Global Energy Technology Strategy

ADDRESSING CLIMATE CHANGE

EXECUTIVE SUMMARY

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

GTSP

Global Energy Technology Strategy Program

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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 pre-industrial 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).

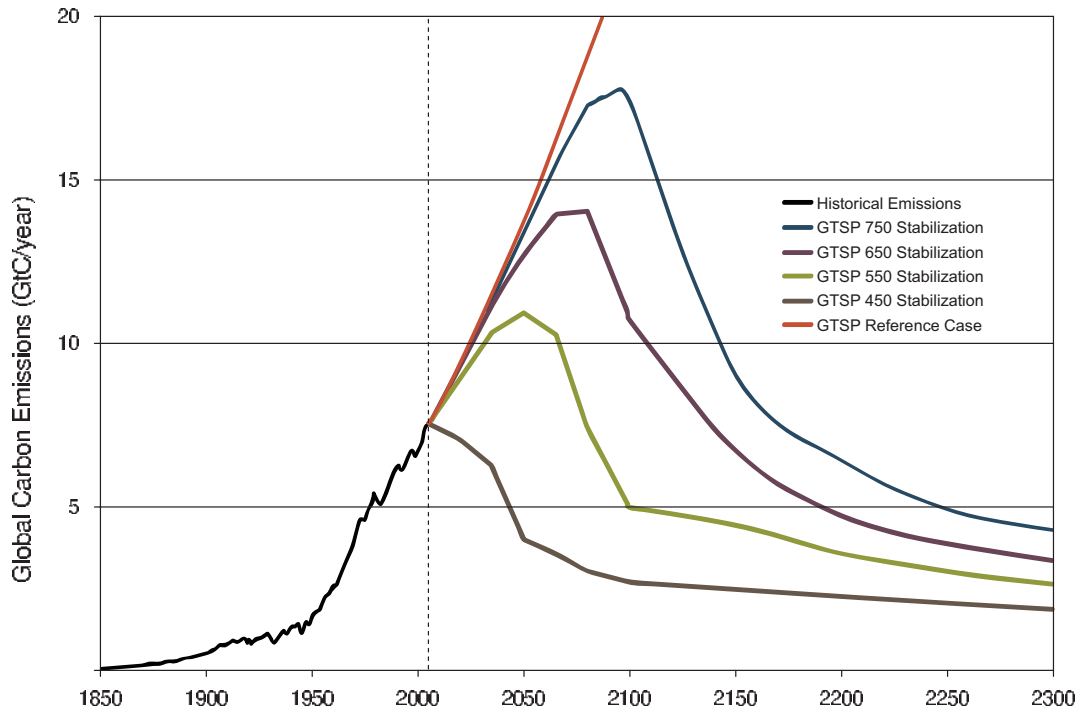
THE CHALLENGE OF STABILIZING CO_2 CONCENTRATIONS

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

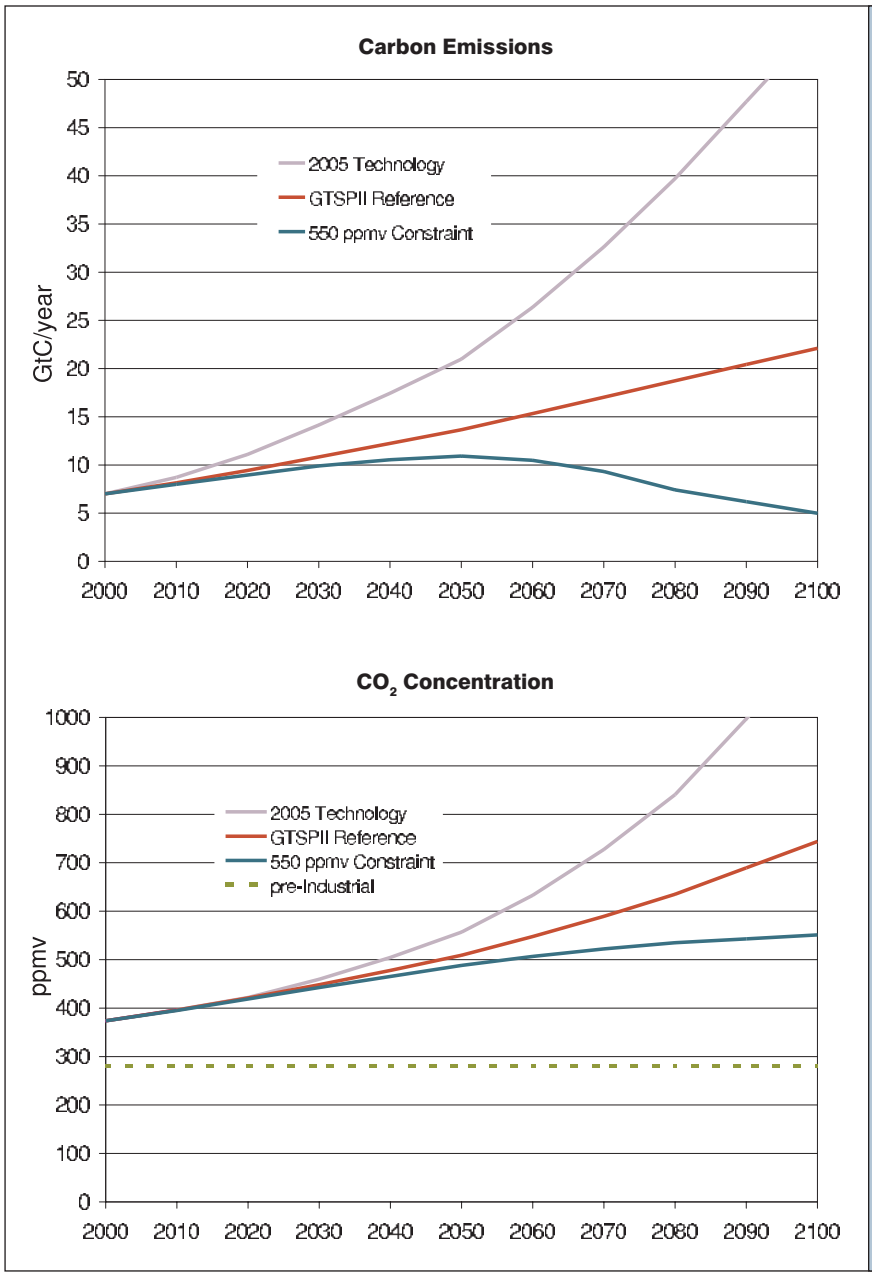


Figure ES-2. The future without technology change (highest curves), with technology change that does not take climate change into account (middle curves), and with technology change aimed at climate stabilization (lowest curves).

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.

