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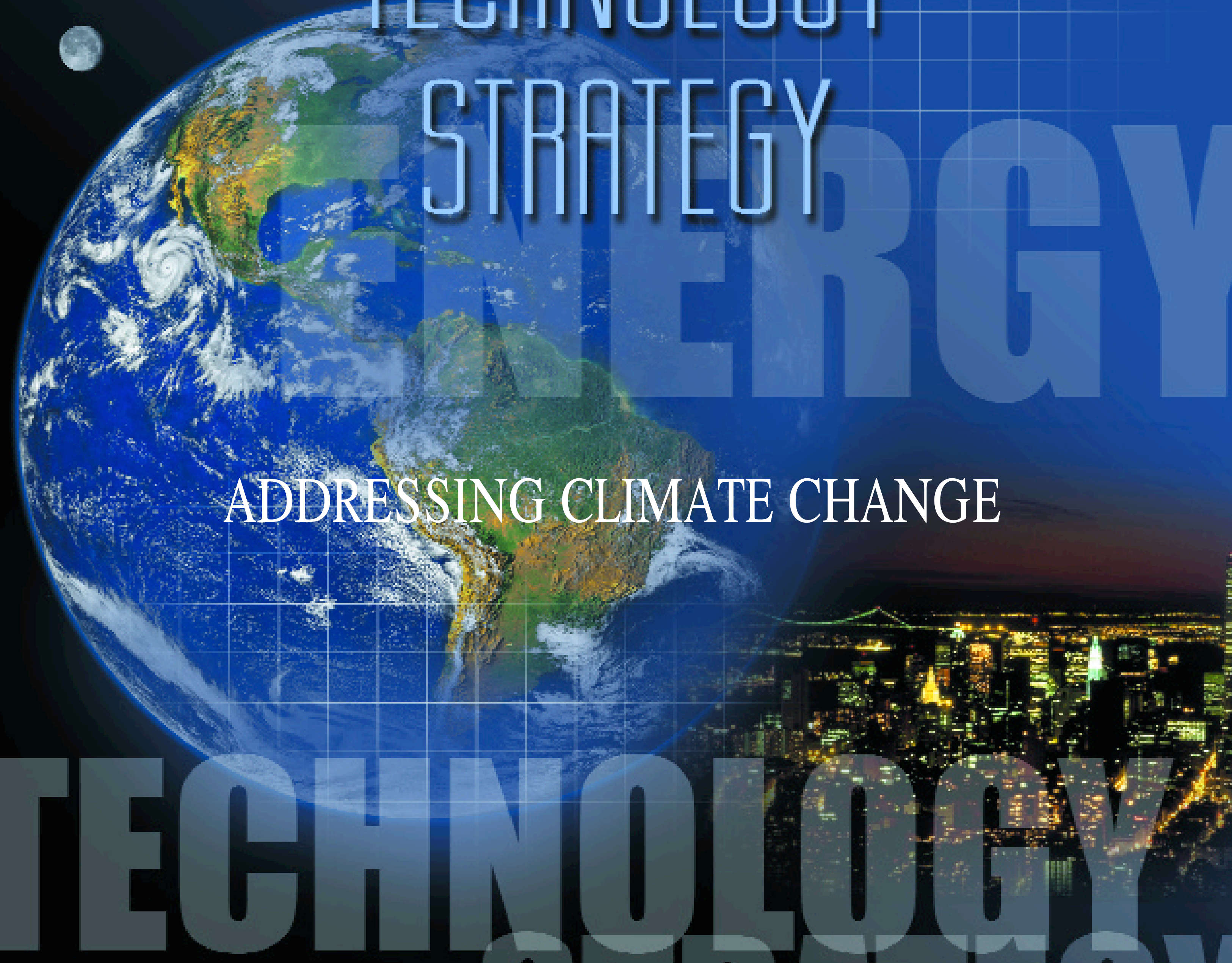
# GLOBAL ENERGY TECHNOLOGY STRATEGY



## ADDRESSING CLIMATE CHANGE

Initial Findings from
an International Public-Private Collaboration

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In 1998, Battelle, together with EPRI, established the ***Global Energy Technology Strategy Program*** with the aim of assessing the role that technology can play in addressing the long-term risks of climate change. Led by a core group of Battelle scientists, the program benefits from analyses and insights provided by a network of partner institutions around the world. The process is guided by an international steering group representing diverse perspectives and is funded by government agencies, research institutions, and private industry. This document was reviewed by the Steering Group and was principally drafted by Jae Edmonds, Tom Wilson, and Richard Rosenzweig with substantive contributions from Richard Benedick, Elizabeth L. Malone, John F. Clarke, James J. Dooley, and Son H. Kim. The authors appreciate the support of Chet Cooper and Bill Pennell. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring or participating institutions.

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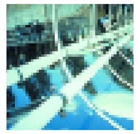
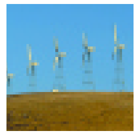
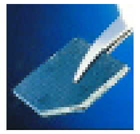
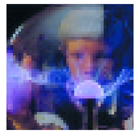
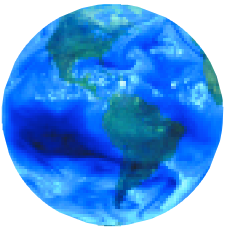










# CHAPTER 1

# Executive Summary

Global climate change is one of the most complex environmental, energy, economic, and political issues confronting the international community. The impacts of climate change are likely to vary considerably by geographic region and occur over a time scale of decades to centuries. The actions needed to manage the risks ultimately require substantial long-term commitments to technological change on the part of societies worldwide.

## The Challenge

The Earth's climate is governed primarily by complex interactions among the sun, oceans, and atmosphere. The increased concentration of heat-trapping "greenhouse gases" in the atmosphere has led to concerns that human activities could warm the Earth and fundamentally change the natural processes controlling climate.

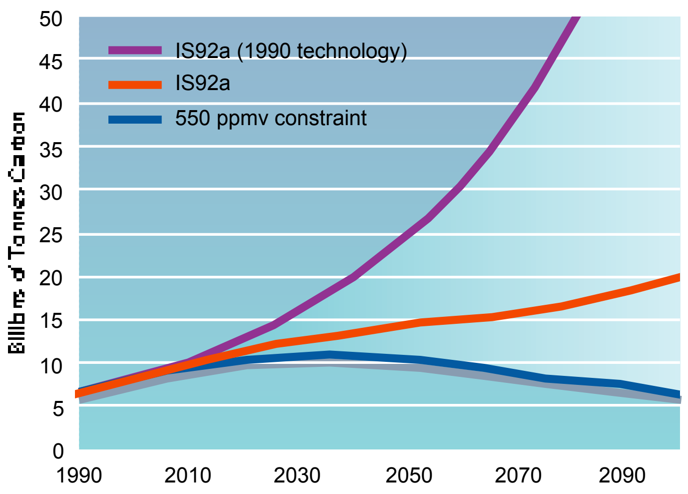
This report focuses on carbon dioxide, the greenhouse gas contributing the majority of the projected human influence on climate. Carbon dioxide emissions can affect the atmosphere for hundreds of years. Some of the carbon dioxide emitted in 1800 is still in the atmosphere—and today's emissions will continue to influence climate in 2100. The total concentration of carbon dioxide in the atmosphere at any given time is much more important in determining climate than are emissions in any single year. Limiting the human impact on the climate system therefore requires that atmospheric concentrations be stabilized.

