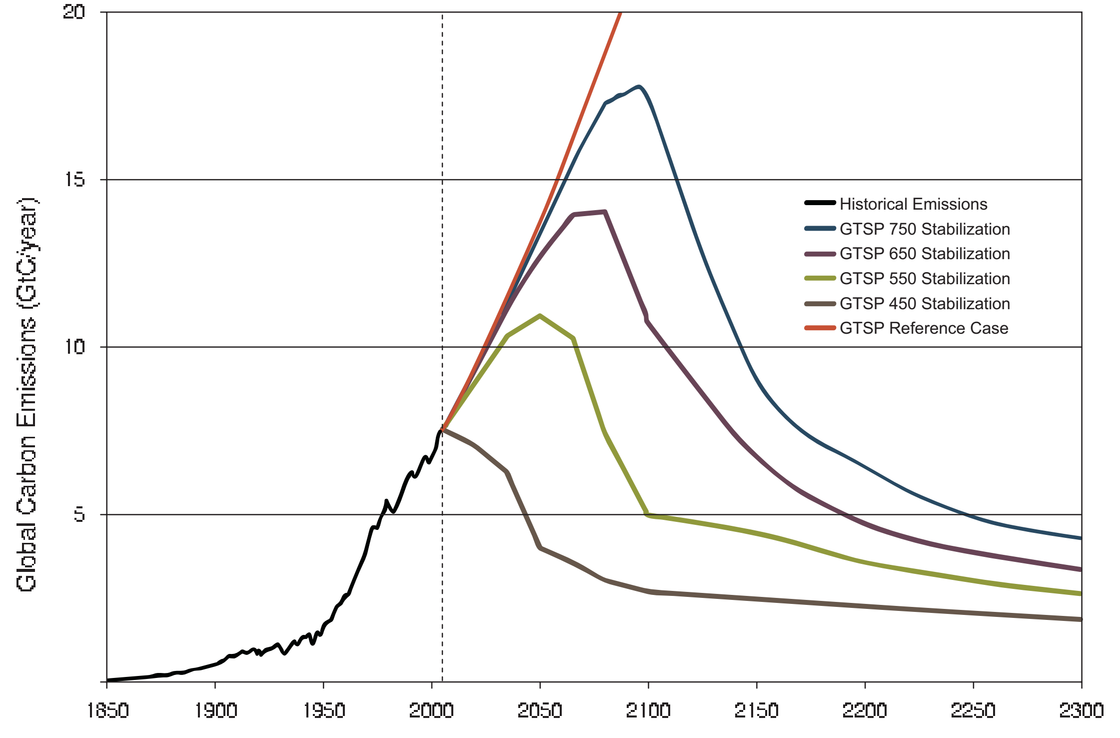
The parties to the UNFCCC have agreed in principle to undertake a huge task. Of the many greenhouse gases emitted by human activities, CO_2 is by far the most important—and by far the largest fraction of CO_2 emissions come from the use of fossil fuels. Stabilizing the concentration of CO_2 presents special challenges unlike those that human society has faced previously (Box 1-2). The concentration of CO_2 depends on cumulative, not annual, global emissions. Figure 1-1 shows that one way to relate global emissions and concentrations is to calculate the cumulative global emissions that would be allowed over the course of the 21st century (2005 to 2100) to achieve each concentration target.



▲ **Figure 1-1.** Various carbon budgets over the period 2005–2100 for stabilizing CO_2 concentrations in the atmosphere at 450 to 750 ppmv. For reference purposes, the amount of carbon released globally to the atmosphere between 1751 and 2004 and the total amount of carbon that would be released between 2005 and 2100 in the reference case are also provided.

In essence, any specified stabilization target has an associated finite amount of CO_2 that can be emitted to the atmosphere—a "planetary CO_2 emissions budget." That budget can be allocated in a number of different ways. The four lines that rise and fall in Figure 1-2 show four paths that are designed to allocate these emissions in an economically efficient manner over time. Each results in a different CO_2 concentration level. The concept of a cumulative global emissions budget has several implications:

- Global annual net CO_2 emissions to the atmosphere must peak and then decline year after year until, eventually, they are virtually zero.
- Every ton of emissions released to the atmosphere counts against a budget, regardless of sector or region of origin. Over time, this planetary CO_2 emissions budget is drawn down and the remaining allowable emissions become scarcer and therefore more valuable.
- Climate change is not a national problem; it is a global problem. No nation alone can control the concentration of CO_2.
- The key reason to develop and deploy advanced energy technologies is to control the cost of stabilizing greenhouse gas concentrations.
- The technical challenge, to invent and globally deploy energy systems that progressively release less CO_2, is unprecedented. The century time scale challenge implies that better technologies will be needed in the near, mid, and long terms if costs are to be controlled.
- Lastly, because it is the concentration of CO_2—and not annual emissions—that drives climate change, minimizing the cost of stabilizing CO_2 concentrations implies that the price of carbon begins relatively low and rises steadily with time. Put another way, in an economically efficient world the price of carbon does



▲ **Figure 1-2.** Emissions Trajectories Consistent with Various Atmospheric CO_2 Concentration Ceilings. The paths pictured here are designed to limit the economic impact of achieving the target concentrations—thereby achieving the goal of the UNFCCC at the lowest economic cost. For all concentration targets, emissions rise, peak, and begin a long decline. The highest line represents an emissions pathway without limits on greenhouse gas emissions.

not begin high and fall over time. Even though periodic adjustments will likely be made to the strategy to address climate change, the overall price of carbon will rise with time.

Although CO_2 is the most important gas, other emissions play significant roles in contributing to increased greenhouse gas concentrations.

THE NON-CO_2 GASES

Although CO_2 is the most important greenhouse gas emitted by human activities, other gases play significant roles in contributing to increased greenhouse gas concentrations. Other greenhouse gases have many different characteristics, origins, and potential for emissions mitigation, including:

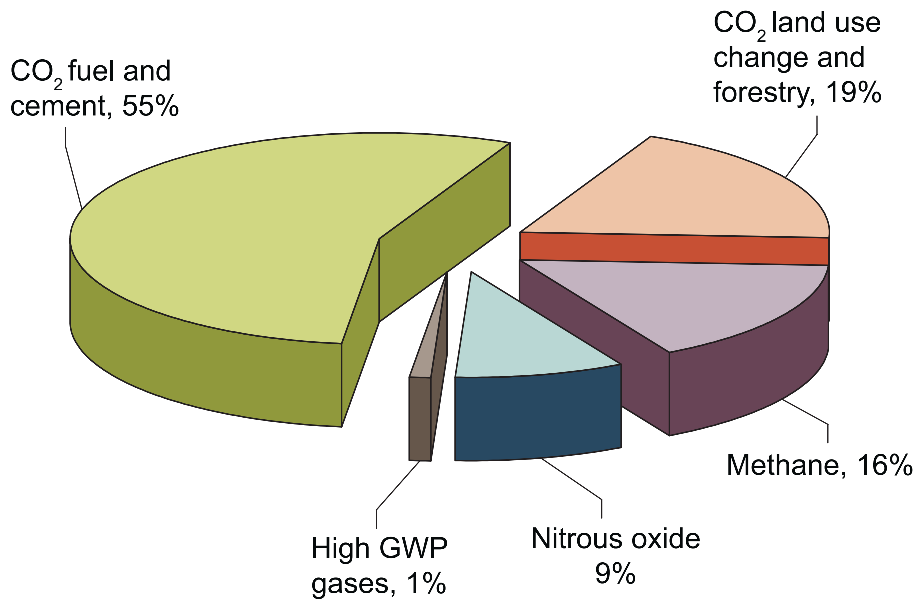
- Gases that occur naturally and from human-made sources: water vapor, methane (the second-largest contributor to greenhouse gas emissions) and nitrous oxide

- Manufactured gases, like the CFCs, HFCs, PFCs, and sulfur hexafluoride

- Gases with indirect effects: carbon monoxide, non-methane hydrocarbons, and nitrogen oxides

- Aerosols, such as sulfur dioxide, black carbon, and organic carbon.

As Figure 1-3 illustrates, the non-CO_2 gases as a group cannot be ignored. Like CO_2 they contribute to climate change. Non-CO_2 gases represent a substantial component of the greenhouse gases that are implicated in climate change, and they play sizeable roles in energy producing, transforming, and consuming activities. Thus, while this report is principally concerned with CO_2 and energy-related sources, non-CO_2 gases influence the cost of meeting any climate change goal and therefore the cost, timing, and degree of deployment of CO_2 emissions mitigation technologies.



▲ **Figure 1-3.** Global emissions of greenhouse gases in 2000 (relative contribution by gas).

THE GLOBAL ENERGY SYSTEM—FROM YESTERDAY TO TODAY

Before the Industrial Revolution, most goods and services were produced with the use of energy from humans, animals, wood and other biomass, and early forms of hydropower. The Industrial Revolution and the growth in the world's energy use were made possible by harnessing ever more powerful and denser forms of energy, as Figure 1-4 shows.

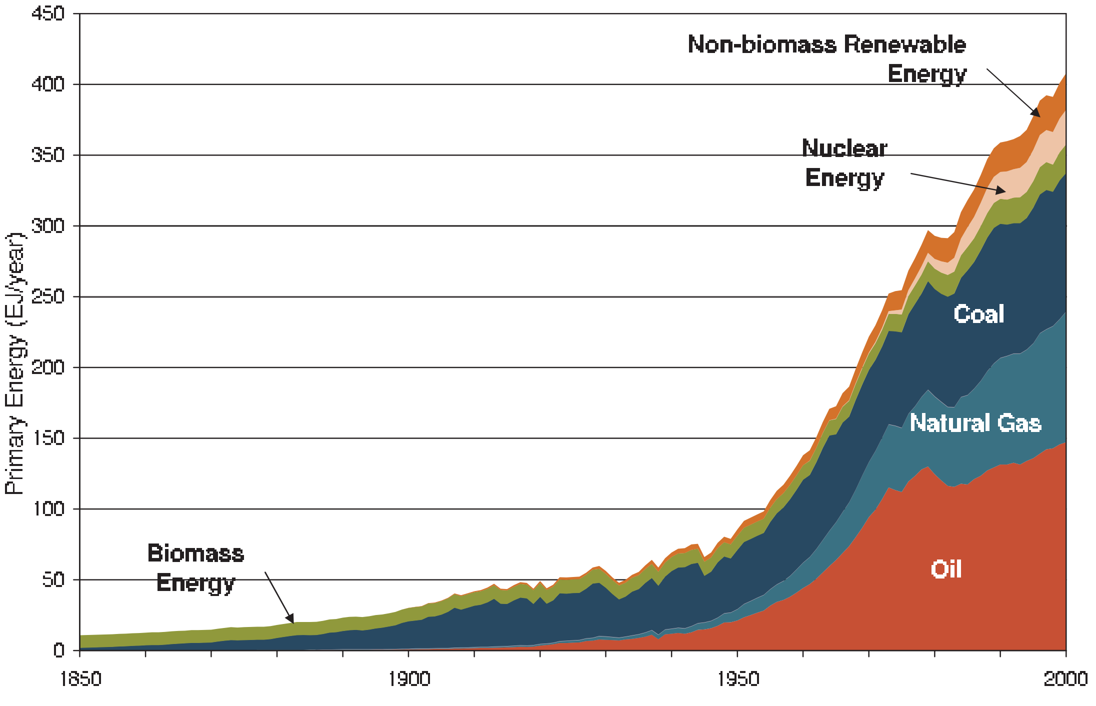
Some of the major transitions in the world's use of energy over the past 150 years include:

- In 1850 the dominant commercial fuel (that is, excluding traditional energy sources like dung, human labor, and animal power) was wood, holding more than 80 percent of the market.
- By 1880, coal had eclipsed wood to become the world's most commonly used fuel. In 1916, coal held 70 percent of the global market.
- Coal was eventually surpassed by oil, which by 1973 held 40 percent of the global market for primary energy.

ENERGY TODAY

Energy is an essential and ubiquitous part of our daily lives. However, while people experience the benefits of energy—heat, light, transportation, manufactured goods and services—they do not usually see the infrastructure supporting energy—coal mines, oil pipelines, power plants, refineries, etc.—nor do they think about the immense scale of the global energy system. Energy touches every aspect of modern life, and the systems providing this energy vary from use to use and from place to place.

Today's energy system—the supply, conversion, transport, and end-use of energy—is dominated by fossil fuels. Of the more than 400 exajoules used today worldwide, 86 percent was supplied by fossil fuels and only 14 percent by non-fossil energy sources such as nuclear, hydroelectric, solar, biomass, and wind power. Each of



▲ **Figure 1-4.** Historically the global energy system has been dominated by carbon-based fuels—initially wood, and more recently coal, oil, and gas. The use of each type of carbon-based fuel continues to grow as the entire energy system grows.

the fossils fuels (natural gas, oil, and coal) individually provided a larger percentage than all of the world's commercial non-fossil energy sources combined in 2003.

Although virtually all global transportation needs are fueled by fossil energy, the electricity sector uses more diverse sources of energy. Approximately one-third of global electricity in 2003 was generated using non-fossil energy. Use of natural gas, another fossil fuel, is growing rapidly—both in direct uses and in electricity generation.

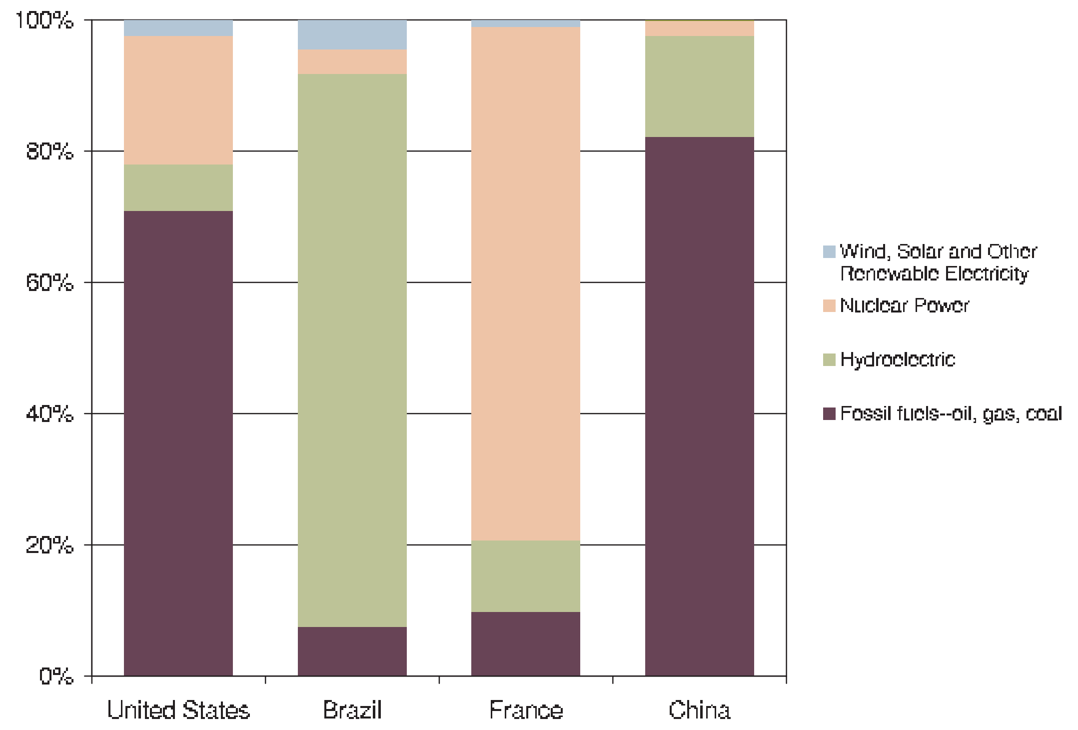
At the national level, the fuels used to generate electricity depend on natural resource endowments, public policy, relative energy prices, and past investments in power plants and their supporting infrastructure. This wide assortment of factors leads to significant differences in national electricity systems. For example, nuclear power provides about 75 percent of electricity in France but only about 2 percent of China's electricity supply.

Figures 1-4 and 1-5 provide another lesson from the 150-year history of the global energy system: the global energy system continues to diversify. No one fuel simply replaced the others. Even fuels whose market shares decline show trends of expanded deployment as the energy system grows overall. For example, production of wood, coal, and oil are larger today than when their market shares were at their peaks.

TOMORROW: EMISSIONS, ENERGY, AND CHANGE

The world of the 21st century will be challenged by the need to expand the energy supply and reduce greenhouse gas emissions, again principally from the use of fossil fuels in the energy system, but also including the wider context of human development and activities that release non-CO_2 greenhouse gases.

The world's future energy system will evolve from today's energy system. Its evolution will be shaped by actions and investments made today and in the coming years.

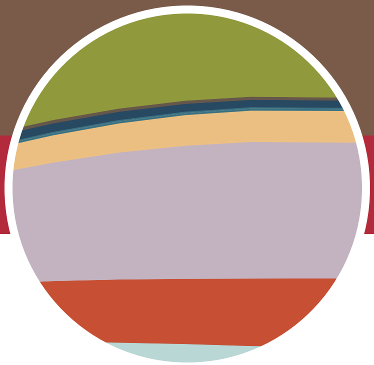


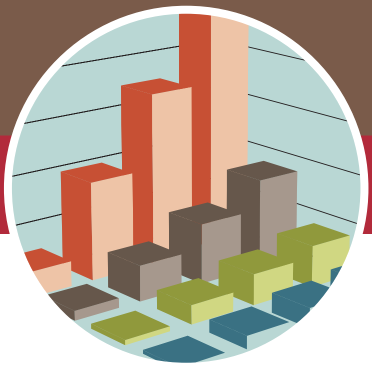
▲ **Figure 1-5.** Electricity is generated using fuels that reflect resource availability and economic opportunities that vary from country to country around the world. This figure shows the fraction of electricity that is generated using four different fuels in four different places around the world: the United States, Brazil, France and China.

Responding to the Challenge of Climate Change

The world's future energy system will evolve from today's energy system. The future system will inherit the investment of the past and the vast remaining resources of fossil fuels, but it also holds the promise of technologies that are and can be developed. Climate change is a long-term issue with implications for today. Understanding the role of technology in addressing the issue of climate change requires thinking about the evolution of the global energy system a century or more into the future. The major points established in this chapter are:

- Energy technology will play a critical role in future emissions, both with and without climate policies.
- Current and previous investments in energy R&D designed to promote clean air, make fuller use of domestic energy resources, improve economic efficiency and begin to address climate change will likely yield substantial improvements in the years and decades ahead. Yet these anticipated technological changes alone cannot be counted on to stabilize greenhouse gas concentrations. Moreover, assumed improvements in energy technologies cannot be taken for granted. They require dedicated resources and effort in both the public and private sectors.
- Stabilizing greenhouse gas concentrations will require even greater technological change. That change will take dedicated resources; supportive policies, including those that facilitate technology innovation, development and deployment; emissions mitigation policies; and the adoption of a timeframe that is consistent with the climate change challenge.
- The portfolio of emissions mitigation technologies and policies that will be cost-effective will evolve over time; therefore, R&D priorities should be revised periodically to reflect new knowledge.





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- A broad portfolio of energy technology investments is needed to manage future risks and uncertainties about climate science, economic development, the price and availability of energy resources, and public policies that are implemented to address the climate issue. The portfolio must accommodate the diversity in regional technology needs, address all major energy flows, and manage the risks that some individual technologies might not be successful in deploying on a large scale.

- Adequate investments leading to successful innovation, development and large-scale commercial deployment of new energy technologies and improvement in existing technologies will help to control the costs of stabilization. Success in controlling the cost of addressing climate change can likely save tens of trillions of dollars. Savings on this scale will allow society to address a myriad of other societal goals along with the goal of addressing climate change.

Success in controlling the cost of addressing climate change will likely save tens of trillions of dollars.

Climate change is a global problem, unprecedented in its time scale, that touches the entire scope of human activities. Addressing the challenge of climate change requires responses in at least four different domains:

- Improved scientific understanding
- Adaptation to climate change
- Emissions mitigation
- Development and implementation of a global energy technology strategy.

The focus of GTSP research is on energy technology. The development of a global energy technology strategy is an important component of a larger, more complete strategy, a component that can help societies control the cost of addressing the climate challenge.

THE FUTURE GLOBAL ENERGY SYSTEM

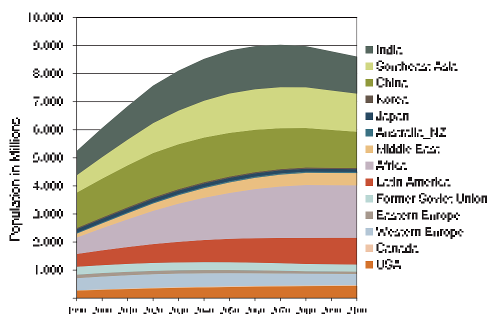
Understanding the role of technology in addressing climate change requires not only understanding the shape of the present global energy system and its historical context, but also forces shaping the future. Chapter 1 described how the global energy system has grown since the start of the Industrial Revolution.

The future global energy system will be shaped by a growing global population and an increasing scale of economic activity both in presently industrialized nations of the world and in nations such as China and India that are engaged in the process of economic transformation. The needs of population and economic growth will create demands to expand the global energy system, as discussed in Box 2-1.

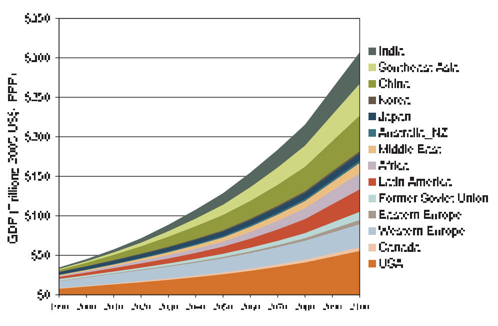
By the end of the 21st century, the global energy system will be dramatically larger than at present. But work carried out by the GTSP demonstrates that the continued deployment of advanced versions of today's energy technologies will most likely only slow the rate of growth in global energy use and greenhouse gas emissions. In the absence of additional policies to limit greenhouse gas emissions, energy demands could more than triple over the course of this century, rising from today's level of 400 exajoules per year (EJ/y) to 1400 EJ/y, shown in Figure 2-1. Fossil fuel CO_2 emissions could rise to more than 20 gigatons of carbon per year

Box 2-1. FORCES SHAPING THE FUTURE GLOBAL ENERGY SYSTEM

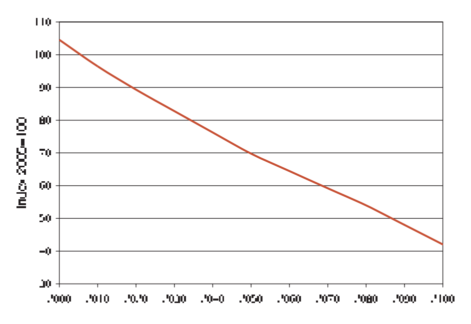
The global population will continue to grow, although it may eventually peak in this century, as shown below.



Economic growth can be expected to continue in both the developed and developing nations, although the rate and extent of economic growth will vary from nation to nation and across time.



Improvements in technology are assumed to continue to reduce the amount of energy required to produce a unit of gross world product (the energy/GDP ratio). Despite these improvements, the global energy system will likely continue to expand in the 21st century.



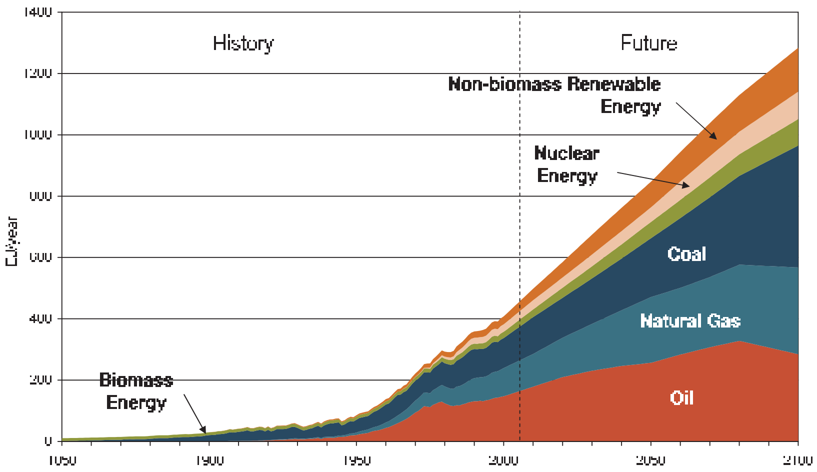


Figure 2-1. The global energy system. The figure shows the past, present and a possible future without climate constraints.

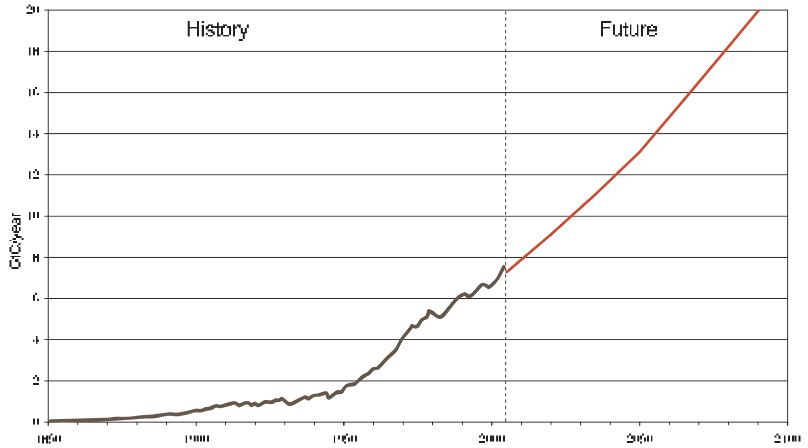


Figure 2-2. Fossil fuel CO_2 emissions. The figure shows the past, present and a possible future without climate constraints.

(GtC/y) by the end of the century, as shown in Figure 2-2, continuing the trend that has been unfolding since the start of the Industrial Revolution. In contrast, stabilizing the concentration of CO_2 means that CO_2 emissions must peak in the 21st century and decline indefinitely thereafter.

Figure 2-1 strongly suggests that even in the absence of greenhouse gas emissions constraints the world will continue to diversify its energy portfolio. However, the assumed large-scale technological progress detailed in Box 2-2 also includes the increased use of more carbon-intensive fossil fuels, as the world transitions away from the era of inexpensive conventional oil. Despite the significant expansion of renewable and nuclear energy in our Reference Case, fossil fuels remain the largest sources of energy throughout the 21st century. The world has more than enough fossil fuel resources in the forms of coal and "unconventional" oil and gas to fuel an expanding global energy system well into the 22nd century. And, as a result, greenhouse gas emissions and concentrations continue to rise over the course of the century.

STABILIZING GREENHOUSE GAS CONCENTRATIONS MEANS FUNDAMENTAL CHANGE TO THE GLOBAL ENERGY SYSTEM

Stabilizing the concentration of greenhouse gases means a fundamentally different path of technology development and deployment during the 21st century. Figure 2-3 shows projected CO_2 emissions and concentrations if the world continues to use today's technologies (top curves), if changes are made without a climate policy (middle curves, the Reference Scenario), and if more transformative changes are implemented to address climate change (lowest curves).

Continuing the analysis, Figure 2-4 compares our Reference Case with one in which technology deployment is consistent with the stabilization of CO_2 at 550 ppm. We have also examined the stabilization of CO_2 at concentrations ranging from 450 to 750 ppm and the following analysis and insights largely hold true for these other stabilization levels.

In Figure 2-4, the left-hand panel shows the reference case, a global energy future in which there are substantial energy technology improvements (Box 2-2 and the middle curves in Figure 2-3), but without any climate-motivated policies in place. The right-hand panel shows a future global energy system as it might evolve if CO_2 concentrations are limited to 550 ppm. Dramatic differences are observed:

- Increased deployment of wind and solar power, biotechnology, and nuclear energy relative to the Reference Case
- Changes in end-use energy technology choices, reducing primary energy requirements
- Continued growth of fossil fuel use because technologies that can capture and store CO_2 are assumed to be available and deployable at scale
- Substantial changes in the underlying technologies that transform primary energy into fuels that end-use consumers purchase, such as electricity, transportation fuels, and hydrogen.

Box 2-2. TECHNOLOGY ASSUMPTIONS IN THE GTSP REFERENCE SCENARIO

Based on historical trends, future energy technologies are *assumed* to improve substantially over the 21st century, including the following advancements:

- Coal-fired power plant efficiency reaches 50% in 2095, was 33% in 2005.
- Gen III nuclear power technology is widespread, with costs decreasing to 5 c/kWh by 2095.
- Wind and solar power continue to improve, generating nearly 15% of the world's electricity in the Reference Scenario.
- Energy end-use technologies in the buildings, industry, and transportation sectors continue to become more energy efficient.
- Technologies that become important in the transportation sector include liquid fuels from sources such as unconventional oils, biomass, gas-to-liquids, and coal liquefaction.
- Hydrogen and fuel cell technologies become viable options in stationary and mobile applications.

Not only are the development and cost-effective operation of this broad portfolio of advanced energy technologies important, but the nature of the climate policy also matters a great deal. Stabilizing CO_2 concentrations at least cost implies that:

- All economic activities everywhere in the world—in both developed and developing nations and in every sector of every economy—face the same price of carbon, and that price of carbon rises in an economically efficient manner.
- Innovations become available everywhere in the world without restrictions.
- Economically efficient technology transitions that stabilize CO_2 concentrations preserve existing capital investments wherever possible.
- The technology mix will change, depending on technology performance and availability around the world, local and regional capacity, and institutions. Initial deployments of new technologies will be modest, at least in comparison to the size of needed systems.

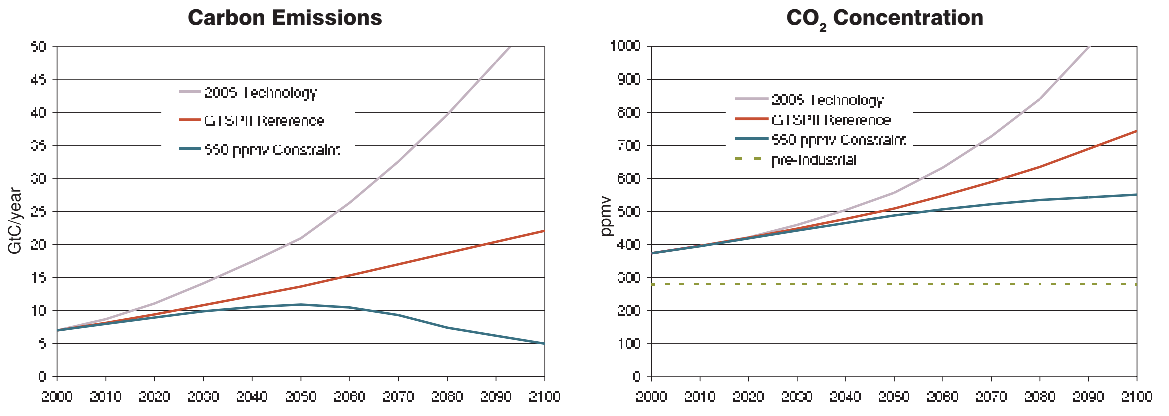


Figure 2-3. Future emissions levels and CO_2 concentrations under the assumptions of (1) no technical changes beyond the year 2005, (2) GTSP Reference Scenario technical change, and (3) technology changes under a 550 ppm CO_2 stabilization climate policy. These figures illustrate the magnitude of the technical change that is assumed to occur in the reference case—changes occurring even in the absence of climate policy. The importance of the Reference Scenario technology improvement in contributing to future emissions should not be overlooked.

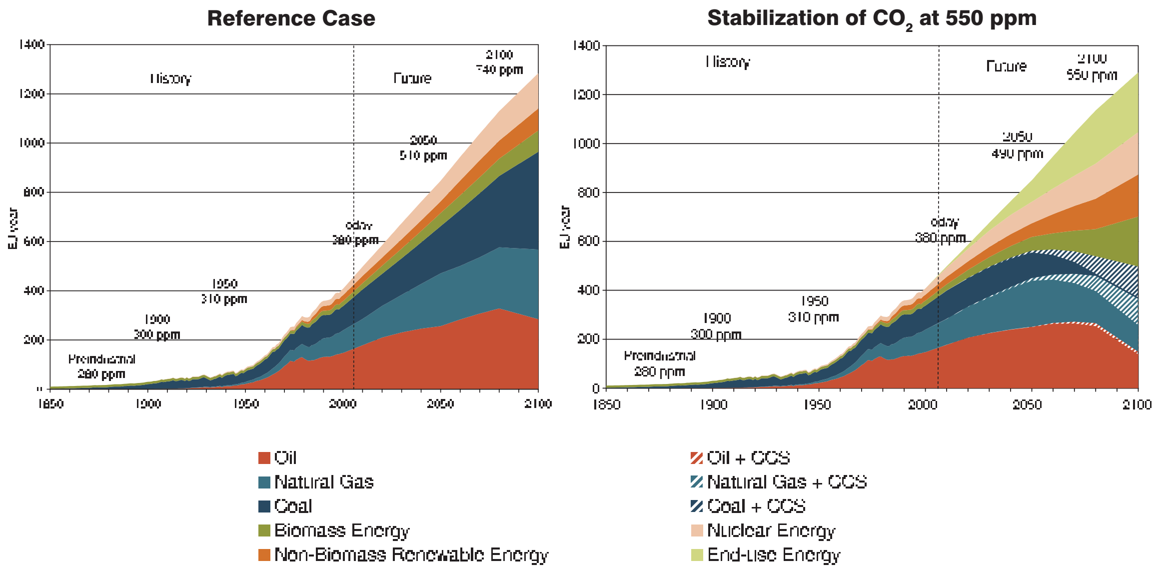


Figure 2-4. Reference Scenario and one stabilization case (550 ppm constraint). Stabilization of CO_2 concentration in the atmosphere implies fundamental change to the global energy system.

THE CHALLENGE OF SCALE

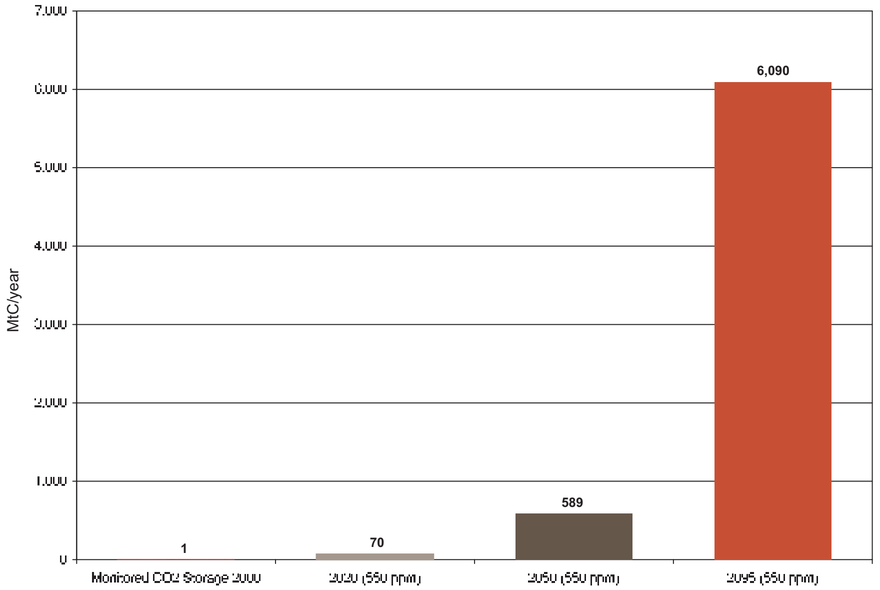
An economically efficient stabilization path is a gradual transition path. Yet the technology challenge should not be underestimated. This can be illustrated by examining the time path for deployment of one technology included in Figure 2-5, CO_2 capture and storage. Figure 2-5 shows the rate at which CO_2 capture and storage is deployed in three years (2020, 2050, and 2095) and compares that to the extent to which CO_2 was stored in monitored sites around the world in the year 2000.

Model projections show that 70 million tons of carbon will be captured and stored in 2020. This is more than an order of magnitude increase over present storage in monitored geologic reservoirs, approximately 1 million tons of carbon per year. In 2050, the GTSP scenario captures and stores almost 600 million tons of carbon, an increase of more than a two orders of magnitude compared to 2000. And, in the year 2095, more than 6,000 million tons of carbon are captured and stored each year. (The issue of potentially available geologic storage capacity is addressed in Chapter 3.)

To deploy CO_2 capture and storage technologies at that scale and speed, many essential developments must occur in a very short time span:

- Emissions of CO_2 would have had to carry an economic cost to justify the requisite substantial expenditures.
- Liability issues relating to long-term storage would have had to have been addressed.
- The appropriate skilled craftsmen would have had to have been trained and licensed.
- Technologies to monitor and verify storage would have had to become available and proven.

And CO_2 capture and storage is just one of the elements in the portfolio of technologies deployed in our stabilization case shown in Figure 2-4. All of the key advanced energy technologies described in this report have similar challenges that must be met in order for them to deploy on a large scale. The degree of challenge will depend at least in part on the concentration at which CO_2 is stabilized. Moreover, the technology challenge grows throughout the 21st century. It is not enough to overcome the near-term and mid-century hurdles. Beyond those lie still greater technology development and deployment challenges.



▲ **Figure 2-5.** CCS deployment over the 21st century. The projected scale of CO_2 capture and storage technologies illustrates the almost-unprecedented rapid growth needed to address climate change—more than several orders of magnitude over the amount of CO_2 captured and stored in 2000.

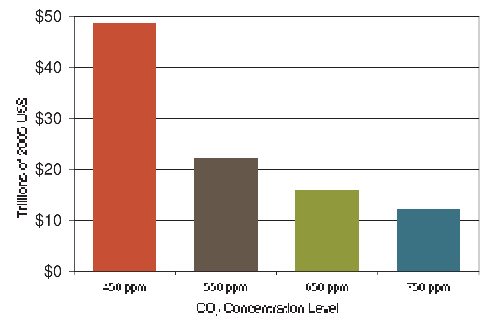
Thus, a technology strategy must not only address the challenges of near-term deployment, but also subsequent technology development and deployment throughout the century. A technology strategy must be capable of laying the foundations for the development and deployment of completely new technologies—technologies for which we presently have no name.

TECHNOLOGY IMPROVEMENTS CAN DRAMATICALLY REDUCE THE COSTS OF STABILIZATION

Countries around the world are implementing a number of individual strategies for reducing near-term greenhouse gas emissions, such as promoting energy efficiency to reduce energy consumption, expanding the use of currently available renewable energy technologies, levying carbon taxes on various parts of their economies and establishing various emissions trading regimes. Although efforts that employ currently available technologies can slow the growth of emissions, considerable technology advancement is needed to reduce the cost of making near-term emission reductions and the much larger reductions required to stabilize concentrations.