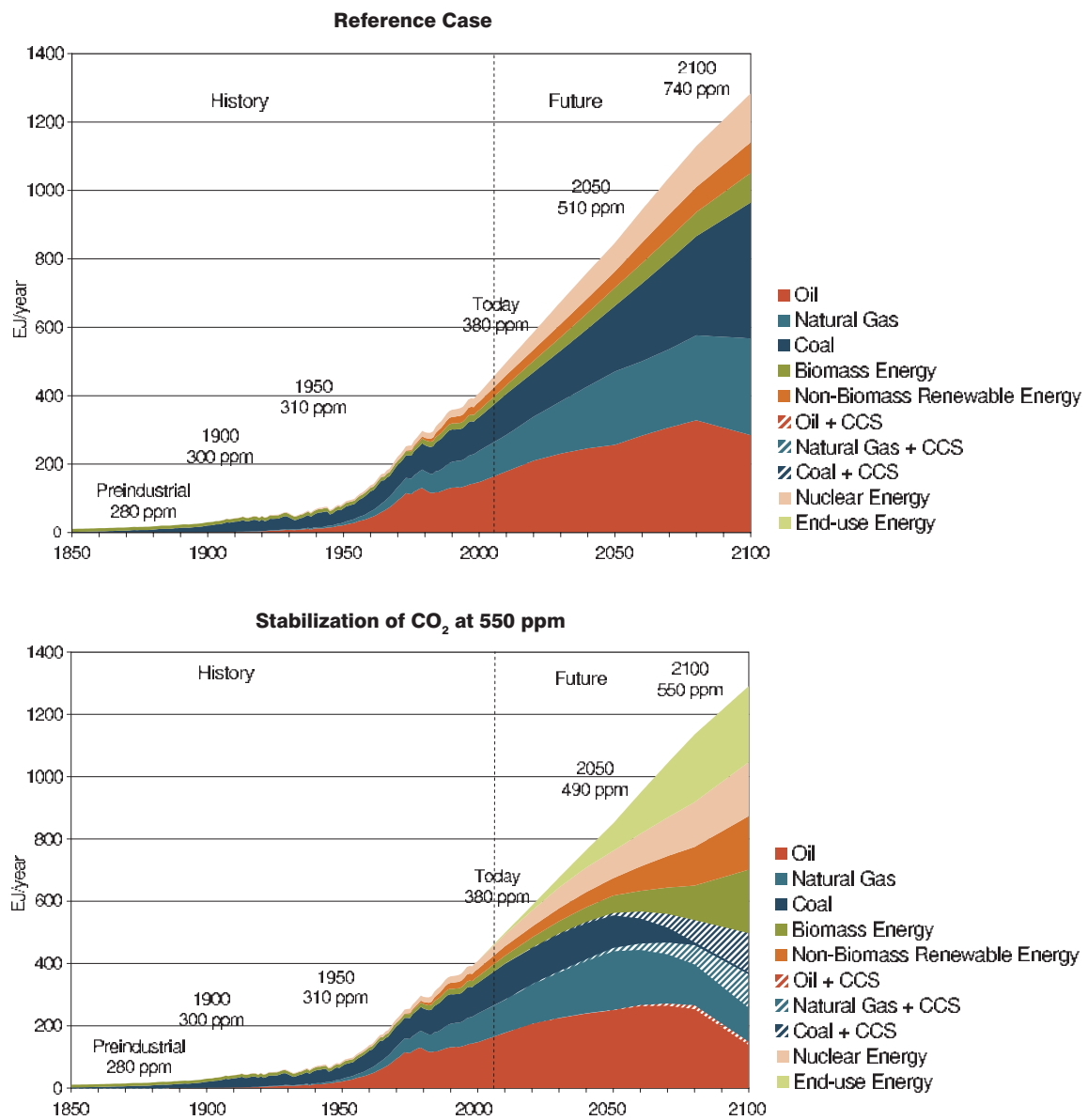
None of these six technology systems is a "silver bullet"—that is, none alone can stabilize greenhouse gas concentrations without cost—but together they have the potential to significantly reduce the cost of stabilizing greenhouse gas concentrations.

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

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.

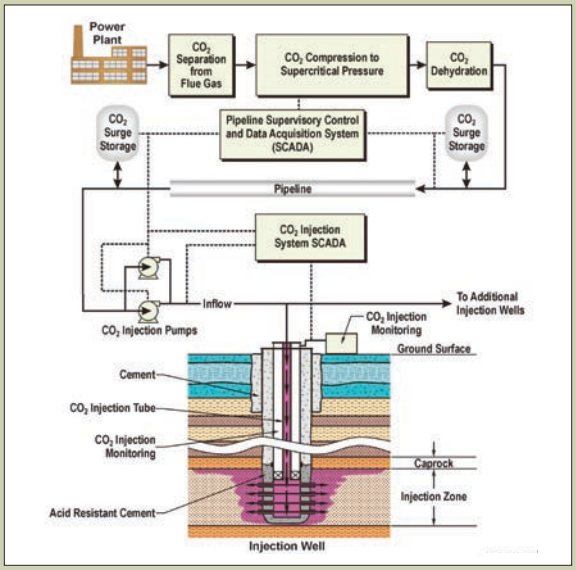
CCS technologies could be widely deployed in many regions of the world as part of a global commitment to reduce greenhouse gas emissions. Such large-scale deployment under such a commitment could greatly lower the cost of emissions reductions. There is potential geological capacity to store more than 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.