Recognizing this fact, more than 180 countries ratified the 1992 United Nations Framework Convention on Climate Change (FCCC), and it has entered into force under international law. The *ultimate objective* of this treaty is to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." (Article 2)

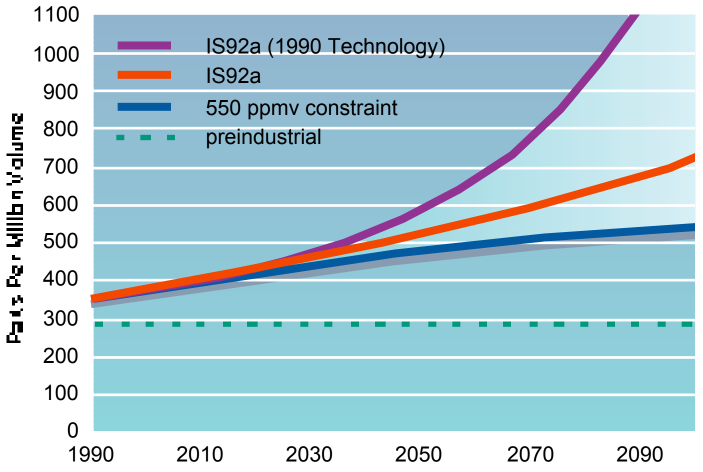
The objective of the FCCC—stabilizing the concentrations of carbon dioxide and other greenhouse gases—is not the same as stabilizing emissions. Because emissions accumulate in the atmosphere, the concentration of carbon dioxide will continue to rise for several hundred years even if emissions are held at current levels or slightly reduced.

The FCCC process has not yet specified a particular target concentration. But in order to stabilize concentrations at any level ranging from 450 parts per million to 750 parts per million, very large reductions of worldwide emissions (from emissions that might be anticipated were present trends to continue) would be required during the course of the present century.

**The Future With and Without Technological Change**



**Carbon Emissions**



**Carbon Dioxide Concentrations**

***The middle curve in the first chart depicts the carbon dioxide emissions associated with the Intergovernmental Panel on Climate Change (IPCC) central scenario, denoted IS92a, and the middle curve in the second chart represents the concentrations in the atmosphere that result from these emissions. This IPCC “business-as-usual” scenario incorporates significant technological advances. In contrast, while the top curves assumes the same population and economic growth as IS92a, they hold energy technology constant at its 1990 level. The difference between the upper and middle curves thus illustrates the technological improvement needed merely to achieve the IS92a emissions path with its corresponding impact on concentrations. The lower curves depict an emissions path and its corresponding concentration path consistent with a 550 parts per million volume (ppmv) concentration ceiling. The dotted line on the concentrations chart indicates the pre-industrial level of carbon dioxide concentrations (i.e., a level virtually unaffected by human activities).***

## Technology is Critical

Energy is central to the climate issue. Energy use appears to be the primary contributor to the global increase in carbon dioxide concentrations. Increasing world population, together with the universal desire for economic development, will lead to growing demand for the products and services that the energy system provides. The future evolution of that system—dominated today by coal, oil, and gas—is the key determinant of the magnitude of future human influence on the climate.

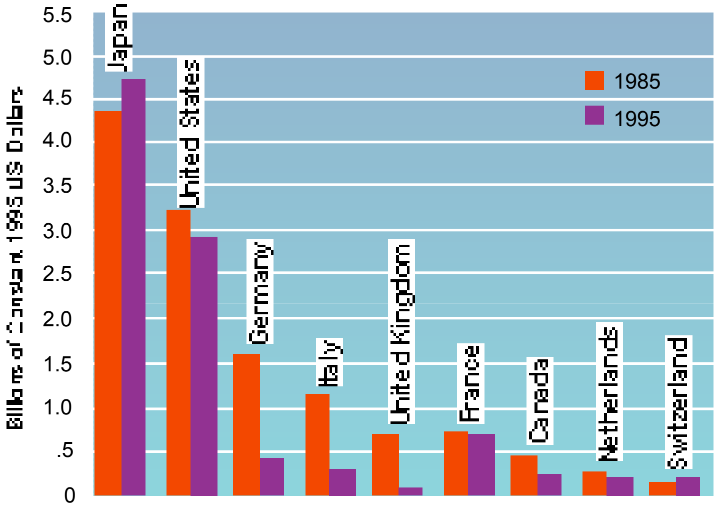
Managing the risks of climate change will require a transformation in the production and consumption of energy. Technology is critical to such a transformation. Improved technology can both reduce the amount of energy needed to produce a unit of economic output and lower the carbon emissions per unit of energy used. Successful development and deployment of new and improved technologies can significantly reduce the cost of achieving any concentration target.

Recent trends in public and private spending on energy research and development suggest that the role of technology in addressing climate change may not be fully understood. Although public investment in energy R&D has increased slightly in Japan, it has declined somewhat in the United States and dramatically in Europe, where reductions of 70 percent or more since the 1980s are the norm. Moreover, less than 3 percent of this investment is directed at a few technologies that, although not currently available commercially at an appreciable level, have the potential to lower the costs of stabilization significantly.

## Energy Technology Strategy

Fundamental changes in the energy system are required to stabilize concentrations of greenhouse gases in the atmosphere.

**Energy R&D Funding is Declining**



***Total public funding of energy research in the OECD is falling. Although Japan's outlays increased slightly, US spending declined and leading European nations reduced their funding dramatically.***

Incremental improvements in technology help, but will not by themselves lead to stabilization.

A technology strategy is an essential complement to national and international policies aimed at limiting emissions, enhancing adaptation, and improving scientific understanding. A technology strategy will provide value by reducing costs under a wide range of possible futures, which is essential given the uncertainties in the science, policies, technologies, and energy resources. The lack of a technology strategy would greatly increase the difficulties of addressing the issue of climate change successfully.

The findings and recommendations of the Global Energy Technology Strategy Program, listed below, represent an initial attempt at delineating the elements that will be needed to guide the development of a technology strategy to address climate change.

# Key Findings

## Stabilizing concentrations of greenhouse gases in the atmosphere requires fundamental change in the energy system.

***Energy is central to the climate change issue.*** Carbon dioxide emissions from the production and consumption of fossil fuels are the largest contributor to human emissions of greenhouse gases. Fossil fuel resources are abundant, and, if used in conjunction with present energy technology, have the potential to increase the concentrations of greenhouse gases in the atmosphere substantially.