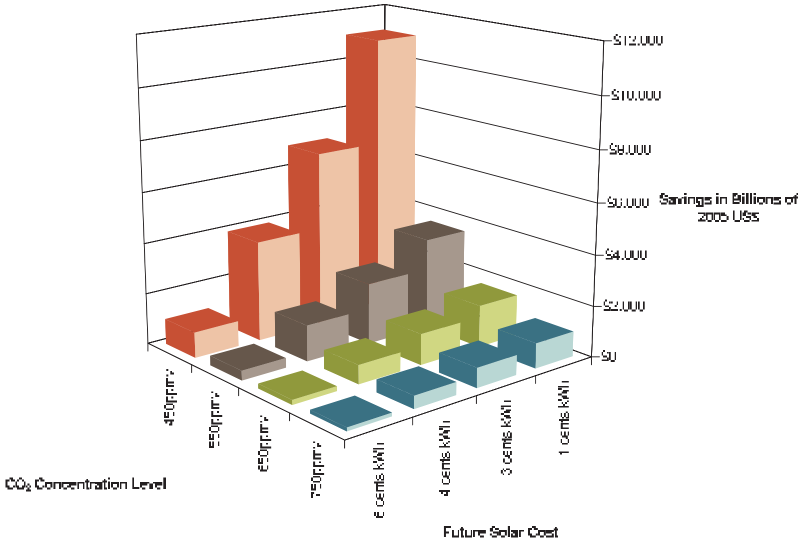
Improvements in the price and performance of currently commercial technologies can save trillions of dollars in the cost of addressing climate change, as illustrated in Figure 2-6, which shows the value of

Box 2-3. THE ECONOMIC SAVINGS FROM REFERENCE CASE TECHNOLOGIES IN STABILIZING CO_2 CONCENTRATIONS



We have estimated the economic savings from the technological improvements assumed in the reference scenario in terms of their contribution to stabilizing the concentration of CO_2 at alternative levels. For example, stabilizing the concentration at 550 ppmv would cost over $20 trillion less if the reference scenario improvements are implemented compared to the cost using 2005 technologies.

The values of technology advances are calculated by comparing the costs of stabilization using the Reference Scenario technologies to the cost of stabilization using no technological advances. The savings, expressed here in terms of present value of cost reductions to the globe over the century, is substantial for all concentration targets analyzed.



◀ **Figure 2-6.** Use and cost of solar power technologies. Improvement in the cost of solar power can result in large cost savings.

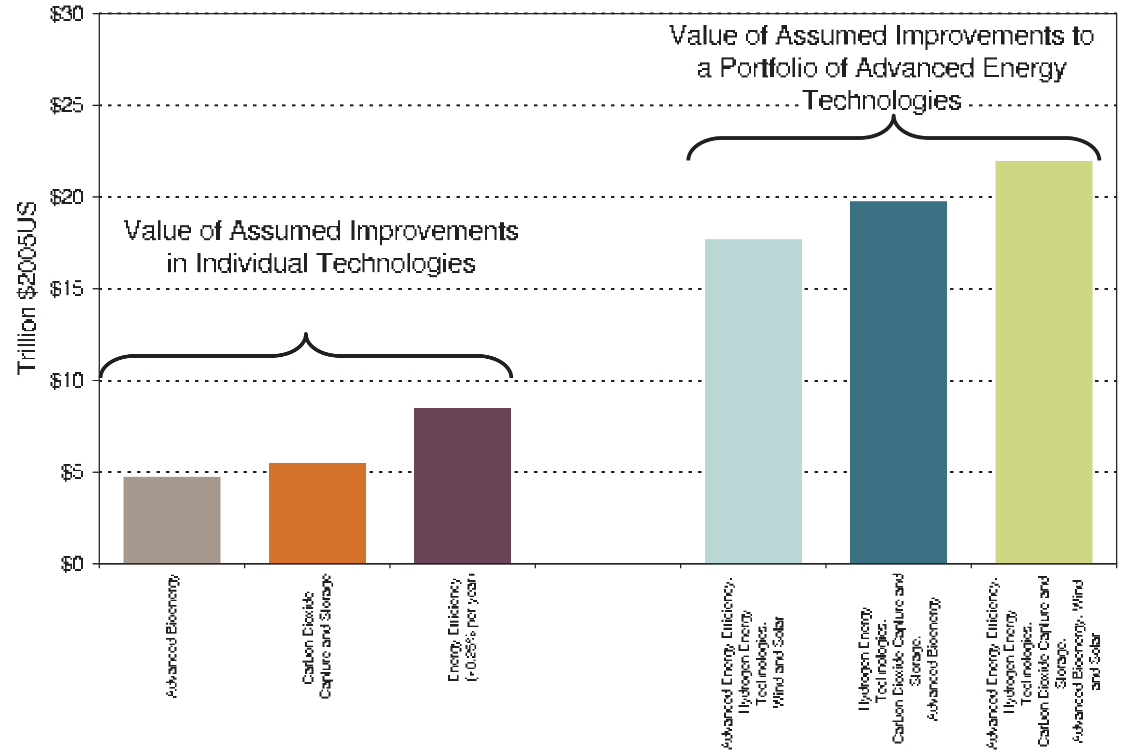
technology improvements in one technology, solar power, against a variety of alternative stabilization scenarios compared to one reference case. Clearly, failure to invest in the improvement of existing technologies that can reduce emissions, such as more efficient end-use technologies, solar and wind power, biomass energy, nuclear energy, and hydropower, would substantially increase the costs of stabilization.

Technology improvements that are assumed in the Reference Case are sufficiently attractive that they are cost-competitive, acquire market share, and reduce greenhouse gas emissions. Such developments, although insufficient to stabilize CO_2 concentrations, are nonetheless extremely important and have additional economic value in a climate-constrained world, as shown in Box 2-3.

In addition, successful investments in technologies that are not yet in widespread commercial use, such as those to capture CO_2 from large point sources and store it in deep geologic repositories, can save additional trillions of dollars in the cost of addressing climate change. All these improvements rely on a supportive, enabling framework for innovation and investment.

Successful advances in a *portfolio* of technologies always reduce the cost of achieving any stabilization goal much further than advances in a single technology area. Figure 2-7 displays the reductions in society's cost of meeting an environmental goal, in this case limiting the change in global mean surface temperature to 2° Centigrade, associated with various alternative hypothesized technology advances. In this case, we assume that reference case technologies are available and explore the benefits of further technological progress.

Similarly, failure to meet assumed reference case technology performance increases the societal cost of meeting any environmental goal. For example, the loss of one quarter of one percent per year in the rate of end-use energy intensity improvement would increase annual emissions at the end of the century by 6 GtC/y, almost as much as global fossil fuel emissions in 1990.



▲ **Figure 2-7.** Developing and deploying advanced energy technologies individually and in combination. The value—i.e., the reduction in cost—is substantial for each individual technology but increases when technologies are implemented in portfolios.

A TECHNOLOGY INVESTMENT PORTFOLIO: A RISK MANAGEMENT APPROACH

The climate problem is essentially a risk management problem. Achieving the necessary technological advances requires investments in a number of technologies at different stages of development. An investment portfolio needs to include a broad array of technologies to be able to deal effectively with critical future uncertainties and to cope with the range of technologies in the energy system and the diversity of regional technology preferences.

A diversified portfolio accommodates evolving knowledge about climate science. The evolving understanding of climate science may either increase or reduce the pressure for emission reductions from the energy sector. For example, improved understanding of the roles of various greenhouse gases other than carbon dioxide in affecting climate or additional information on the possibilities for carbon sequestration could significantly affect research priorities.

A diversified portfolio also accommodates uncertainties about future energy technology developments. At present, we cannot forecast which technologies will develop and penetrate the global energy market. Technology development depends not only on the technological opportunities that currently exist, but also importantly on evolving opportunities created by the ever-changing science and technology landscape.

A broad portfolio can lower costs. Investments in a wide range of technologies are needed to accommodate uncertainty in the outcome of research and development. We will encounter dead ends as some technology paths turn out to be too costly or unrealizable, and almost certainly breakthroughs will be achieved that cannot be anticipated. The key challenge in exploring technological routes to a stabilization goal is funding enough research to determine whether the approach is practical and knowing when to terminate the research if appropriate. The technology strategy should provide practical guidance on how to initiate and terminate focused research efforts.

Although having additional technologies available always makes sense from an analytical standpoint, there must be a winnowing process to recognize real-world budget constraints.

The long-term nature of the climate problem also implies a need to lay down the scientific foundations that are necessary for the creation of entirely new technologies over succeeding decades—technologies that will emerge from the combination of new scientific discoveries.

A portfolio can meet the differing needs of key regions. Technology needs vary from one country and region to another. For example, India has considerable potential to produce modern commercial biomass, but China does not. China has significantly greater space heating needs than India. Although both have rapidly growing economies and energy demands, neither country faces exactly the same challenges as the United States, Europe, or Japan, which have extensive existing infrastructure. On a regional basis, energy use will continue to be influenced by available energy resources, available technologies, and the mix of energy services needed.

However, regional fuel choices also will be influenced by public policies, such as environmental regulations, energy subsidies, concerns about energy security, and foreign investment in energy supplies. All of these factors are hard to project. Even the restructuring and privatization of electricity and natural gas markets around the world may affect the energy mix significantly in the future, by changing the fundamental dynamics of energy capital investments.

The diversity in indigenous energy resources, energy services required and demands for them, and a number of non-economic issues affect the technologies that might be used in a country or region to achieve stabilization. A technology investment portfolio must have the flexibility to address these differences in geography, energy resources, technical capacity, culture, institutions, and economic systems.

A flexible portfolio can accommodate alternative policy responses to the climate issue. A technology strategy can be consistent with a wide range of possible national and regional climate policies, including standards, taxes, and trading. A flexible investment portfolio can change as policies evolve. For example, the stringency of carbon emissions limitation policies will affect the value of carbon and, accordingly, the fundamental economics and potential competitiveness of technologies. This may lead to substantial changes in R&D investment priorities over time. The goals of the investment portfolio should also evolve to reflect the impacts of broader changes in policies that could affect the climate issue indirectly (e.g., controls on other air pollutants or on urban growth).

A broad portfolio also can reflect the diversity of the energy system and other relevant activities. The diversity of the energy system suggests that innovation is needed in a wide array of technologies. Improvements are needed in the overall efficiency of energy use as well as in efforts to limit the free venting of carbon from the energy that is used.

Improvements in the efficiency of energy use are critical. Economic development is driven by growth in energy services, not by growth in energy use. Providing energy services more efficiently is a key element of a technology portfolio and helps achieve other societal objectives.

Investments to develop technologies for reducing emissions from electric generation and distribution need to focus on non-fossil systems to generate power, such as biotechnology, nuclear, wind and solar, as well as CO_2 capture and storage technologies that could allow the continued use of fossil fuels.

Removing carbon from transportation will require fundamental changes in personal and heavy duty vehicles, possibly so that they operate on hydrocarbons derived from biological sources or carbon-free energy carriers such as hydrogen. Shifting to hydrogen or electricity would require the development of methods to produce large amounts of these energy carriers without venting carbon to the atmosphere. A hydrogen-based transport system also would require new hydrogen transport and storage technologies and the development of a fueling infrastructure.

Non-CO_2 greenhouse gases are emitted by activities as disparate as waste disposal, agriculture, and aluminum and cement manufacturing. Again, this diversity calls for a highly differentiated portfolio.

Technology investment priorities need regular reassessment. The priorities for technology investment will change as the 21st century evolves. Technology investments must be reviewed on a regular basis to incorporate new information. Some of the information, such as fuel costs and availability, and climate-motivated energy policies, are uncertainties that will guide investment priorities but are not directly controlled by the technology research effort. Technological uncertainty, on the other hand, will be resolved only through a process of research, application, assessment, and improvement, probably requiring further research.

One goal of these periodic assessments will be to evaluate how well we are doing in terms of the overall development and deployment of the technologies needed to achieve stabilization. Specific technology milestones need to be developed based upon integrated analysis of the energy system in order to guide this assessment. A periodic assessment of this type can help refocus the R&D effort, can identify issues associated with technology deployment and can provide an indication of the adequacy of funding. In addition, this type of assessment can assist in the important objective of halting inquiry into technologies that have failed to realize their initial promise.

SIX ENERGY TECHNOLOGIES THAT COULD MAKE A CRITICAL CONTRIBUTION TO ADDRESSING CLIMATE CHANGE

We have argued that it is critical for the public and private sectors to continue to fund research that improves present energy technologies and lays the foundation for the next generation of technology innovation. We have argued that the key elements of a technology investment strategy involve developing a broad-based portfolio and revisiting it on a regular basis to determine progress. R&D priorities should be reviewed on a regular basis within the context of the overall climate strategy including the climate science, adaptation strategies, and regional and national approaches to emissions mitigation, to re-optimize the portfolio.

While it is impossible to know what technologies will prove to be successful and which will be left behind, and what totally new technologies will be created by the innovative process, we have identified six technology systems as worthy of further examination. Each has the potential to play a major role in a climate-constrained world. These technology systems are:

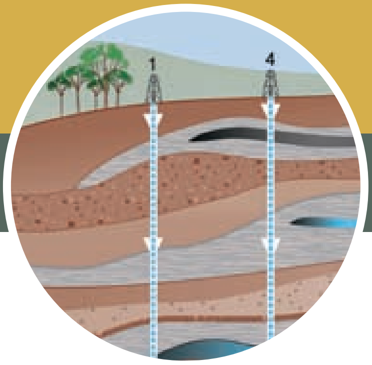
- CO_2 capture and storage
- Biotechnology and biomass
- Hydrogen systems
- Nuclear energy
- Wind and solar power
- End-use energy technologies.

In the pages ahead, Chapters 3 through 8, we will discuss why each technology area is potentially important, describe the technology, assess potential limits on its deployment, consider its present and potential future costs and performance, highlight insights from the analysis conducted within the GTSP, and provide references to more detailed work. In a separate chapter, we will examine the potential contribution of technologies to limit non-CO_2 greenhouse gases.

Carbon Dioxide Capture and Geologic Storage

Carbon Dioxide Capture and Storage (CCS) has been a research focus for the GTSP over the past decade. CCS systems offer the potential for continuing to use the Earth's abundant fossil fuel resources while preventing their CO_2 emissions from release to the atmosphere. CCS technologies would only be widely deployed as part of a global commitment to reduce greenhouse gas emissions, but their deployment under such a commitment would greatly lower the cost of achieving the necessary emissions reductions. GTSP insights include the following:

- Work conducted under the GTSP indicates that there is potentially more than 11,000 billion tons of carbon dioxide (3,000 GtC) storage capacity in deep geologic formations around the world. This is likely many times more than what would be required in response to even the strictest climate mitigation policies over the course of this century.
- Like other natural resources, candidate geologic CO_2 storage reservoirs are not distributed evenly throughout the world. Countries—such as the United States—that have an abundant supply of these deep geologic CO_2 storage formations will be able to maintain a robust, diversified fuel mix well into the future.
- CCS technologies have the potential to deploy in many regions of the world and within many different economic sectors. The large-scale deployment of CCS technologies across numerous different parts of the global economy over the course of this century could reduce the cost of stabilizing atmospheric concentrations of greenhouse gases by trillions of dollars.
- The electric power sector will be the largest potential market for CCS technologies. Within the electric power sector, CCS systems will be most economical when deployed with new advanced coal-fired baseload electric power plants.



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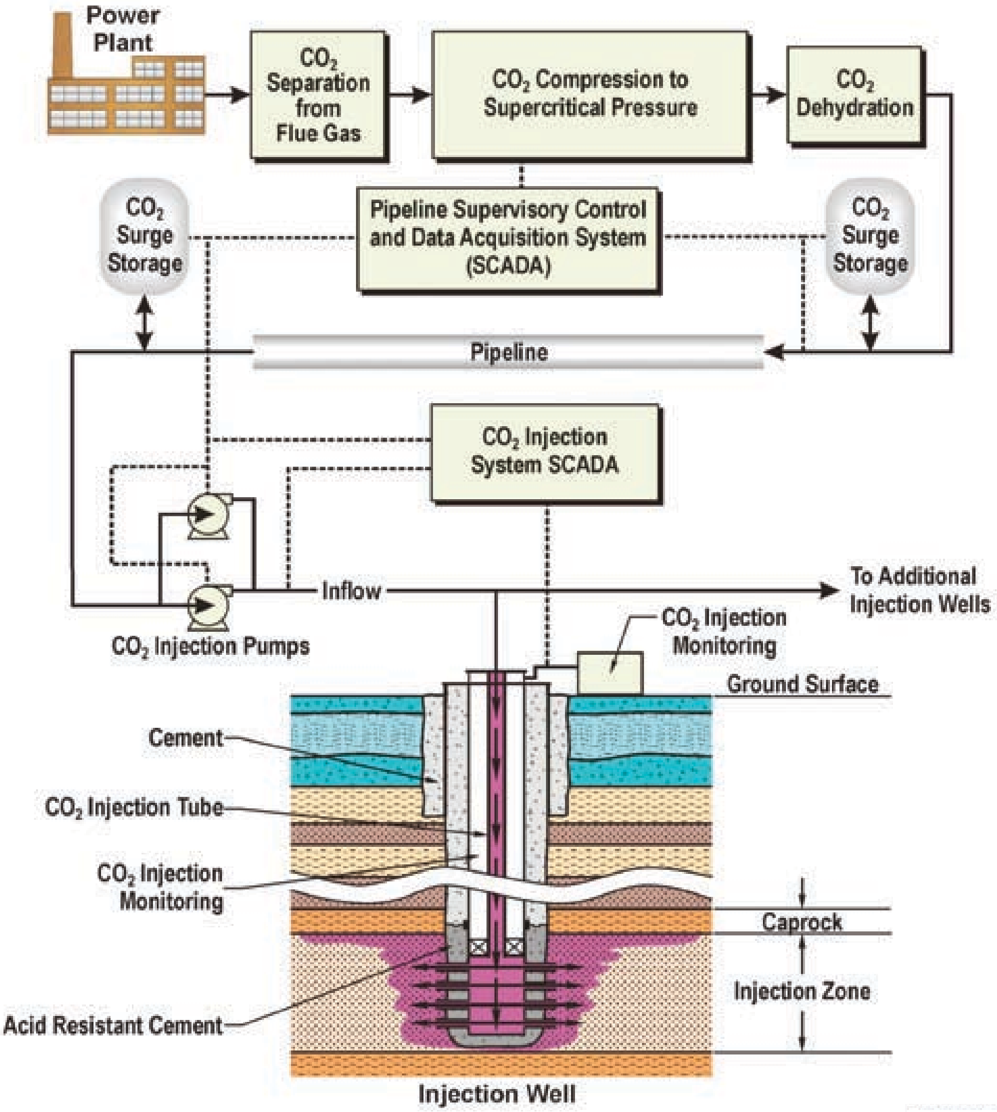
- Large-scale deployment of CCS systems will likely not begin until carbon permit prices exceed \$25/ton CO_2 (\$90/ ton C). This cost level is comparable to—and in some cases significantly less than—other large-scale CO_2 emissions reduction and abatement options.
- The next 5–10 years constitute a critical window for research and field experimentation in which to amass needed real-world operational experience with CCS systems before large-scale commercial adoption of CCS technologies begins.
- Much work needs to be done to ensure that the potentially large and rapid scale-up in the deployment of CCS can be safely accomplished.

CCS systems offer the potential for continuing to use the Earth's abundant fossil fuel resources while preventing their CO_2 emissions from release to the atmosphere.

DESCRIPTION OF CCS SYSTEMS AND THEIR CURRENT MARKET DEPLOYMENT

Many component technologies for CCS systems already exist, including CO_2 capture, transportation via pipeline, and injection into geologic formations deep underground (Figure 3-1). However, the scales of key existing CCS system component technologies (such as commercially available off-the shelf CO_2 capture systems) are far too small and too inefficient to be the basis for the economically efficient large-scale deployment of CCS technologies.

Also, the number of operational commercial CCS facilities and large-scale CCS field demonstration projects is very small compared to the scale necessary to deliver significant and sustained CO_2 emissions reductions. Therefore, public and private decision makers lack a robust, experiential knowledge base from which to answer questions about how CCS systems and their potentially large supporting infrastructures will work under real-world operational conditions.

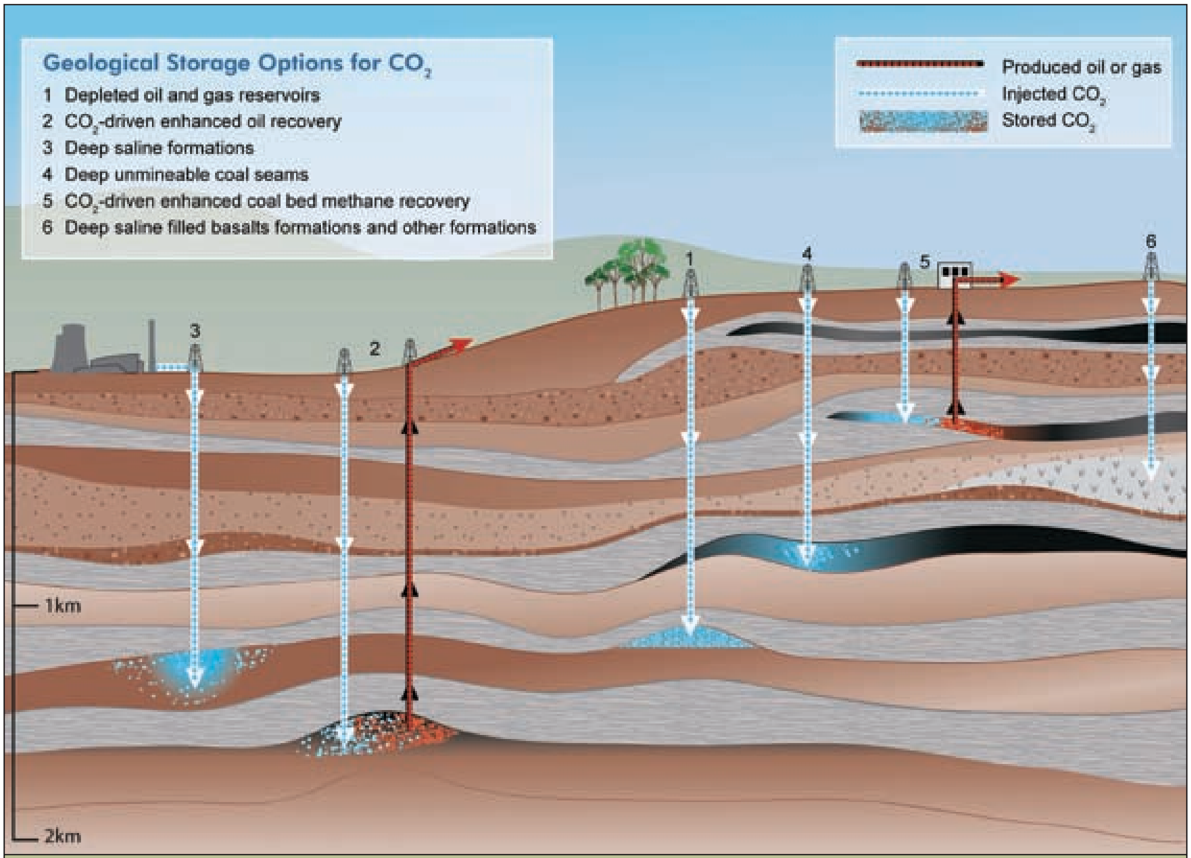


▲ **Figure 3-1.** Most of the components of CCS systems already exist, but their use as complete systems encompassing capture, transport, storage and monitoring remains relatively limited.

Indeed, the very newness of CCS systems and a lack of real-world operational experience in essential applications such as electric power production impede the expanded adoption of CCS technologies.

An essential prerequisite for employing CCS technologies on a large enough scale to make a major contribution to addressing climate change is the identification of significant numbers of suitable deep geologic reservoirs that can safely and effectively store large quantities of CO_2 coupled with the means for monitoring and verifying the long-term storage of the injected CO_2. These candidate deep geologic storage formations vary in type, quality, and extent, but they share three features: they are located many hundreds of feet below the Earth's surface, far away from drinking water sources; they contain coarse-grained rock with pores where CO_2 can be stored; and they are overlain by impermeable caprocks that will keep the CO_2 stored over the long term. Figure 3-2 shows different types of candidate deep geologic CO_2 storage reservoirs.

Many component technologies for CCS systems already exist, including CO_2 capture, transportation via pipeline, and injection into geologic formations deep underground.



▲ **Figure 3-2.** Example of candidate deep geologic formations that could be used for the long-term storage of anthropogenic CO_2. (FIGURE COURTESY OF THE AUSTRALIAN CO2CRC).

CCS technologies' deployment is almost exclusively motivated by the need to reduce greenhouse gas emissions...

Globally, there are currently more than 8,100 large CO_2 point sources (accounting for emissions of more than 15 $GtCO_2$ per year, or approximately 60 percent of current anthropogenic CO_2 emissions) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions (Figure 3-3). These 8,100 large CO_2 point sources are predominantly fossil-fuel-fired electric power plants, but there are also hundreds of steel mills, cement kilns, chemical plants, and oil and gas production and refining facilities.

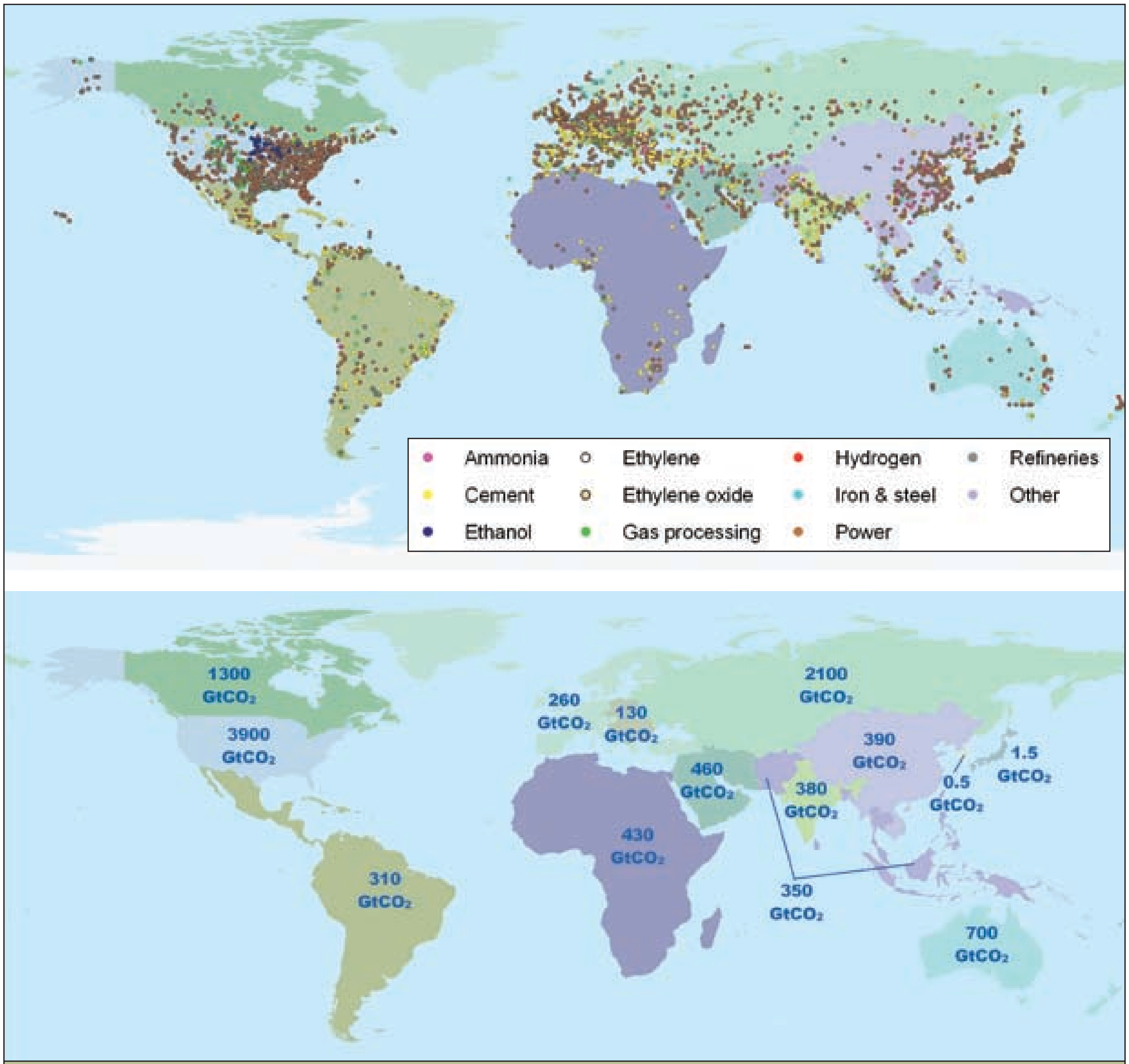
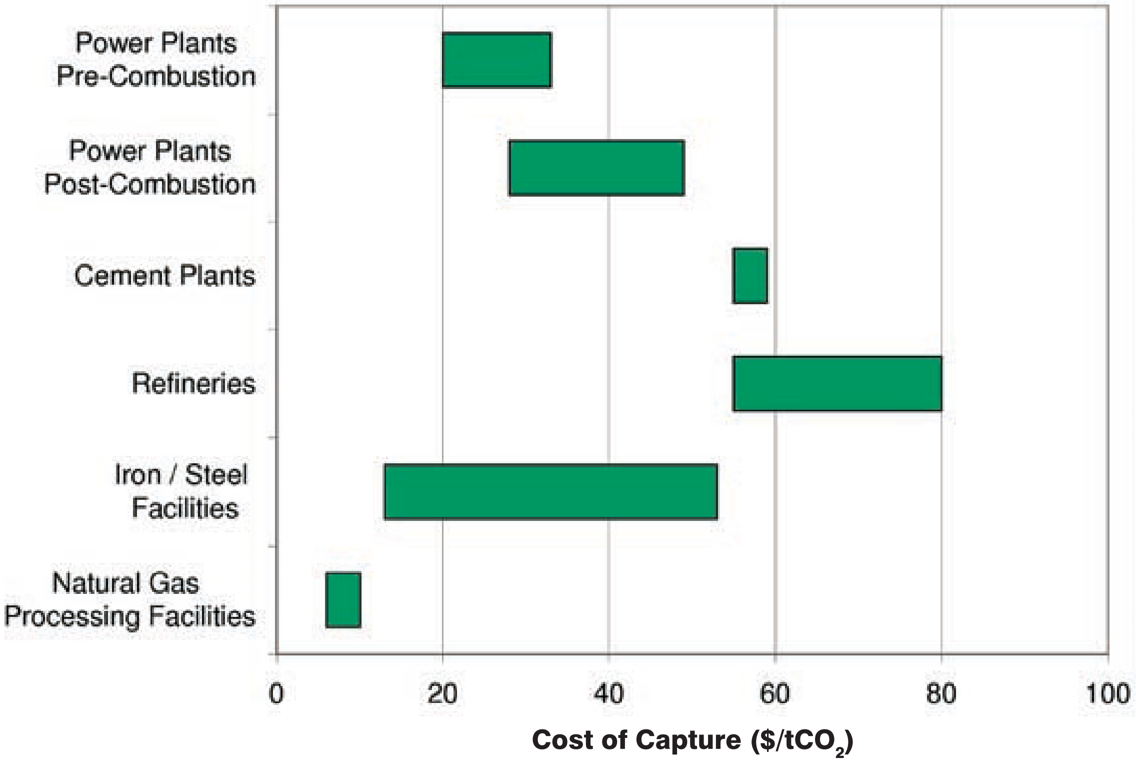


Figure 3-3. The location and type of the more than 8,100 large CO_2 point sources (accounting for approximately 60 percent of global emissions) and a first-order assessment of the regional distribution of candidate deep geologic CO_2 storage formations.

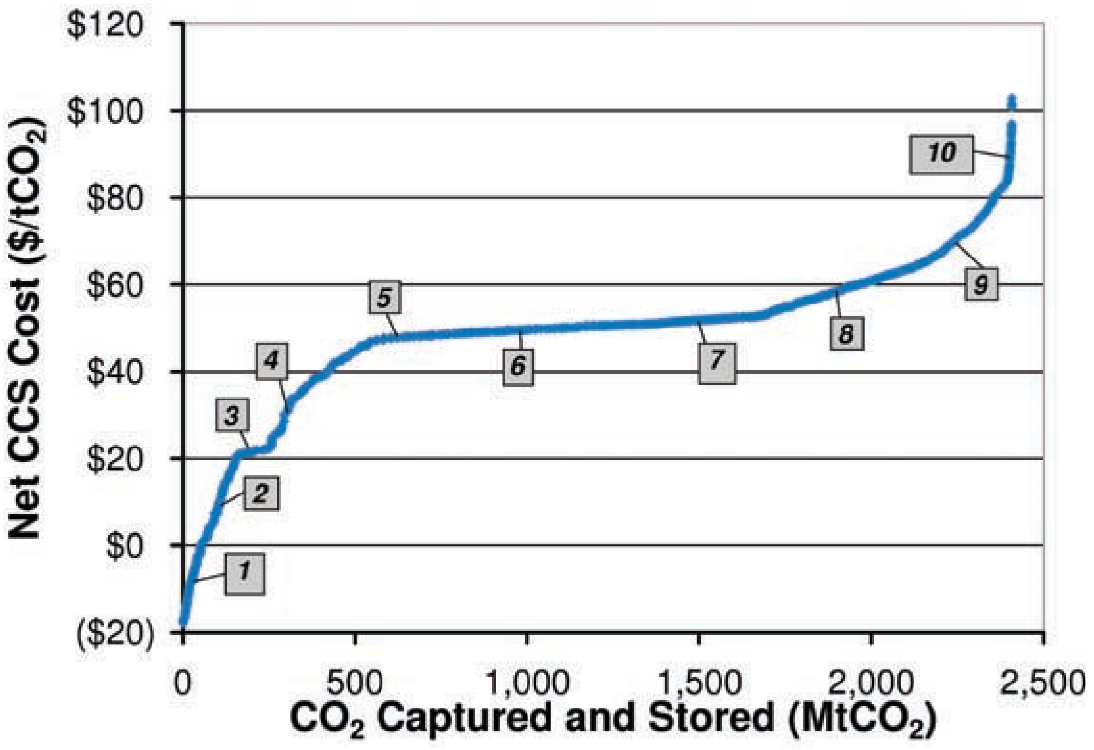
A very small number of these facilities are already capturing and selling CO_2, suggesting that in a few niche markets companies are already making profits by deploying some CCS component technologies to produce and deliver commercial quantities of compressed, pipeline-quality CO_2. However, well over 99.9 percent of the world's existing electric power generation and large CO_2-emitting industrial facilities have not adopted CCS systems. Moreover, the vast majority of the new power plants and other large industrial CO_2 point sources that are being built and that are on the drawing board are also not planning to install CCS systems. This reveals an important point: CCS technologies' deployment is almost exclusively motivated by the need to reduce greenhouse gas emissions; therefore, their large-scale adoption depends upon explicit efforts to control such emissions.

COST AND PERFORMANCE OF CCS SYSTEMS UNDER EMISSIONS CONSTRAINTS

The component costs of employing CCS systems at these large power and industrial facilities can be segmented into CO_2 capture, transport (likely via pipeline), storage, and monitoring. For most CCS applications, the cost of CO_2 capture is the largest cost. This cost is also highly variable, depending upon the emissions source the CCS system is being mated to. Figure 3-4 demonstrates that capture costs can vary by almost an order of magnitude, with power plants' costs lying in the middle of the range. Reductions in the cost of capture could reap large benefits under a climate mitigation regime.



▲ **Figure 3-4.** The cost of CO_2 capture varies widely across industries and even within industries, depending upon the specifics of the capture system being employed and upon the characteristics of the facility the CO_2 is being captured from.



1 **High purity ammonia plant** / nearby (<10 miles) EOR opportunity

2 **High purity natural gas processing facility** / moderately distant (~50 miles) EOR opportunity

3 **Large, coal-fired power plant** / nearby (<10 miles) ECBM opportunity

4 **High purity hydrogen production facility** / nearby (<25 miles) depleted gas field

5 **Large, coal-fired power plant** / nearby (<25 miles) deep saline formation

6 **Coal-fired power plant** / moderately distant (<50 miles) depleted gas field

7 **Iron & steel plant** / nearby (<10 miles) deep saline formation

8 **Smaller coal-fired power plant** / nearby (<25 miles) deep saline basalt formation

9 **Cement plant** / distant (>50 miles) deep saline formation

10 **Gas-fired power plant** / distant (>50 miles) deep saline formation

▲ **Figure 3-5.** Site-specific factors, including the distance from the point of CO$_2$ capture to the selected deep geologic storage formation, the amount of CO$_2$ being captured, the type of facility the CO$_2$ is being captured from, how technologically advanced the capture system is, and the monitoring costs for CO$_2$ storage in different classes of geologic formations, all play a role in determining the overall cost of employing CCS for different industries and for specific facilities.

The factors that determine the cost of transporting and storing CO_2 once it has been captured include the distance from the source to a suitable geologic formation, the design/size of the pipeline, the capacity and depth of the formation, and the opportunity (if it exists) to produce a valuable hydrocarbon—oil or methane—by CO_2 injection into what is called a "value-added reservoir." Because these value-added reservoirs represent a relatively small portion of the storage capacity and because the specific requirements of the value-added activity will add to the CCS cost, GTSP research tells us that the greatest impact associated with CO_2 storage in value-added reservoirs could well relate much more to their ability to produce additional domestic oil and gas than to reducing the cost of CO_2 transport and storage.

Figure 3-5 displays a cost curve composed of the estimated cost of deploying complete CCS systems at actual U.S. power plants and industrial facilities. The ten specific points give a sense of the wide range of circumstances that affect the overall costs.

The GTSP has also explored the economic value of having CCS in the broad portfolio of emissions mitigation options that will likely be employed in the short, mid and long terms to address climate change. Our research demonstrates that the ability to deploy CCS technologies could reduce the cost of stabilizing atmospheric concentrations by trillions of dollars.

THE PERMANENCE OF STORED CO_2

A properly designed and well-managed CO_2 storage site would have one or more injection zones that can accept and store large quantities of CO_2, would be overlain by suitable caprocks to ensure long-term storage of the injected CO_2; and would not be located in areas that have a high incidence of seismic activity. Moreover, before any injection would begin at a CO_2 storage site, detailed seismic surveys would be conducted to assess the presence and extent of any faulting or abandoned wells. Either these potential leakage pathways would need to be remediated, or another site would need to be selected.