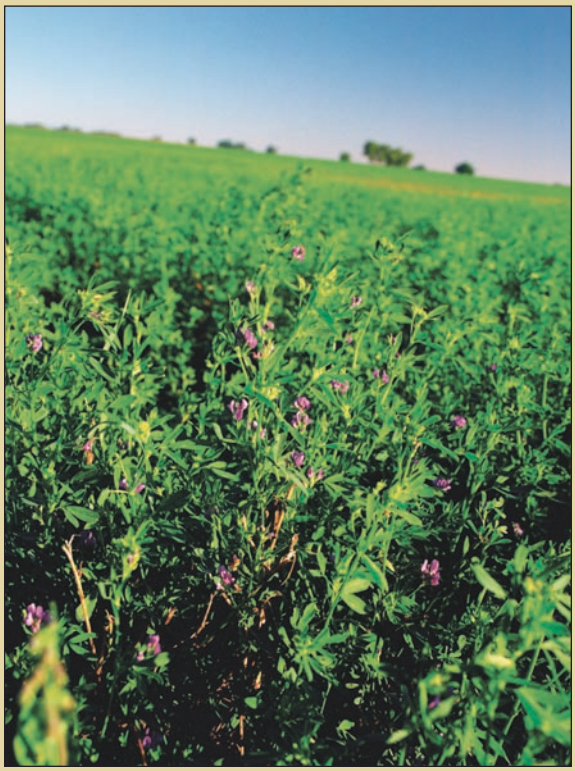
R&D and Deployment Challenges

- 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

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

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

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

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

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.