***If present trends continue, carbon dioxide emissions from energy will continue to grow.*** The influences of future population growth and economic development on the demand for energy services are likely to exceed currently projected improvements in energy intensity and the ongoing transition to less carbon-intensive fuels. However, trends are not destiny—a global technology strategy could help change the present course.

***In order to stabilize concentrations of greenhouse gases in the atmosphere, global carbon emissions must peak during the 21st century and then decline indefinitely.*** This can occur only if lower carbon-emitting technologies are deployed worldwide.

## Technology breakthroughs are essential both to stabilize greenhouse gas concentrations and to control costs.

***Although incremental technology improvements are essential, they will not lead to stabilization.*** Even with significant improvements in the performance of existing commercial technologies, the concentration of carbon dioxide in the atmosphere would grow to more than 2.5 times pre-industrial levels by 2100.

***Technology breakthroughs can reduce the cost of greenhouse gas stabilization dramatically.*** Technological advances can reduce the annual cost of stabilizing atmospheric concentrations of greenhouse gases by at least 1-2 percent of global world product. The savings will depend upon the concentration target and the level of technology improvement.

***It is time to get started.*** The energy system is capital-intensive, and the development and deployment of new technologies can take decades. Given the lead-time necessary to develop and deploy new technologies with their associated systems and infrastructure, we must begin the process without delay.

## A portfolio of technologies is necessary to manage the risks of climate change and to respond to evolving conditions.

***A diversified portfolio accommodates future uncertainties.*** Changing scientific knowledge and economic conditions, combined with uncertainty in the resource base, require a diversified initial portfolio of technology investments. Portfolio investment priorities will evolve over time as these uncertainties are better understood.

***A broad portfolio can control costs.*** A portfolio encompassing a broad suite of technologies can lower the costs of stabilization significantly. However, the public and private sectors cannot fund every idea. Technology investment priorities must be established to reflect available funding.

***A broad portfolio can meet the differing needs of key regions.*** Countries will need and employ different technologies based on their geography, indigenous resources, and economic, social, and political systems.

***A flexible portfolio can accommodate alternative policy responses to the climate issue.*** A technology portfolio complements a wide range of possible national and international policies, including trading, taxes, and other policies and measures.

***A broad portfolio also can reflect the diversity of the energy system.*** Technologies are needed to improve the efficiency of energy use, develop non-carbon energy sources, and limit the free venting of carbon from the fossil energy that will continue to be burned.

## Current investments in energy research and development are inadequate.

***Energy research and development outlays are declining.*** Both public and private sector investments in energy research and development have declined significantly since the 1980s.

***Energy research and development expenditures are unfocused and poorly coordinated.*** Neither public nor private sector investments are adequately focused on the technologies that could be critical for stabilizing concentrations in the long term. Among the few governments with national energy research and development programs, investments are poorly coordinated and fail to take advantage of possibilities for joint, complementary, or specialized research.

***Terrestrial sequestration, hydrogen, and carbon capture, use, and storage technologies*** potentially play an important role in stabilizing concentrations, but are currently funded at minimal levels.

# Recommendations

### Emissions limitations and controlling costs complement a technology strategy.

Emissions limits are needed to stabilize concentrations. Without such limits, individual nations have little incentive to reduce greenhouse gas emissions. It is unlikely that the required technologies to achieve stabilization will be developed and deployed if there is not any value placed on developing such technologies.

Controlling the costs of stabilization is necessary. The costs of stabilizing concentrations of greenhouse gases are uncertain and are distributed unevenly across generations, nations, and sectors of the economy. Better definition and control of these costs is critical to achieving societal consensus to take action.

### Increase global investments in energy research and development.

Increase investment in energy research and development to improve the performance of existing technologies and to develop the next generation of technologies that are required to stabilize greenhouse gas concentrations.

Develop dedicated long-term funding sources for energy research and development to support the necessary technology transformation.

Direct investments to specific technologies that have significant potential to substantially reduce greenhouse gas emissions over the long term.

Build broad-based public support by communicating the climate and ancillary benefits of energy research and development.

### Improve the implementation and performance of energy research and development.

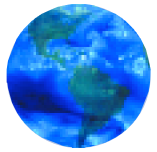
Incorporate climate change when revisiting current energy research and development priorities.

Better coordinate the roles of the public and private sectors in the research and development process to reflect their specific strengths.

Fund all stages of the innovation process from basic research to market deployment of the most promising technologies.

Establish long-term goals and near-term milestones for technological performance to drive progress and to maximize returns on technology investments.

Design flexible research and development programs to allow for the shifting of resources to accommodate new knowledge and conditions, particularly when sufficient technological progress is not being achieved.



### Reflect the international nature of the research challenge.

Develop and coordinate international and national energy technology research and development strategies to take advantage of national scientific strengths and regional needs.

Provide assistance to key developing countries to build their technical and institutional capacities for implementing energy research and development programs effectively and for deploying advanced technologies.