Although the issue of the permanence of CO_2 stored in deep geologic formations remains a subject of intense research, there is time to conduct needed field research to better understand this issue and how it might impact the commercial adoption of CCS technologies.

Once CO_2 injection and long-term storage has begun at an appropriately selected site, measuring, monitoring, and verification (MMV) systems would be needed to ensure that injected CO_2 remains in the target formation. Some technologies needed to monitor certain aspects of CO_2 storage are commercially available. However, the large-scale deployment of CCS technologies will depend in part on developing a much more robust and accurate suite of MMV technologies. Companies will draw upon this suite to create tailored, site-specific MMV systems that will be designed to detect potential leaks long before they pose any danger to drinking water supplies or surface ecosystems.

Although the issue of the permanence of CO_2 stored in deep geologic formations remains a subject of intense research, there is time to conduct needed field research to better understand this issue and how it might impact the commercial adoption of CCS technologies. And because the majority of any potential large-scale CCS deployment is still likely decades away, the next decade's worth of planned field experiments and potential early commercial CCS deployments can be used to improve our knowledge about this key issue.

THE EFFORT REQUIRED FOR LARGE-SCALE COMMERCIAL DEPLOYMENT

The challenge is to scale up from the limited number of today's small-scale projects that are typically injecting less that 1 million tons of CO_2 per year to hundreds or thousands of CCS-enabled plants that are collectively storing gigatons of CO_2 each year.

Fulfilling the potential that the large-scale use of CCS technologies could hold will take significant effort. Despite recent technical successes and growing budgets for the development and critical field demonstration of CCS technologies, much hard work remains to transition CCS technologies—perhaps quickly—from their current status as potential solutions to climate change to safe, effective, and trusted and widely deployed aspect of the global energy system. If the world can do this, CCS systems have the potential to be an economic, cost-effective means for facilitating the stabilization of greenhouse gases in the atmosphere as part of a portfolio of technologies to address climate change.

Early adopters of CCS systems will likely lie outside of the electric utility industry and will seek opportunities that move beyond today's niche markets in CO_2-driven enhanced oil recovery. However, if there were an explicit climate policy in place that called for substantial and sustained emissions reductions, the electric power industry would likely be the largest market for CCS systems. GTSP research has shown that CCS systems will be most economical when deployed with advanced coal-fired baseload electric power plants, which operate around the clock with only occasional brief outages for routine maintenance. This is a powerful insight, implying that, for these facilities, a key criterion for locating suitable storage reservoirs is that those reservoirs have sufficient capacity to hold perhaps more than 50 years' worth of the facility's CO_2 plus some margin for growth. Because of this need for large quantities of reliable CO_2 storage, decade after decade, CCS-enabled electric power plants will most likely look to deep saline formations, which tend to have large storage capacities.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

A broad array of research, development and demonstration activities need to be successfully completed in the next 5–10 years to rapidly build the knowledge base needed for CCS systems to fulfill their significant potential for mitigating large quantities of CO_2 emissions over the course of this century. Selected R&D, demonstration, and commercial deployment challenges and opportunities for CCS include:

- Continually improve CO_2 capture technologies and ensure that they are being developed and tuned to a wide array of industrial sectors that can potentially benefit from adopting CCS systems.

- Survey global candidate CO_2 reservoirs so that we can better understand the distribution and ability of the world's deep geologic CO_2 storage reservoirs to safely, securely, and permanently store large volumes of CO_2. This is particularly crucial in rapidly developing countries such as China and India. Helping developing nations site new, long-lived electricity generation or other large CO_2 emitting industrial facilities while giving forethought to potential deployment of CCS will allow them to avoid stranding those assets should there be a need to adopt CCS systems at those facilities at some point in the future.

- Develop a more advanced and broader set of MMV technologies for stored CO_2 in order to meet the needs of a potential future large-scale deployment of CCS systems with CO_2 being stored in many different kinds of formations and circumstances. New MMV technologies need to be invented; and the cost, performance and other operating characteristics of existing MMV technologies need to be improved.

- Obtain more experience with end-to-end CCS systems in real-world conditions and make specific efforts to increase understanding of the behavior of CO_2 in the subsurface (such as various dynamic mechanisms that trap CO_2), develop a base of empirical data to facilitate the development of MMV systems and MMV regulation, train and educate a larger cadre of individuals who are capable of running commercial-scale CCS systems, garner public support for CCS deployment, and otherwise lay the foundation for the larger-scale deployment to come.

GTSP research has shown that CCS systems will be most economical when deployed with advanced coal-fired baseload electric power plants, which operate around the clock.

Biotechnology and Biomass

Technologies based on biological processes are attractive both from a climate perspective and for their potential to diversify energy supplies. Biotechnology includes increasing the quality and quantity of biomass energy supply, the use of bio-based fuels, and the enhancement of carbon sequestration in soils and forests. Biomass fuels, whose combustion-related CO_2 emissions are roughly nullified by the CO_2 removed during plant growth, have both foundations as the oldest energy sources used by people and new promise as engineered fuels that can be utilized in many different economic sectors. GTSP insights include the following:

- Fuels derived from biomass energy crops could make a significant contribution to the global energy system whether there are climate policies or not. Biomass "byproducts," such as corn stover, rice straw, or forest residues are particularly attractive in the near term. If demand for biomass increases sufficiently, then the production of biomass crops, such as switchgrass, could be ubiquitous.

- The production of bioenergy crops will increase faster and will be larger in absolute terms in a world that has constraints on greenhouse gas emissions. By the end of this century, bioenergy could contribute an amount of carbon-neutral energy equal to the world's current use of oil.

- Improving cellulosic conversion processes (i.e., breaking down the cellulose in plants to make liquid fuels) can greatly reduce both the cost and net energy requirements for bio-liquid fuel production. The continued development and deployment of technologies that are capable of using various biofuels are also necessary components of expanding the use of bioenergy crops.

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- In the mid to long term, whether bioenergy crops can become a truly significant aspect of the global energy system is a function of available cropland that can be freed from other uses (e.g., growing food crops), which in turn is a function of the extent to which continued advances in agricultural productivity for food crops can be sustained.

- As carbon prices increase under stabilization scenarios, the market for bioenergy changes. At relatively low carbon prices, biomass is employed predominantly in the production of electricity. At higher carbon prices, biomass becomes increasingly attractive as a carbon-neutral liquid fuel in transportation.

- If the widespread deployment of CO_2 capture and storage systems coupled to bioenergy-fueled electric power plants is possible, the use of biomass to generate electricity and capture and store CO_2, would result in negative emissions with potentially large reductions in the cost of stabilizing atmospheric CO_2 concentrations.

- In order to avoid a large, inadvertent release of carbon to the atmosphere from the excessive clearing of land to grow bioenergy crops, emissions mitigation regimes must also value carbon emissions from deforestation and soils in the same way as they value carbon emissions from fossil fuels.

- Increased carbon sequestration in plants and soils can have an early, significant impact on net emissions.

WHAT DO WE MEAN BY BIOMASS AND BIOTECHNOLOGY?

In this report, biomass refers to material that contains hydrocarbons created through photosynthesis. Land-use change has altered the amount of carbon stored in soils and plants, and opportunities exist to increase these stores of carbon as part of climate mitigation (see Box 4-1). Biotechnology refers to the set of processes to improve the quality of biomass through traditional agronomics and to convert it to more useful forms through genetic engineering.

The critical physical process in the production of biomass is photosynthesis, through which the energy in sunlight creates hydrocarbons from water and CO_2. The most important characteristic of biomass for climate stabilization is that the use of sustainably produced biomass as a fuel is a mechanism for recycling CO_2 from the atmosphere. Unlike burning fossil fuels, this rapid cycling of carbon does not lead to an increase in the overall CO_2 content of the atmosphere.

This chapter focuses on biomass and biotechnology in their role as energy technologies that can help play a critical role in addressing climate change, although they have other values in terms of energy security and the development of new sources of chemical feedstocks.

BIOMASS FOR ENERGY

Biotechnologies that produce energy are versatile. Biofuels can be made available in the forms of liquids, gases, or solids. In research conducted by the GTSP as well as by researchers around the world, there is a clear expectation that the use of bioenergy will grow in the future regardless of whether there are explicit climate policies or not.

Figure 4-1 shows the contribution of bioenergy since 1850, along with future scenarios to 2100: the GTSP Reference Scenario and a 550 ppm CO_2 stabilization scenario. Until the 1970s, biomass use was fairly constant, but then the curve began to rise. After 2000, the model results show projected bioenergy use under a reference case and under a 550 ppm CO_2 stabilization case. These two scenarios suggest a doubling of bioenergy in the next few decades with even more pronounced growth in the second half of the century. By the end of the century, bioenergy's contribution to the global energy system could be as large as today's global oil industry.

Bioenergy today is more than the developing world's use of wood and other traditional fuels. In Denmark, wind only recently passed biomass combustion as a primary source of energy; and in Korea 92 percent of non-hydro renewable energy comes from the combustion

Box 4-1. ALTERING LAND-USE PRACTICES AS A PART OF CLIMATE MITIGATION PORTFOLIO

Soils around the world contain an enormous quantity of stored carbon, and land management practices in agriculture in particular have a significant effect on soil carbon. Approximately 1200 to 1500 gigatons of carbon (GtC) is currently stored in soils around the world.

Conventional agricultural soil tilling practices expose soils to the air and thereby oxidize some of the stored carbon, moving it from the soils to the atmosphere. Estimates of the historic losses of carbon from soils due to agricultural practices are estimated at about 55 GtC. However, agricultural cultivation practices such as low-till and no-till expose less soil to the atmosphere and can lead to increases of soil carbon levels. Low-till and no-till practices already make economic sense in some areas even without consideration of climate change. If undertaken for climate reasons, these practices must result in effective and verifiable reduction in net emissions to the Earth's atmosphere. Measuring and monitoring the carbon content of land is a major challenge.

Approximately 550 GtC is stored in above-ground biomass, mostly in trees. From 1850 to 1998, approximately 136 GtC has been released into the atmosphere through land-use change, largely deforestation. Planting trees and allowing them to grow to maturity would sequester rather than emit CO_2 to the atmosphere. In contrast, deforestation continues—and every ton of carbon not deforested and thereby not released as CO_2 to the atmosphere is equivalent to the mitigation of a ton of fossil fuel CO_2. Placing a value on carbon stored in ecosystems (discussed in the main body of the chapter) provides an incentive to preserve carbon in existing ecosystems and to expand their extent.

of municipal waste, largely biomass. Much of Brazil's transportation sector utilizes biofuels from sugarcane. And in the United States biomass provides about as much primary renewable energy as hydroelectricity.

In the future, the large-scale expansion of a bioenergy industry is contingent upon a transition from waste and residue biomass, e.g. crop residues and landfill gas, to purpose-grown bioenergy crops. Residues are a broad class of feedstocks, ranging from agricultural and forestry residues to municipal solid waste. Residues are an important component of some industrial (e.g., pulp and paper production) and even national energy systems.

Purpose-grown energy crops are even more varied and range from the oil crops like soy and palm oils to corn and the cellulose crops like switchgrass and hybrid poplar trees. Figure 4-2 shows three options for biomass energy crops. Large-scale bioenergy crop production differs from the use of residue streams in that the primary purpose of the crop is energy, and the value of the energy product motivates the growing, processing, transport, concentration, and refining of the fuel.

By the end of the century, bioenergy's contribution to the global energy system could be as large as today's global oil industry.

The current technology for using biomass is generally direct combustion. This is the simplest and least expensive method of use. Biomass is also a hydrocarbon and therefore in principle amenable to transformation into liquid, gas, or solid forms. But plant material is more complex than fossil fuels and therefore more difficult to transform, particularly in comparison to, for example, natural gas. In order to use biomass in higher-valued end uses such as liquid fuels, advanced technologies that enable lower-cost transformation of biomass feedstocks are needed.

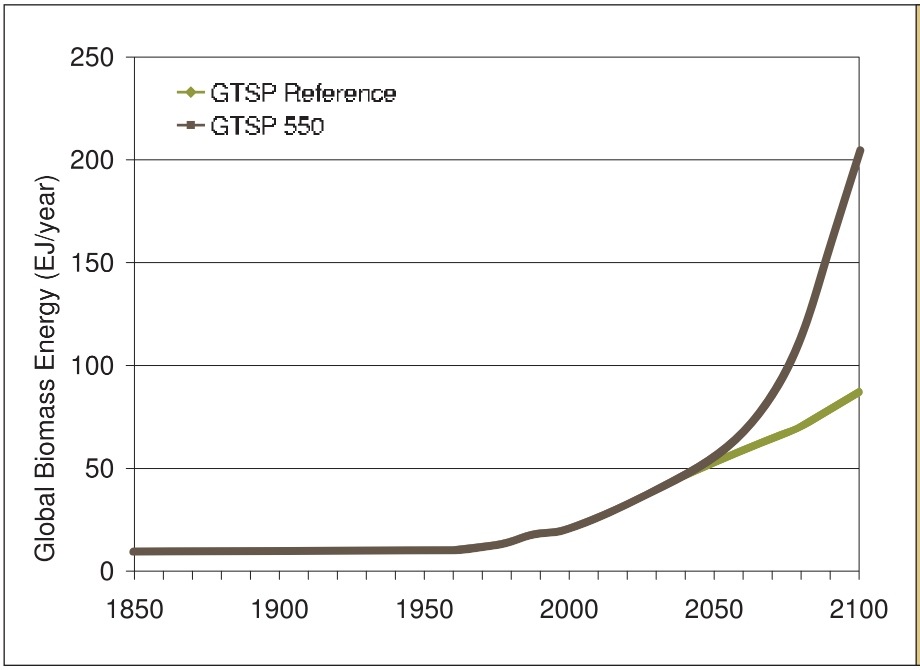


Figure 4-1. Biomass deployment with and without greenhouse gas emission constraints.

One particularly promising technology is cellulosic production of ethanol. In this process, the tightly bound sugars that comprise plant cellulose and hemicellulose are released and converted to ethanol. Unlike current ethanol production processes, a cellulosic conversion plant would use no net energy, with the process heat needed for the conversion coming from non-cellulosic plant material. Greatly improved cellulosic conversion processes are needed in order to lower the cost of ethanol derived from cellulosic feedstocks such as rice straw, switchgrass, or wood.

In the longer term, whether or not bioenergy crops can become a truly significant aspect of the global energy system is a function of available cropland that can be freed up from other uses (e.g., growing food crops), which in turn is a function of the extent to which continued advances in agricultural productivity for food crops can be sustained. (See the later section on Resource Limitations.) Another factor is the potential for the genetic engineering of energy crops (see Box 4-2).

Figure 4-3 reveals a key GTSP insight about the shifting nature of bioenergy utilization in the economy over the course of this century and in the context of varying carbon prices and technology availability. The upper left-hand chart shows the allocation of biomass in a no-climate policy reference case. As can be seen, the dominant use of bioenergy shifts from stationary industrial applications (the "other" category, e.g., the use of biowaste products in a pulp and paper mill) towards the use for electricity production. In this reference case, bioenergy also makes a contribution to the transport sector (bio-liquids), but this is not a dominant use for bioenergy.

Figure 4-2. Purpose-grown biomass energy crops. Various energy crops include switchgrass, sugarcane, and alfalfa.

Box 4-2. ADVANCED BIOTECHNOLOGY

The genomics revolution is rapidly opening up new knowledge of how biological processes work. It has led to new therapies for diseases and new diagnostic approaches. Genomic research may also make it possible, for instance, to isolate an organism that produces hydrogen by splitting water into its constituent parts using waste heat. It is likely that advances in knowledge will provide more efficient means by which to transform biological materials such as switchgrass into ethanol.

Other roles for advanced biotechnology might include

Using biological processes to lower energy input requirements for key conversion processes. While these processes operate at relatively low temperatures, research is needed to improve reaction and throughput rates.

Genetically engineering energy crops to not only improve yields, but to better "match" crop properties to the conversion processes that turn them into more useful fuels.

Using biological processes to generate energy products from low-grade resources such as waste heat.

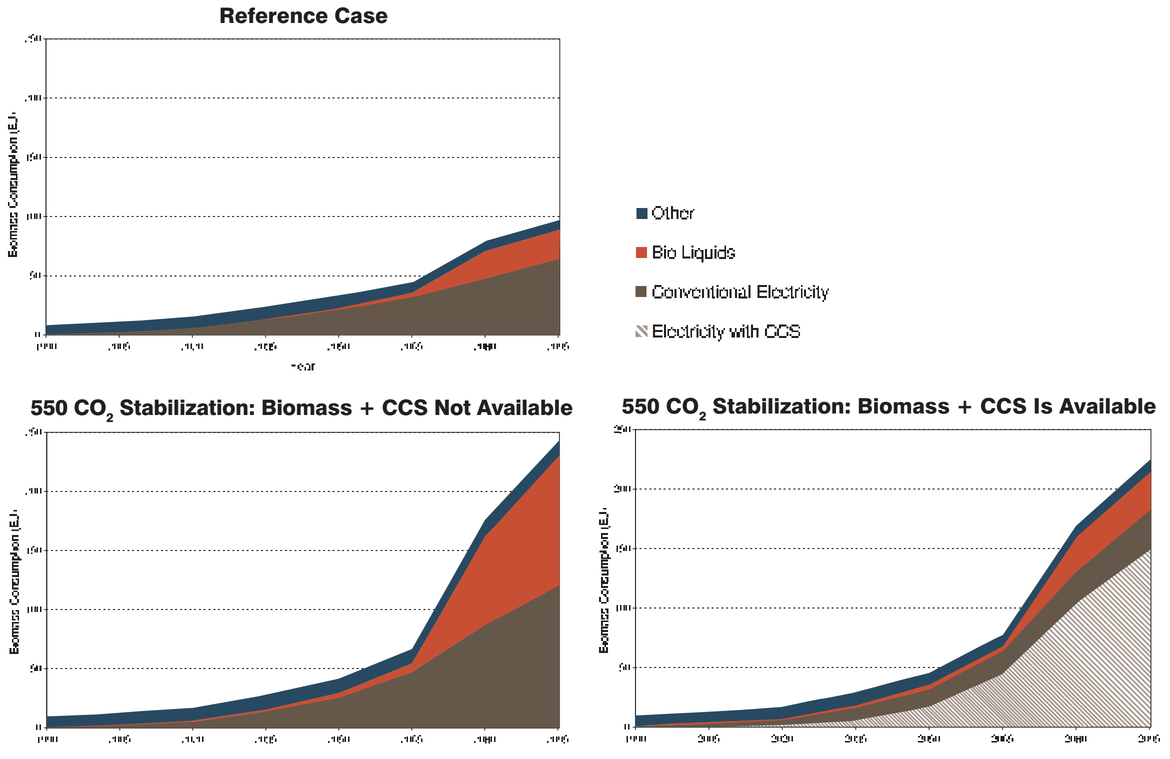


Figure 4-3. Biomass production and use with and without CCS. How biomass is used in the global economy depends on the presence of a climate policy and the existence of the complementary technologies of carbon dioxide capture and storage (CCS). See the text for a discussion of the reference case (top) and emissions policy cases without CCS (lower left) and with CCS (lower right).

The lower left-hand chart shows how the use of bioenergy production changes in the presence of an emissions policy that is designed to stabilize atmospheric concentrations of greenhouse gases. The general allocation of bioenergy across these economic uses is roughly the same as in the reference case; however, the amount of biomass in this stabilization case is significantly larger than in the reference case. It is only towards the end of the century, when carbon prices rise to hundreds of dollars per ton of carbon, that a significant fraction of the bioenergy being grown on the planet is dedicated to biofuels for the transport sector. The point at which biomass use shifts to the production of liquid fuels depends strongly on the cost of cellulosic conversion technologies.

These two cases demonstrate an important trend. As carbon prices increase in stabilization scenarios, societies will use bioenergy crops in progressively higher value-added applications. A significant shift towards biomass in the production of electricity appears to be a dominant use of bioenergy.

The lower right-hand chart in this figure explores how the use of bioenergy might change, if CO_2 could be captured and stored from facilities that produce electricity from biomass (bio-electricity with CCS). At present there are no operational biomass-fueled electric power plants with CCS. Yet there is considerable interest in the possible deployment of these systems because of the potential for net carbon removal from the atmosphere. A biomass-fired power plant that captured and stored CO_2 in a suitable deep geologic reservoir would not only generate clean electricity but also generate emissions offsets. These "negative emissions" could be used to lessen the need to reduce emissions from sectors of the economy that have particularly high abatement costs. Bio-electricity with CCS would produce both electricity and in effect scrub the atmosphere of some of its CO_2.

In the stabilization case, assuming that bio-electricity with CCS systems are developed and built, and that institutional arrangements can be crafted to pay the price of carbon to those who store carbon obtained from bio-electricity with CCS facilities. Bio-electricity with CCS becomes the dominant use of bioenergy shortly after the middle of the century. The stored CO_2 can be used to offset a significant portion of emissions from sectors where mitigation is more expensive, e.g., the tailpipe emissions from the transportation sector.

RESOURCE LIMITATIONS

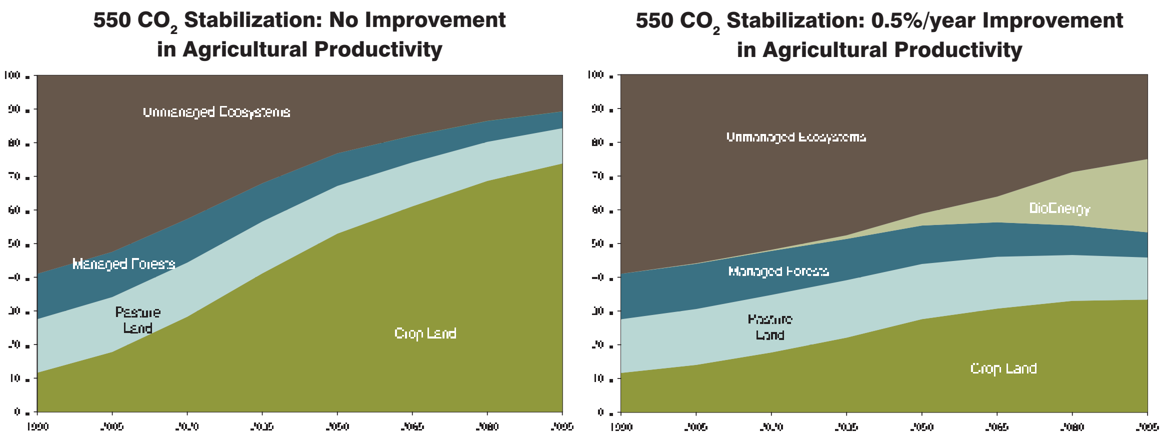
The question of widespread deployment of bioenergy crops as a significant climate technology relates to the availability of and competition for land. All renewable energy sources that rely on solar energy as the primary input use the land as the collector of energy. In the long run, food, fiber, and energy production may all compete for land. The models used within the GTSP explicitly account for these interactions with a finite amount of potential agricultural land available for food, bioenergy, or other uses. In addition, there are other critical uses of the land which include support of biodiversity, ecosystem services (i.e., provision of clean water), recreation and preservation (as in parks).

Research by the GTSP has demonstrated that a successful deployment of large-scale bioenergy depends not only on progress in growing, processing, and using bioenergy crops, but also on continued productivity improvements in traditional crops. Without that productivity gain there will be no land for bioenergy. All of the land will be needed just to feed a larger and richer world population, as illustrated in Figure 4-4. Worse still, failure to continue productivity improvements in crops will place heavy pressure on forests, which will be an attractive target as potential new land for food production. Even with growth in agricultural productivity, the production of hundreds of exajoules per year or more of bioenergy crops requires significant land.

In Figure 4-4, the left panel shows the pattern of global land use when the concentration of CO_2 is stabilized at 550 ppm and agricultural productivity does not improve. Not only is there no biomass energy production when agricultural productivity growth is zero, but the share of land that remains in unmanaged ecosystems falls precipitously. The loss of unmanaged ecosystems means significantly higher land-use emissions, e.g., deforestation. As a counter example, the right panel shows the land-use implications of a 0.5 percent per year rate of agricultural crop productivity growth combined with a limit on the CO_2 concentration of 550 ppm. Demand for cropland and pressure on unmanaged ecosystems are reduced and land made available for biomass energy production.

A recent innovation in the GTSP's work reveals another potential limit to the adoption of bioenergy technologies. In a greenhouse-gas-constrained world with a rising carbon price, a strong economic incentive is sent to clear additional land in order to grow bioenergy crops, e.g., to turn a forest into cropland to meet the market's demand for more biofuels. However, the clearing of new land for growing bioenergy crops can release a significant amount of carbon stored in the forests and soils into the atmosphere, which is counterproductive in terms of stabilizing concentrations of greenhouse gases.

In order to avoid such a large, inadvertent release of carbon to the atmosphere from the excessive clearing of land to grow bioenergy crops, emissions mitigation regimes must also place a value on the carbon in forests, other ecosystems, and soils. Since all carbon is alike to the atmosphere, the appropriate value to place on the carbon on the land, in forests and soils and other lands, is the same as the value on carbon resident in fossil fuels.


550 CO_2 Stabilization: No Improvement in Agricultural Productivity

550 CO_2 Stabilization: 0.5%/year Improvement in Agricultural Productivity

Figure 4-4. The effect of agricultural productivity growth on land allocation under an emissions-reduction policy. Without improvement in agricultural productivity (left panel), less and less land will be available for energy crops. Continued improvement in agricultural productivity allows land to be used for bioenergy (right panel).

If the price of carbon is low, the effect of less-than-ideal valuation of natural carbon stocks is modest. But if the carbon price is high, then the effect can be large. Figure 4-5 shows the amount of carbon emitted by land systems, including the effects of increased carbon uptake by plants as previously deforested areas regenerate and CO_2 levels rise as well as the release of carbon through deforestation. At present, a small net uptake of carbon by land was estimated, resulting in the negative emissions seen in the figure. In other words, plants and soils are thought to be removing more carbon from the atmosphere than being released by deforestation. The lower line tracks the net uptake of carbon by plants and soils in a scenario that stabilizes CO_2 concentrations at 450 ppm, with a price of carbon applied equally to carbon emissions wherever they occur regardless of whether the source is from deforestation or fossil fuel use. The upper line shows the consequence of only valuing fossil fuel carbon, i.e., ignoring the value of terrestrial carbon. In this scenario, emissions from land-use change such as deforestation overwhelm the land's ability to absorb carbon as a consequence of too much land clearing to create places to grow biomass.

As can be seen from Figure 4-5, not taking into account the need to value the carbon stored in forests and soils can lead to over-exploitation of natural resources and excessive production of bioenergy.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

To realize the large-scale potential for commercial bioenergy and terrestrial sequestration, continued advancement across a wide variety of biological, agricultural, and engineering fields will be required.

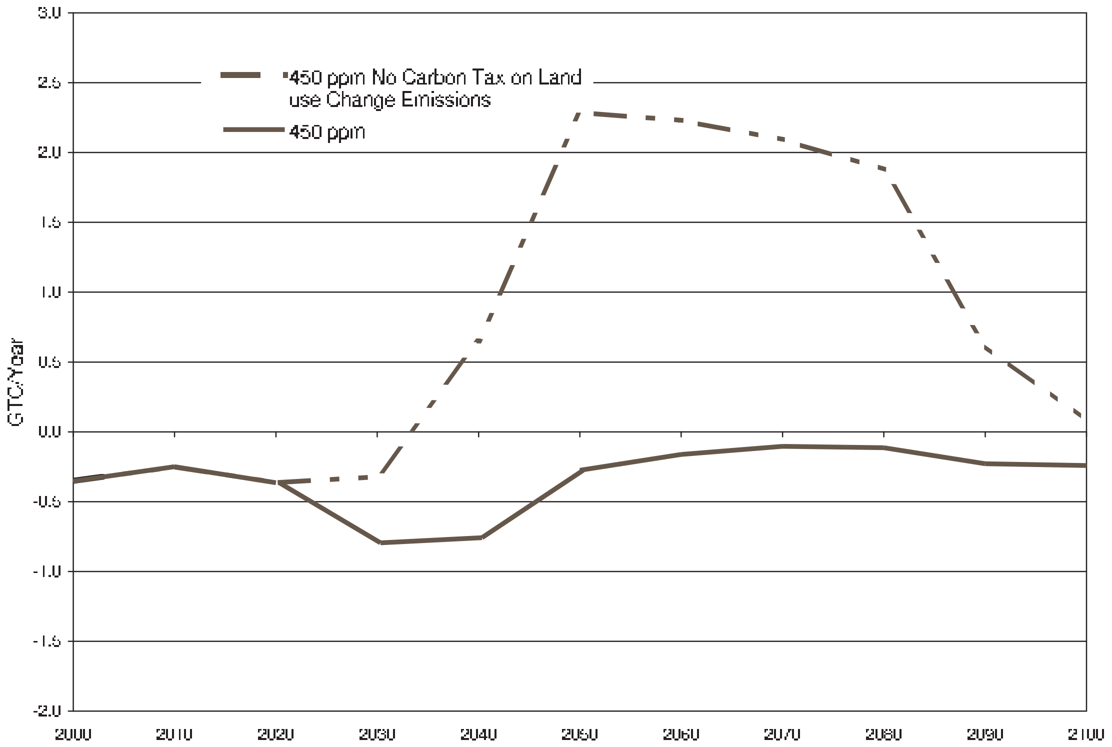


Figure 4-5. These two climate-stabilization cases have the same goal; however, the upper line demonstrates the potential consequence of not accounting for the value of carbon emissions from deforestation and other land-use changes.

Selected R&D, demonstration, commercial deployment challenges and opportunities for biotechnology and bioenergy include:

- Continue to improve the efficiency and lower the cost of cellulosic conversion processes.
- Continue to deliver increases in agricultural productivity for both food and energy crops, increases that must be sustained over the course of this century.
- Develop and deploy end-use energy systems across a number of different economic sectors that are adapted and optimized to the use of biofuels.
- Conduct research, field testing and likely large-scale demonstration projects to better understand the real-world potential for biomass energy systems coupled with CO_2 capture and storage technologies.
- Actively pursue the rapidly expanding field of genomic research to better understand how these techniques and technologies can be applied to produce and transform biological materials into large-scale clean energy.
- Improve methods for measuring and monitoring of carbon stocks in soils and standing biomass to help significantly expand already established practices such as low-till and no-till agricultural practices.

To realize the large-scale potential for commercial bioenergy and terrestrial sequestration, continued advancement across a wide variety of biological, agricultural, and engineering fields will be required.

Hydrogen Systems

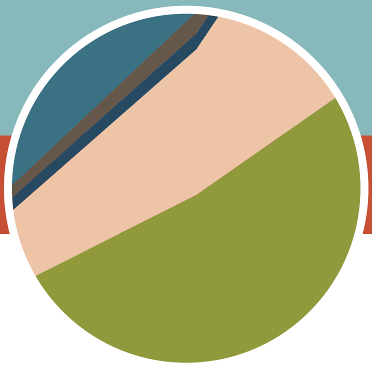
Hydrogen is appealing in the context of climate change because it is a portable energy carrier that does not emit any CO_2 as it is consumed. Hydrogen is also appealing in terms of conventional pollutants since water vapor is the only byproduct of its use. Hydrogen can be used to serve transportation energy demands—to operate automobiles, trucks, and other commercial carriers—that are now almost completely met by fossil fuel-based liquids that emit CO_2. Hydrogen can also displace fossil fuel-based end-use applications in buildings and industry. Among the key insights from the GTSP regarding hydrogen are the following:

- The major challenge for hydrogen and climate change policy is to develop and use production methods that do not release CO_2 emissions. Depending on the fuels and methods used, substantial CO_2 emissions may be involved in producing hydrogen.

- Without a carbon price, a hydrogen system would not necessarily reduce CO_2 emissions. Emissions would be reduced only to the extent that low-carbon or carbon-free hydrogen production technologies are economically competitive with hydrogen production from fossil fuels.

- Moreover, hydrogen energy systems may not deploy to as great an extent in a climate-constrained world because hydrogen production from fossil fuels (with CO_2 capture and storage to limit emissions) is more costly.

- The wide-scale deployment of hydrogen depends much more on significant improvements in the performance of future hydrogen technologies (e.g., for storage, distribution, and use) than on the price of CO_2.



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- Biomass and nuclear thermal sources of hydrogen will be more important sources of hydrogen in a greenhouse-gas-constrained world than in a world without climate policies.
- Hydrogen has a very low energy density compared to liquid transportation fuels. Since the transportation sector has been the principal focus of discussion for hydrogen, storage of hydrogen in vehicles is a critical technical and economic challenge.
- In addition to the transportation sector, hydrogen use in stationary applications such as buildings and industrial facilities may be just as be important and should also be a focus of research and development.

> *Technologies to produce hydrogen are already commercially viable, but its use is in small niche markets and not directly as an energy carrier.*

HYDROGEN SYSTEMS TECHNOLOGY

Hydrogen energy systems have three principal components: (1) production; (2) transport, storage, and dispensing; and (3) end-use.

Hydrogen Production. Technologies to produce hydrogen are already commercially viable, but its use is in small niche markets and not directly as an energy carrier. About 15.9 trillion cubic feet of hydrogen are presently produced globally per year, mostly to manufacture ammonia, but also for chemical processes, e.g., in gasoline refining. However, these processes produce hydrogen today at a price that cannot compete with traditional transportation fuels such as gasoline.

Although most hydrogen today is produced by chemically reforming natural gas, there are many other options. Hydrogen can be produced from fossil fuels or biomass feedstocks using conventional chemical processes. It can also be produced by dissociating water using electricity or heat, or by using specialized micro-organisms and an external energy source, such as sunlight.

The use of fossil fuels as feedstocks for hydrogen production creates a waste stream of CO_2 emissions. Since energy is required to transform fossil fuels into hydrogen, the resulting energy content of hydrogen is less than the total energy content of the fossil fuel input. Consequently, more CO_2 is emitted in transforming fossil fuel into hydrogen than from the direct combustion of fossil fuel for an equivalent energy content of hydrogen. However, these transformation losses to produce hydrogen may be acceptable in that, much like with conversion from fossil fuels to electricity, energy is required in converting a source to a more useful energy carrier.

Hydrogen from fossil fuel feedstocks could provide a major avenue of CO_2 emissions reduction if the CO_2 is captured and stored rather than vented to the atmosphere. The CO_2 emissions from hydrogen production are in a concentrated stream amenable to capture.

Without CO_2 capture and storage, fossil fuel-based hydrogen use could still lower overall CO_2 emissions for society, but only if the efficiency of its use were sufficiently greater than the efficiency of its production from fossil fuels. This is especially relevant in stationary applications such as buildings, where the excess heat generated by converting hydrogen in a fuel cell can be used in addition to the electricity produced. However, the amount of emissions reductions would be limited relative to using a non-carbon source.

Several alternative processes that do not use fossil fuels are available, including producing hydrogen from water, or using nuclear energy or biomass fuels.

Hydrogen can be produced by splitting water into its constituent parts, hydrogen and oxygen. This can be accomplished through electrolysis or thermal decomposition. If the electricity is taken from the grid, CO_2 emissions will be produced from that portion of power generation that employs fossil fuels in the production of hydrogen. However, dedicated electrical sources using wind or solar power could potentially provide carbon-free hydrogen.

Nuclear energy can be used to produce hydrogen without any direct emissions of greenhouse gases, either via electrolysis or thermal decomposition. Current light-water nuclear reactors that are in operation do not reach temperatures high enough for thermal decomposition of water. Nuclear reactor concepts capable of producing high temperatures suitable for hydrogen production are under investigation.

Biomass feedstocks can be used to produce hydrogen by gasifying the biomass and separating the hydrogen from the resulting syngas. If biomass comes from crops grown for this dedicated purpose, the net CO_2 emissions balance in producing hydrogen from biomass is small.

Transport and Storage. Once produced, the hydrogen must be moved from the point of production to the point of use. Compared to other energy sources such as fossil fuels and electricity, transport and storage may be problematic because the hydrogen must be converted to a highly concentrated form. Hydrogen is the smallest and lightest of all the elements; it tends to disperse rapidly at room temperature and therefore has a very low energy density unless it is concentrated.

That concentration can be accomplished either by increasing the pressure or lowering its temperature. However, raising the energy density of hydrogen to levels that make it useful as an energy carrier can be expensive. In fact, 30 to 40 percent of the energy content of hydrogen may be required to liquefy and store it. Again, just as with the energy losses in producing hydrogen, this additional energy requirement is acceptable if the economics signal a high value of having hydrogen available at the end-use.

The proximity of the production site to the point of use strongly affects hydrogen transport and storage costs. Current transport methods include truck, rail, barge, and pipeline. Over relatively short distances hydrogen can be transported as compressed gas, over longer distances as a liquid. It is presently stored in high-pressure cylinder tanks or cryogenic liquid containers.

Although storage of hydrogen for end-use demand is not an issue for all hydrogen applications, it is a major concern for hydrogen use in vehicles for transportation services. Safe storage capacity must be provided for sufficient vehicle range.

When the hydrogen is stored on board the vehicle, several problems emerge. Tanks that contain sufficient energy to move a vehicle 300 miles are presently large and heavy. Furthermore, because hydrogen easily penetrates many common materials and its boiling point is extremely low (21°K), hydrogen fuel loss from the tank can be significant if the vehicle is left unused for a significant period. Advanced methods are under study including reversible solid systems. But these are not yet practical

In a different approach, hydrogen can be produced on board the vehicle from a feedstock, presumably a fossil fuel and potentially a gasified biofuel, eliminating the need for hydrogen storage. However, unless the feedstock fuel comes from carbon-neutral biomass, on-board hydrogen production would release CO_2 to the atmosphere, reducing the climate benefit of hydrogen use. Again, if fossil fuels are used, CO_2 emissions reductions would be realized only if the overall gain in system efficiency of the hydrogen system is greater than the traditional fossil fuel combustion system.

Hydrogen use. Hydrogen is presently used industrially to upgrade vehicle fuels at refineries and to manufacture ammonia, but not generally as an energy carrier. However, the technology to use hydrogen to produce energy via a fuel cell or direct combustion does exist today, although it is far from being economically competitive for most uses.

Hydrogen could be burned in furnaces or boilers instead of natural gas to provide space heat, with the side benefit that it would produce water vapor that could be used to humidify the air in winter. It could also be combusted directly in internal combustion engines in vehicles. But for producing electricity as well as heat and water without pollutants or CO_2, hydrogen fuel cells are the technologies with the most promise.