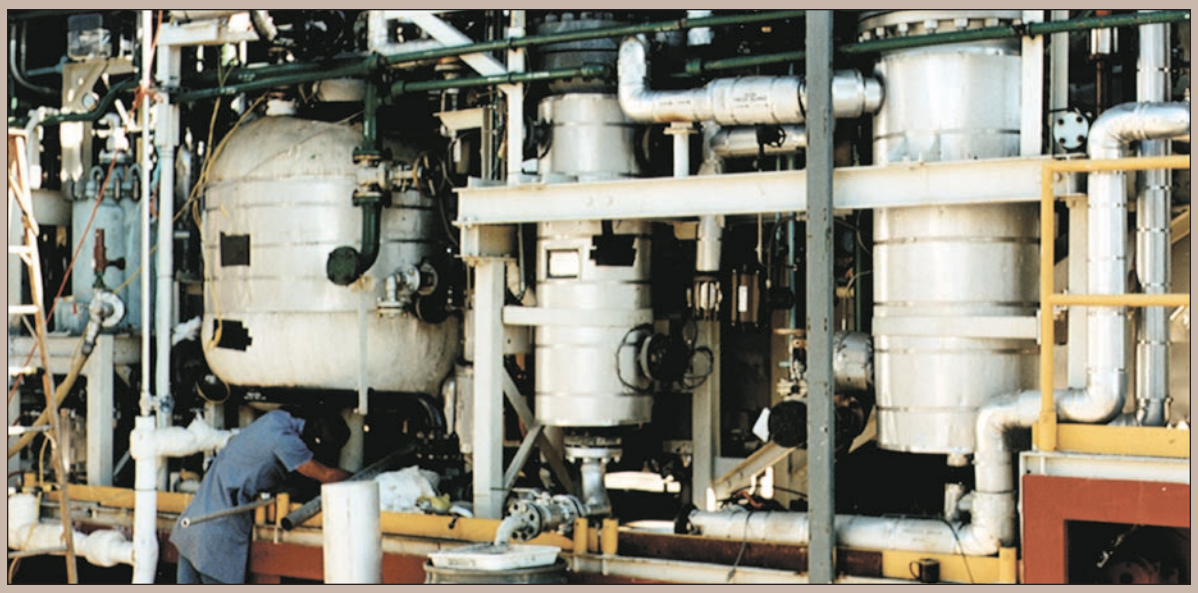
NON-CO_2 GREENHOUSE GASES

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

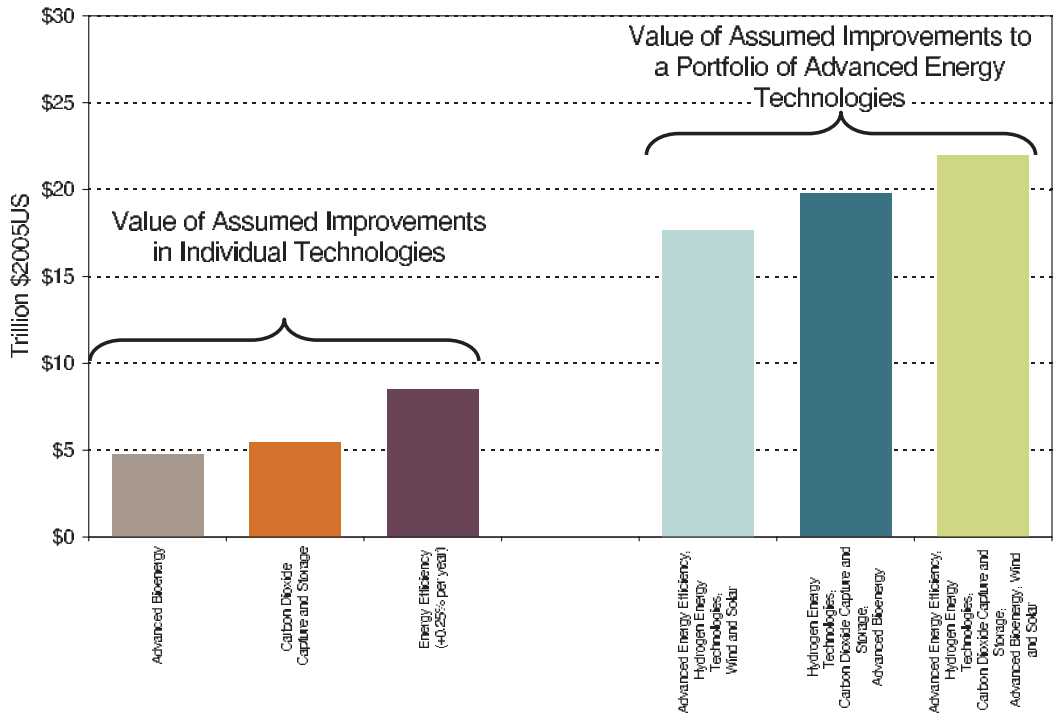
technologies. The large-scale deployment and use of these advanced energy technologies has the potential to reduce the cost of stabilization by trillions of dollars. Removing any one of them from the mix will increase the cost.

- 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.

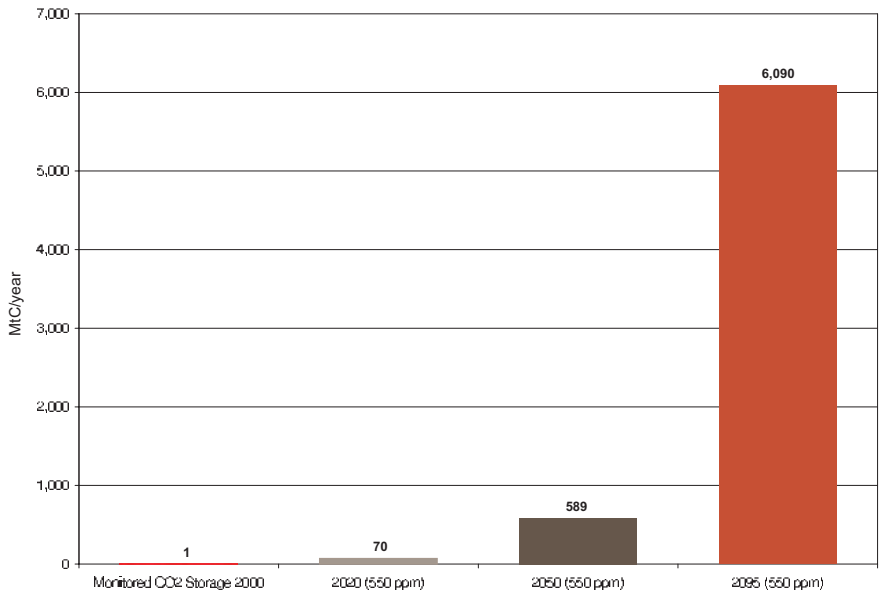
5. **Realizing the potential of energy technologies and technology systems presents challenges in expanding the scale of deployment at every time and spatial scale ranging from the next few years to the entire century.**

- 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.

APPENDIX 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.

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.

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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