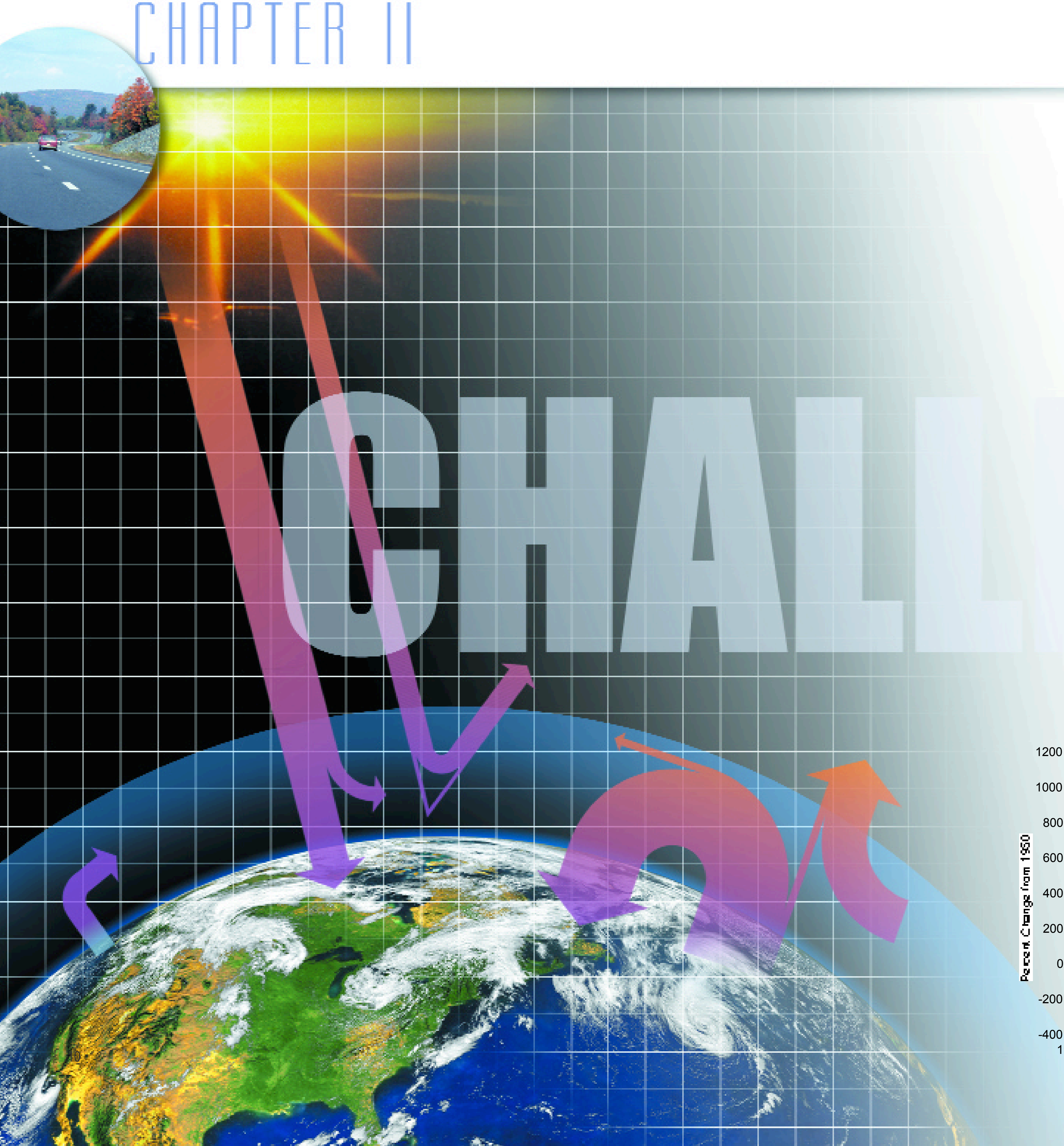
## Next Steps

These findings and recommendations demonstrate the importance of technology in addressing climate change and provide general principles for moving forward. These results will be actively communicated to all global climate change stakeholders, and particularly those involved in the international discussions. However, they are only a beginning.

Over the next three years, the Global Energy Technology Strategy Program will explore in more depth some of the key issues and principles outlined here. In particular, the program will examine approaches for improving international collaboration in technology research and deployment, analyze in more detail key carbon-free resources and technologies, and expand the research to address non-carbon dioxide greenhouse gases and additional options for enhancing carbon sinks. The program also will conduct technical analyses and communications efforts to help stakeholders and decision makers better understand principles for implementing an energy technology strategy for climate change.

Through periodic reports and the existing website (http://gtsp.battelle.org), the program will continue to communicate insights gained through collaborative research on the technological and policy pathways that governments, businesses, institutions, and individuals can take to minimize the risks of human interference with the climate system.

# CHAPTER II



# The Challenge

Stabilizing atmospheric concentrations of carbon dioxide and other greenhouse gases ultimately requires the reduction of global emissions to levels that are significantly below current emissions. Global population and economic growth, and the consequent increases in demand for the services that energy provides, suggest that fundamental changes in the energy system will be required to achieve the reductions in emissions needed to achieve stabilization.

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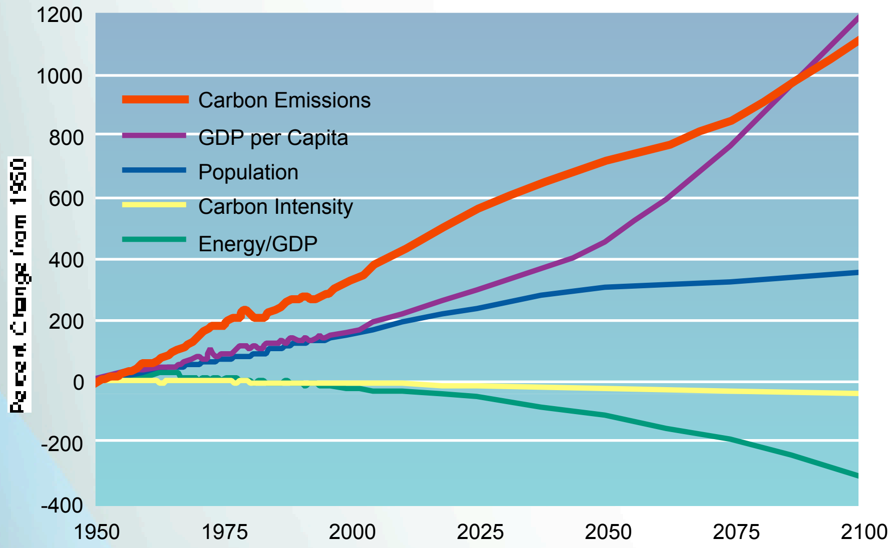
The Earth's climate is governed primarily by complex interactions among the sun, oceans, and atmosphere. To clarify why sustained research to develop new technologies is essential to manage the risks of climate change, let us begin by considering the basic principles at work, starting with the greenhouse effect.

Most 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. Rather than passing through the atmosphere to space, most of that heat is absorbed by gases in the atmosphere and redirected back to the surface where it further warms the Earth. Various constituents of the atmosphere—water vapor, carbon dioxide, methane, nitrous oxide, and minor trace gases—retain heat and create a natural greenhouse effect.

The heat-trapping property of these greenhouse gases is well established, as is the role of human activities in the buildup of

**Factors Driving Emissions**



*Changes in population, per capita income, energy intensity, and carbon dioxide intensity can be totaled up to calculate changes in emissions. Since 1950, population and per capita income increases have exceeded decreases in energy and carbon intensity, leading to an increase in carbon dioxide emissions. Each of these trends is projected to continue through the 21st century under the International Panel on Climate Change's (IPCC) IS92a scenario, resulting in significantly increased emissions in 2100.*

these gases. Uncertainty remains about when and how significantly we might be affected by the resulting intensified greenhouse effect. However, global climate change poses significant risks that we need to be prepared to manage.

## Framework Convention on Climate Change

Concerns about possible changes in climate induced by a rapid increase in greenhouse gases from human activities led nations worldwide to sign the United Nations Framework Convention on Climate Change (FCCC). The Convention was drafted for signature at the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992. Since then, 186 nations—including the United States, Japan, most of Western Europe, the Russian Federation, and many of the rest of the nations of the world—have ratified the Convention. It entered into force under international law on 21 March 1994.

The FCCC establishes both a short-term aim and a long-term objective. In the short term, the Convention directs developed countries to take actions aimed at returning *emissions* of greenhouse gases to their 1990 levels by the year 2000. The ultimate objective, contained in Article 2 of the FCCC, is that the *concentrations* of greenhouse gases in the atmosphere should be stabilized "at a level that would prevent dangerous anthropogenic interference with the climate system." The stabilization is to be achieved "within a timeframe 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, the Parties to the Convention agreed, "that polices and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." Within this Framework, they agreed to adopt national policies and take corresponding measures to mitigate (moderate or lessen) climate change. The mitigation measures involve limiting the Parties' anthropogenic emissions of greenhouse gases and enhancing carbon sinks worldwide.