Hydrogen fuel cell vehicles offer the potential for high transportation vehicle fuel economy with zero CO_2 and pollutant emissions. (Figure 5-1 shows a concept bus powered by a fuel cell.) Because of their modularity, fuel cells can be sized to the application and therefore

▲ **Figure 5-1.** Fuel cell-powered bus. Hydrogen fuel cell vehicles release no emissions in operations except water vapor.

are considered for potentially diverse applications, such as sources of combined heat and power for stationary applications in buildings and industry, in addition to their use in vehicles. The opportunity to utilize the heat as well as the electricity can lead to improved economic competitiveness in buildings and industry.

However, safety is a key consideration that must be addressed if hydrogen is to become a viable energy carrier at the end-use. Hydrogen is extremely volatile, leaks easily (although it disperses quickly), and burns with an invisible flame.

COST AND PERFORMANCE

The degree to which hydrogen can be supplied without concurrent greenhouse gas emissions will depend on the options for hydrogen production and the specific technology employed to produce the hydrogen. And that in turn will depend on costs—the cost of feedstocks, the cost of conversion processes, and the price of CO_2.

The relative costs of hydrogen production technologies will evolve over time as feedstock fuel prices change and technology costs and performance characteristics improve. Climate policies that place a cost penalty on emitting CO_2 will also significantly affect the relative costs. Figure 5-2 illustrates hydrogen production costs at two points in time: the year 2035 and the year 2095, for a GTSP scenario in which a climate policy sets a price path on emitting CO_2 so that atmospheric concentrations of CO_2 are stabilized at 550 ppm.

In the scenario shown in Figure 5-2, year 2035 carbon prices are low enough that production from natural gas and coal with the CO_2 vented (emitted) to the atmosphere are relatively cheaper than carbon-free options. However, by 2095, the carbon price is sufficiently high that venting CO_2 becomes very costly. The viability of CO_2 capture and storage technologies dramatically affects the competitiveness of coal and natural gas as hydrogen feedstocks under a climate policy. The cost of producing hydrogen from non-carbon sources is also expected to improve over time, and they would become even more competitive under a climate policy.

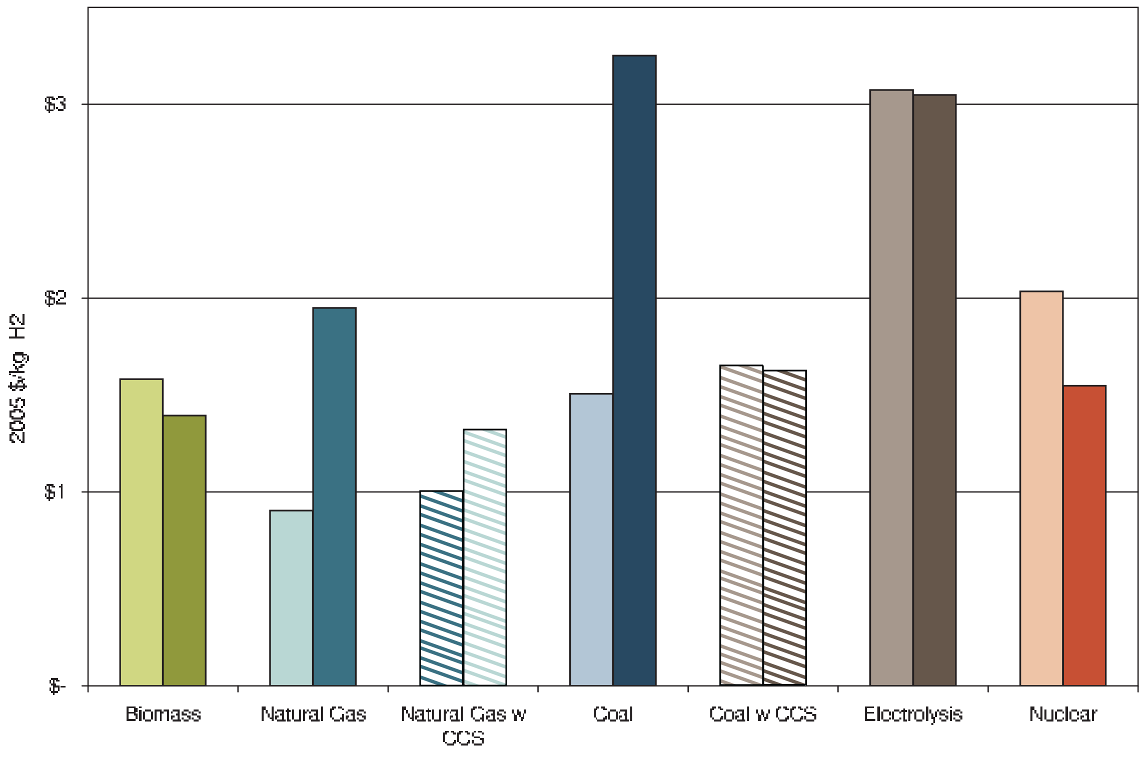


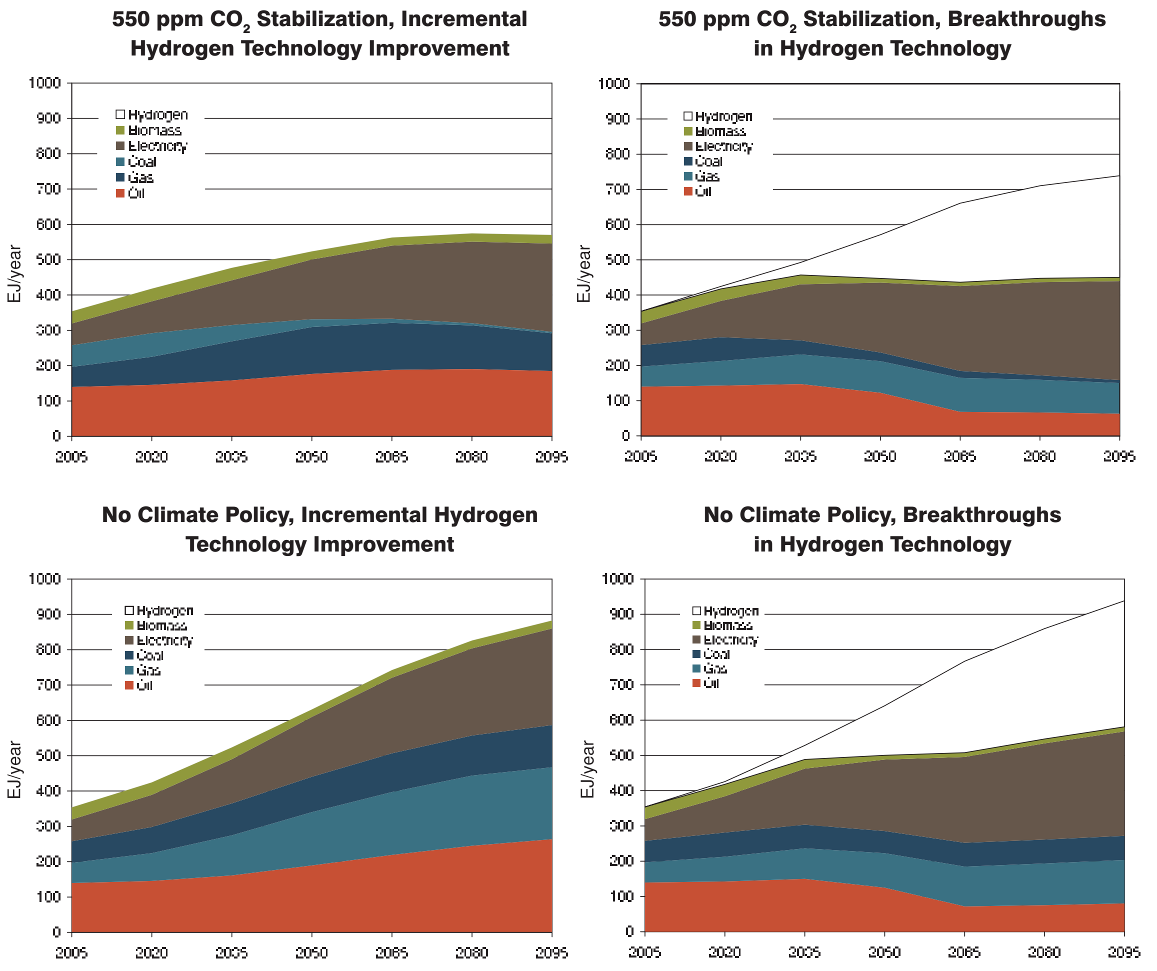
Figure 5-2. Cost of hydrogen production in 2035 (*left-hand bars*) and 2095 (*right-hand bars*), under a 550 ppm climate policy. The relative cost of hydrogen production technologies will change over time as fuel prices for feedstocks, carbon prices, and technology cost and performance evolve.

THE FUTURE DEPLOYMENT OF HYDROGEN

Most of the technologies discussed in this report benefit greatly from carbon constraints, but the net impact of climate policy on hydrogen will be conditional on how its technology is developed and used. One of the central insights from GTSP analysis is that the hydrogen must compete with other technologies primarily on the basis of its technical performance. Put simply, hydrogen cannot rely on a climate policy to make it economically viable.

In fact, hydrogen may not deploy to as great an extent in a greenhouse-gas-constrained world as it would in a reference world because carbon constraints force hydrogen to compete with energy conservation and energy efficiency technologies, and because hydrogen from fossil fuels (with CO_2 capture and storage to limit emissions) is more costly.

Figure 5-3 illustrates this point by comparing four scenarios, each pairing an assumption about future climate policy with future improvements in hydrogen technologies. With only incremental improvements in hydrogen technology, there is no large-scale deployment of hydrogen, even under a climate policy that holds CO_2 concentrations to 550 ppm. But with breakthroughs in hydrogen technology, hydrogen would deploy widely both with and without this climate policy. The impact of the climate policy may in fact be to reduce the demand for hydrogen relative to what it would have been without a climate policy.


550 ppm CO_2 Stabilization, Incremental Hydrogen Technology Improvement

550 ppm CO_2 Stabilization, Breakthroughs in Hydrogen Technology

No Climate Policy, Incremental Hydrogen Technology Improvement

No Climate Policy, Breakthroughs in Hydrogen Technology

Figure 5-3. GTSP scenarios of global final energy consumption. Under four sets of assumptions about climate policy and hydrogen technology development, the figures show that the deployment of hydrogen depends not on the presence of a climate policy but on the development of improved hydrogen technology.

Without a constraint on emitting CO_2 in general, hydrogen's climate benefits would be limited to the extent of overall system efficiency improvement and competitiveness of non-carbon hydrogen production sources. Because the cheapest source of hydrogen is fossil fuels, reductions in CO_2 emissions beyond what is achieved through improved systems efficiency will depend on the carbon price.

Figure 5-4 illustrates two alternative pathways of future hydrogen production under a climate policy. Each panel of the figure shows a scenario in which hydrogen systems are economically attractive and in which a climate policy limits the concentration of CO_2 to 550 ppm. On the left panel, CO_2 capture and storage technologies are assumed to be available and cost competitive, and hydrogen is produced from multiple sources: coal, natural gas, nuclear thermal, and biomass. Most production from fossil fuels employs CCS.

The availability of CO_2 capture and storage is an important determinant of the role of natural gas and coal in a greenhouse-gas-constrained world where hydrogen is a competitive fuel. If CO_2 capture and storage are available, natural gas and coal continue to be used as hydrogen feedstocks. If CCS technologies are not available, then fossil fuels are largely driven out of hydrogen production.

The right panel of Figure 5-4 shows the same climate policy scenario except that CCS is assumed not to be available and non-fossil means of producing hydrogen are assumed to improve. In this scenario, nuclear thermal dissociation of water and biomass sources of hydrogen dominate the second half of the century as the price of carbon makes them increasingly cost effective relative to fossil fuel feedstocks.

Biomass and nuclear thermal sources of hydrogen will be more important sources of hydrogen in a climate-constrained world than in a reference world. Whereas natural gas and coal are the cheapest sources of hydrogen in the absence of climate policy, a carbon price imposes significant costs on these methods and shifts hydrogen production toward other feedstocks and fuels such as biomass and nuclear.

Hydrogen use in stationary applications may be as important as in transport, as shown in Figure 5-5. The infrastructure that would be built to support hydrogen production and distribution to large stationary applications could provide the foundation for later expansion to a more dispersed set of hydrogen distribution points for transportation.

From Figure 5-5, assuming successful development of hydrogen systems and a 550 ppm CO_2 climate policy, hydrogen begins to deploy in all sectors, but the largest deployments in the period through 2035 are in buildings and industry (i.e., stationary applications). Deployment in transportation (i.e., mobile applications) might not exceed stationary applications until the second half of the century.

Finally, the challenges of developing large-scale hydrogen use are enormous. Not only must hydrogen be capable of providing all of the desirable characteristics of existing technology, expand services and amenities where possible, deliver fewer problems in the realms of environment, health, and safety, all at a competitive price, but society must simultaneously develop both a sophisticated infrastructure and a sophisticated set of end-use technologies.

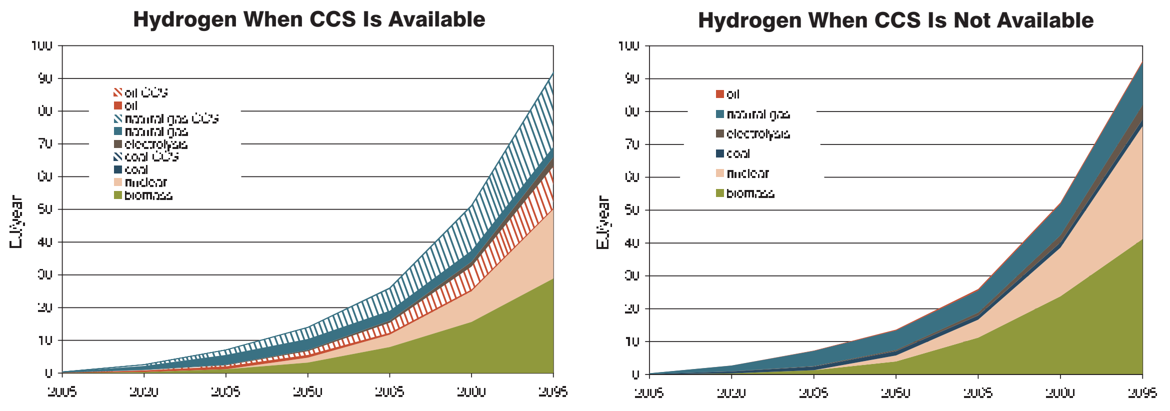


Figure 5-4. GTSP scenarios of global hydrogen production under a 550 ppm climate policy. CO_2 capture and storage (CCS) enables fossil fuels to be used as feedstocks for hydrogen production under a climate policy. Without CCS, non-fossil sources must be developed and used.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

The introduction of hydrogen into the global energy system requires several simultaneous changes to occur. System components must develop in parallel. That is, the capability to produce, distribute, store and use hydrogen must be developed and the costs lowered. Although hydrogen production is relatively well established and could go into service relatively quickly, transport, storage, and use remain to be developed.

The economic challenge for a new technology seeking to penetrate the market is to provide all of the desirable characteristics of existing technology, expand services and amenities where possible, and deliver fewer problems in the realms of environment, health, and safety, all at a competitive price.

To accomplish that goal, hydrogen technologies must improve substantially from their present state. Moreover, technology must chase a moving economic and performance target, since other technologies are also capable of improvement. In transportation this means continuous improvements in internal combustion engine, hybrid, biofuel, natural gas, and electric vehicles.

All aspects of hydrogen systems may improve, from production to transport and storage to end use. The greatest uncertainty in future cost and performance is associated with transport, storage, and end-use technologies.

If the potential for hydrogen technologies to contribute to CO_2 emission reductions is to be realized, all aspects of hydrogen production, transport, storage and use must be significantly improved in terms of cost and performance. Selected R&D, demonstration, commercial deployment challenges and opportunities for hydrogen energy systems include:

- Develop methods for producing hydrogen without emitting CO_2, such as CCS, biomass, renewable electricity, or thermonuclear, and demonstrate the ability to commercially deploy these methods on a large scale.

- Significantly improve the cost competitiveness and performance of vehicle fuel cells so that fuel-cell-based vehicles could play a significant role in decarbonizing the transportation sector.

- Reduce the cost of transporting hydrogen in order to build an economic hydrogen distribution system.

- Reduce the cost and improve the performance of storing hydrogen in sufficient energy quantities on board vehicles to allow safe use with driving ranges comparable to conventional vehicles.

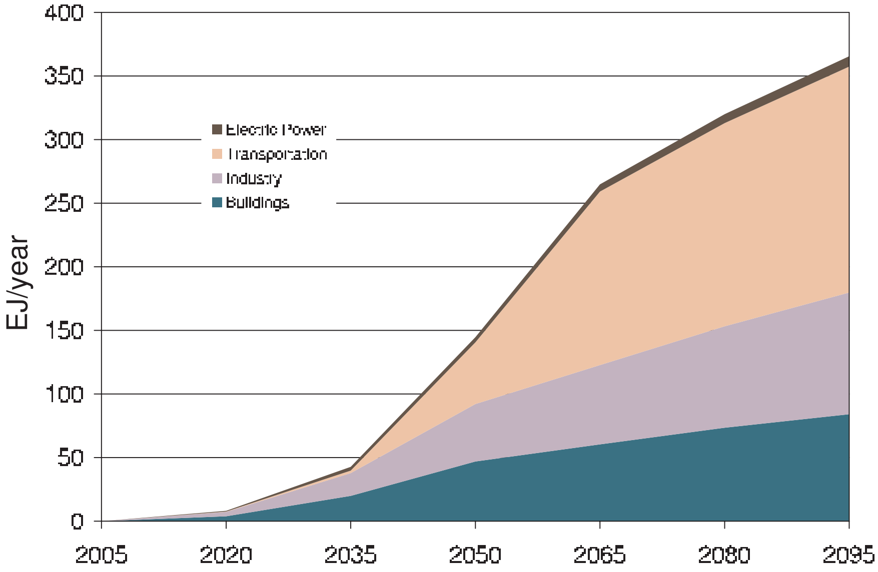


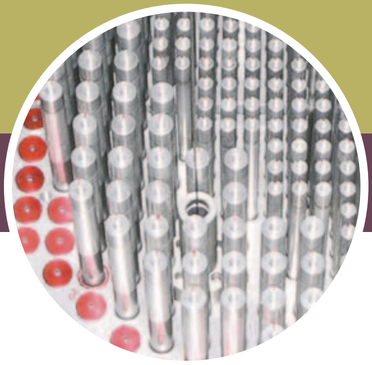
Figure 5-5. GTSP scenario of future global hydrogen use by sector. Hydrogen deployment may occur first in buildings and industry before expanding in transportation.

Nuclear Energy

The attractions of nuclear energy in addressing climate change are clear.

Nuclear power production has no direct CO_2 emissions and is already a significant component of the global energy system. In 2006, 435 operational nuclear power stations around the world generated approximately 16 percent of global electricity production. Improved economic competitiveness and safety of nuclear power along with concern for energy security and climate change are leading to a steady increase in worldwide nuclear power capacity. Waste disposal and proliferation concerns associated with expanding nuclear energy use remain important and unresolved issues. Key GTSP insights include the following:

- Nuclear power is cost-competitive with other means of generating baseload electricity in many parts of the world. Nuclear power is steadily expanding; 24 new nuclear power plants were under construction around the world in 2006.
- The world's reliance on nuclear power is expected to grow whether or not there are constraints on greenhouse gas emissions. In a carbon-constrained world, nuclear power would expand even further. The majority of this future deployment will occur outside of the present day Organization for Economic Cooperation and Development (OECD) nations.
- The cost savings from using nuclear technology in a carbon-constrained world are denominated in trillions of U.S. dollars.
- The supply of uranium, which is the principal feedstock for nuclear power, is not likely to be a limiting factor on the future deployment of nuclear power. The potentially significant expansion of nuclear power will require the



use of lower quality and more expensive grades of uranium in the long term, but this will have only a modest impact on the cost of electricity from nuclear power.

- Sufficient uranium is likely to be available to support an expansion of nuclear energy without reprocessing well into the second half of the century. If uranium should prove to be in short supply, then reactors capable of breeding nuclear fuels, along with recycling of used fuels, could continue to support the global expansion of nuclear energy; otherwise, nuclear energy use would decline in the second half of the century.

- If nuclear power expands rapidly in the United States and around the world, permanent waste repositories many times the capacity of the U.S. Yucca Mountain repository will be required. This concern has motivated reactor designs that recycle nuclear materials and minimize high-level wastes. Limited availability of permanent waste disposal capacities around the world could induce an earlier transition to advanced reactors that can recycle used fuels.

- The global expansion of nuclear energy implies greater movement of nuclear materials and proliferation risks. However, new concepts for nuclear fuels, fuel cycles, and reactor designs, along with innovative international agreements, may reduce these proliferation concerns.

THE EVOLUTION OF NUCLEAR POWER PLANT TECHNOLOGIES

Commercial electricity generating nuclear power reactors are fission reactors in which a sustained chain reaction causes atoms (e.g., uranium) to split, causing other atoms to split and so on, releasing energy at each split. To control the rate of splitting, a moderating substance is needed. The most common medium for controlling the reaction is normal or "light" water.

The Currently Installed Fleet of Nuclear Power Plants

All of the 435 present-day nuclear reactors currently licensed to operate in the world are nuclear fission reactors and can be broadly categorized as second generation reactors (Gen II); Figure 6-1 shows an operating reactor and a reactor core. The first generation included early prototype reactors of the 1950s and 1960s. The majority of the currently installed reactors are light-water reactors, either boiling water reactors (BWRs) or pressurized water reactors (PWRs).

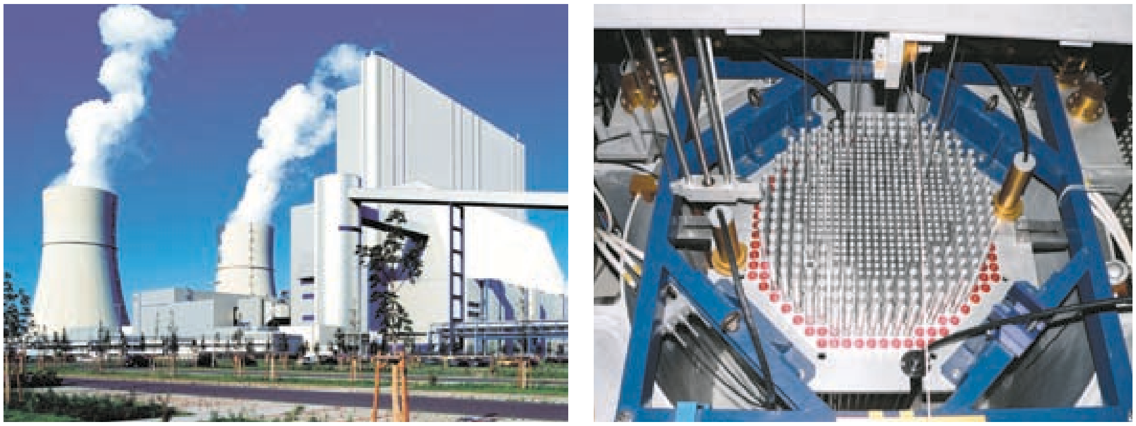
In 2006, existing commercial nuclear power stations accounted for approximately 16 percent of global electric power generation, 20 percent of United States electric power generation, 45 percent in South Korea, and more than 75 percent of power generation in France.

No new Gen II reactors are being built today. By the middle of the century, all of these legacy reactors will reach the end of their physical lifetimes and probably be retired. These reactors are being replaced by the next generation of reactors, so-called Gen III reactors.

Advanced Nuclear Power Plants

Decades of experience with existing reactors have resulted in the next generation of advanced reactors with cost and reliability improvements and passive safety features. These reactors, including advanced light-water reactors currently available for deployment, are referred to as third generation reactors (Gen III). These advanced reactors, including BWR and PWR designs, are being built around the world and are technically superior in many ways.

Other third-generation reactors not based on light-water reactor designs are also available for deployment, such as the pebble bed reactor, a high-temperature gas-cooled reactor. The pebble bed reactor replaces water with an inert gas as the coolant and has the advantages of greater thermal efficiency and modularity. Moreover, the pebble bed reactor is designed to withstand high core temperatures and shut down without an active system in the event of a loss of coolant. Pebble bed reactors are smaller in size and require lower capital investments and less time for construction than larger units. Pebble bed reactors are sometimes referred to as Gen III+ reactors.



▲ **Figure 6-1.** Nuclear power today. Nuclear plants are an important component of the world's energy system.

The Next Generation of Advanced Nuclear Power Plants

Future reactor technologies and fuel systems for the fourth generation of reactors are currently being explored with the explicit goal of improving the nuclear energy system in the areas of fuel utilization, economics, safety, waste minimization, and proliferation resistance. These reactor designs are referred to as Gen IV and may have the potential for creating or breeding nuclear fuels and for minimizing long-lived high-level wastes. Successful realization of next-generation nuclear systems can support the long-term future of nuclear energy in the global energy system.

Several candidate reactor concepts have been identified for development: gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), sodium-cooled fast reactor (SFR), supercritical-water-cooled reactor (SCWR), very high temperature reactor (VHTR), and molten salt reactor (MSR).

These candidate reactors vary markedly in design: nuclear fuel composition, coolant, moderator, and containment structure. Their similarities, however, are in their ability to utilize converted or recycled fuels, effectively achieving the goals of extending the life of natural uranium resources and minimizing the high-level waste requiring permanent disposal. Other similarities in these candidate reactors are their smaller size, modularity, passive safety features, higher thermal efficiencies, and continuous refueling or long refueling intervals that contribute to their improved economics, safety, and proliferation resistance.

The Nuclear Fuel Cycle

The present (Gen II) fuel cycle begins with natural uranium (see Figure 6-2). Natural uranium is enriched with higher concentrations of fissile uranium-235, processed into fuel pellets and fabricated into fuel assemblies that are inserted into the core of a nuclear reactor.

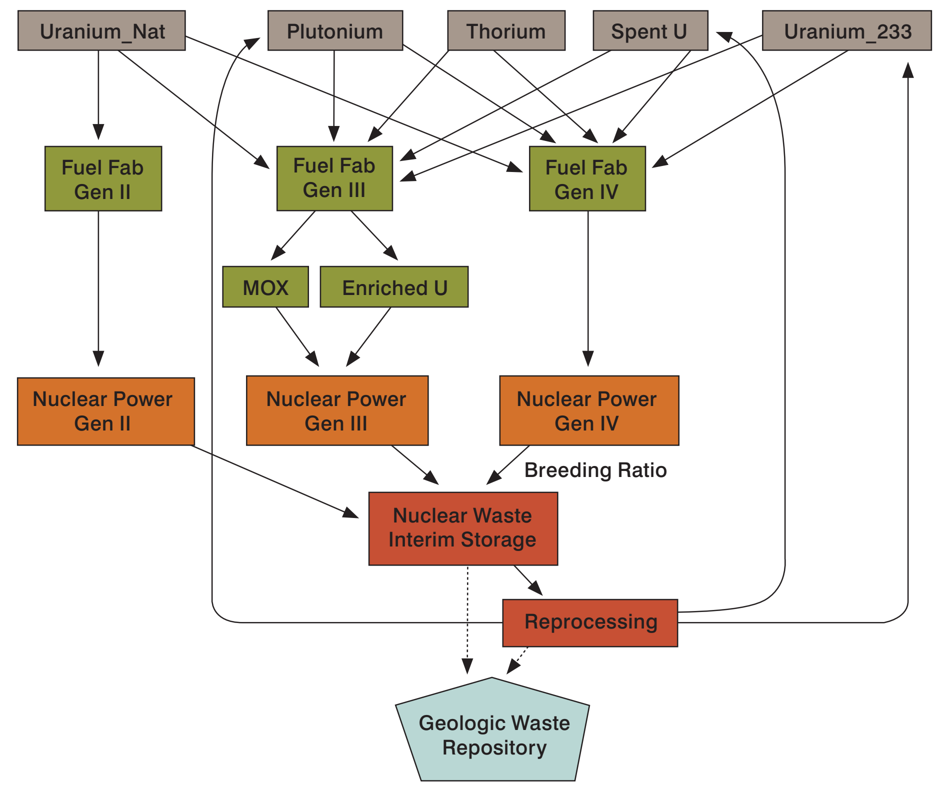


Figure 6-2. The nuclear fuel cycle. This diagram shows a schematic of the nuclear fuel cycle with potential alternative pathways for energy production from nuclear power.

Uranium is the principal natural resource used in the production of nuclear energy, and therefore the availability of uranium resources is an important consideration in shaping the role that nuclear energy can play in meeting future energy needs and in addressing climate change.

As nuclear chain reactions occur in the nuclear reactor, the fissile uranium and some fertile uranium are consumed, producing heat energy, and are transformed into a spectrum of nuclear waste, which includes products that retain high levels of radioactivity for up to thousands of years.

Currently, the spent fuel assemblies, which retain significant amounts of fertile and fissile material as well as fission fragments and minor actinides, are stored in intermediate storage facilities near the power plant. The present Gen II fuel cycle is a once-through system, i.e., it does not recycle the fertile and fissile material in the spent fuel. Long-term storage would be at a permanent, geologic waste repository. In the United States, that permanent repository is planned to be at Yucca Mountain in Nevada.

New Gen III reactors, as well as existing reactors, use enriched uranium or can be modified to utilize alternative nuclear fuel options. These options include uranium and plutonium mixed oxide (MOX) fuels, and the use of thorium along with uranium. As with traditional nuclear fuels in any light-water reactor, the use of these alternative fuels creates a spectrum of radioactive waste products, which need to be stored.

Solutions for disposing of intermediate to high-level radioactive nuclear waste in a safe manner for extremely long periods of time need to be realized. If nuclear power expands rapidly in the United States and around the world, permanent waste repositories many times the capacity of Yucca Mountain will be required. This concern, in part, has motivated reactor designs that recycle nuclear materials and minimize high-level wastes.

Gen IV technologies can potentially utilize reprocessed fuels, in which case the spent fuel would be shipped to a reprocessing plant where fertile and fissile material in the spent fuel is separated or isolated and used to produce new fuel. Reprocessing spent fuel in a manner that minimizes long-lived high-level wastes can reduce the fraction of original spent waste requiring permanent geologic disposal.

Reactors designed for breeding nuclear fuels can produce more fuel than is consumed, actually extending the amount of potential nuclear energy available from existing uranium resources. The proliferation concern with breeder reactors and reprocessing is that the fissile material, which is also used in nuclear weapons, is created in greater quantities and is potentially more accessible. Thus, while breeder and “near breeder” reactors reduce the problem of uranium resource limitation, they inherently create a potentially larger nuclear proliferation problem.

URANIUM: THE KEY FUEL RESOURCE FOR NUCLEAR POWER

Uranium is the principal natural resource used in the production of nuclear energy, and therefore the availability of uranium resources is an important consideration in shaping the role that nuclear energy can play in meeting future energy needs and in addressing climate change.

Other than the limited quantities of known conventional uranium resources, there is no consensus on the ultimate size of the global uranium resource base or on the cost of mining and processing speculative conventional and unconventional sources of uranium.

Various estimates exist of conventional uranium resources. A joint report by the OECD's Nuclear Energy Agency and the International Atomic Energy Agency (IAEA) contains the most authoritative estimates of known and undiscovered conventional uranium resources, otherwise known as the *Redbook*. According to the *Redbook*, the amount of uranium available at a price less than $130/kg is approximately 11 million tonnes of uranium (MTU). An additional 3 MTU is reported available without a cost range assigned.

Beyond these conventional resources, the existence of unconventional resources in which uranium exists at very low grades is not well established. Unconventional resources are, however, likely to be available, although at increasingly lower uranium concentrations and higher costs.

While the *Redbook* estimates are a good start to understanding the uranium resource base, the GTSP study looks out over a hundred years or more and must consider technological progress not only in new reactor designs but also in new resource extraction technologies. Technologies for recovering natural resources have improved significantly in the past and will likely continue to improve in the future. Also, the market price and our willingness to pay for natural resources will change with time.

A natural uranium supply curve that extends beyond the amounts reported in the *Redbook* was developed for modeling purposes. Using a geological estimate of the relationship between uranium abundance and ore concentration, a relationship between uranium cost and abundance was fitted to the *Redbook* cost estimates to continuously extend the supply curve beyond the *Redbook* totals (see Figure 6-3). A wide range of uranium supply curves are found in the literature, both more and less optimistic than the uranium supply curve as represented in Figure 6-3.

While significantly more uranium is likely to exist around the world in lower concentrations than the *Redbook* amount, the assumption of uranium availability limited to the *Redbook's* estimate of conventional resources implies that either nuclear energy production will decline in the second half of the 21st century or nuclear technologies that breed fissionable fuels will be needed.

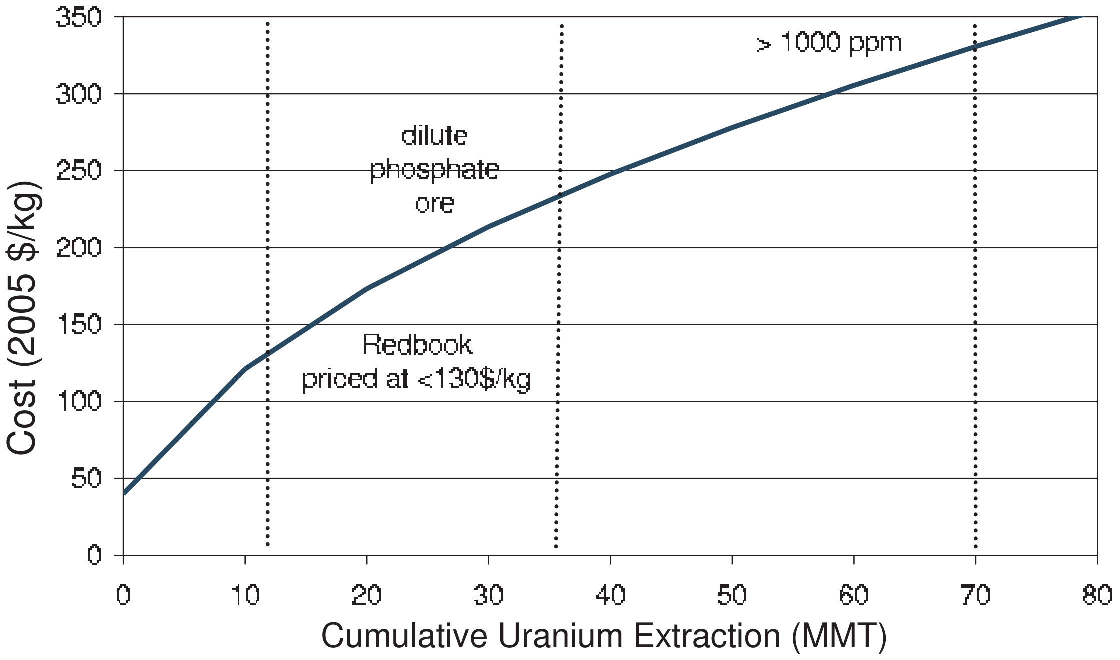


Figure 6-3. Natural uranium supply curve. In the future, demand for uranium will likely require the use of what is currently seen as unconventional grades, although the use of these unconventional grades will have only a modest impact on the cost competitiveness of nuclear power.

SCENARIOS OF NUCLEAR ENERGY DEPLOYMENT

GTSP has examined the market penetration of nuclear technology on the basis of cost and performance in a world in which other technologies compete for market share and in which all technologies improve over time. This analysis presumes that the issues of safety, waste disposal, and weapons proliferation are adequately addressed.

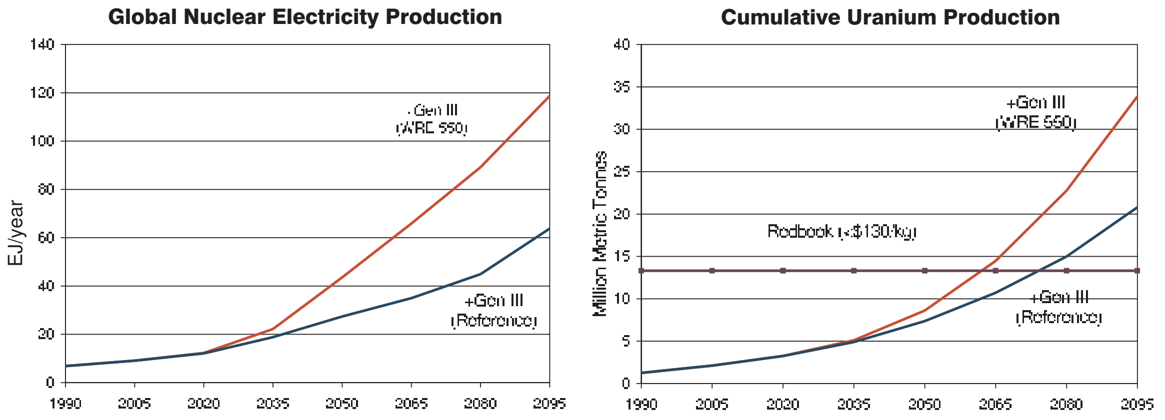
The paired figures in Figure 6-4 show the deployment of Gen III nuclear power for electricity generation in a reference case without climate policy and in a scenario where global CO_2 emissions are constrained so that stabilization of CO_2 concentration at 550 ppmv is achieved. As can be seen in the reference case, the deployment of nuclear power multiplies seven-fold while in the 550 case nuclear power deployment grows thirteen-fold by the end of the century.

While most of the world's current reactors are presently located in highly industrialized regions and nations such as Europe, North America, Japan, South Korea, and nations of the former Soviet Union, rapidly growing demands for electric power in developing countries such as China, India, and South Africa imply growing potential for deployment of nuclear technology. Figure 6-5 shows that in the reference case depicted above, by the middle of the century the majority of deployment in nuclear power occurs in the developing nations (so-called non-Annex 1).

The cost of stabilizing the concentration of CO_2 at 550 ppm without a nuclear option was about $4 trillion (present discounted costs at five percent per year over the period 2005 to 2095). That cost is idealized and assumes that all nations participate in limiting CO_2 emissions in the most cost-effective way possible. Adding an option to deploy Gen III nuclear reactors to the portfolio for electric power reduces the cost of CO_2 concentration stabilization by half or nearly $2 trillion. Figure 6-6 shows the cost reduction resulting from adding a nuclear technology option for alternative CO_2 stabilization concentrations. The reduction in cost associated with adding the nuclear power option to the portfolio of technologies for stabilization varies with the target concentration of CO_2. The lower the target concentration level, the more valuable it is to add nuclear power as an option. The higher the stabilization concentration, the lower the overall cost and therefore the smaller the incremental value of adding a technology to the portfolio.

In order for this deployment to take place, the world must be able to access and utilize significantly more uranium ore than the 11 MTU that is estimated in the Redbook as being available for less that $130/kg.

The cost of uranium ore, however, plays a relatively minor role in the overall cost of generating power. The power production cost is dominated by capital, operating, fuel enrichment, and fabrication costs. The original uranium resource accounts for only a few percent of the final cost of electricity from a new power plant today. In the scenarios above, the cost of uranium ore exceeds $200/kg, which corresponds to an increase in the



▲ **Figure 6-4.** The future of nuclear. Nuclear power production expands in the future, but the expansion is considerably more extensive in a greenhouse-gas-constrained world (top curves). Consequently, the expansion of nuclear power in response to climate change implies demands for uranium resources well beyond the *Redbook* estimates(right graph).

cost of nuclear power of approximately 0.4 cents/kWh. For this reason, GTSP analysis suggests that nuclear power could be competitive in the future at higher uranium prices, and unconventional resources drawn from more dilute and expensive deposits could be utilized.

Estimates of capital and operating costs (non-fuel costs) are given in Table 6-1, which is representative of the range of estimates for Gen III and Gen IV technologies. There is a wide range of construction costs, from $1,100 per kW to $2,300 per kW, for nuclear reactors that are classified as Gen III. Firmer estimates of cost will become available as reactors currently under construction are completed. The Gen III non-fuel costs used in the GTSP analysis are representative of the cost of advanced light-water reactors. The typical capital cost difference between a light-water reactor and a fast reactor is in the range of $0–$400/kWe or 0 to 27% based on light water reactor cost of $1,500 per kW. Gen IV reactor designs can be anticipated to have additional capital and operating costs, but potentially reduced waste disposal costs in the long term.

Nuclear fuel costs include the cost of uranium ore; and the conversion, enrichment, and fabrication of the ore into fuel assemblies. In the scenarios above, uranium ore costs were determined by the model from the interplay of the supply curve and the demand for uranium over time. Fixed charges for interim storage and permanent disposal of spent fuel waste were also included in the nuclear power costs. Gen IV reactors capable of breeding and using recycled nuclear fuels are expected to have lower interim storage and permanent waste disposal costs, but have higher fuel fabrication costs and include the additional cost of reprocessing.

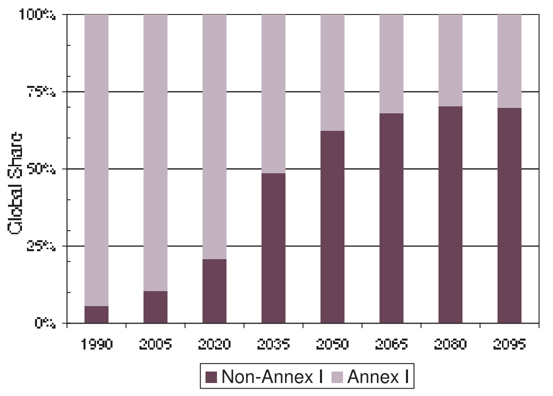


Figure 6-5. Nuclear electricity generation reference scenario. Over the 21st century, the majority of nuclear power generation shifts to developing nations.

Table 6-1. Nuclear power generation technology non-fuel costs for new plants (2003 USD/MWhr)

Year	Gen II	Gen III	Gen IV
2005	60	50	n/a
2035	n/a	48	57
2050	n/a	47	56
2095	n/a	45	54

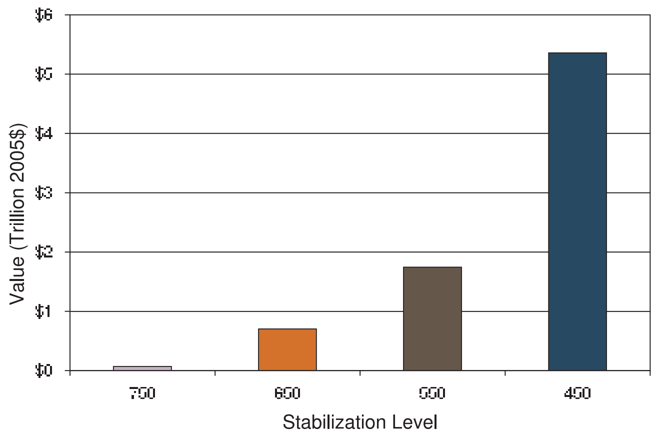


Figure 6-6. Value of nuclear in the GTSP portfolio. The cost of stabilizing greenhouse gases in the atmosphere is significantly reduced when nuclear power technologies are a part of society's broad portfolio of responses to climate change.

The four graphs in Figure 6-7 examine two critical elements that are often discussed in analyses of nuclear energy: (1) the global supply of uranium and (2) the need for breeder reactors. All four of these graphs assume that global emissions of CO_2 are constrained to reach stabilization in concentration of 550 ppm and that a broad array of other technologies is available and capable of generating competitively priced electricity.

The top set of graphs assumes that the availability of uranium is not limited and that more uranium is available at higher costs and lower concentrations than the Redbook estimates. In this case, as shown earlier, Gen III reactors based on a once-through fuel cycle continue to expand throughout the century. The addition of advanced Gen IV reactors does not expand the nuclear share of the power market; rather, Gen IV technologies compete with Gen III technologies.

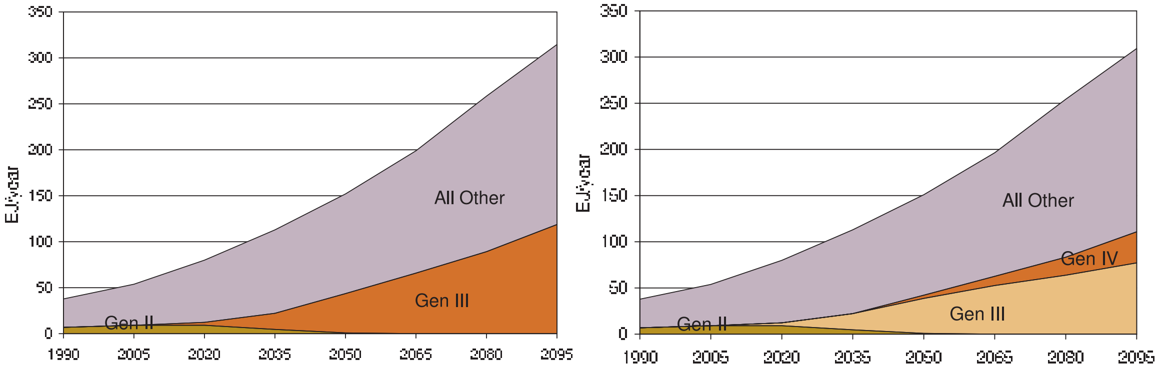
The bottom set of graphs assumes that the availability of uranium is limited to 11 MTU. Under these circumstances, it is clear that reactors with fuel breeding capability are needed in the second half of the century in order for nuclear power to maintain its role as an important contributor to the world's source of electricity and response to climate change. If uranium resources are limited and Gen IV reactors are not available, nuclear power's ability to contribute to electricity generation will peak around mid-century and then decline.

OTHER CONSIDERATIONS

While cost and performance are critical to any commercial future of nuclear power, nuclear energy technology must address other issues as well: nuclear

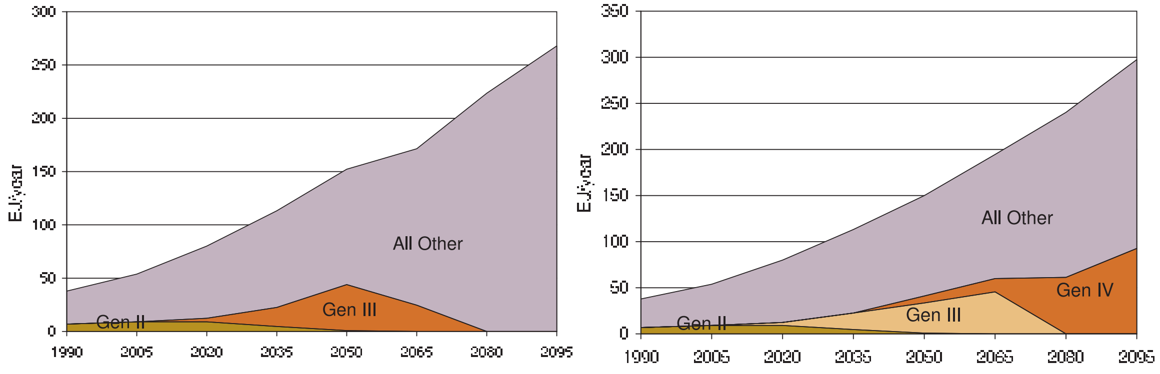
Gen III Reactors, Uranium Available beyond 11 MTU

Gen III and Gen IV Reactors, Uranium Available beyond 11 MTU



Gen III Reactors, Uranium Limited to 11 MTU

Gen III and Gen IV Reactors, Uranium Limited to 11 MTU



▲ **Figure 6-7.** Global nuclear power production relative to other sources of electricity under a 550 ppm CO_2 stabilization case. The size of the uranium resource base and whether breeder reactors are deployed both strongly influence the scale of future nuclear power generation and which types of reactor technologies are employed. The top graphs show stabilization cases in which uranium fuel is available, the bottom graphs with limited uranium. Left-hand graphs do not include breeder (Gen IV) reactors, while right-hand graphs do.

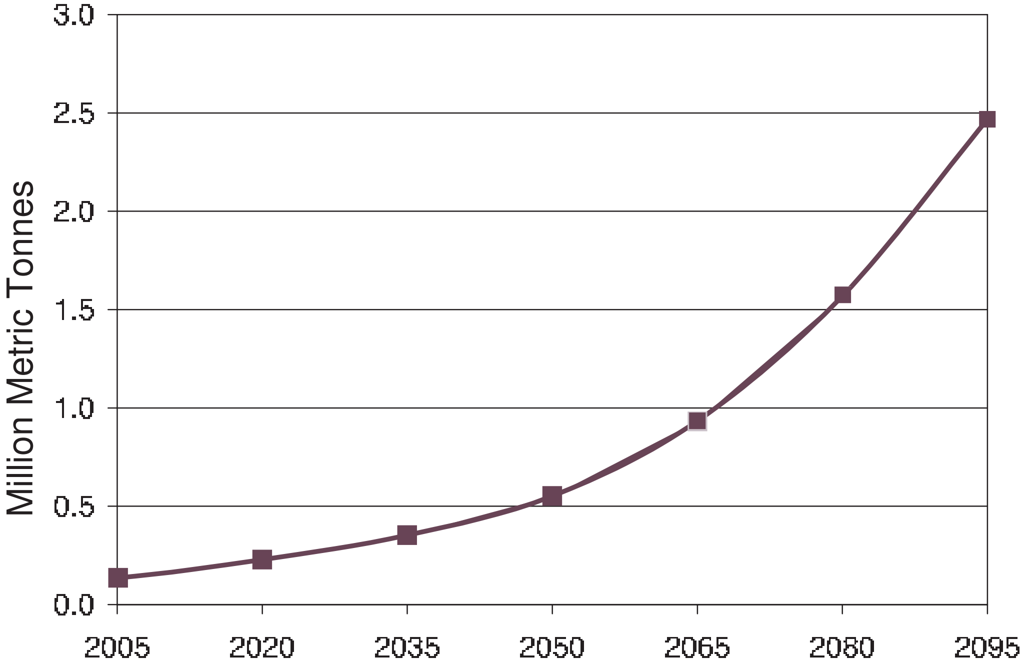
waste disposal, safety, and proliferation. Each issue is complex, and all three are ultimately interconnected with cost and performance.

The availability of uranium resources and geologic waste repositories, and the choice of nuclear reactors and fuel systems affect all three of these issues. The potential improvements to nuclear technology for increased safety, waste minimization, and increased proliferation resistance have not been exhausted, and new nuclear technologies and systems that can alleviate these issues are under investigation.

Waste Disposal

In the scenarios above, we have assumed that interim storage of spent fuel and permanent waste disposal costs are fixed and that the disposal of nuclear waste does not present an obstacle to nuclear energy use. Expansion of global nuclear energy use and reliance on the once-through fuel cycle, however, results in significant spent fuel waste accumulation. Up to 2.5 million metric tons of spent fuel could be generated by the end of the century (see Figure 6-8). The accumulated global waste of

The potential improvements to nuclear technology for increased safety, waste minimization, and increased proliferation resistance have not been exhausted, and new nuclear technologies and systems that can alleviate these issues are under investigation.



▲ **Figure 6-8.** Waste generation in a stabilization case. Significant quantities of spent fuel are created and need to be disposed of during this century with large-scale global deployment of advanced (but not breeder) reactors.

this scenario would require storage capacity equivalent to 36 times the legislated capacity of the United States' Yucca Mountain repository site.

It is unknown at this time whether multiple geologic waste repositories or other disposal options located throughout the world will be acceptable, available, and economical. The inevitable by product of nuclear energy use is the generation of nuclear waste. In this regard, nuclear technologies that minimize waste production and consequently, reduce the demands for geologic waste repositories are likely to be increasingly valued but only to the degree that they do not jeopardize the economic competitiveness of nuclear power.

Safety

The issue of safety has always been a concern with nuclear energy. However, two accidents, at Three Mile Island in 1979 and at Chernobyl in 1986, dramatically increased safety and health concerns. These incidents, along with decades of accumulated experience with nuclear reactor operation, have resulted in new reactor designs with reduced potential for catastrophic events. These designs are evident in the additional passive safety features of advanced light-water and other reactor designs such as the pebble bed reactor. Safety of nuclear reactors, fuel systems, and waste handling remains an important issue for nuclear energy, however.

Weapons Proliferation

Nuclear weapons remain a feature of the modern world, and the same nuclear materials that provide energy for peaceful use are also used in nuclear weapons. Expansion of nuclear energy use globally implies greater movement of nuclear materials, both fuel and waste, and potential for their easier access. New concepts for nuclear fuels, fuel cycles, reactor designs, and trade in nuclear technology are being pursued that may reduce these proliferation concerns. However, we must recognize that proliferation issues are not purely technical in nature, and that international agreements, institutions, and monitoring must remain central in addressing proliferation concerns.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

Nuclear power is already a significant part of the global energy system. However, the extent to which it can maintain its current market share or significantly expand it in a greenhouse-gas-constrained world depends in part upon continued R&D. Also, with the bulk of new nuclear power plant deployment occurring outside the present-day OECD nations, new improved reactor designs and features may be developed outside of the traditional Western nuclear powers. Selected R&D, demonstration, and commercial deployment challenges and opportunities for nuclear power include:

- Establish the economic viability of next-generation nuclear energy systems.
- Demonstrate the capability of safe high-level waste disposal.
- Develop recycling and fuel processing technologies for breeder reactors to enable a transition from a once-through to a closed nuclear fuel cycle. The commercial deployment of these advanced reactor and fuel system technologies could reduce the quantities and toxicity of spent nuclear fuels and reduce the need for geologic waste disposal.
- Develop the nuclear capacity to generate hydrogen for use in transportation and other end-use sectors. Advances in thermo-chemical and high-temperature electrolysis based on nuclear technology will determine the economic viability of nuclear-based hydrogen production.
- Create innovative international policies for trade in nuclear technology and fuel that allow for global expansion of nuclear energy for electric power generation while addressing proliferation concerns.

> ***Expansion of nuclear energy use globally implies greater movement of nuclear materials, both fuel and waste, and potential for their easier access.***

Wind and Solar Power

Wind and solar are iconic renewable resources, characterized by large potential, no direct emissions of pollutant or greenhouse gases, and the capability to produce sustainable energy indefinitely. Consequently, wind and solar technologies have enormous potential to meet a significant portion of the world's future energy demands with little impact on the atmosphere. However, large-scale deployment of wind and solar raises unique research and systems analysis issues.

The first issue involves limits on availability. In contrast to other sources of electric power, wind and solar are intermittent resources in that their availability, while predictable, cannot be completely controlled. In addition, wind and solar power generators must be located where the physical resources exist, often requiring an investment in transmission capacity to deliver power to populated load areas.

Moreover, current wind and solar technologies require large up-front capital investment, although they offer low recurring costs. The present and future potential of these technologies will be determined in large part by the extent to which technological developments can lower their capital cost. Finally, wind and solar generators are typically much smaller than fossil and nuclear plants, requiring multiple units over a wide area to build up to a large scale. This dispersion results in challenges for land use and environmental aesthetics. The extent of eventual deployment of these technologies will depend on land-use decisions and social acceptability. Key GTSP insights include:

7

- With or without a climate policy, the contribution of wind and solar power technologies will continue to increase. Their role would become even more important under greenhouse gas emissions constraints.

- Reducing the capital cost of solar technologies to make them competitive with other sources of electricity is a critical R&D challenge.

- Intermittency of solar and wind energy resources must be considered as part of the cost of wind and solar power. The cost is small for low penetration levels, but will increase as wind and solar gain higher market share. Improved grid management and storage technologies may play a role, particularly at high penetration levels.

- Wind is already cost-competitive with other technologies in several locations and applications. Thermal central station solar electric plants are currently the most cost-effective solar electric technology, although only practical in fairly cloud-free regions.

- If deployed at a large scale, wind and solar facilities would be both much more numerous and spread over a larger area than the equivalent fossil-fired facilities. This provides both benefits, such as lower cost variability and income to landowners, and new challenges, such as the need for additional transmission infrastructure.

WIND POWER

Wind power is a well-known and commercially successful technology for electric power. It is rapidly growing in the United States and in other parts of the world. Although wind is still a small fraction of U.S. total electric capacity, its deployment has more than doubled in the past several years (see Figure 7-1). Generation costs are competitive or nearly competitive with fossil-fueled power plants in many places. This expansion has been accelerated not only by policies such as tax incentives and renewable portfolio standards but also by an evolving market for green power in which firms or individuals are willing to pay to secure generation from renewable sources like wind to meet their electricity demands. Under a climate policy that increased the costs of fossil fuels, wind power would expand substantially.

The technology for generating electricity from wind is fairly straightforward. Most commonly, double or triple blade turbines are mounted high overhead on cylindrical towers; the turbines capture the blowing winds and generate electricity. For large utility-scale applications, multiple wind turbines are generally placed together, either along a line or spaced in an array configuration (Figure 7-2). Wind turbines are a fairly mature technology with commercial deployment and management worldwide.

SOLAR POWER

Solar energy can be utilized in many forms. The least expensive technology for generating electricity with solar power is central station thermal or concentrating solar power (CSP), where solar energy heats a working fluid to high temperatures to power a turbine (Figure 7-3). This technology requires direct sunlight and thus must be sited in fairly cloud-free locations to operate.

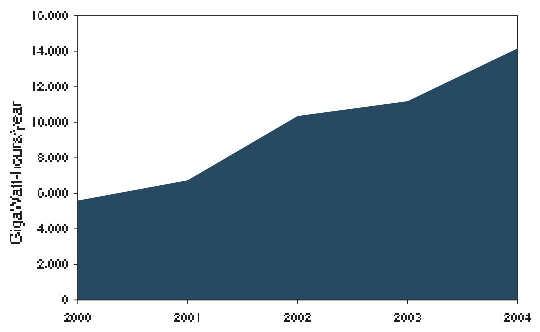


Figure 7-1. US wind electricity generation. Wind generation has been growing rapidly in the United States since 2000.

Figure 7-2. An Array of Wind Turbines. Typical new wind turbine size is on the order of 1.5-2.5 megawatts (MW). Turbines are sited in wind farms to build economies of scale for transmitting electricity to load centers.

The most versatile technology for utilizing solar energy is photovoltaic (PV) conversion (Figure 7-4). PV technology can be deployed in any location, with output roughly proportional to the amount of sunlight. PV systems can be mounted at a fixed angle or in configurations that track the sun in one or two axes. There are two broad approaches to photovoltaics: crystalline and thin film. Crystalline PV cells offer higher efficiency but are more expensive. Thin film PV systems are less expensive but have lower conversion efficiencies.

Outside of electricity generation, the least expensive method of using solar energy is as a source of direct heat. Residential solar hot water systems are economically attractive in many locations and are widely deployed in a few countries (Israel, Greece, and Cyprus).

WIND AND SOLAR IN THE ELECTRIC SYSTEM

Although both wind and solar are intermittent resources, they operate much differently from each other within the electric system. Since wind may be available at all hours, wind largely operates to supply baseload generation (defined as generation that operates at all hours). Thus, wind competes most directly with electric generation plants such as coal or nuclear plants. This also means that the potential contribution from wind is very large, as the largest fraction of total electric supply falls into this category.

In contrast, solar power is only available during hours of sunlight—i.e., the daytime. Fortunately, solar power's availability does generally coincide with the peak electricity demands that also occur in the daytime. Consequently, solar power competes in the market for intermediate and peak power, which typically receives a much higher market price than baseload power. To operate beyond daylight hours, solar hot water and CSP systems can be constructed with thermal storage that can extend the time over which they can effectively operate. However, this is not true for solar PV systems; they convert the light directly to electricity rather than using heat from the sunlight, which can be stored. Therefore, external storage would be needed to allow PV systems to provide services outside of daylight hours.

▲ **Figure 7-3.** Concentrating solar power from a central station such as this is currently the least expensive solar electricity generation technology.

Although windy and sunny conditions can potentially be predicted, they cannot be controlled. Therefore, to provide reliable energy services either backup capacity needs to be provided or the provision of services delayed until power becomes available. If a relatively small portion of power is supplied by wind and solar (for example, around 10-15 percent, although each situation will be different), the reserve capacity already present in the electric generation network is likely to be sufficient to compensate for these variations. Beyond these penetrations of wind and solar, additional capacity or reserves would be required.

As larger amounts of power are supplied from intermittent sources, the remedies available to ensure reliable energy service delivery depend on the time scale. Over relatively short time scales, minutes to perhaps tens of minutes, some services (such as cooling) could be postponed or accelerated using advanced load management. For longer variations, some sort of backup generation or storage would be necessary. Countering this to some extent is the geographic dispersion of sources that will tend to come with greater penetration.

The variation in wind is thought to be fairly randomly distributed across a large enough regional scale (e.g., it is unlikely that the wind would stop blowing in several places at once). However, solar irradiance can decrease coherently over large regions. This coherence means that an electric system could see much of its solar capacity reduce its generation all at the same time, potentially causing supply problems. While the intermittency of these resources should not be considered insurmountable, understanding the impact of these effects at the high levels of wind and solar penetration that could be realized under a climate policy is still at a rudimentary level.

THE ROLE OF STORAGE

Because electricity generation must be timed to coincide with electricity demand, the intermittency of wind and solar provides an additional challenge beyond reliability. The availability of these resources will not always coincide with the timing of the demand for them. The development of effective and economic storage technologies would attenuate this problem and allow further use of wind and solar power.

Figure 7-4. An array of solar photovoltaic (PV) panels. PV is the most versatile solar technology. It can be deployed in any location, with output roughly proportional to the amount of sunlight.

For example, consider a system with a high penetration of wind capacity. In such a system, there may be times when more wind energy is available at night than what is needed without turning down electricity generation from baseload plants. In the absence of storage, it may be less costly or even physically necessary to throw away some wind electricity than to turn down the baseload plants. But with the development of advanced storage technologies such as compressed air energy systems (CAES) or large-scale batteries, this wind power could be stored for use during the day. Using storage in this manner would increase the amount of electricity generation met by wind without additional reliability considerations.

Electricity generated from wind and solar resources can also be used to produce hydrogen. While hydrogen can be considered a form of storage in the electric sector, it tends to be a relatively expensive form of storage because of the combined effect of capital costs and conversion losses. Hydrogen is more likely to be supplied from wind and solar if there is a direct end-use demand for hydrogen fuel.

RESOURCES

Wind turbines extract energy from the kinetic energy of moving air. The amount of energy extracted is proportional to the wind velocity cubed. Energy generation, therefore, falls rapidly with a decrease in wind speed. This implies that high-speed wind resources are much more valuable than low-speed wind resources—although this value can be reduced if the resulting electricity must be connected over long distances to available transmission lines or load centers.

Large physical wind resources are present in many regions of the world. An International Energy Agency study of global wind resources estimated some 40,000 terawatt hours/year may be available globally, several times total world electric demand. How much of this resource would be used depends on generation cost, site selection issues, transmission to load centers, and integration with the electric grid at high penetration levels. Wind turbines have a relatively small footprint, allowing other uses of the land (Box 7-1). The height of wind turbines, which make them visible for some distance, partially offsets this advantage.

Box 7-1. LAND AREA AND RENEWABLES

Harnessing relatively diffuse wind and solar resources on a large scale would result in the widespread deployment of wind turbines or solar photovoltaic arrays. The land-use consequences of these technologies differ considerably. Consider the use of residential rooftops for the generation of solar power in the United States. 100 million households with an average of 850 square feet each of usable rooftop area might produce around 700 TW-hr of electricity annually.[a] This would represent 18% of current electricity generation.

Expansion of solar beyond this level would require additional land area. Photovoltaic cells have the advantage that there is no fundamental need for contiguous space so they, could in principle, be placed wherever land is not otherwise needed. In contrast, central station solar plants, which are significantly less expensive currently than photovoltaics, require contiguous land area for operation.

Wind power has a very different profile in terms of land use. In order to generate the same amount of power, wind turbines would be more ubiquitous—spaced out over seven times the area (compared to total rooftop area) and visible for miles around each turbine facility. The land surface area dedicated to wind power in terms of tower footprint and associated land, however, is much smaller—only one fifteenth of the space used by solar panels.[b]

[a] Assuming 1250 residential square feet per household, accounting for multi-story dwellings, and assuming 50% of the rooftop space is installed with solar panels that operate at 12% efficiency with an average effective radiance of 4 kWh/m^2/day.

[b] Assuming 2 MW turbines operating at 30% capacity factor and requiring an acre per turbine and compatible land uses such as agricultural activities immediately adjacent to the turbines.

Solar resources are even larger than those for wind. The primary limit for solar resources is the amount of land that society is willing to dedicate to this purpose. In terms of land surface fraction, 0.1% of the land surface of the earth could supply several times the total wind resource. While small in fractional terms, 0.1% of the land surface area is comparable to the global area of cultivated land. Thus, supplying solar energy at this magnitude would entail a significant land-use change. More modest, but still significant, amounts of solar power could be supplied using rooftops, for example (Box 7-1).

Although fossil fuel resources are not uniformly distributed geographically, they can be transported over long distances at relatively modest costs. Solar and wind resources, however, vary substantially across the globe. Solar resources are concentrated largely in lower mid-latitude and equatorial regions (Figure 7-5). Wind resources vary as well, although there is substantially more uncertainty in global wind resources.

Comparisons to current energy demands, while useful, underestimate the scale of the future challenge. For example, in GTSP scenarios used in this report, global electric generation expands more than fourfold by 2100.

COST AND PERFORMANCE

Reporting costs for wind and solar technologies is more difficult than for fossil technologies. First, the cost of energy production for these technologies depends on the quality of the resource being used. Second, there can be a tradeoff between generation cost and location. Generation costs are lowest where the highest quality resources are located. Some of these locations may be located far from load centers, incurring costs for transmission lines. Finally, the intermittent and non-dispatchable nature of these sources means that, as penetration increases, additional costs may be required to assure reliable power.

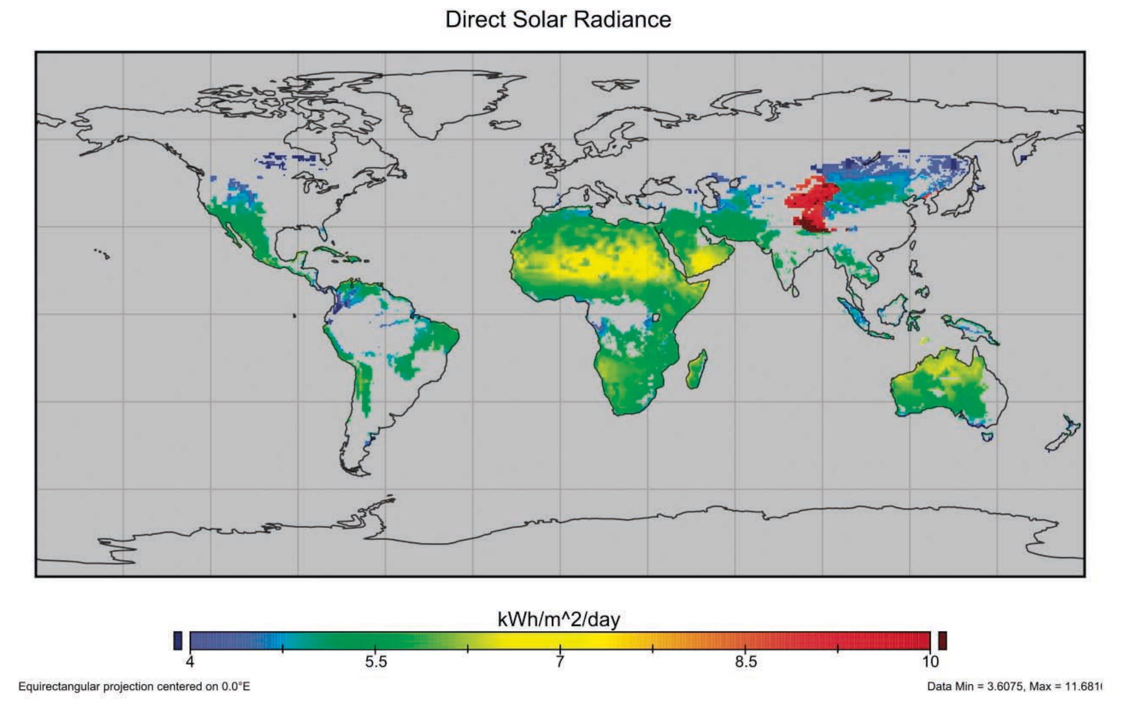


Figure 7-5. Direct solar irradiance on a horizontal plate for potential solar resource areas with less than 50 no-sun days per year (dense forest and croplands excluded). The colored areas show where large scale deployment of concentrating solar thermal plants could take place.

Table 7-1 shows costs for the dominant technologies: wind turbines, CSP, and photovoltaics for different resource categories. Currently wind is the most cost-effective, with CSP showing promise if technological advances are made in storage technologies. Photovoltaics are the most expensive, but also the most versatile of these technologies.

OTHER CONSIDERATIONS

Wind and solar power are generally perceived positively, with strong advocacy from some due to their lack of emissions and other potential benefits such as low cost volatility, rural income support, and energy independence. The use of these dispersed resources on a large scale would require widespread deployment of wind turbines or solar generation facilities. Construction of wind farms has encountered public resistance in some locations. Environmental concerns about wind turbines center on bird and bat mortality, although noise and road construction can also be issues. Visual issues are sometimes a significant concern as the presence of wind turbines alters the appearance of pristine areas. This has been of particular concern for some ridge-top and near offshore locations.

Solar power has not become widespread enough to test its societal acceptance. Aside from use of rooftops, solar energy generation generally requires dedicated land use.

Most currently utilized electric generation technologies can be sited at locations that offer the best combination of distance to load centers, ease of fuel delivery, and access to water for cooling. Solar and wind plants, in contrast, must be sited at the location of suitable resources. In most cases this will require the construction of electrical transmission lines to connect high resource regions to sometimes distant load centers. The construction of overhead transmission lines can also meet with opposition. Modest reinforcement of existing transmission lines would likely be more acceptable, but may not provide sufficient capacity to utilize some potential resource sites.

Table 7-1. Current Renewable Energy Technology Costs

		Solar PV	
Received Irradiance (W/m ^ 2-yr)	*1700*	*2000*	*2300*
Electricity Cost (cents/kW-hr)	29	25	21
		Concentrating Solar Trough	
Direct Irradiance (W/m ^ 2-yr)	*1700*	*2000*	*2300*
Electricity Cost (cents/kW-hr)	26	22	19
		Onshore Wind Turbines	
Wind Class	*4*	*5*	*6*
Electricity Cost (cents/kW-hr)	4.6	3.8	3.4
		Offshore Wind Turbines *(Shallow water)*	
Wind Class	*4*	*5*	*6*
Electricity Cost (cents/kW-hr)	5.3	NA	4.5

All costs are generation costs, exclusive of grid connection costs, backup costs, and tax policies.
Note that actual market costs will fluctuate due to business cycles in the supply and demand of the capital equipment.

Any new technology, particularly if highly visible, can cause concern due to unfamiliarity. It is not clear if these issues will abate over time as, for example, wind turbines become more common and people become accustomed to their visual presence in the landscape. Improved implementations, such as wind turbines with reduced noise and lower avian mortality, can also lessen impacts.

THE FUTURE DEPLOYMENT OF WIND AND SOLAR

Research on the large-scale deployment of wind and solar technologies at levels that may occur under a climate policy is in its early stages. GTSP's current analysis indicates that wind energy can contribute substantially to meeting electricity demands (see Figure 7-6). Based on a reserve margin formulation of backup costs we find, in line with other studies, that the cost of backup capacity is relatively modest, although there may be additional issues at higher penetration levels. The principal limit to wind contribution is not its intermittency but rather its costs relative to other electric power technologies. The resource cost of wind will tend to increase with higher levels of deployment. As higher quality and closer wind resources are used, the remaining resource becomes less competitive with alternative electric generation options.

Perhaps the biggest challenge for large-scale solar power is reducing the high capital cost. Managing the temporal pattern of solar power in the system is another critical issue, as is the regional heterogeneity of availability and quality of solar resources. Some solar technologies, such as residential hot water heating, are relatively low cost and could potentially make significant contributions in many regions.

Concentrating solar power technologies, in contrast, are only practical in fairly cloud-free regions, although the energy is partially dispatchable and backup is relatively inexpensive. Further, solar technologies can require the operation of separate backup power or storage in times when the sun is not shining (nights and cloudy days).

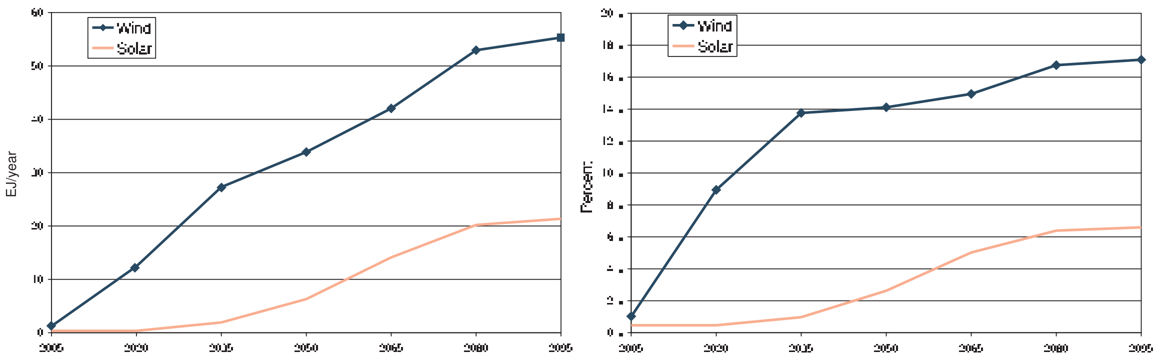


Figure 7-6. Potential future global deployment of wind and solar power under a 550 ppm CO_2 stabilization policy. In this scenario, wind power deployment expands dramatically, generating nearly 14% of total global electricity by 2035. Wind generation continues to grow in the second half of the century, but its share grows more slowly as total electricity generation increases at an escalating rate. Solar generation increases by 2050 as its costs become more competitive.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

The deployment of wind and solar power systems around the world makes these renewable energy systems some of the fastest growing aspects of the global energy system. However, the extent to which wind and solar power can significantly expand their current market share in a greenhouse-gas-constrained world is in part dependent upon continued research and development. Selected R&D, demonstration, commercial deployment challenges and opportunities for wind and solar power energy systems include:

- Reduce the capital costs of solar photovoltaic and concentrating thermal technologies to be more competitive with conventional sources.

- Improve grid management systems to incorporate the intermittency of wind and solar energy.

- Reduce costs of storage so that wind and solar resources can be fully utilized when their periods of availability do not coincide with periods when their electricity is needed or most valued.

- Continue to develop and refine turbines that are optimized to work in offshore environments and low wind speeds.

- Reduce the cost of transmission from remote sites with large wind and solar potential to electric load centers.

End-Use Energy Technologies

The focus of this chapter is on services for businesses and individuals that require energy. Energy services, also called energy end-uses, include demands such as cooling, heating, and lighting homes; transporting people and freight; and heating and powering a range of industrial processes. The set of energy services across the economy and the set of end-use technologies that provide them are extremely diverse.

Efficiency gains in end-use technologies reduce the demand for energy to provide the specific energy service, e.g., lighting; allow the use of carbon-free energy sources; and reduce the losses of energy in the process of converting primary fuels to electricity and delivered fuels. More efficient end-use technologies also help to conserve natural resources, reduce the impact of energy production on the environment (air quality, other pollution), and enhance energy security.

The importance of increased electrification in response to a CO_2 stabilization policy is one of the key findings of our research on end-use energy. The development of improved, more cost-effective, end-use energy technologies that use electricity can reduce emissions through both efficiency improvements and the use of electricity from low-carbon emission sources.

The opportunities for improving and deploying end-use technologies vary substantially across the portfolio of end-uses in the buildings, transportation, and industrial sectors.

8

Buildings Sector

- Make substantial efficiency gains in specific end-uses such as solid state lighting and heat-pump-based technologies for space conditioning, but also through integrated building design.
- Develop smart appliances that could also help stabilize the grid, increasing reliability and perhaps facilitating the deployment of non-dispatchable renewable energy.

Transportation Sector

- Realize the substantial potential for efficiency gains in light-duty vehicles, with further opportunities for shifting to low-emission technologies such as electricity, hydrogen, and biofuels. The deployment of hydrogen will depend substantially on the development of fuel cell, and hydrogen storage and distribution technologies.
- Improve battery technologies to benefit all electric-based vehicles, whether fuel-cell, hybrid, or plug-in hybrid.

Industrial Sector

- Re-engineer industrial processes to require less energy services, such as the use of membrane technologies for chemical separation processes that would use much less heat and steam.
- Explore burning commercial biomass as a non-fossil option where processes still require high temperatures for steam or heat. For some applications, the economic response may be to continue using fossil fuels even while paying an emissions penalty.

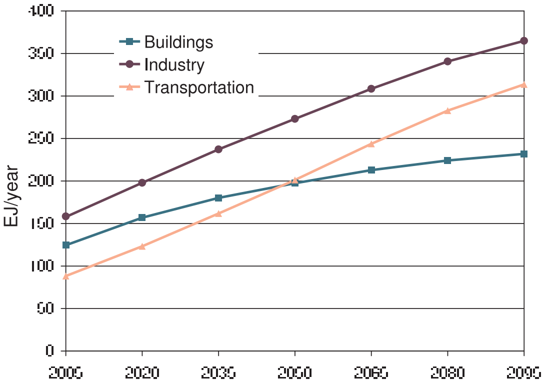
A GLOBAL PERSPECTIVE ON END-USE ENERGY DEMANDS

End-use energy consumption patterns in the future will be governed by several interacting forces, including increasing prosperity, particularly in the developing countries; changes in urban land-use patterns; greater ease of long-distance travel; the spread of emerging end-uses, such as computing and information technologies; and the development of new and improved end-use technologies.