### Stabilization of GHG Concentrations—At What Level?

Science has not determined the level of concentration of greenhouse gases (GHG) in the atmosphere that would have to be avoided to "prevent dangerous anthropogenic interference with the climate system," as mandated by the FCCC. Accordingly, we have performed the analyses presented in this report for levels ranging from 350 ppmv (parts per million volume) to 750 ppmv.

Although the numerical results presented in the report's graphics vary depending on the concentration level analyzed, the qualitative insights hold across the various targets. To simplify the presentation, we sometimes present results for only one concentration target, 550 ppmv, rather than for a range of levels. The choice of 550 ppmv was not based on any evaluation of the criterion laid out by the FCCC.

## The Role of Carbon Dioxide and Energy Use

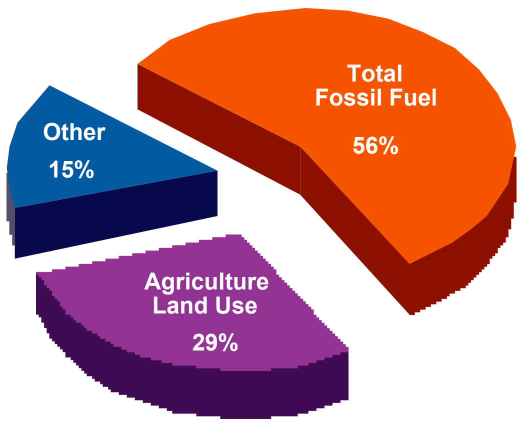
Carbon dioxide emissions comprise the majority of humanity's annual contribution to greenhouse gas concentrations. The majority of these carbon emissions result from energy use. Although all greenhouse gases are important, this document focuses on efforts to control carbon dioxide emissions. The other gases will be the subject of future research efforts by the Global Energy Technology Strategy Program.

Carbon dioxide has been accumulating in the atmosphere at an accelerating rate since the start of the Industrial Revolution. Increases in carbon emissions from energy use have resulted in corresponding increases in concentrations. Stabilizing the concentration of carbon dioxide in the atmosphere requires reversing the current trend of increasing emissions.

## Concentration Ceilings and Cumulative Emissions

The relationship between carbon emissions and concentrations is governed by the global exchange of carbon among the oceans, vegetation, and the atmosphere. One relatively straightforward way to relate emissions and

**Distribution of Global Greenhouse Gas Emissions in 1989**



***The majority of greenhouse gas emissions are associated with energy production, transformation, distribution, and end use. The remainder are produced by agriculture, land-use changes (including deforestation), and other sources including industrial processes that produce specialty chemicals such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride.***

### Tonnes and Joules

*Most people think of weight in terms of kilograms or pounds, and consider quantities of energy in terms of litres or gallons of gasoline, barrels of oil, or kilowatt-hours of electricity. Because global energy use dwarfs personal energy use, less widely known measures are often used. In this document, we consistently present energy in joules, megajoules (million joules or in mathematic notation, 106 joules), or exajoules (1 018 joules). Weights are presented in tonnes (metric tons).*

1 tonne = 1 metric ton = 1000 kilograms = 2204 pounds

1 exajoule = $10^{18}$ joules = 163 million barrels of oil equivalent

concentrations is to calculate the cumulative emissions that would be allowable (over the next three centuries) to achieve each concentration target. In other words, each concentration target has a corresponding cumulative emissions budget. For a 450-ppmv ceiling, the cumulative budget is approximately 1,225 billion tonnes of carbon. For a 550-ppmv ceiling, the budget is about 1,800 billion tonnes, and for a 650-ppmv ceiling, it is approximately 2,350 billion tonnes.

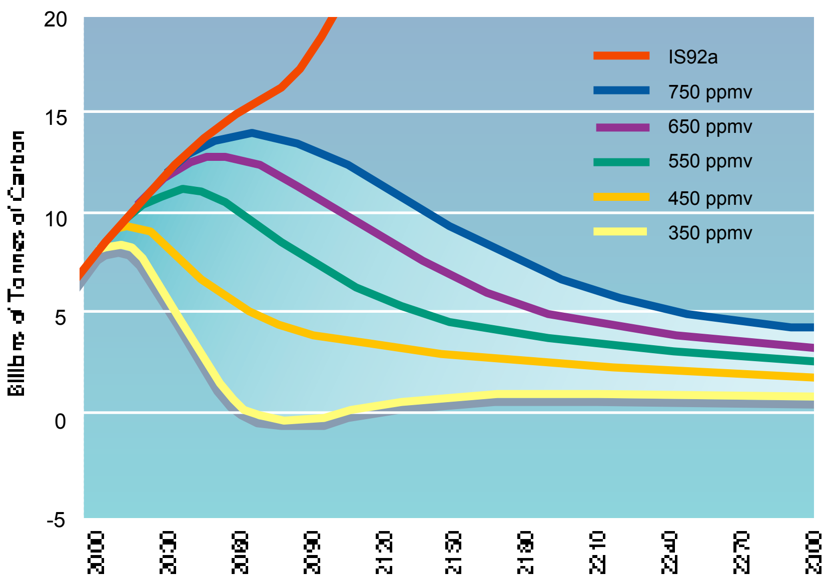
The concept of a cumulative emissions budget yields two insights. First, cumulative emissions matter much more than the level of emissions in any single year. A second key insight relates to the magnitude of the challenge that we face in limiting concentrations. Even if annual global emissions of carbon dioxide were to remain indefinitely at their 1990 level of approximately 7.5 billion tonnes, the concentration of carbon in the atmosphere would continue to increase for centuries.

## Factors Driving Carbon Emissions

Understanding the key drivers of historic and future carbon emissions is critical to developing policies to control emissions. According to an equation developed by Yoichi Kaya, director of the Research Institute of Innovative Technology for the Earth and a member of the Global Energy Technology Strategy Program's Steering Group, the global increase in carbon dioxide emissions since the Industrial Revolution is a byproduct of four interrelated factors: (1) population growth, (2) per capita economic development, (3) reliance on increased energy use to fuel this economic growth, and (4) the dominance of fossil fuels in providing this energy. Expressing this concept as an equation yields the following:

Population growth rate
\+ per capita economic growth rate
\+ energy intensity growth rate
\+ carbon intensity growth rate
= growth rate in carbon dioxide
($CO_2$) emissions

### Emissions Trajectories Consistent With Various Atmospheric $CO_2$ Concentration Ceilings



*Any concentration ceiling can be attained through an unlimited set of possible global emission paths. The paths pictured here are ones designed to limit the economic impact of achieving the target concentrations—thereby achieving the twin goals of the FCCC of stabilization at the lowest economic cost. For concentrations 350 ppmv and above, global emissions rise for a period of time, peak, and then begin a long decline.*