In GTSP, we performed detailed modeling and analysis of end-use energy demand in the United States. We used the insights gained from the detailed U.S. analysis to inform our modeling of end-use demand for the rest of the world, taking into account regional-specific determinants, such as socioeconomics, population density, technology, and regional climate. Figure 8-1 shows a future scenario of energy end-use demands that we have constructed for the GTSP considering these interacting forces.

In this scenario, demand for energy increases substantially in the transport and industrial sectors. In the buildings sector, end-use demand growth is relatively lower, but still significant. Most end-uses in buildings are now met by electricity, natural gas, and fuel oil. However, most of the buildings end-use services could be served by electricity. The end-use services in the industrial sector are more diverse, and the potential to switch away from fossil fuels to electricity may be more limited.

These aggregate characteristics demonstrate the potential scale of the challenge that climate change provides. Fuel mixes may shift over time, providing very different opportunities for climate change mitigation across sectors. The relative importance of the sectors is itself not static. However, within each sector are a multitude of different energy end-use services, each of which may evolve in very different ways over time and across regions and have very different challenges and opportunities for improved technology and climate change mitigation.



▲ **Figure 8-1.** GTSP scenario of global energy end-use demand growth by end-use sector. Transportation and industry see the largest growth in energy use.

BUILDING ENERGY SERVICES AND END-USE ENERGY TECHNOLOGIES

The buildings sector includes a diverse set of buildings types, from detached family homes to condominiums and apartments, as well as commercial buildings such as shopping malls, high-rise offices, and refrigerated warehouses (Figure 8-2). Although end-uses differ among these types and purposes of buildings, several are common across building types and can explain most building energy use. These end-uses include space heating, space cooling, water heating, and lighting. Beyond this set are a range of additional end-uses, such as appliances and information technologies, which we have aggregated together in a category called “other.”

In the United States and elsewhere, the mix of end-uses has evolved over time and will continue to do so throughout the century. Figure 8-3 shows a future scenario of building service demands, indexed to the demand in 2005 (i.e., the value in 2005 is set to 1). The demand for “other” technologies, which includes appliances and information technologies such as computers, has increased substantially over the past 15 years, and will probably continue to do so over the coming decades. Most of the technologies for meeting these service demands use electricity, which will help to continue the trend of electrification in the buildings sector.

Figure 8-2. Demand for energy services in commercial buildings will grow over the century as incomes rise across the globe.

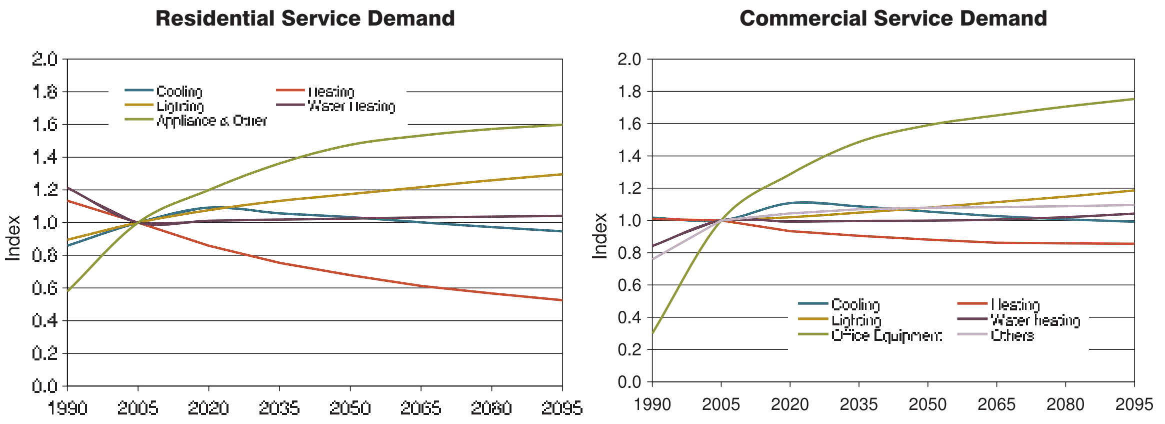


Figure 8-3. A future scenario of U.S. building service demands by end-use (indexed to 1 in 2005). Demands for energy for appliances and other electronic equipment are the biggest source of growth.

Information technology, appliances, and other end-uses generate heat within buildings as an unintended byproduct of their use; this reduces the need and demand for space heating but increases the need and demand for space cooling. Fifty years ago, space cooling did not constitute a meaningful demand for energy. With improving technologies and people moving to traditionally hotter climates, space cooling is now one of the major building end-uses in the United States. In the future, the demand for space cooling will surely expand dramatically in developing countries such as India that have the need, but not yet the resources to meet the need.

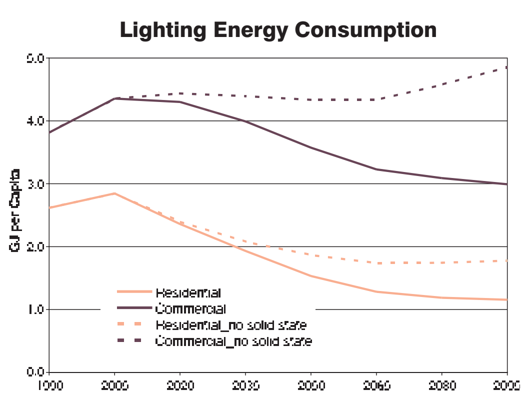
End-use efficiency gains present a substantial opportunity to reduce the CO_2 emissions that result from service demands in the buildings sector. Space heating may rely more heavily on highly efficient heat pump technologies rather than furnaces and electric resistance heating. Space cooling will continue to be based on existing technologies, but there are opportunities to improve the efficiency of current cooling equipment.

Better insulation and windows can be used to improve building shell performance, which will reduce the needs for heating and cooling. Solid state lighting could substantially reduce the energy requirements for lighting (see Box 8-1). Controls can better utilize heating, cooling, lighting, and other technologies so that they provide services only where and when they are needed.

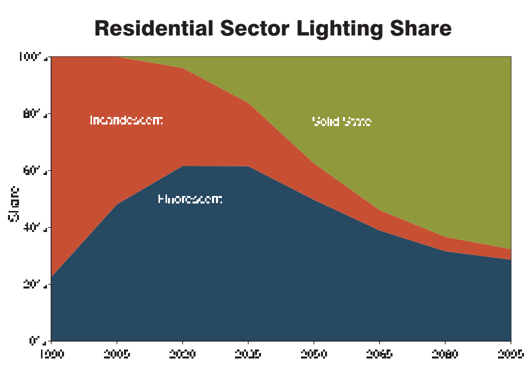
Many end-uses are already primarily supplied by electricity, including space cooling, lighting, and the rapidly growing end-uses of information technology and appliances. The primary opportunity for additional electrification is in heating, where electric heat pump technologies could both increase efficiency and allow for a shift from fuels such as natural gas and fuel oil, as well as the substantial quantities of biomass used in developing countries.

As future energy costs rise, many opportunities for increased efficiency may be undertaken irrespective of climate concerns. The role of building energy technologies in mitigating climate change will be to further reduce the energy required to provide building services in an expanding global economy and to further push the trends toward electrification.

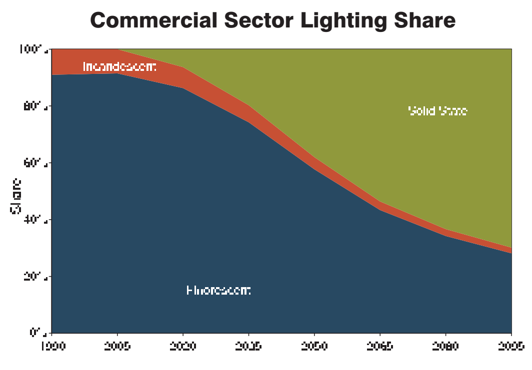
Box 8-1. Solid state lighting could result in dramatic gains in lighting efficiency. Today, lighting is predominantly provided by fluorescent lights and incandescent lights. Fluorescents provide the majority of lumens in the commercial sector; incandescents provide the majority in the residential sector. The increased market share of fluorescent lights in the future will reduce lighting energy use.The introduction of solid state lighting could lead to large-scale deployment and associated additional energy demand reductions in both sectors.



Lighting Energy Consumption



Residential Sector Lighting Share



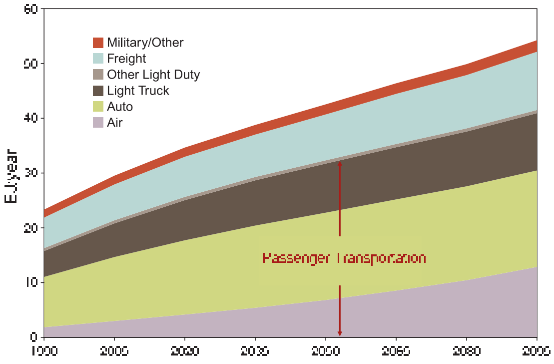
Commercial Sector Lighting Share

TRANSPORTATION ENERGY SERVICES AND END-USE TECHNOLOGIES

Transportation energy services are used to move people (passenger transportation) and products (freight). Although freight constitutes an important demand for transportation energy, passenger transportation is today the dominant consumer of transportation energy (Figure 8-4). The most important modes of passenger transportation are light-duty vehicles in ground transportation and airplanes for air travel. Light-duty vehicles—that is, automobiles and light trucks—are the largest source of energy use in the transport sector in today's industrialized nations and are the fastest growing segment in developing nations. The second-largest source of transportation energy use is heavy-duty trucks providing freight services, followed by airplanes for both freight and passenger services. In the United States, energy use by light-duty vehicles, freight trucks, and airplanes contributes to 59, 17, and 10 percent, respectively, of total transportation energy use. Modes such as buses and trains make up a much smaller component of transportation energy consumption.

▲ **Figure 8-4.** Automobiles and light trucks for passenger travel, and heavy-duty trucks for freight consume the vast majority of energy in today's transportation sector.

The distribution of modes varies today across different regions, and it will evolve as well in the future as a function of a variety of interacting forces. As people become more affluent, their time becomes increasingly valuable and they increasingly value faster modes of transportation. Increasing global prosperity, accompanied by the expansion of the air travel infrastructure more generally will lead to a rapid expansion of air travel and associated energy consumption over the coming century. Air travel in the United States could replace freight trucks as the second-ranked source of fuel consumption before the middle of the century (see Figure 8-5).



▲ **Figure 8-5.** A future scenario of U.S. transportation energy demand growth by end-use category. Air travel and freight are expected to grow as incomes rise.

Globally, the biggest driver of increasing transportation energy consumption will be the developing countries. If countries like China and India emerge as projected, then transportation demand will dramatically increase as these countries take on the transportation characteristics of developed economies.

Despite the diversity of end-uses, liquid fuels such as gasoline are far and away the dominant source of energy for transportation applications because they are so portable. For this reason, without efforts to constrain carbon, the transportation sector will probably remain largely dependent on liquid fossil fuels. Advances in hydrogen production, batteries, and fuel cells could change this. In addition, liquid biofuels can be directly substituted for liquid fossil fuels.

Despite the diversity of end-uses, liquid fuels such as gasoline are far and away the dominant source of energy for transportation applications because they are so portable.

Vehicle Technologies. A wide range of technologies may be available to improve efficiency in the transportation sector as well as to allow for substitution either to bio-derived liquid fuels or to energy carriers such as electricity or hydrogen. Ethanol or natural gas can be used in existing vehicle technologies with minimal modification, thus achieving lower emissions at little cost. Options available or in development include advanced diesel, alternative fuel, hybrid and plug-in hybrid, electric, and fuel-cell vehicles. Opportunities are also available in air travel and freight, but these may be more limited.

Diesel engines provide an opportunity for efficiency gains in liquid fuel use. The drawback of traditional diesel engines is that they produce more pollutant emissions than gasoline engines, including particulate matter, nitrogen oxides, hydrocarbons, and sulfur. Advances in diesel technology have produced new diesel engine vehicles with emissions and performance characteristics similar to gasoline engine vehicles but with significantly higher fuel economies. “Clean” diesel vehicles are expected to gain market share in the United States and globally.

Hybrid vehicles that combine an electric motor and related system with a combustion engine have fuel economies that are two and half times greater than a comparable gasoline engine vehicle. Hybrids are rapidly gaining market share.

Plug-in hybrid vehicles are a variation on the hybrid vehicle concept that further improves vehicle fuel economy. Larger battery packs that can be recharged through an electrical outlet are incorporated into the hybrid vehicle so it can be utilized for local travel in an all-electric mode. The extended range in an all-electric mode combined with a combustion engine burning gasoline, diesel, ethanol, or other fuel has the potential for even higher fuel economy and lower greenhouse gas emissions than the hybrid vehicle. The plug-in hybrid technology is just emerging; multiple technical and economic issues remain to be resolved, but demonstration vehicles have shown fuel economy as high as 100 miles per gallon. Even accounting for greenhouse gas emissions from central station electricity, the overall improvement to the total systems efficiency of the plug-in hybrid vehicle could result in further reductions in total greenhouse gas emissions.

Fuel-cell vehicles represent yet another future transportation technology option and possibly one with the potential for the highest fuel economy and lowest greenhouse gas emissions, although these are substantial technical hurdles. See Chapter 5 for a further discussion of hydrogen.

The Importance of Batteries. Common to hybrid, plug-in hybrid, and fuel-cell vehicles is their use of electricity for motive power. Therefore, the development of more effective storage and control of electricity and related systems is crucial to their success.

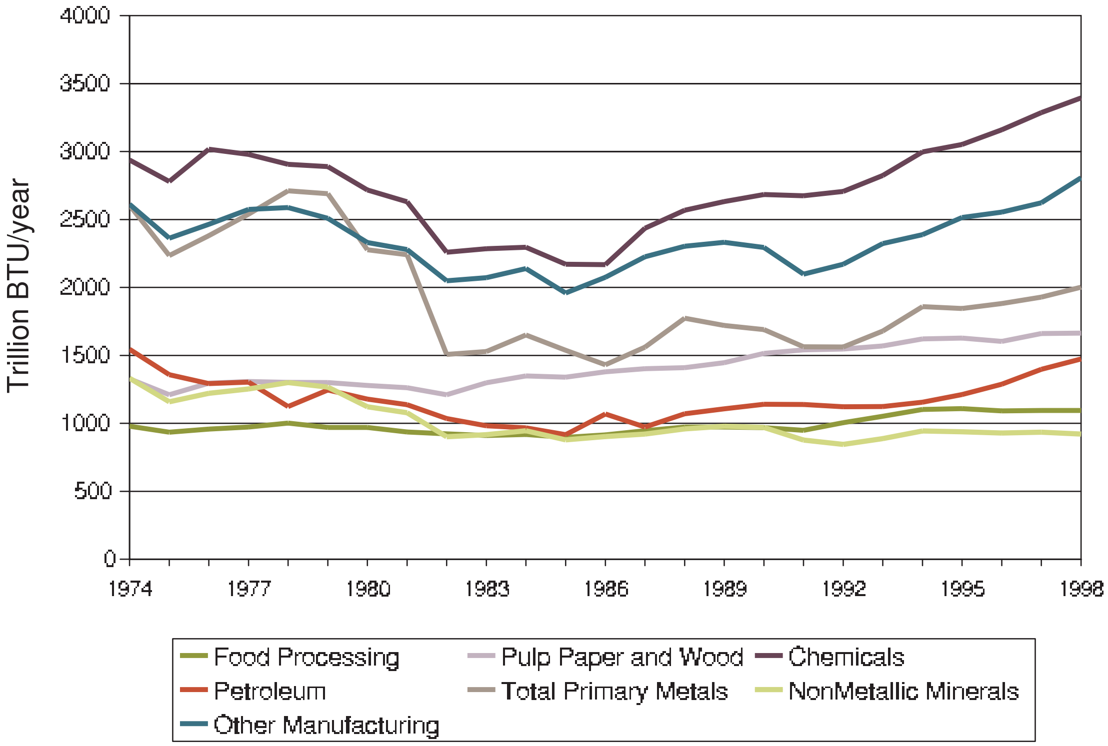
Although they have to improve further to become commercially viable, new batteries are emerging with improved performance and lower costs. New lithium ion batteries that have more power; can recharge faster; and are lighter, more reliable, safer, and cheaper are being introduced to the marketplace. Further battery developments would enable the increasing electrification of the transportation sector, with potentially wide-reaching impact on the electricity market and society as a whole.

INDUSTRIAL ENERGY SERVICES AND END-USE TECHNOLOGIES

The industrial sector spans an enormous and heterogeneous range of individual industries. Energy consumed to produce goods ranging from food products, furniture, petroleum, automobiles, and computers is all considered industrial sector energy consumption. In the United States, total industrial energy consumption has not grown relative to what it was 30 years ago. However, as Figure 8-6 shows, consumption has grown steadily over the past decade in key energy-intensive industries such as chemicals and petroleum refining.

Heavy industry has been shifting its energy-intensive manufacturing from developed to rapidly developing regions of the world. A climate policy limited to developed nations could accelerate that trend, with implications for changing emissions profiles and policies. The international scope of climate policies is critical to controlling emissions from the industrial sector. Otherwise emissions can be shifted rather than reduced.

Despite the heterogeneity of the industrial sector, most of the demand for energy across all industries is driven by the demand for a small set of key, common energy services such as process heat, steam, machine drive, and chemical feedstocks. This commonality of energy services means that mitigation efforts can focus on a key subset of energy technologies.



▲ **Figure 8-6.** U.S. industrial energy consumption. Although total U.S. industrial energy consumption has not been growing, key energy-intensive industries such as Chemicals have been growing steadily.

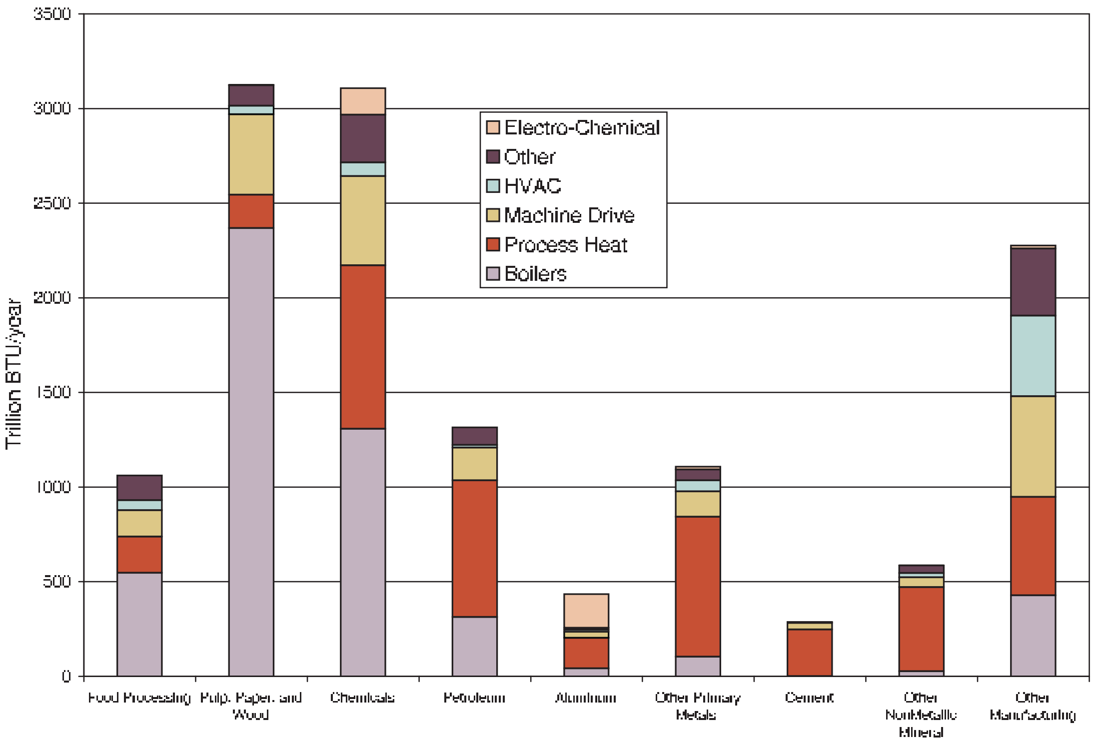
As shown in Figure 8-7, pulp and paper, chemicals, and food processing are major consumers of steam (from boilers). Several industries, including chemicals, petroleum, and metals also require process heat (dry heat rather than steam).

Electricity provides most of the energy for electrochemical; machine drive; and heating, ventilation, and air conditioning (HVAC) services in industry. Process heat has been mainly generated by natural gas, because a clean-burning fuel is required for this service. Electricity can also be used to generate process heat in some applications, but it is limited by the cost.

In contrast, steam can be generated using a number of fuels, and the fuel mix for steam does vary across industry, based on availability of fuels (Figure 8-8). Currently, the pulp and paper industry relies on biomass, since it has access to waste products. Some coal and oil are also used, but many industries still rely on gas. Under a climate policy, emissions could be reduced by using commercial biomass to generate steam in more industries.

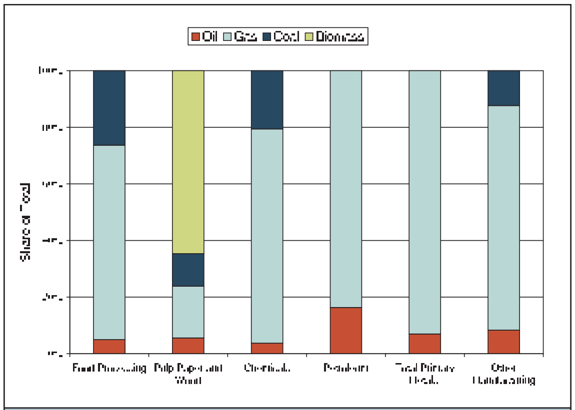
Many of the specific technologies that produce basic industrial energy services such as heat and machine drive are already highly efficient. For example, current efficiencies to produce steam or heat from burning natural gas exceed 80 percent, while the efficiencies of electric motors exceed 90 percent.

Because of the high energy efficiencies of the service technologies, future reductions in industrial energy intensity are more likely to come from redesigns and fundamental changes in the processes used to manufacture industrial products—for example, a re-design of a manufacturing system or an advance in materials so that less heat or steam is required to produce an item. The potential for process changes is more industry-specific than the more generic industrial energy services, although there are some promising new processes like membranes that would reduce the steam requirements for separation in industries such as chemicals and petroleum.



▲ **Figure 8-7.** U.S. manufacturing industrial energy consumption, by industry and energy service, 1998. The mix of energy end-use services required to manufacture products varies substantially by industries.

Cogeneration of electricity along with steam and heat increases the net energy efficiency of the system; electricity is generated from steam and heat that would otherwise be wasted. This electricity could be used on-site or sold to the grid. Cogeneration would not reduce direct emissions and energy use in the industrial sector, but it could reduce economy-wide emissions by reducing the amount of fossil fuels used elsewhere in generating electricity. Cogeneration is best suited to large facilities with a steady demand for steam or heat.



▲ **Figure 8-8.** U.S. fuel consumption for steam by industry. Steam can be generated by various fuels, and different industries have used what is available and economic.

In a carbon-constrained world, however, CO_2 limits may eventually reach a point that cogeneration with fossil fuels is not economical, since it can not compete with electricity from non-fossil sources such as nuclear, wind, and solar. Cogeneration from commercial biomass may then become the choice.

Although electrification will be an important response to a climate policy, some industries may continue to require burning fuels when intense sources of heat or steam are needed. It may be possible, although expensive, to electrify some of these requirements. Burning commercial biomass to generate steam and gasifying biomass to create biogas for process heat may be the best non-fossil options. For some applications, the economic response may be to continue using fossil fuels even while paying a high emissions penalty.

In addition to emissions from burning of fossil fuels, some industries (such as cement, Figure 8-9) also have a substantial amount of direct CO_2 emissions as a by-product of their materials processes. Under an efficient carbon policy, potential mitigation of these emissions must also be considered, through means such as materials substitution or CO_2 capture.

▲ **Figure 8-9.** Cement production and emissions. In addition to the emissions from energy consumption, a cement factory has direct process emissions of CO_2 that result from its conversion of limestone. Mitigation of process emissions of CO_2 and other greenhouse gases must also be considered in an economically efficient policy.

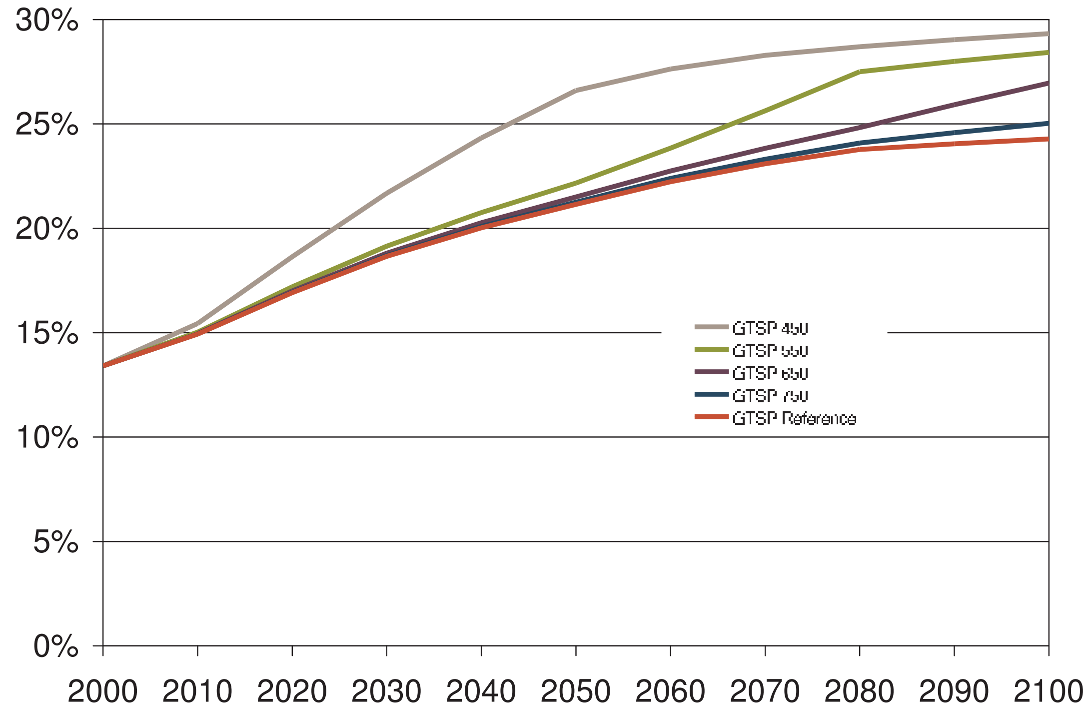
ACROSS ALL SECTORS: THE ROLE OF ELECTRIFICATION, EFFICIENCY GAINS, AND THE COSTS OF MITIGATION

A robust finding of our GTSP modeling analysis on end-use technologies is the importance of the ability to use electricity (or another carbon-free energy carrier) to provide energy services under a CO_2 emissions constraint. The more emissions have to be reduced, the more important this becomes (Figure 8-10). Put simply, at some point it becomes more costly and more difficult to reduce emissions further in some services by only increasing efficiency, and it becomes more economical to switch to a carbon-free source of energy to provide that service. Electricity generated by low-carbon resources and technologies fits that need and can provide services for several applications, although, as we have discussed, some more easily than others.

Electrification will be more of a challenge in transportation and certain industrial processes. There, the spread of low-carbon energy sources would require improvements in batteries for electrification or advances in other energy carriers and sources such as hydrogen technology and biofuels.

But the other aspect of end-use technology—increasing energy efficiency—remains vitally important. Energy efficiency has the potential to substantially reduce the economic burden of emissions mitigation. Improved end-use technologies provide benefits by lowering the demands for energy—benefits that accrue irrespective of climate concerns—and by decreasing the economic costs of stabilization by reducing the requirements for lower-carbon energy sources.

The potential economic benefits of end-use technologies are substantial. Increasing the rate of energy intensity improvement by only 0.25 percent annually could reduce the costs of stabilization by trillions of dollars over the course of this century (Figure 8-11).



▲ **Figure 8-10.** Electricity relative to total primary energy. GTSP analysis shows that electricity as a share of global energy use increases under tighter CO_2 emissions policies. Therefore, the ability of end-use technologies to use carbon-free energy sources such as electricity becomes critical to managing the cost of meeting tighter policy targets.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

If the potential for end-use energy technologies to contribute to CO_2 emission reductions is to be realized, R&D should focus on the following:

Buildings Sector

- Optimize building shell design to reduce the need for active heating, space conditioning and lighting; and make use of advanced materials.
- Realize further cost reductions and efficiency gains in specific end-uses, such as solid state lighting and heat-pump-based technologies for space conditioning.
- Develop smart appliances that could participate in grid regulation, increasing reliability and perhaps increasing the potential of non-dispatchable renewable energy.

Transportation Sector

- Increase the efficiency of light-duty vehicles using hybrid technology with gasoline, diesel, or biofuels.
- Pursue advances in battery technologies, which would benefit all electric-based vehicles—hybrid, plug-in hybrid, or fuel cell.
- Reduce the need for light-duty vehicles by community planning, mass transportation, and information systems.

Industrial Sector

- Re-engineer industrial processes to reduce the need for energy services, such as using membrane technologies for chemical separation processes that would use much less heat and steam.
- Where processes still require high temperatures for steam or heat, make burning commercial biomass an available technology option.
- In generating heat and steam from biomass, exploit opportunities for cogenerating electricity.
- Reduce the cost of capturing or substituting material to reduce the process CO_2 emissions from cement production.

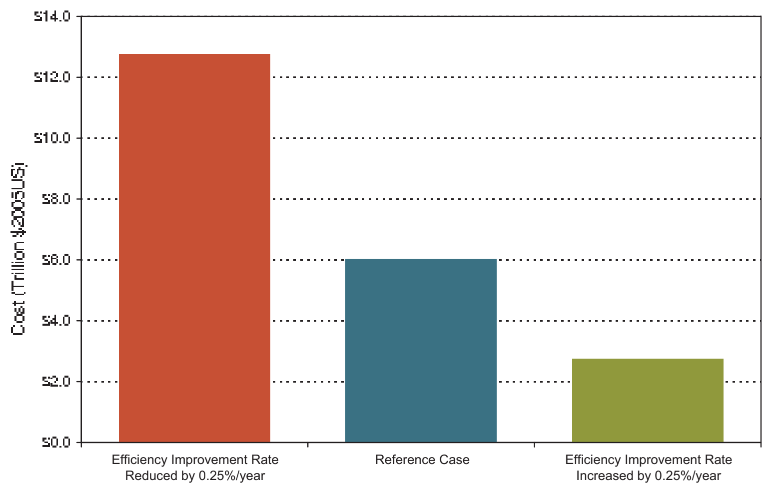
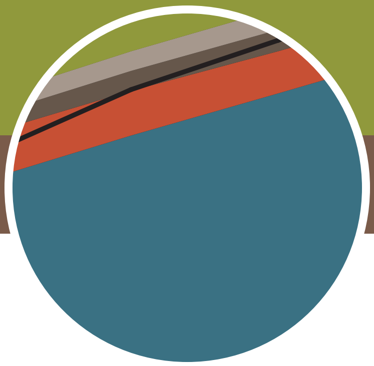


Figure 8-11. The effect of energy efficiency on costs for a 550 ppm CO_2 stabilization level (measured as discounted global costs incurred over the century in reducing emissions to the target). Energy intensity growth improvements of only one-quarter of one percent can have enormous economic benefits for addressing climate change.

Non-CO_2 Emissions and Projections of Future Climate Change

Early studies of climate change mitigation focused almost exclusively on CO_2 emissions from the energy sector. While anthropogenic CO_2 emissions are the most important driver of climate change, a number of other greenhouse gases also have a substantial effect on the climate system. The roles of non-CO_2 gases are becoming much better understood, as are the means of cost-effectively reducing the emissions of these gases. Key insights on the role of non-CO_2 gases from the GTSP include:

- While CO_2 is the most important greenhouse gas, non-CO_2 greenhouse gases also need to be part of a comprehensive and cost-effective technology strategy.
- Technologies to mitigate non-CO_2 greenhouse gas emissions can play a significant role in reducing future climate change. Many of these technologies could potentially see widespread deployment in the next decade.
- Economic and engineering analysis points to significant opportunities to reduce methane emissions throughout the economy, but especially in the energy sector, followed by agriculture. Because of methane's short atmospheric lifetime, reducing its emissions can reduce radiative forcing in the mid term.
- Much of the reduction in non-CO_2 greenhouse gas emissions can occur at very low carbon prices or even without a carbon price.



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- Over the course of the century the contribution of technologies that reduce emissions of these non-CO_2 gases could be equivalent to cumulative reductions of hundreds of billions of tons of CO_2.

- Aerosols have a large impact on climate change over the next half century, but their likely impact is small by the end of the century.

- Because non-CO_2 greenhouse gas emissions originate from a particularly diverse set of processes throughout the economy, information dissemination and deployment policies may be particularly important for these technologies.

…the roles of non-CO_2 gases are becoming much better understood, as are the means of cost-effectively reducing the emissions of these gases.

RADIATIVE FORCING TODAY

Human activities have resulted in increasing atmospheric concentrations of methane, nitrous oxide, tropospheric ozone, aerosol particles, and a variety of fluorinated gases (Table 9-1). The sources, applicable control strategies, and atmospheric behavior differ for each of these substances. Aerosols, in particular, are very different from greenhouse gases.

To evaluate the climate effects of these substances on a common basis, we use the contribution to global anthropogenic radiative forcing as a comparison metric (see Box 9-1). Radiative forcing is a measure of the imbalance in planetary energy fluxes. Comparing the changes in radiative forcing for different gases gives a measure of the relative contribution of each gas to global climate change. This allows disparate substances to be evaluated with a common metric. Radiative forcing is the most practical metric to use over the long-time scales and global scales relevant for this problem.

Table 9-1. Anthropogenic non-CO_2 gases, their atmospheric lifetimes, and emissions sources.

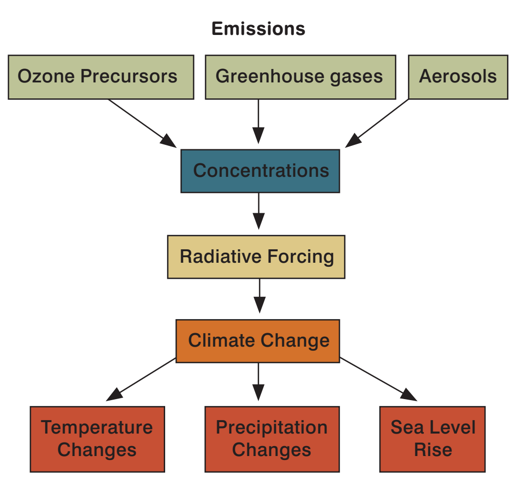
	Gas	**Anthropogenic Sources**	**Lifetime**
Natural GHGs	Methane (CH_4)	Rice cultivation, ruminant livestock, feedlots, waste water treatment, coal mining, natural gas production & distribution, landfills	10–14 years
	Nitrous oxide (N_2O)	Agricultural soils, mobile sources, feedlots, nitric & adipic acid production	120 years
Manufactured GHGs	HFC-134a (CH_2FCF_3)	Refrigeration systems, solvents, foam	14 years
	HFC-125 (CHF_2CF_3)	Refrigeration systems	33 years
	Perfluoromethane (CF_4)	Aluminum production, semiconductor manufacture	6500 years
	Sulphur Hexafluoride (SF_6)	Magnesium production, electric power equipment, fire suppression, medical applications, other systems	23900 years
Gases with indirect effects	Carbon monoxide (CO)	Transportation, low-temperature combustion, open burning	months
	Non-methane hydrocarbons (NMHCs)	Transportation, low-temperature combustion, fuel production and distribution	hrs to years
	Nitrogen oxides (NO_x)	Transportation, high-temperature combustion (electric utilities, industrial boilers), agricultural soils	hrs to years
Aerosols	Sulfur dioxide (SO_2)	Fossil fuel use (coal, diesel, and residual oil)	days
	Black carbon (BC)	Low-temperature combustion (biomass and coal in buildings), diesel vehicles and equipment, open burning	days
	Organic carbon (OC)	Low-temperature combustion, open burning (deforestation, savannah burning, deforestation, agricultural waste, forest fires)	days

Anthropogenic radiative forcing is dominated by CO_2, methane, tropospheric ozone, and aerosols. Fluorinated gases and nitrous oxide also contribute. Figure 9-1 shows the relative contribution of each substance with error bars as summarized in the IPCC Third Assessment Report. The historical radiative forcing contribution from greenhouse gases is relatively well known because current concentrations can be measured and radiative properties of gases are generally well quantified. In contrast, the contribution from aerosol particles is still very uncertain. The uncertainty in aerosol forcing is one of the largest contributors to the uncertainty in the climate response to increasing greenhouse gases. If the aerosol forcing were known to a much higher level of confidence, then the historical temperature record could be used to more precisely bound the level of future climate change.

The largest contributor to radiative forcing to date is CO_2. Increases in CO_2 concentrations are driven largely by the combustion of fossil fuels and land-use changes. Current carbon emissions from fossil fuel use are relatively well known, while there is larger uncertainty about emissions from land-use changes.

Methane is the second most important greenhouse gas. Methane has a relatively short atmospheric lifetime, around 10 years, depending on atmospheric composition. This means that methane emissions today have little impact on atmospheric concentrations a century from now (although a portion of the warming from current emissions will still be felt a century from now due to ocean thermal "memory"). Because of methane's short lifetime, methane mitigation also has the potential to reduce the rate of climate change in the mid term. This is because emissions reductions in methane will have a more rapid impact on atmospheric concentrations, and hence radiative forcing, than emissions cuts in longer-lived gases. In addition to the forcing from methane itself, methane emissions also contribute to climate change by enhancing stratospheric water vapor and tropospheric ozone.

Box 9-1. RADIATIVE FORCING



Radiative forcing is a key link in the causal chain from emissions to climate changes. Emissions of greenhouse gases have increased atmospheric concentrations. Increased concentrations of greenhouse gases and the effect of aerosols have changed planetary radiant energy fluxes. Radiative forcing at the top of the atmosphere is a measure of this imbalance in radiant energy fluxes. Radiative forcing is measured in Watts per square meter (W/m^2) and is always specified as a change relative to some reference period (commonly the pre-industrial period).