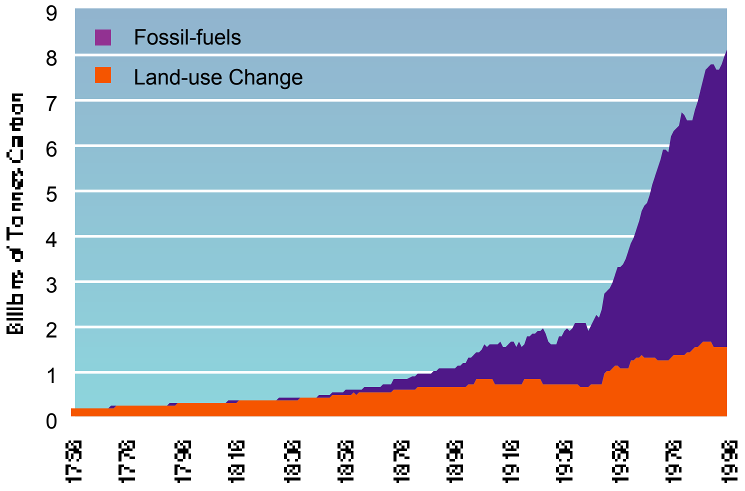
Energy intensity refers to the amount of energy needed to produce a unit of economic output, and carbon intensity means the amount of carbon released for each unit of energy produced.

Using this equation, it is possible to project future emissions based on projections of the four factors. For example, if population were to double over the next century and the other three factors—economic growth per capita, energy use per dollar of income, and the role of fossil fuels in supplying energy services—did not change, carbon dioxide emissions would double.

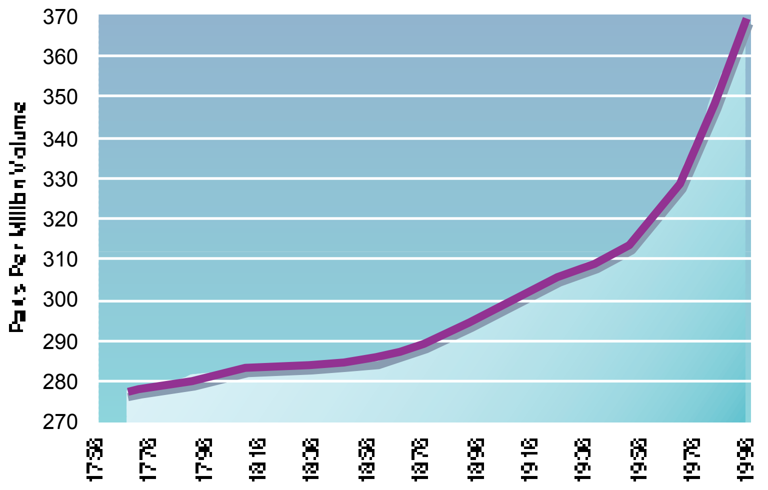
Most scenarios of the future suggest that the expected increases in population and economic growth will outweigh the continued decreases in energy and carbon intensities. For example, a plausible scenario would be a doubling of population over the next century combined with continued annual economic growth rate of 1.8 percent in per capita income, resulting in a global economy in 2100 that is 12 times the current size. If the other two factors did not change, then a 12-fold increase in carbon dioxide emissions would occur during the 21$^{st}$ century.

With these population and economic growth rates, the only way to stabilize concentrations of greenhouse gases at any level that is currently under serious discussion would be to reduce the carbon emissions per dollar of economic output to less than one-twelfth of their current value, more than a 92 percent reduction. Part of this reduction would be accomplished through improvements in the amount of energy used to create a dollar of economic output (energy intensity), and part through dramatically reducing carbon emissions from the energy sector (carbon intensity). In other words, population and economic growth will lead to rising emissions unless a fundamental technological change occurs.

### Global Carbon Emissions



### Carbon Dioxide Concentrations



***Increases in global carbon emissions over the past 150 years, driven primarily by increased use of fossil fuels for energy, have led to consequent increases in the concentration of carbon dioxide in the atmosphere.***

## Increasing Population

Global population continues to increase, although the rate of growth is declining. In 1999 it reached 6 billion people. IPCC estimates developed in the early 1990s suggested that global population could increase to almost 18 billion by 2100. More recent estimates are somewhat more modest, but follow the same basic patterns. For example, the most recent United Nations estimates for 2050 range from a low of 7.3 billion to a high of 10.7 billion, with 8.9 billion currently considered as most likely. By 2100 the global population could climb to 15 billion people, or it could begin a decline by mid-century that would eventually bring it back close to present levels.

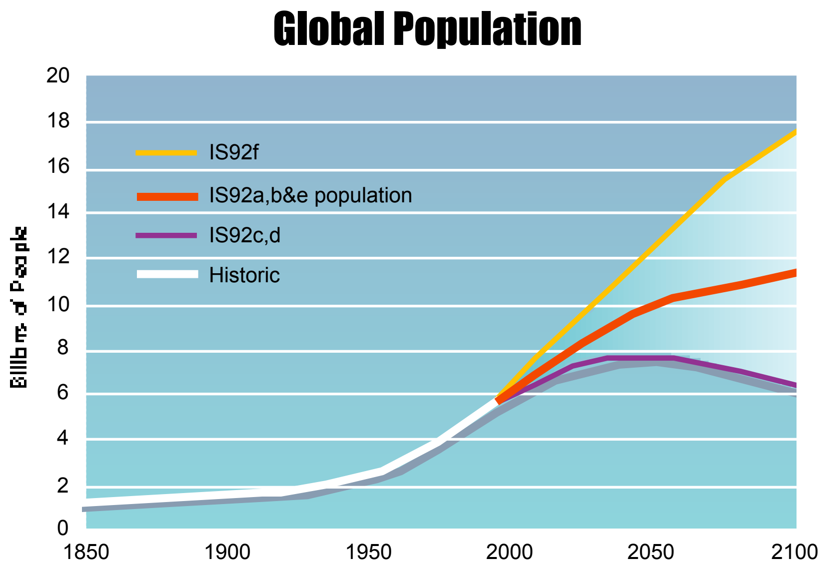
### Uncertainties in Future Scenarios

Forecasting changes in population, economic growth, and energy technology over the course of a century is fraught with uncertainties. The Intergovernmental Panel on Climate Change (IPCC), established by the United Nations Environment Programme and the World Meteorological Organization in 1988, developed an extensive set of future scenarios for use in its Second and Third Assessment reports – IS92 and SRES scenarios respectively. We used IS92 because the SRES was available only recently. Even so, the ranges of the IS92 and SRES scenarios are similar. And, regardless, all of the scenarios envision substantial economic growth over the next century and consequently require dramatic reductions in carbon per unit of economic output in order to stabilize concentrations of carbon dioxide.