The mechanisms behind this imbalance differ depending on the source. For greenhouse gases such as CO_2, methane, and tropospheric (low-level) ozone, this imbalance is caused largely by the absorption of infrared radiation. Light-colored aerosols, such as sulfate particles, reflect radiation back into space, causing cooling. Although the mechanisms are different, these forcings can be combined to determine the magnitude of long-term temperature change. Absorbing aerosols, such as black carbon, have additional effects, although these are not well quantified.

The net positive radiative energy imbalance to date from anthropogenic emissions drives the temperature within the Earth system to increase. Along with temperature increases, precipitation patterns may change and sea levels will rise.

Radiative forcing is a more accurate measure of the climatic impact of different substances than Global Warming Potentials (GWPs). Carbon equivalent emissions calculated using a GWP do not provide a robust comparison of emissions over century time scales, although they are useful as a rough measure of relative emissions in one time period and can be sufficiently accurate for emissions trading purposes and some economic comparisons.

Tropospheric ozone is also a significant greenhouse gas as well as an air pollutant, the levels of which are regulated in many countries. Background levels of ozone in the lower atmosphere, or troposphere, are significantly higher than pre-industrial levels, although the pre-industrial level is not precisely known. Ozone is a highly reactive and short-lived gas formed from chemical reactions among precursor gases such as methane, nitrogen oxides, carbon monoxide, and volatile organic hydrocarbons. Background ozone levels continue to be significantly higher than pre-industrial values, in part because emissions of nitrogen oxides (NO_x) have proven to be challenging to mitigate in a number of important source areas.

Nitrous oxide and fluorinated gases are the remaining anthropogenic greenhouse gases. Nitrous oxide is a long-lived greenhouse gas, the largest source of which is agricultural soils. Nitrous oxide is a stable molecule with an atmospheric lifetime of about 120 years. Fluorinated gases are used in a variety of industrial processes and as working fluid in refrigeration systems. The properties that make them industrially useful also result in some of these gases having very strong radiative effects; in addition, some have atmospheric lifetimes of 10,000 years or more.

Although the forcing effects of greenhouse gases are relatively well known, the effects of aerosol particles are more uncertain. Atmospheric aerosols are, however, thought to be one of the most important anthropogenic influences on the planet's current radiative energy balance. Aerosols are small particles that can absorb and/or reflect light and play a central role in determining cloud properties. Sulfate aerosols are one of the most important anthropogenic aerosol components. Sulfate particles are light colored and reflect sunlight, resulting in a negative forcing. Carbonaceous aerosols include organic and black carbon. Organic carbon aerosols are also light-colored and similar in their effect to sulfate aerosols. Black carbon particles absorb sunlight and cause a positive direct forcing; they also re-distribute energy within the atmosphere. Aerosol particles are generally composed of multiple constituents, which complicates the study of their effects.

In addition to their direct effects on radiation, aerosol particles also can act as cloud condensation nuclei, making clouds denser and more reflective. This is called an indirect forcing and is negative—that is, a cooling effect on the climate (Figure 9-1). Other indirect forcings also exist, including a potential positive forcing as absorbing aerosols "burn off" the edges of clouds. There is general agreement that the net effect of aerosols is a negative radiative forcing, but the uncertainty is very large, particularly for the indirect effects.

The net effect of anthropogenic greenhouse gas emissions is a substantial increase in greenhouse gas forcing relative to pre-industrial times. Offsetting some of this forcing is the net negative (or cooling) effect of aerosols. The largest contribution to uncertainty in anthropogenic forcing of climate change is uncertainty in the effect of aerosols.

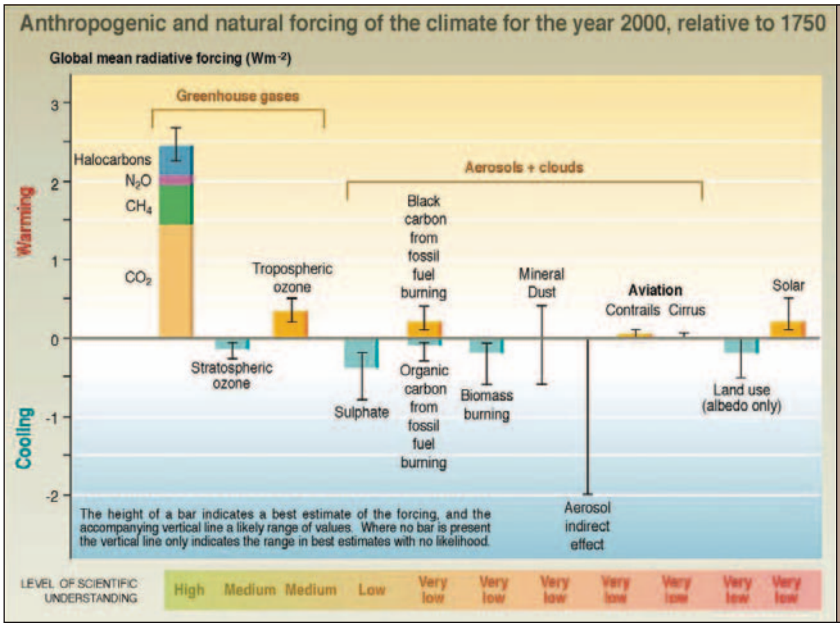


Figure 9-1. Anthropogenic radiative forcing by substance from pre-industrial times to the year 2000. Radiative forcing (see Box 9-1) shows the relative effect of each anthropogenic change on global climate.

THE ROLE OF TECHNOLOGY

The options to reduce emissions of non-CO_2 greenhouse gases are numerous and cover a wide range of economic sectors. Emissions reduction options are determined through engineering and economic analysis of available technologies and their potential application in different locations and systems. A useful summary of these calculations can be given as a marginal abatement curve, or MAC. A MAC shows the total mitigation potential as a function of the carbon price.

Figure 9-2 shows global MAC curves from a recent EPA analysis. By far, the largest potential reductions occur for methane. (Figure 9-3 shows one example of methane avoidance.) Mitigation opportunities occur throughout the economy, with the largest mitigation potential in the energy sector followed by agriculture.

In general there are two classes of emission control technologies, those that reduce formation of the gas and those that capture the emission and then recycle, transform, or destroy the gas. The lowest cost option for some industrial gases is capture and re-use. Reduction of nitrous oxide (N_2O) emissions from agriculture is best achieved by reducing emissions levels through process changes while N_2O from many industrial processes can be cost-effectively destroyed.

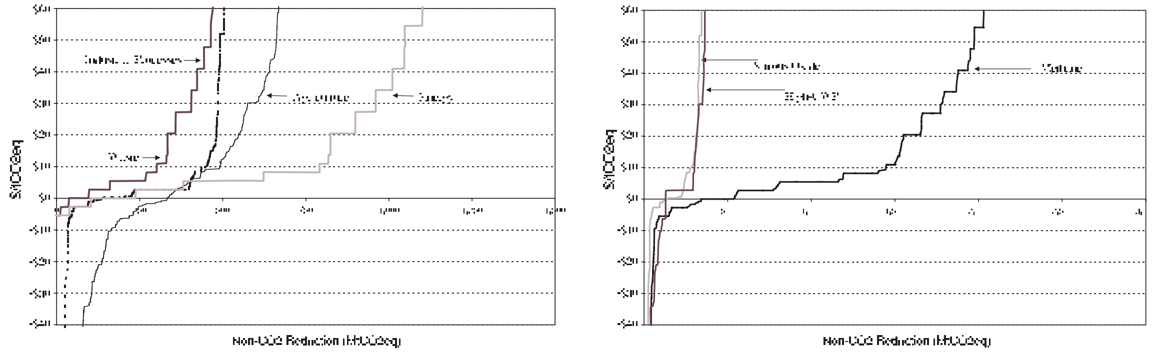
Methane provides a rich example of the role of technology in the reduction of non-CO_2 greenhouse gas emissions. Methane emissions from underground coal mining can be reduced, and there are similar opportunities in other economic sectors. As with many non-CO_2 emissions, methane emissions from coal mining are a byproduct of the primary activity in this sector. This means that there may be opportunities to reduce emissions without substantial impacts on the primary activity.

Methane emissions can often be mitigated easily, particularly since methane has economic value as an energy source.

Technologies that could reduce methane emissions from coal mining include degasification and injection into pipeline distribution systems, on-site power production, flaring, and catalytic oxidation. Figure 9-4 shows a marginal abatement curve for methane emissions vented from coal mines. The curve shows the cumulative emissions reductions that are economically viable at a given carbon price. Several features of this curve are notable.

First, a large fraction of methane emissions from U.S. coal mining can be potentially mitigated. The analysis shown here found that emissions could be potentially reduced by 80 percent by the technologies considered.

Second, mitigation is relatively inexpensive. Methane emissions can often be mitigated easily, particularly since methane has economic value as an energy source.



▲ **Figure 9-2.** Global non-CO_2 greenhouse mitigation options. By economic sector or by emitted gas, many low- or no-cost mitigation options are available. Note: prices in these graphs are given in terms of CO_2, instead of carbon (1 Tonne C = 3.66 Tonnes CO_2; 3.66 \$/TC = 1 \$/TCO_2).

Methane can also be burned where use of the energy content is not feasible.

Finally, the analysis presented here indicates that a portion of current methane emissions can be avoided economically even without a carbon price. In these cases, the cost of the mitigation technology is more than offset by the income provided by the use of methane as an energy source.

More generally, in all sectors of the economy and for most gases, analysis indicates that cost-effective mitigation options exist, as indicated by the portions of the MAC curves in Figure 9-2 below a zero carbon price. Why are such activities not being implemented? One possibility is that additional costs or other limiting factors exist but were not included in the analysis. An alternative explanation might be that they are being deployed, but that large-scale deployment takes time. Information takes time to disseminate and there are costs to acquiring new technology information. Thus, while these technologies may be economically attractive, deployment to the extent indicated by the MAC only takes place over an extended period of time.

Reality is likely to be a combination of these explanations. In coal mines, for example, the primary focus of methane management activities is mine safety. Managers would need to evaluate the risk of a new technology as small before they adopted it. There are also opportunity costs associated with the adoption of a new technology.

Demonstration and information dissemination activities can potentially accelerate the adoption of economically attractive, but perhaps unfamiliar, technologies by increasing awareness of their potential benefits. Experience with real-world deployment will also either demonstrate that problems can be overcome or identify improvements that may need to be made to facilitate wider use.

▲ **Figure 9-3.** Systems that convert waste to energy would reduce methane emissions from landfills and produce useful energy.

The effect of deployment assumptions for global methane emissions is shown in Figure 9-5, which shows the radiative forcing due to methane for several technology and policy cases. In the reference case (solid blue line) economically driven reductions are allowed and methane recovery options are assumed to improve over time. With these assumptions, methane forcing is relatively flat over the century, with forcing roughly equal to today's value by the end of the century. Methane recovery rates are enhanced by both the assumed technological improvements in recovery options and increasing natural gas prices in this scenario.

In a hypothetical case where no economically or policy-driven methane emissions reductions are allowed, methane forcing increases through the century (dashed blue line). This demonstrates the importance of technological change even in the absence of a climate policy. Technology improvement and some amount of deployment are nearly certain, although as with any technology the amount of deployment cannot be predicted with great precision. Deployments at the scale implied in these model simulations have not been demonstrated for all sectors.

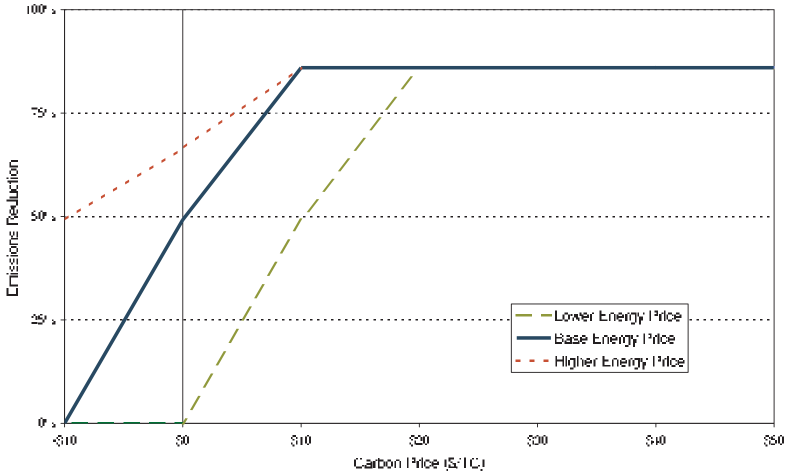


Figure 9-4. Marginal Abatement Cost (MAC) curves showing the abatement potential for methane from coal mines in the United States. Many of the abatement opportunities are low-or no-cost, implying that they could be implemented without a climate policy.

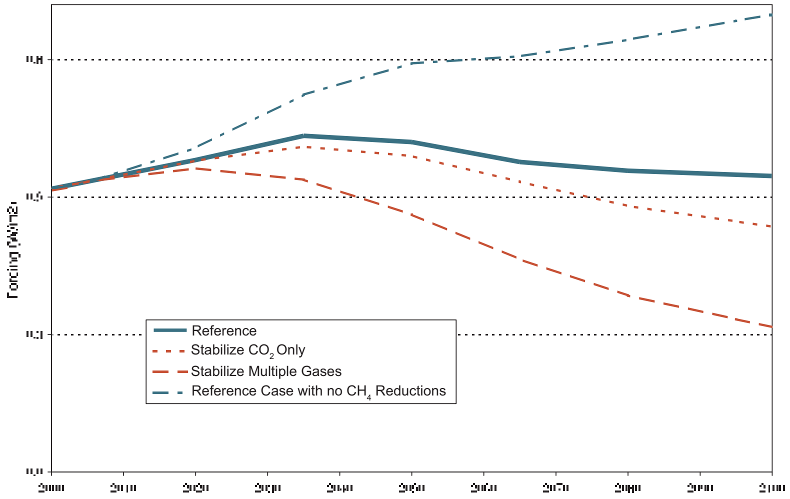


Figure 9-5. Methane radiative forcing resulting from different assumptions. Under reference case technology assumptions about methane recovery options, methane forcing remains roughly constant (solid blue line). Without these reductions and technological advances, forcing would be much higher (top line). CO_2-only emission mitigation policy results in a small reduction of methane emissions (dashed line below solid blue line), while a climate policy focused on reducing all greenhouse gases would reduce forcing even further (bottom line).

With the implementation of a climate policy, methane forcing is even lower. A small reduction in methane forcing is due to CO_2 emissions reduction efforts as lower fossil fuel use results in lower associated methane emissions. The largest reductions obtained through climate policy, however, stem from directed actions to further deploy methane abatement technology. A fully implemented climate policy results in methane forcing that is nearly half of its present value by the end of the century.

These findings demonstrate that development and deployment of technologies that address non-CO_2 greenhouse gas emissions can be an important component in an overall technology strategy to address climate change. In fact, the potential reductions represented here are equivalent to cumulative reductions of CO_2 amounting to hundreds of billions of tons of carbon by the end of the 21st century.

Moreover, most non-CO_2 abatement technologies can deploy relatively early in a climate policy regime. Even larger reductions early in the policy phase could be achieved if the abatement potential of non-CO_2 abatement technologies were increased by research and development.

Methane is a particularly important example due to the wide range of no-or low-cost mitigation options, but analogous analysis can be applied to other emissions. Nitrous oxide (N_2O) emissions will be affected by fertilization management practices, which in turn may be largely determined by surface and groundwater quality issues. Air quality (and acid deposition) controls will lessen emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2); these controls can have significant climate mitigative effects.

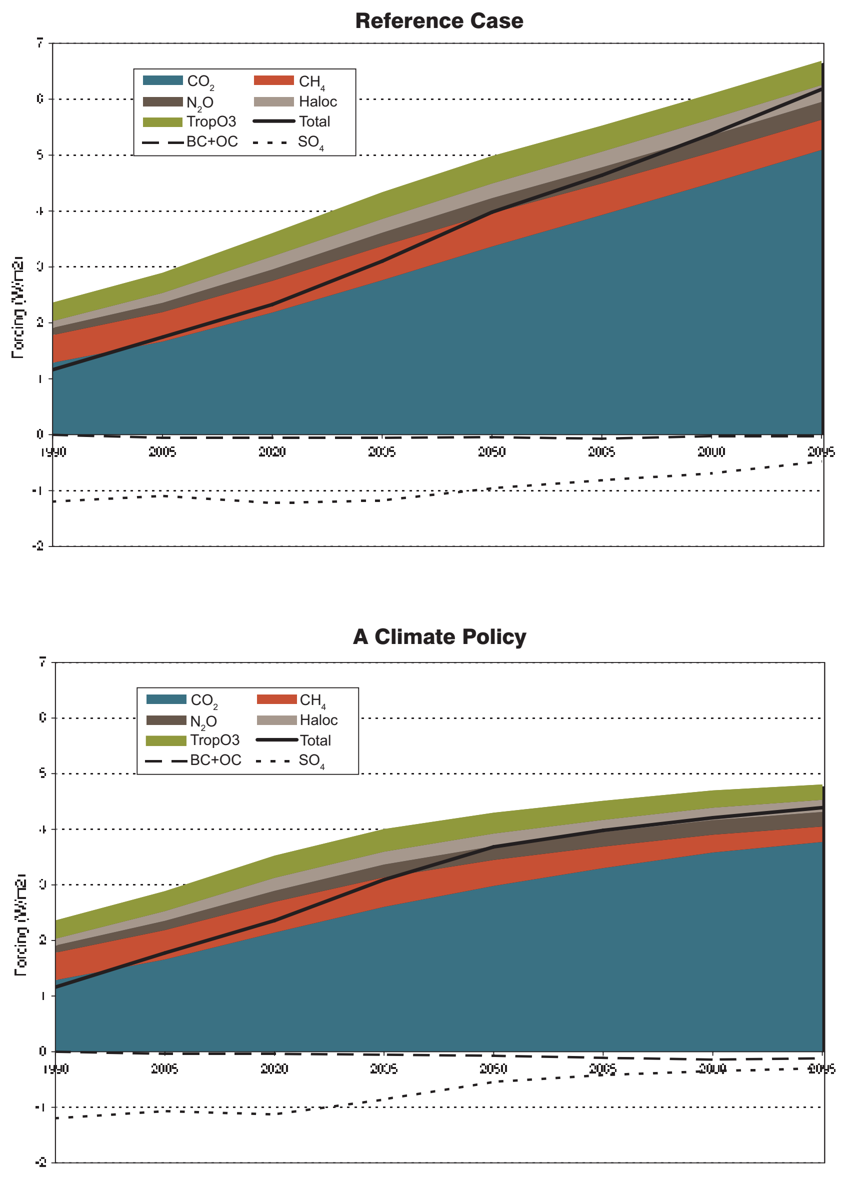
FUTURE RADIATIVE FORCING

Future climate change will be driven by radiative forcing, and the relative importance of different forcing agents can be determined by examining their contribution to global forcing. Radiative forcing depends on future emissions, the behavior of gas cycles, and the assumptions made for present-day aerosol effects. Figure 9-6 shows radiative forcing by gas for a reference case and a climate policy case. The reference case places no emphasis on reducing greenhouse gas emissions, and greenhouse gas forcing increases two and a half times over the century.

In the reference cases, policies to reduce local air pollution are assumed to be implemented. As incomes rise, increased controls will be placed on local air pollutants such as sulfur dioxide and nitrous oxide. As a result, the net effect of aerosols by the end of the century is small. Tropospheric ozone forcing is, however, still slightly larger by 2100.

The policy case constrains greenhouse gas emissions such that total radiative forcing is stabilized. The response of CO_2 is significantly different from that of other greenhouse gases. CO_2 forcing is still much larger in 2100 than at present. Total non-CO_2 greenhouse gas forcing is lower by 2100 than today, reflecting both the shorter lifetime of some gases and the significant mitigation opportunities available.

The assumptions made about emissions reductions in the reference case have a large impact on future projections of greenhouse gas emissions. In addition to pollution controls, economically driven reductions in greenhouse gas emissions, particularly methane, are assumed to take place in the reference case shown here. These policies significantly reduce greenhouse gas forcings and the net aerosol effect compared to a case where these reductions are not allowed to take place.



◀ **Figure 9-6.** Radiative forcing by gas. Shown are a reference case without climate policies (*top*) and a climate policy case (*bottom*). In both cases air pollution controls and economically driven greenhouse gas reductions are assumed to be implemented. Most of the reduction in radiative forcing over the course of this century results from efforts to control CO$_2$ emissions.

FUTURE CLIMATE CHANGE

The magnitude of the climate change issue can be most simply represented by global mean temperature change. Although climate impacts will be determined by regional temperature, precipitation, and other changes, the magnitude of these changes will generally scale with global temperature change.

Figure 9-7 shows the global mean temperature change that results from the radiative forcing pathways shown in Figure 9-6. An intermediate value for the climate sensitivity of 2.5° Celsius per CO_2 doubling was used. While radiative forcing has nearly stabilized by the end of the century in the policy case (Figure 9-6), global mean temperatures are still increasing due to ocean thermal inertia.

The amount of global mean temperature under a policy case does not significantly deviate from the reference case until the latter half of the century. This is due to inertia in the climate system plus the offsetting effect of reductions in aerosol forcing. When aerosols are reduced, their net cooling effect over the next 50 years temporarily offsets reductions in greenhouse gas forcing over this time period.

Because of these interactions, a net reduction in total radiative forcing from all sources before 2050 does not seem likely. While it may be possible to decrease non-CO_2 greenhouse gas forcing, CO_2 forcing will likely continue to increase over this time period.

Local air pollution and climate change are linked through emissions of methane, ozone precursors, and aerosol compounds. As incomes increase, local pollutant levels are expected to decline. A greenhouse gas mitigation policy would be expected to further decrease the levels of these pollutant emissions as a secondary effect (sometimes referred to as an "ancillary benefit").

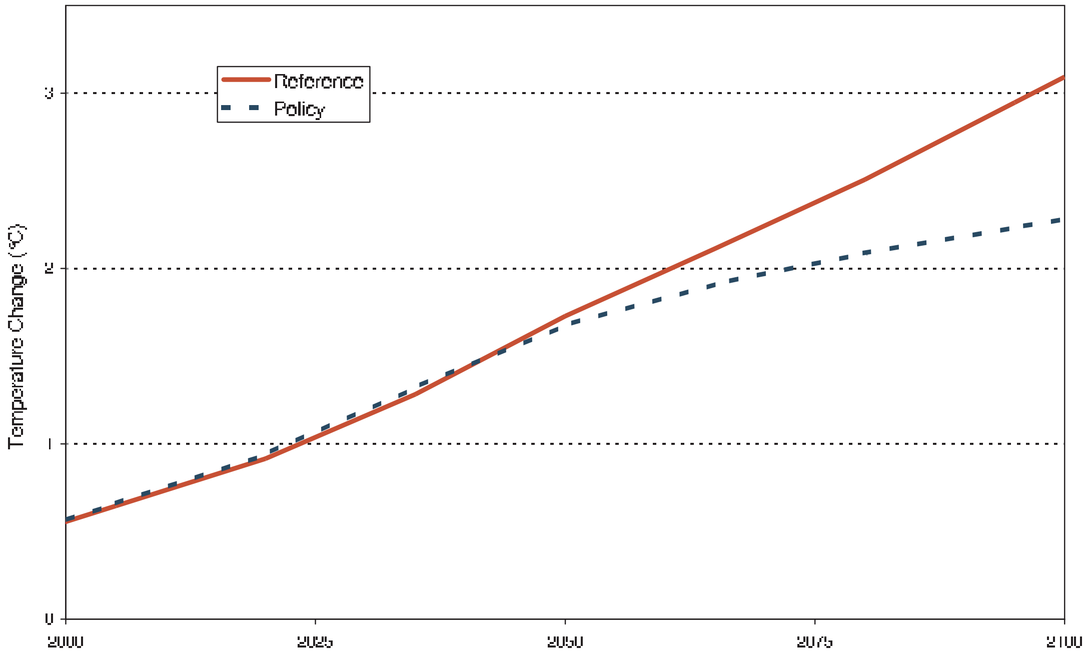


Figure 9-7. Global-mean temperature change for reference and policy cases assuming a climate sensitivity of 2.5° C per CO_2 doubling. Due to climate system inertia and offsetting effects of aerosols, global-mean temperature change does not significantly diverge from the reference case trajectory in this scenario before 2050.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

While anthropogenic CO_2 emissions are the most important driver of anthropogenic climate change, a number of other greenhouse gases also have a substantial effect on the climate system. The GTSP's research shows that it is important to develop and commercially deploy a wide variety of technologies to address emissions of non-CO_2 gases. Some reductions appear to be cost-effective at present, offering opportunities for early mitigation efforts. Because non-CO_2 greenhouse gas emissions originate from a particularly diverse set of processes throughout the economy, information dissemination and deployment policies may be particularly important for these technologies.

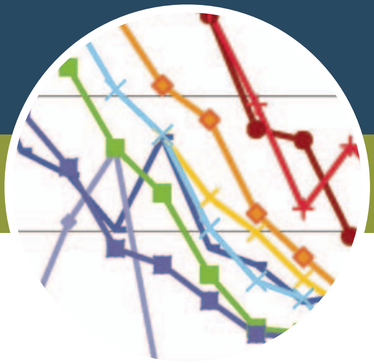
…it is important to develop and commercially deploy a wide variety of technologies to address emissions of non-CO_2 gases.

Research, Development, and Large-Scale Commercial Deployment

A central element of the GTSP has been to document and explain the need for the continued development, demonstration and deployment of new energy technologies as a pillar of a cost-effective strategy to address climate change. Key insights from this GTSP research theme include the following:

- Energy technologies that have been used since the beginning of the Industrial Revolution, that exist today, and that might be used in the future all make an enormous difference in the global society's ability to meet future environmental goals as well as the cost of achieving those goals.

- The public and private sectors of a small number of large industrialized nations are the principal sponsors of nearly all energy R&D. Their response to the oil crises of the 1970s was to rapidly and significantly expand investments in energy R&D. However, subsequent energy and environmental events have been addressed via a broader set of policy and market-based tools. Governments have placed decidedly less focus on the rapid development and deployment of new energy technologies. Measured as a percent of gross domestic product, nations' investments in the development, demonstration and deployment of cleaner energy technologies in each of these countries have been declining for more than three decades.



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- The large-scale transformation of the global energy system needed to stabilize greenhouse gas concentrations is possible. However, it will require purposeful investment in a broad array of energy R&D programs, coupled with the creation and adoption of new policy instruments and market conditions that favor an ongoing, large-scale adoption of progressively less-emitting energy systems. The GTSP's analysis suggests the need for a set of concrete, substantial, and durable incentives—both market-push and market-pull—to create the energy technologies needed to address climate change.

- A Global Energy Technology Strategy complements an economically efficient emissions mitigation policy. Both are needed to achieve a goal as demanding as stabilizing atmospheric concentrations of greenhouse gases, although the balance between the two may change over time and across different economic sectors.

- GTSP has identified six energy technology systems whose large-scale global deployment could have a profound impact on the cost of addressing climate change and therefore make it easier for society to take on the challenge of addressing climate change while simultaneously meeting a myriad of other societal needs. These key advanced energy technologies are:

    - CO_2 capture and storage
    - Biotechnology and biomass
    - Hydrogen systems
    - Nuclear energy
    - Wind and solar energy
    - End-use energy technologies.

For more than 10 years, the GTSP has been studying historical investment patterns in energy R&D. This examination sheds light on the incentive system that motivates public and private sector investments in energy R&D. More recently, the GTSP has focused on conditions that might facilitate innovation and commercial adoption of the six key energy technologies discussed in the body of this report.

THE RECENT HISTORY OF SUPPORT FOR ENERGY R&D

Most major industrialized countries now have well-established energy R&D systems that perform research across a broad range of established and emerging technology areas. The development of this capacity was catalyzed in large part by the acute energy crises of the 1970s. Yet, as Figures 10-1 and 10-2 show, support for energy R&D since the 1970s has fluctuated considerably. For example, Figure 10-1 shows that, in real terms, energy R&D investments have now fallen back to levels comparable to those that preceded the 1973 oil embargo by the Organization of Petroleum Exporting Countries (OPEC). Moreover, Figure 10-2 shows that, when measured as a percent of gross domestic product, energy R&D has been in continuous decline for more than 30 years.

While today's energy R&D establishment grew out of the OPEC oil crises, the high levels of policy priority and industrial interest in funding experienced in the late 1970s were short-lived phenomena. GTSP research reveals that public and private sector energy R&D investments are the outcome of a complex decision process in which many considerations are weighed. Yet, ultimately, energy R&D investment decisions resemble other investment decisions in that they are made with an expectation of positive return

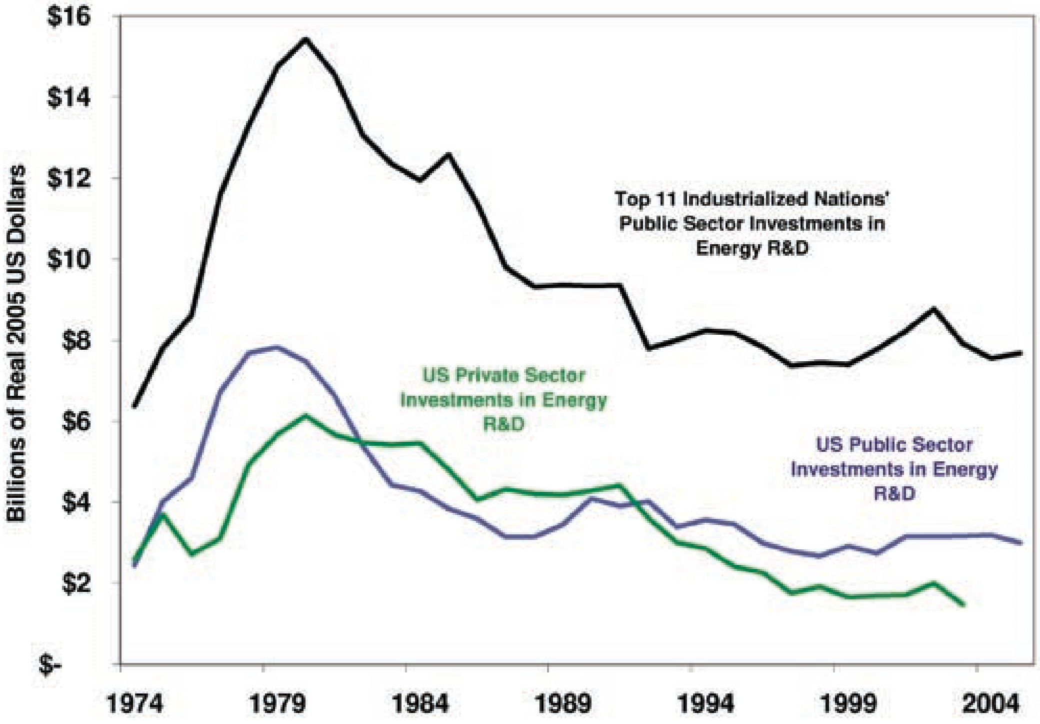


Figure 10-1. Energy R&D investment 1974–2004. Public and private investment in energy R&D rose sharply following the OPEC crisis of 1973. By 1980, a combination of factors had begun to undermine continuation of such high investment levels.

within a reasonable period. For energy R&D, returns on investment—whether private financial returns or public/social returns—can only be realized if energy R&D projects lead to the development and commercial deployment of new technologies.

Viewing the pattern of support for energy R&D over the past 30 years through the lens of investment decision making yields valuable results. In the period between 1973 and the early 1980s, for example, many people feared that the era of cheap energy resources was over, the world was actually running out of energy and a few countries had the collective capability of wielding an "oil weapon" by restricting access to remaining oil supplies.

In response to these threat perceptions, national governments and the private sector turned to quickly boosting domestic energy production using current technologies and to promoting innovation with the intention of creating new energy technologies for further developing domestic energy resources. In this crisis environment, there was a clear signal that investments from the public and/or private sectors in energy R&D would find large and ready markets for the resulting energy technologies. This strong market pull resulted in an unprecedented surge in energy R&D investments. Between 1974 and 1980, for example, U.S. public and private sector support for energy R&D programs increased by more than a factor of 6, from $2 billion to more than $12 billion; across the top 11 nations who support the vast majority of energy R&D, government-sponsored energy R&D increased by more than a factor of 2.5, from $6 billion to $16 billion over the same period.

However, since the early 1980s the public and private sectors have developed and employed a far broader suite of tools with which to address energy and environmental issues. As a result, the energy marketplace is far different than it was in the 1970s.

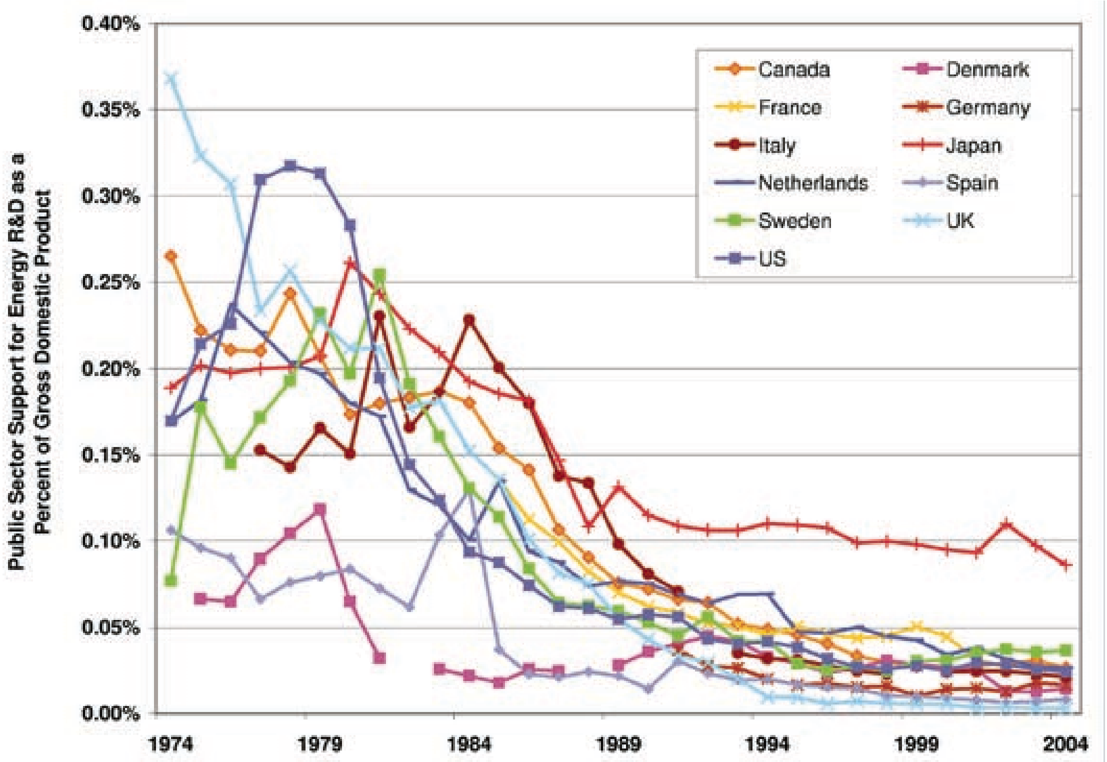


Figure 10-2. Public sector energy R&D investments as % of GDP in selected IEA countries. Unlike investments in other technology areas, notably health and biotechnology, energy R&D has not kept pace with economic growth in leading industrialized countries.

Diverse strategies have aimed at ensuring a steady supply of energy and avoiding production-related crises. Key developments include:

- Accelerated development of strategic energy reserves, which now stand at more than 4.1 billion barrels of oil across the member countries of the International Energy Agency.
- Geographic diversification of energy suppliers, including augmented domestic production in many countries. Diversification was facilitated in part by the successful development and deployment of a suite of technologies (e.g., 3D seismic imaging, horizontal drilling, and deep water drilling) that enabled the economic production of energy resources in geographic regions that presented lower political risks than the Middle East.
- Deregulation of the energy industries and the establishment of energy futures markets, both of which allowed market forces to play a more significant role in dealing with future supply imbalances. Deregulation and restructuring of energy markets also led to a significant consolidation in the energy industries, which had the additional unintended consequence of reduced private sector energy R&D investment.
- Conservation, efficiency, and reduced energy intensity due to regulatory and economic structural changes. For example, the elimination of energy price controls in several countries spurred widespread fuel switching in the electric power industry from oil to coal, gas, and nuclear for electricity generation. Across the OECD, oil-fired power generation fell from more than 25% in 1973 to less than—for many nations significantly less than—10% percent of generation today.

Taken together, these and other developments helped to allay fears of enduring energy insecurities like those that led to the unprecedented increases in energy R&D investments in the 1970's. The history of energy R&D investment after 1980 can be understood as a history of competition among policy and market instruments during an era in which the tool set has grown broader continually. Since the crisis conditions that catalyzed the creation of today's energy R&D establishment have not recurred since the late 1970s, the priority accorded to energy R&D investments and therefore the level of investment has continued to decline.

Although energy R&D competes with other policy tools for investment resources and policy priority, energy R&D may have a unique role to play in future efforts to address the risks and challenges of climate change. The persistent pattern of declining support for energy R&D since 1980 raises concerns about whether or not new classes of energy technologies will be approaching commercial viability when they are needed as part of climate change mitigation strategies. With decades-long lead times not uncommon for the research, development, and deployment of new energy technologies, current trends raise serious questions about the need to create an enduring change in the perceived return for energy R&D investments to ensure both a steady stream of technological innovation to address climate change and also to ensure the health of the overall energy R&D enterprise.

RESEARCH, TECHNOLOGY, AND MANAGING THE RISKS OF CLIMATE CHANGE

From a technology perspective, managing the risks of climate change requires making investments in a portfolio of research programs that, taken together, can help reduce the cost of stabilizing the concentrations of greenhouse gases in the near, mid, and long terms. These technology investments include:

- Investments in the most basic scientific research, such as biological, earth, materials, and computational sciences to lay the foundation for continued advancement of existing climate mitigation and energy technology systems as well as the creation of new means of reducing emissions
- Directed, applied research needed to facilitate commercial deployment of key advanced energy technologies such as advanced energy storage systems
- Commercial-scale demonstrations of new technologies so the private sector and the public will have confidence in how technologies such as CO_2 capture and storage and the potentially large supporting infrastructures will work under real-world operational conditions
- Research and product development to optimize and refine already commercial technologies such as improving energy control systems.

A technology investment portfolio designed to address climate change must reflect the nature of the problem (e.g., its century-long timescale) and accommodate a number of key uncertainties and other criteria that distinguish it from the portfolio of research that underpinned truly transformative but narrowly focused, short-term programs like the Apollo Program (1961–1972) to put a man on the moon or the Manhattan Project (1941–1945) to develop the first nuclear weapons.

A climate mitigation portfolio is influenced by uncertainties in climate science; about how future policies will evolve and be implemented; in the rate and eventual extent of technological change that can be achieved across a number of needed advanced energy technologies; and the size, cost, and ease of exploiting natural resources such as fossil fuels, land for growing bioenergy crops, and CO_2 storage reservoirs.

A climate change mitigation technology portfolio must also account for "public good" considerations. A healthy, stable climate is a non-appropriable public good; therefore, many entities will free-ride instead of supporting the needed research at appropriate levels. Moreover, climate is a public good that spans generations; how to value a future public good is even more challenging.

In addition, a climate mitigation portfolio must be broad enough to include the range of technologies needed to address all major sources of CO_2 and other greenhouse gas emissions and to reflect diverse regional economic, social, political and technological circumstances.

As the 21st century evolves, we will gain a better understanding of the science of climate change and the risks that it presents. We will learn what policies nations will choose to implement in order to limit greenhouse gas emissions. We will find out whether oil and natural gas will remain abundant and inexpensive during this century or through only part of it. We will develop a better understanding of potential geologic repositories for CO_2. We will discover whether current concerns about nuclear power that currently hobble its further deployment in many industrialized nations can be overcome. We will learn whether large-scale bioenergy production will be acceptable from both economic and environmental perspectives.

Clearly, society cannot adopt a climate mitigation technology development and deployment plan today and blindly follow it over the next 100 years. Research programs, investment levels, and policies all can and will need to be modified as the decades pass. A Global Energy Technology Strategy must be flexible and adaptable.

As the 21st century evolves, we will gain a better understanding of the science of climate change and the risks that it presents.

Technological innovation, development, and deployment must be managed over time. Shifting the dominant fuels that run the energy system from wood to coal, oil, and natural gas took decades, even a century, as shown in Chapter 1. The shifts were slow because of the time needed to develop and deploy individual technologies, and associated infrastructure and institutions; and because of the intricacies of the energy system. The larger, more complex, more value-added and more central to the global economy an energy system and its associated supporting infrastructure are, the greater the incentive will be to not make abrupt fundamental changes in the system or substantially disrupt its operations.

The process of innovation, development, and early commercial deployment can take decades before new technologies become widely accepted and economically competitive. During this period, it is common for many new technologies to vie for supremacy in the marketplace. For several decades, the internal combustion engine was one of many options that competed to become the power plant of the automobile. Many early cars were powered by electricity during this period of technology competition.

The rate of improvement in overall energy efficiency and therefore the emissions mitigation benefit is also limited by the rate at which capital stock turns over and by government policy. However, change can be initiated on an incremental basis that over time delivers large-scale changes. For example, since 1974 government efficiency standards, direct financial incentives, and R&D (both public and private) all played roles in reducing substantially the energy required by household refrigerators even while the average refrigerator's usable space increased. While the individual savings due to the purchase and use of these slowly improving refrigerators is small, when replicated over and over again across something as large as the U.S. economy and across nearly three decades, these changes can play a significant role in slowing the growth of energy use. The large-scale adoption of more efficient energy technologies like these refrigerators as well as structural changes in the economy resulted in the energy intensity in the United States falling 42 percent between 1970 and 1999, continuing a pattern of decline observed since the 1920s.

Technical capacity development is necessary to achieve global deployment. New technology is useful only to those who are capable of using it productively and maintaining it. A key limiting factor in the global deployment of technology is the lack of or differences in institutions and strategies for spreading these capabilities. In some places, market economies are not adequately developed. In other places, additional scientists and engineers are needed to move technology ahead. In still others, procedures, best practices, rules and regulations do not yet exist to enable technologies to penetrate.

Technologies must meet the test of the market. Stabilization of greenhouse gas concentrations implies the development and deployment of technologies that, compared to their higher-emitting alternatives, provide similar or better performance and safety, lower greenhouse gas emissions, equivalent or lower cost, and similar or better amenities to the consumer.

The degree to which such technologies compete will determine the cost of stabilizing the concentration of greenhouse gases at any level, and will thereby have a major influence on society's implicit or explicit choice of a long-term stabilization goal.

Short-term actions need to be linked with strategic goals. When looking toward the future, society faces the challenge of crafting climate policy that induces the development, demonstration, and commercial adoption of advanced energy technologies like those described in this report. Policy development would likely require at minimum the creation and implementation of economically efficient greenhouse gas emissions mitigation régimes. However, the details of the emissions mitigation régime matter a great deal if the emissions mitigation policy is also going to help spur innovation. In order to do this, the policy must not only engage the world's major emitters and address all economic sectors but it must also *predictably* become more restrictive over the course of the century (e.g., carbon permit prices that rise at a predictable rate over time). Knowing the likely trajectory of carbon prices gives public and private-sector decision makers the ability to plan R&D and capital investment decisions. Long-term, consistent support for technology development and demonstration is also needed. Much of the support for the early stages of this process will likely come from the public sector or some other means of collective action, given the public good nature of a healthy stable global climate.

The potential large-scale deployment of advanced energy technologies implies a need for thoughtful anticipation and development of institutions and infrastructure as well as technology. In particular, the challenge before society is how to meaningfully link successive short-term emissions mitigation regimes in a way that not only yields a long-term strategic public good but that successively incorporates evolving knowledge about the long-term goal.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

GTSP has analyzed six energy technology systems whose large-scale, mitigation-motivated expanded global deployment could have a profound impact on the cost of addressing climate change and therefore make it easier for society to take on the challenge of addressing climate change while simultaneously meeting a myriad of other societal needs. These key advanced energy technologies are:

- CO_2 capture and storage
- Biotechnology and biomass
- Hydrogen systems
- Nuclear energy
- Wind and solar energy
- End-use energy technologies.

Figure 10-3, which is repeated from Chapter 2, shows that the progressively larger deployment of these technologies along with an emissions mitigation policy can significantly reduce atmospheric CO_2 concentrations while still delivering the energy services needed to raise standards of living around the world and to power a growing global economy. A key theme of the GTSP is that society has the ability to profoundly impact how the future will unfold and that stabilizing atmospheric concentrations of greenhouse gases in an economically efficient manner is possible.

The following section highlights selected high-impact R&D objectives that, if successfully accomplished, would allow these six advanced energy technologies to become key components of a larger portfolio of technology development and deployment and emissions mitigation that would effectively address climate change.

The potential large-scale deployment of advanced energy technologies implies a need for thoughtful anticipation and development of institutions and infrastructure as well as technology.

The R&D needs for each of the six key advanced energy technologies examined in this report differ based in their current state of technological development and market deployment as well as in the potential for these technologies to improve their performance and be competitive technologies in the altered economic environment of a greenhouse-gas-constrained world. That is, the nature of the research, education, training, and policy development needed to facilitate the deployment of the first 100 CCS-enabled coal-fired power plants likely differs significantly than what is needed for the next 10,000 MW of wind turbines to be deployed across the globe, or for the first 1,000,000 solid state lights to make their way from the laboratory to homes, offices, and factories all around the world. The significantly expanded deployment of these technologies will require dedicated, tailored efforts; there should be no expectation that the same programs or incentives would be equally effective in different circumstances.

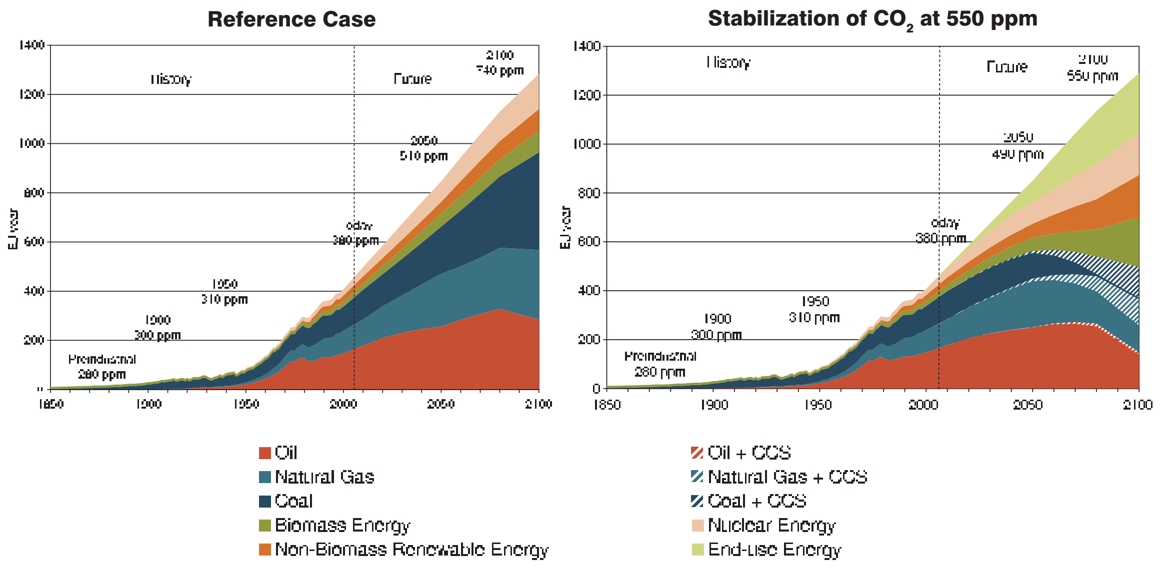


Figure 10-3. Stabilization implies fundamental change to the global energy system. A commitment to limit net greenhouse gas emissions and develop and deploy cleaner energy technologies can cost-effectively yield a solution to the challenge of climate change.

But similarities do exist across the identified R&D needs for these six key advanced energy technologies when framed in the context of the challenge of deploying ever more efficient and lower-emitting energy systems over the course of a hundred years or more. Advances in materials, biological, computational, and earth sciences will be needed to sustain innovation over the required century-long time frame. Continued investments in basic science are a critical complement to the more applied research described below.

Carbon Dioxide Capture and Storage—A broad array of research, development and demonstration activities need to be successfully completed in the next 5–10 years to rapidly build the knowledge base that will allow CCS systems to fulfill their significant potential for mitigating large quantities of CO_2 emissions over the course of this century. Selected R&D, demonstration, and commercial deployment challenges and opportunities for CCS include:

- Continually improve CO_2 capture technologies and ensure that they are being developed and tuned to a wide array of industrial sectors that can potentially benefit by adopting CCS systems.

- Survey global candidate CO_2 reservoirs so that we can better understand the true nature and distribution of the world's deep geologic CO_2 storage reservoirs. This is particularly crucial in rapidly developing countries such as China and India. Helping developing nations site new long-lived electricity generation or other large CO_2 emitting industrial facilities while giving forethought to potential deployment of CCS will allow them to avoid stranding those assets should there be a need to adopt CCS systems at those facilities at some point in the future.

- Develop a more advanced and broader set of measurement, monitoring, and verification (MMV) technologies for stored CO_2 in order to meet the needs of a potential future large-scale deployment of CCS systems with CO_2 being stored in many different kinds of formations and circumstances. New MMV technologies need to be invented; and the cost, performance and other operating characteristics of existing MMV technologies need to be improved.

- Obtain more experience with end-to-end CCS systems in real-world conditions and make specific efforts to utilize the opportunity presented by these early commercial and research demonstration CCS facilities to increase our understanding of the behavior of CO_2 in the subsurface, such as developing a more robust and dynamic understanding of the various mechanisms that trap CO_2 in the deep subsurface; develop a base of empirical data to facilitate the development of MMV systems and MMV regulation; train and educate a larger cadre of individuals who are capable of running commercial-scale CCS systems; garner public support for CCS deployment; and otherwise lay the foundation for the larger-scale deployment to come.

Biotechnology and Biomass—Continued advancement across a wide variety of biological, agricultural, and engineering fields will be required for the large-scale potential for commercial bioenergy and terrestrial sequestration to be fulfilled. Selected R&D, demonstration, and commercial deployment challenges and opportunities include:

- Continue to improve the efficiency and lower the cost of cellulosic conversion processes.

- Continue to deliver increases in agricultural productivity for both food and bioenergy crops, increases that must be sustained over the course of this century.

- Develop and deploy end-use energy systems across a number of different economic sectors that are adapted and optimized to the use of biofuels.

- Conduct research, field testing, and likely large-scale demonstration projects to better understand the real-world potential for biomass energy systems coupled with CO_2 capture and storage technologies.

- Actively pursue the rapidly expanding field of genomic research to better understand how these techniques and technologies can be applied to produce and transform biological materials into large-scale clean energy.

- Improve methods for measuring and monitoring carbon stocks in soils and standing biomass to help significantly expand already established practices such as low-till and no-till agricultural practices.

Hydrogen Energy Systems—If the potential for hydrogen technologies to contribute to CO_2 emission reductions is to be realized, all aspects of hydrogen production, transport, storage, and use must be significantly improved in terms of cost and performance. Selected R&D, demonstration, and commercial deployment challenges and opportunities for hydrogen energy systems include:

- Develop methods for producing hydrogen without emitting CO_2, such as CCS, biomass, renewable electricity, or thermonuclear. Such methods must be developed and commercially deployed on a large scale for hydrogen to contribute to CO_2 emissions reduction.

- Significantly improve the cost competitiveness and performance of vehicle fuel cells and hydrogen storage systems so that fuel-cell-based vehicles will play a significant role in decarbonizing the transportation sector.

- Reduce the cost of transporting hydrogen in order to build an economic hydrogen distribution system.

- Reduce the cost and improve the performance of storing hydrogen in sufficient quantities on board vehicles to allow safe use with driving ranges comparable to conventional vehicles.

Nuclear Power—Nuclear power is already a significant aspect of the global energy system. However, the extent to which it can maintain its current market share or significantly expand it in a greenhouse-gas-constrained world is in part dependent upon continued R&D. With the bulk of new nuclear power plant deployment occurring outside the present-day OECD nations, improved reactor designs and features may be developed outside of the traditional nuclear powers. Selected R&D, demonstration, and commercial deployment challenges and opportunities for nuclear power include:

- Establish the economic viability of the next-generation nuclear energy systems.

- Demonstrate the capability to safely dispose high level nuclear waste.

- Develop recycling and fuel processing technologies for breeder reactors to enable a transition from the current one-through fuel cycle to a closed nuclear fuel cycle. The commercial deployment of advanced reactors and fuel system technologies could reduce the quantity and toxicity of spent nuclear fuels, and reduce the need for geologic disposal.

- Develop the nuclear capacity to generate hydrogen for use in transportation and other end-use sectors. Advances in thermo-chemical and high-temperature electrolysis based on nuclear technology will determine the economic viability of nuclear-based hydrogen production.

- Create innovative international policies for trade in nuclear technology and fuel for commercial power reactors to reduce waste products and proliferation concerns while allowing a global expansion of nuclear energy use.

Wind and Solar Power—The on-going deployment of wind and solar power systems around the world makes these renewable energy systems some of the fastest growing aspects of the global energy system. However, the extent to which wind and solar power can significantly expanded their current market share in a greenhouse-gas-constrained world is in part dependent upon continued research and development. Selected R&D, demonstration, and commercial deployment challenges and opportunities for wind and solar power energy systems include:

- Reduce the capital costs of solar photovoltaic and concentrating thermal technologies to be more competitive with conventional sources.

- Continue to develop and refine turbines that are optimized to work in offshore environments and at low wind speeds.

- Improve grid management systems to incorporate the intermittency of wind and solar energy.

- Reduce costs of storage to maximize potential use of intermittent sources.

- Reduce the cost of transmission from remote sites with large wind and solar potential to electric load centers.

End Use—End-use energy technologies are the broad set of devices and technologies that turn energy into the services consumers, businesses and homeowners desire, such as cooling, heating, and lighting homes; transporting people and freight; and heating and powering a range of industrial processes. The opportunities for improving existing end-use technologies and deploying novel end-use technologies vary substantially across the portfolio of end uses within the buildings, transportation, and industrial sectors. Selected R&D, demonstration, and commercial deployment challenges and opportunities for end-use energy systems for the buildings, commercial and transport sector include:

- Buildings Sector: Optimize building shell design to reduce the need for active heating, space conditioning and lighting and make use of advanced materials. Further cost reductions and efficiency gains are possible in specific end-uses such as solid state lighting and heat-pump-based technologies for space conditioning. Develop smart appliances that could participate in grid regulation, increasing reliability and perhaps increasing the potential of non-dispatchable renewable energy.

- Transportation Sector: Increase the efficiency of light-duty vehicles using hybrid technology with gasoline, diesel, or biofuels. Pursue advances in battery technologies, which would benefit all electric-based vehicles—hybrid, plug-in hybrid, or fuel-cell. Reduce the need for light-duty vehicles by community planning, mass transportation, and information systems.

- Industrial Sector: Re-engineer industrial processes to require less energy. For example, use membrane technologies for chemical separation processes that would use much less heat and steam. Where processes still require high temperatures for steam or heat, make burning commercial biomass an available technology option. In generating heat and steam from biomass, exploit opportunities for cogenerating electricity. Reduce the cost of capturing or substituting material to reduce the process CO_2 emissions from cement production.

Non-CO$_2$ Gases—Although CO$_2$ emissions are the most important driver of anthropogenic climate change, a number of other greenhouse gases also have a substantial effect on the climate system. The GTSP's research shows that it is important to continue commercial deployment of a wide variety of technologies to address emissions of non-CO$_2$ gases. Success in expanding current efforts to reduce the release of these non-CO$_2$ gases as well as the creation of new mitigation technologies can have important implications for global, national, and regional energy systems and for the rate and ultimate extent of the development and adoption of these six advanced energy technologies.

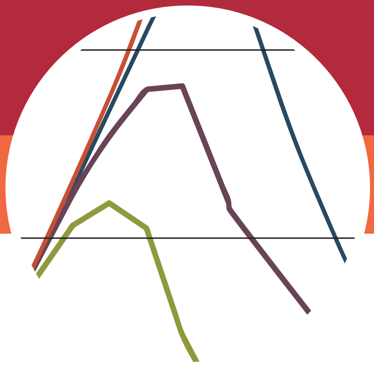
THE POWER LIES IN THE PORTFOLIO

This chapter has articulated a broad portfolio of R&D needs, challenges and opportunities that, if successfully addressed, could transform society's ability to address climate change. It is not necessary for each of these R&D needs to be addressed simultaneously but it is necessary to make progress on the broad front of research articulated here. There is no silver bullet for addressing climate change, but there is a powerful and promising set of R&D and policy measures that can be implanted to help society meet the challenge presented to it by climate change.

Overall Findings of the GTSP

Significant progress has been made in recognizing and analyzing the potential role of energy technology and the importance of developing an energy technology strategy to address climate change since the inception of the GTSP in 1998. In 1998 the notion of an energy technology strategy was new and foreign to most participants in the climate change conversation. The concept has since become universally recognized and discussed. It is part of the language of virtually every nation's approach to climate change and forms the central theme of a number of international initiatives. Yet creating a global energy technology strategy remains an elusive goal.

Fundamental insights stemming from of GTSP research frame the economic, policy, and technology issues associated with climate change. These insights affirm the nature of the challenges and pathways to meet those challenges for those who make decisions about R&D and technology deployment.



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1. Stabilizing atmospheric concentrations of greenhouse gases requires fundamental transformations, especially in the energy system.

- Energy is central to the climate change issue. Carbon dioxide (CO_2) emissions from the production and consumption of fossil fuels are the largest contributor to human emissions of greenhouse gases.

- If present trends continue, CO_2 emissions from energy will continue to grow, resulting in increased concentrations of greenhouse gases in the atmosphere. The influences of future population growth and economic development on the demand for energy services are likely to outstrip currently projected improvements in energy intensity and the ongoing transition to less carbon-intensive fuels.

- Stabilization of greenhouse gas concentrations will require commitments for both limiting net global emissions of greenhouse gases and for developing and deploying a broad portfolio of advanced energy technologies across the globe.

2. Technology development and deployment are essential both to stabilizing greenhouse gas concentrations and to controlling costs.

- The role of technology is to help control costs. Limiting cumulative global CO_2 emissions implies economic costs, but these can be minimized through the development and deployment of advanced technologies.

- If non-CO_2 emissions reduction technologies are developed and deployed, the energy sector can minimize the extent of premature retirement of capital assets, which will lessen the cost of stabilizing concentrations. If deployed widely, non-CO_2 emission reduction technologies could achieve the equivalent of hundreds of billions of tons of carbon emissions reductions over the course of the 21st century.

3. A portfolio of technologies is necessary to manage the risks and costs of climate change and to respond to evolving conditions, including the challenge of ever increasing emissions mitigation needed to stabilize greenhouse gas concentrations.

- No single advanced energy technology can do it all. Carbon dioxide capture and storage, biotechnology, hydrogen, nuclear, solar and wind, and end-use energy technologies all have roles in addressing climate change, but none is capable of delivering all possible energy services (e.g., electricity, transportation, heat, industrial steam) across the globe and over the course of this century. The portfolio must also include non-CO_2 greenhouse gas technologies.

- Investing in research, development, and implementation in multiple technology areas provides the foundation for the deployment of a broad portfolio of advanced energy technologies. The large-scale deployment and use of these advanced energy technologies has the potential to reduce the cost of stabilization by trillions of dollars. Removing any one of them from the mix increases cost.

- The value of this portfolio increases as technologies are added and as the complementarity of certain technologies is realized.

4. A portfolio of advanced energy technologies also helps manage the risks and costs of climate change presented by diverse national and regional energy systems, natural resource endowments, and rates of economic development and growth—current heterogeneities that will likely persist during this century.

- Society and even individual nations and firms benefit from the development and deployment of a broad suite of energy technologies to meet the diversity of technology needs likely to be present over time and across regions.

- The mix of technologies deployed around the world varies over time and from place to place. The heterogeneous distribution of resources potentially relevant to a technology strategy as well as regional differences in culture, institutions and economic systems imply heterogeneous technology needs that must evolve over time.

5. Realizing the potential of energy technologies and technology systems presents challenges in expanding the scale of deployment at every time and spatial scale ranging from the next few years to the entire century.

- The scale of the technology challenge implied by the goal of stabilization is daunting. The technology challenge grows throughout the century for any given stabilization goal.

- Technology deployment will vary with time and place for any given stabilization goal.

- Technology deployment depends on not only the technology's own performance, but also on the performance of other available technology options—both direct competitors and technology complements. The deployment of bioenergy crops depends not only on the productivity of the bioenergy crop itself, but also on the continued growth of food crop productivity. If food crop productivity does not increase, the demand for food could take most productive lands, leaving little for bioenergy crops. Similarly, the use of CCS with bioenergy holds the potential of large-scale energy production with negative CO_2 emissions.

- Technology choice depends on the policy environment—as do economic costs. That is, different policies (taxes, trading regimes, standards, voluntary programs, corporate policies, R&D tax credits, etc.) will result in different sets of technology choices and those choices in turn will have cost implications.

MEETING THE CHALLENGE: GTSP PROVIDES ESSENTIAL INSIGHTS FOR MITIGATING CLIMATE CHANGE

Although much progress has been made, economically efficient greenhouse gas emissions reductions will remain an elusive goal without a long-term global technology strategy.

The challenge is to craft policies that promote the development, demonstration and commercial adoption of the advanced energy technologies described in this report.

- Economic efficiency requires the creation and implementation of mitigation régimes that engage the world's major emitters and that become predictably and progressively more restrictive over time (e.g., carbon permit prices that rise at a predictable rate over time). Knowing the likely trajectory of future carbon prices enables public and private-sector decision-makers to rationally plan their R&D and capital investment decisions.

- Long-term, consistent financing for technology development and demonstration is also essential. Much of the support for the early stages of this process will likely come from the public sector or other means of collective action.

Both the overall level and the allocation strategy for energy R&D are integral parts of a global energy technology strategy. After declining for almost a quarter-century, global funding for energy R&D has been stable over the past decade—but it continues to decline relative to the size of the economy (GDP).

The large-scale deployment of advanced energy technologies also requires the development of institutional and policy infrastructure.

- To be most cost-effective, institutional mechanisms should treat all carbon as having equal value, regardless of the sector of origin. Thus, policies should treat carbon emissions from land-use change as having the same value as carbon emissions from fossil fuels.

- Varied institutional developments—from setting standards to public education—are necessary to realize the full potential of any given technology.

- Institutions will also be critical in effectively communicating, to both investors and consumers, the value of reducing CO_2 and other greenhouse gases.

As the GTSP research program further evolves, it will build on its established foundations—its capacity to describe and analyze the complex interactions among energy, the economy, technology, and natural systems over century-long time scales for global, national, and regional systems; its ability to explore in depth specific technology systems and to articulate the strategic and tactical implications of their deployment; and its ability to work at geographic scales ranging from the power plant to the planet. GTSP will continue to conduct policy relevant research and report results.

An important lesson for society, given the uncertainties, is this:

Act, then learn, then act again. No strategy to address climate change can anticipate all future developments. Society will need to regularly review and revise technology strategies in the light of new information in the realms of science, technology, economics, and society.

APPENDIX 1 Acronyms and Abbreviations

CCS	Carbon Dioxide Capture and Storage
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
$GtCO_2$	10^9 tons (a gigaton) of CO_2 = 10^{15} grams of CO_2 (a petagram) = billion tons of CO_2
GTSP	Global Energy Technology Strategy Program
IGCC	Integrated Gasification Gas Combined Cycle power plant
IGCC+CCS	An Integrated Gasification Gas Combined Cycle power plant that also includes all of the necessary systems needed for Carbon Dioxide Capture and Storage
mmBtu	Million British Thermal Units
MMV	Measurement, Monitoring and Verification
$MtCO_2$	10^6 tons (a megaton) of CO_2 = million tons of CO_2
MW	Megawatt (one million watts)
NO_x	Nitrogen Oxides (formed during the combustion of fossil fuels)
O&M	Operating and Maintenance
OPEC	Organization of Petroleum Exporting Countries
OECD	Organization for Economic Co-operation and Development
ppm	Parts Per Million
SO_2	Sulfur Dioxide (formed during the combustion of fossil fuels)
TW	Terawatt (one trillion watts)
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States of America

APPENDIX 2 Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/$tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

Executive Summary Notes: Figure ES-1. Historical data on global carbon emissions from the Industrial Revolution until the present are from G. Marland, R.A. Boden and R.J. Andres, *A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN (2006).

Figure ES-2 highlights the extent of assumptions about future technology change if climate change is not a factor in technology development. The middle curve in the first chart depicts the CO_2 emissions associated with a typical reference case scenario of future CO_2 emissions and the middle curve in the second chart represents the concentrations in the atmosphere that result from these emissions. This reference case scenario, like all "business-as-usual" scenarios, incorporates significant technological advances. In contrast, the top curve in each figure holds energy technology fixed at 2005 levels, but assumes the same population and economic growth. The difference between the upper and middle curves, therefore, illustrates the magnitude of technology improvement that is assumed in the Reference Case and its associated impact on the CO_2 concentration. The lowest curves depict an emissions path and its corresponding concentration path consistent with a 550 parts per million (ppm) concentration ceiling. The dotted line on the concentrations chart indicates the pre-industrial level of CO_2 concentrations.

Figure ES-3. The upper panel shows a global energy future as it might evolve if climate change were not a consideration. Note that this case already incorporates substantial technological change. See Figure ES-2. Despite those improvements, the scale of the global energy system could triple compared to its scale in the year 2000. While renewable and nuclear energy might be expected to expand their share of the global energy market, fossil fuels remain the largest sources of energy throughout the 21st century. Historical data on global energy use disaggregated by fuel type are from A. Grübler, *Technology and Global Change*, Cambridge University Press, Cambridge, UK (1998). Revised and updated data set were provided by A. Grübler.

Figure ES-4. The figure shows examples in which the performance of technologies was assumed to improve individually and in combination with other technologies while climate change was stabilized by limiting climate change to no more than 2 degrees Centigrade. Other values to technology improvements, such as energy security, were not measured.

Figure ES-5. The rate of global deployment CO_2 capture and storage for a scenario in which the concentration of CO_2 was stabilized at 550 ppm. The scenario assumed idealized conditions, including full global participation in the stabilization regime and full economic efficiency.

Chapter 1 notes: For more information about the UNFCCC, please see http://unfccc.int/essential_background/convention/items/2627.php. While there is general agreement that stabilization of greenhouse gas concentrations is the best way to frame decisions about addressing climate change, there is no scientific consensus yet regarding the ideal levels of atmospheric concentrations or the potential impacts associated with higher concentrations.

Figures 1-1 and 1-2. At the beginning of the Industrial Revolution concentrations of CO_2 in the atmosphere were approximately 270 parts per million (ppm). Currently, CO_2 concentrations are around 370 ppm and rising. Whether the appropriate stabilization level is as low as 450 ppm or as high as 750 ppm, the goal of stabilization carries with it requirements to produce and sustain deep reductions in GHG emissions over the course of this century (see for example, T.M.L. Wigley, R. Richels., and J.A. Edmonds, "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature* 379, 6562 [1996]: 240-243). Also see Marland et al. (2006) in note on Figure ES-1.

Figure 1-4 data from Grübler (1998); see Note on Figure ES-3.

Chapter 2 notes: Figure 2-3. See note on Figure ES-2.

Figure 2-7. See note at ES-4.

Chapter 3 notes: Much of the data here on large CO_2 point sources and candidate geologic storage formations within the United States comes from a report that was coauthored with colleagues at other institutions and supported by the International Energy Agency's Greenhouse Gas R&D Programme. Dahowski, RT, Dooley, JJ, Davidson, CL, Bachu, S and Gupta, N. *Building the Cost Curves for CO_2 Storage: North America*. Technical Report 2005/3. International Energy Agency Greenhouse Gas R&D Programme.

More detailed information on our research into CO_2 capture and storage, as well as references to the technical papers and articles documenting this research can be found in the companion brochure, J.J. Dooley, R.T. Dahowski, C.L. Davidson, M.A. Wise, N. Gupta, S.H. Kim, and E.L. Malone, *Carbon Dioxide Capture and Geologic Storage: A Core Element of a Global Energy Technology Strategy to Address Climate Change*, Joint Global Change Research Institute, College Park, MD (2006).

Chapter 4 notes: Box 4-1. The estimate of carbon lost from soils comes from V. Cole, C. Cerri, K. Minami, A. Moser, N. Rosenberg, and D. Sauerbeck, "Agricultural Options for Mitigation of Greenhouse Gas Emissions," in Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, eds. R.T. Watson, M.C. Zinyowera, and R.H. Moss, Cambridge University Press, Cambridge (1996). The estimate of loss from land-use change is from R.C. Watson, I.R. Nobel, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken, *IPCC Special Report on Land Use, Land-Use Change, and Forestry*, Cambridge University Press, Cambridge (2000).

References of interest for further exploration of this topic include the following:

J.A. Edmonds and S. Smith, "The Technology of Two Degrees," in *Avoiding Dangerous Climate Change*, eds. H.J. Schellenhuber, W. Cramer, N. Nakicenovic, T.M.L. Wigley, and G. Yohe, Cambridge University Press (2006).

J.A. Edmonds, L. Clarke, J.J. Dooley, S.H. Kim, R.C. Izaurralde, N.J. Rosenberg, and G. Stokes, "The Potential Role of Biotechnology in Addressing the Long-Term Problem of Climate Change in the Context of Global Energy and Ecosystems," in *Greenhouse Gas Control Technologies*, eds. J. Gale and Y. Kaya, Pergamon, Amsterdam (2003).

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Chapter 5 notes: Figure 5-3. This figure depicts results of modeled scenarios exploring broadly the impact of technical improvements in hydrogen systems. "Incremental improvements" in hydrogen technology were modeled as a 50 percent increase in fuel cell performance over the century. "Breakthroughs" in hydrogen technology were modeled as fuel cell performance doubling over the century while the cost decreases by a third. For more detail, see J. Edmonds, J. Clarke, J. Dooley, S.H. Kim and S.J. Smith, "Stabilization of CO_2 in a B2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies," *Energy Economics*, 26 (2004), 517-537.

References of interest for further exploration of this topic include the following:

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Chapter 6 notes: References of interest for further exploration of this topic include the following:

M. Bunn, S. Fetter, J.P. Holdren, and B. van der Swaan, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," Harvard University, Cambridge, MA (2003).

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G.S. Tolley, and D.W. Jones (directors of the study), *The Economic Future of Nuclear Power*, University of Chicago (2004). http://www.anl.gov/Special_Reports/NuclEconSumAug04.pdf

Chapter 7 notes: Figure 7-1. Data were taken from U.S. Department of Energy/Energy Information Administration, *Annual Energy Review 2005*, DOE/EIA 0384-2005, Washington, DC (2006).

The International Energy Agency report referred to on page 89 is International Energy Agency, *The Potential of Wind Energy to Reduce CO_2 Emissions*, International Energy Agency Greenhouse Gas R&D Programme Report No. PH3/24, Paris (2000).

Box 7.1. Wind and PV costs are from National Renewable Energy Laboratory, *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs: FY 2006 Budget Request*, NREL/TP-620-37931, Golden, CO (2005). CSP costs are GTSP calculations.

Figure 7.5. The solar irradiance chart comes from the National Aeronautics and Space Administration, "Surface meteorology and Solar Energy" http://eosweb.larc.nasa.gov/sse/

References of interest for further exploration of this topic include the following:

L.E. Clarke, M.A. Wise, M. Placet, R.C. Izaurralde, J.P. Lurz, S.H. Kim, S.J. Smith, and A.M. Thomson, *Climate Change Mitigation: An Analysis of Advanced Technology Scenarios*, PNNL-16078, Pacific Northwest National Laboratory, Richland, WA (2006).

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Y. Zhang, and S.J. Smith, *Long-Term Modeling of Solar Energy: Analysis of PV and CSP Technologies*. Pacific Northwest National Laboratory, Washington, DC (2007).

Chapter 8 notes: The estimates of energy uses by light-duty vehicles, freight trucks, and airplanes are from U.S. Energy Information Administration, *Annual Energy Outlook 2005 with Projections to 2025*, U.S. Energy Information Agency, Washington, DC (2005a).

Advanced battery technologies are discussed in the *MIT Technology Review*, February 2006.

Data for Figures 8-5, 8-6, 8-7, and 8-8 come from the Manufacturing Energy Consumption Survey (MECS), U.S. Energy Information Administration (EIA) (2002). http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/shelltables.html; 2002.

Figure 8-9 credit: Andrew L. Malone.

References of interest for further exploration of this topic include the following:

J.A. Edmonds, J.F. Clarke, J.J. Dooley, S.H. Kim, and S.J. Smith, "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 (2004): 517-537.

F. Rong, L.E. Clarke, and S.J. Smith, "Climate Change and the Long-Term Evolution of the U.S. Buildings Sector," PNNL-SA-48620, Pacific Northwest National Laboratory, Richland, WA (2006).

M.A. Wise, P. Sinha, S.J. Smith, and J.P. Lurz, *Long-Term U.S. Industrial Energy Use and Carbon Dioxide Emissions*. Pacific Northwest National Laboratory, Richland, WA (2007).

Chapter 9 notes: Much of the work presented here on non-CO_2 greenhouse gases and aerosols has been conducted under an interagency agreement with the U.S. Environmental Protection Agency.

Figure 9-1. This figure is taken from V. Ramaswamy, et al., "Radiative Forcing of Climate Change," *Climate Change 2001: The Scientific Basis*, eds. J.T. Houghton et al., Cambridge University Press, Cambridge (2001).

Figure 9-2. Prices in these graphs are given in terms of CO_2, instead of carbon (1 Tonne C = 3.66 Tonnes CO_2; 3.66 \$/TC = 1 \$/TCO_2). See U.S. Environmental Protection Agency, *Global Mitigation of Non-CO_2 Greenhouse Gases*, EPA 430-R-06-005, Washington, DC (2006).

Figure 9-6. Note that this is an idealized temperature projection—in reality there would be significant variability in the climate change response shown here.

References of interest for further exploration of this topic include the following:

U.S. Environmental Protection Agency, *Global Mitigation of Non-CO_2 Greenhouse Gases*, EPA 430-R-06-005, U.S. Environmental Protection Agency, Washington DC (2006).

S.J. Smith, and T.M.L. Wigley, "Multi-Gas Forcing Stabilization with the MiniCAM," *Energy Journal* 3 (Special Issue) (2006).

V. Ramaswamy, et al., "Radiative Forcing of Climate Change," Chapter 6 in *Climate Change 2001: The Scientific Basis*, eds. J.T. Houghton, et al., Cambridge University Press, Cambridge (2001).

Chapter 10 notes: This chapter's discussion of patterns in public and private sector investment in energy research and development draws upon a number of publications produced as a part of the GTSP and some that predate the formation of the GTSP. Key publications in this area include:

L.E. Clarke, J. Weyant, and A. Birky, "On Sources of Technological Change: Assessing the Evidence," *Energy Economics* 28 (2006):579-595.

L. E. Clarke, and J. Weyant, "Modeling Induced Technological Change: An Overview," in *Technological Change and the Environment*, eds. A. Grubler, N. Nakicenovic, and W. Nordhaus, Resources for the Future, Washington, D.C (2002).

J.J. Dooley, "Unintended Consequences: Energy R&D in Deregulated Market," *Energy Policy* (June 1998), 547-555.

J.A. Edmonds, and L.E. Clarke, "Endogenous Technological Change in Long-term Emissions Stabilization Scenarios," *IPCC Expert Meeting on Emissions Scenarios*, ed. M. Hoogwijk, IPCC, Bildhoven, The Netherlands (2005).

J.A. Edmonds, and G.M. Stokes, "Launching a Technology Revolution," in *Climate Policy for the 21st Century: Meeting the Long-Term Challenge of Global Warming*, The Brookings Institution, Washington DC (2004).

P.J. Runci, and J.J. Dooley, "Energy Research and Development," *Encyclopedia of Energy*, Elsevier Science (Spring 2004).

P.J. Runci, J.J. Dooley, and L.E. Clarke, "Energy R&D Investment in the Industrialized World: Historic and Future Directions," *Issues in Science and Technology* (Spring 2006): 10-11.

Data on public sector investments in energy R&D in major industrialized nations used in Figures 1 and 2 are taken from International Energy Agency, "R&D Statistics Database (2006 Edition)," http://www.iea.org/Textbase/stats/rd.asp

The decline in the amount of energy used by refrigerators in the United States and the role that R&D and appliance standards played in bringing this about is documented in a 2001 report by the U.S. National Research Council and is described by the report's authors as "one of the last half-century's more remarkable technological achievements." See National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000*, National Academies Press, Washington, DC (2001).

THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

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