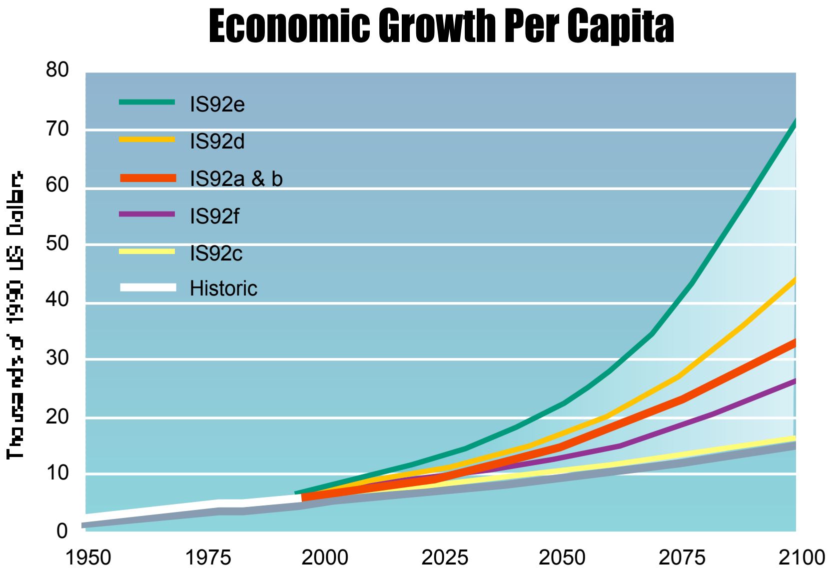
In some developed countries—France, Germany, and Japan, for example—populations are already in decline. The population of the United States continues to grow, but immigration is an important factor contributing to that growth. Certainly, rates of growth are in decline across a broad spectrum of nations. But total population, driven by growth in developing countries, continues to rise.

## Expanding Economic Growth

The world economy continues to grow at a faster rate than population. Since the late 1940s, national economic growth has been measured in terms of “gross national product”—the total value of goods and services produced by residents of a nation during a year. Gross world product is calculated by summing the gross national products of individual nations, adjusting for differences in currencies. Today’s world economy is more than five times larger than it was in 1950, and per capita income has grown at 2.7 percent annually during that period.



***Global population has grown consistently over the past 150 years. Most scenarios predict continued, but slower, growth over the next 100 years.***



***The global economy has historically grown much more rapidly than global population. Most scenarios project continued growth, slowing as more developing countries mature.***

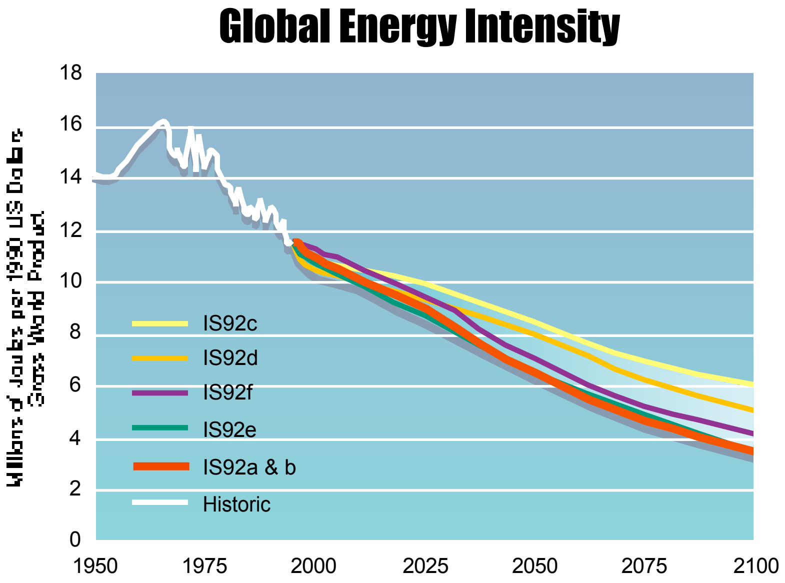
Like population growth, economic growth is slowing in developed countries, which are the nations that provided much of the growth over the last 50 years. Developing countries such as China and India continue to grow rapidly, both in absolute terms and on a per capita basis. Most projections for the next century suggest a slowing in the growth of the world economy. But even if the growth rate per capita were slowed to 1.8 percent annually (two-thirds of the rate during the past 50 years), it would still result in a six-fold increase in per capita goods and services over the next century.

## Declining Energy Intensity

Commercial energy intensity typically increases for a period of time and then declines as a country develops. The initial increase in energy use per dollar of real goods and services produced is caused by the shift from nonmarketed energy such as wood, dung, and straw to commercial fuels, as well as the shift from agricultural to manufacturing economies. In later development stages, the value of new goods and services grows faster than the energy needed to provide them. The cause is a shift away from high energy-intensive products such as steel toward less energy-intensive goods and services.

For the United States, the peak in energy intensity occurred around 1920. Since then, US energy intensity has declined, sometimes dramatically over the last three decades. For example, from 1973 to 1986, US economic growth in excess of 40 percent was accompanied by no increase in energy use.

Global energy intensity is declining, with the reductions in the developed countries exceeding the increases in some developing coun-



*Global energy intensity has declined for the past 50 years, with decreases in developed countries outweighing increases in developing countries as they make the transition to commercial fuels. Most scenarios suggest that this factor will continue to decline, perhaps substantially.*

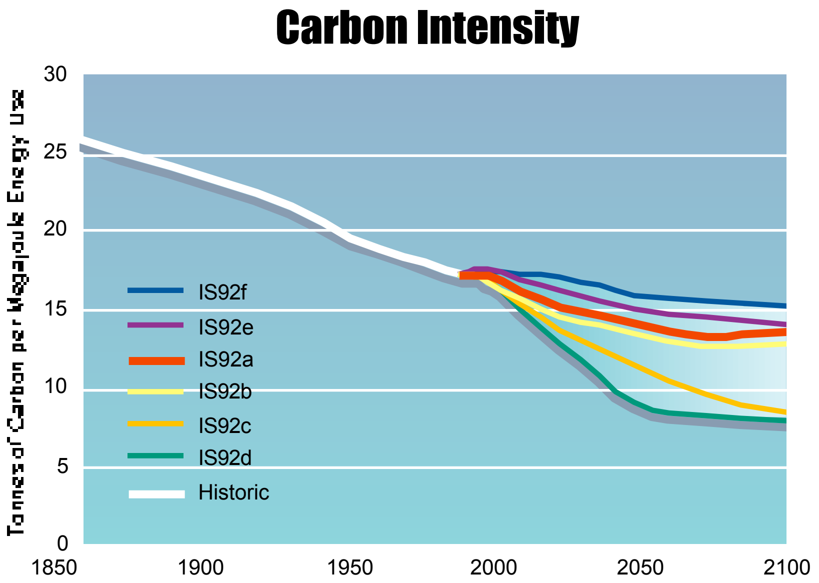
tries. It is expected to continue to decline in the future as the energy intensities of more developing countries begin to decrease.

## Declining Carbon Intensity

Fossil fuels differ in the amount of carbon that is released for each unit of energy produced. Wood is more carbon-intensive than coal. Coal is more carbon-intensive than oil, and natural gas has the lowest carbon intensity of all of the fossil fuels. Technologies such as nuclear fission, nuclear fusion, wind, solar, and hydropower generate no direct releases of carbon.

The average carbon intensity of all fuels used to produce energy has declined over the past century. In 1860, the average was about the same as wood. By 1920 it had fallen to about the rate associated with coal. By 1990, the average rate had declined to about the same level as oil. The higher carbon intensity of the coal used in 1990 was balanced by the lower carbon intensity of the natural gas, nuclear, and renewable energy that were increasingly coming into use.

Carbon intensity may continue to decline in the future. If natural gas turns out to be abundant and renewable energy technologies continue to improve, the average intensity could decline still further. On the other hand, if oil and gas resources ultimately are restricted to conventional forms, then coal and its synthetic derivatives may become increasingly important, and the decline in average carbon intensity could reverse.

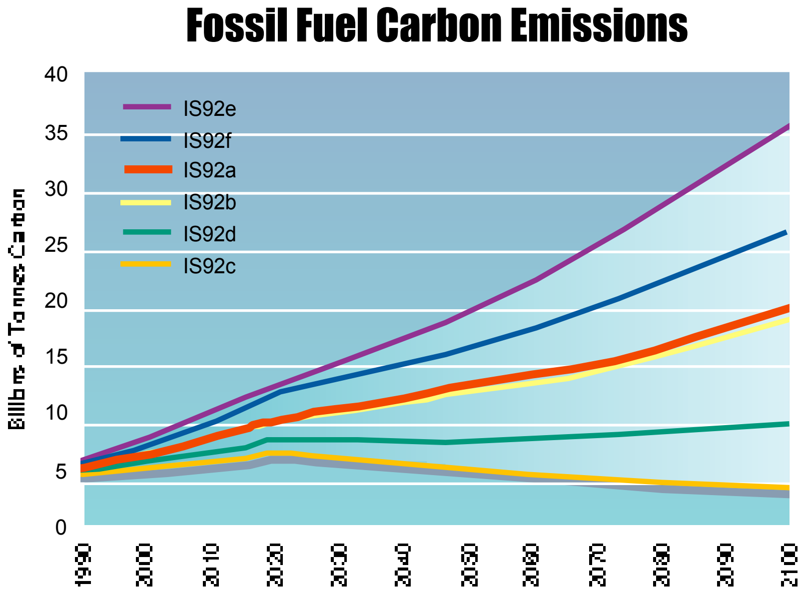


*Carbon intensity fell over the past 150 years as society switched from wood to coal to oil and gas. The introduction of nuclear and large-scale hydroelectric power has contributed significantly to the reductions in intensity over the past few decades.*

## Future Carbon Emissions

Combining these four factors can provide insights into how the future might evolve in the absence of a carbon policy. The IPCC prepared such an analysis for use in its Second Assessment Report.

The IPCC scenario IS92a (the most commonly cited scenario) assumes a world population growing from 5.2 billion in 1990 to more than double that number in 2100, moderate economic growth, and no strong action to reduce carbon dioxide emissions—best known as the "business-as-usual" scenario or the "reference emissions path." This IS92a scenario shows nearly a threefold rise in total emissions during the 21st century.



*The IPCC Second Assessment Report developed a set of possible scenarios for future carbon emissions in a world without carbon policy intervention. The more recent set of Standard Reference Emissions Scenarios (SRES), developed for the Third Assessment Report, cover roughly the same range of emission futures.*

Current emission trends suggest that the emissions increases envisioned in IS92a or even in the higher emissions scenarios are plausible. However, trend is not destiny. A sustained effort to improve the performance of existing technologies and to develop and deploy new energy technologies can halt and reverse this trend, leading to lower emissions in the future. The remainder of this report describes in more depth the nature of this technological challenge and the characteristics of a technology strategy for limiting emissions.

## Changes in Geographic Diversity of Emissions

Emissions were once limited largely to the developed world. In 1900, Western Europe and North America accounted for 87 percent of the world's fossil fuel carbon dioxide emissions. In 1995, their share had fallen to 39 percent. Developing countries, on the other hand, accounted for only 1 percent of global emissions in 1900, but their share had grown to 39 percent by 1995.

As more and more countries develop economies that provide their people with material goods and services, the need for energy services will increase. The developing countries' share of global emissions will pass 50 percent and continue to grow. If fossil fuels remain abundant and reasonably priced, they are likely to remain the energy source of choice for the world's growing demand for energy.

# CHAPTER III

## Energy Today and Tomorrow

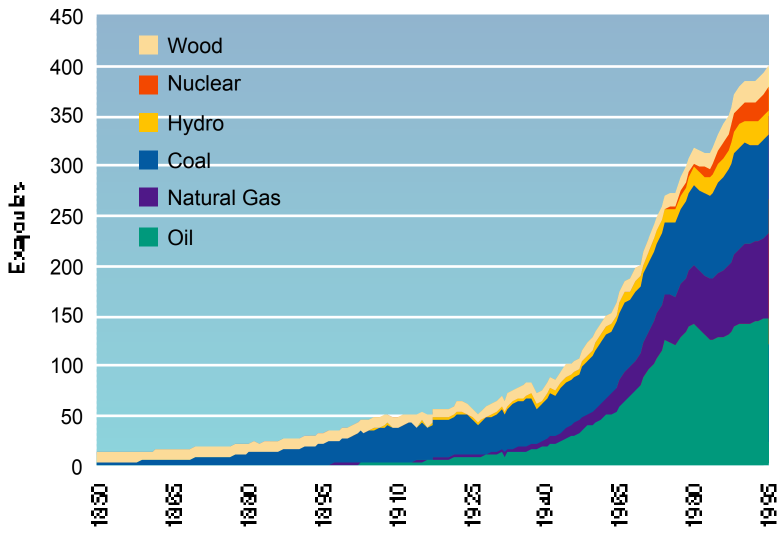
The energy system today is dominated by fossil fuels, which are abundant and relatively inexpensive. Carbon dioxide emissions resulting from the use of fossil fuels are responsible for most of the projected human influence on climate. Today, coal is the primary energy resource in the two most populous countries in the world, India and China, and is likely to fuel their future economic development. Accordingly, tomorrow's energy system also will be dominated by fossil fuels in all likelihood. Achieving fundamental change in the energy system is a slow process, requiring coordinated changes in energy supply, conversion, distribution, and end use.

Prior to 1900, most goods and services were produced with the use of energy from 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. Wood was surpassed by coal, which was predominant from the late 1800s through the late 1960s. Oil, driven primarily by the increase in demand for transportation, has been the predominant fuel since then.

During the latter half of the 20th century, large-scale hydroelectric, natural gas, and nuclear power were added to the energy mix. Renewable technologies such as solar and wind power have only recently come into use, but to date they have had a minimal impact on the overall picture.

As the production of goods and services has grown worldwide, so too has the global use of energy. In 1850, global energy use was about 9 exajoules. Since then, energy use has grown steadily to almost 400 exajoules in 1995.

**Global Energy Production and Consumption**



*Historically, the global energy system has been dominated by carbon-emitting fuels—first wood, then coal, and now oil.*

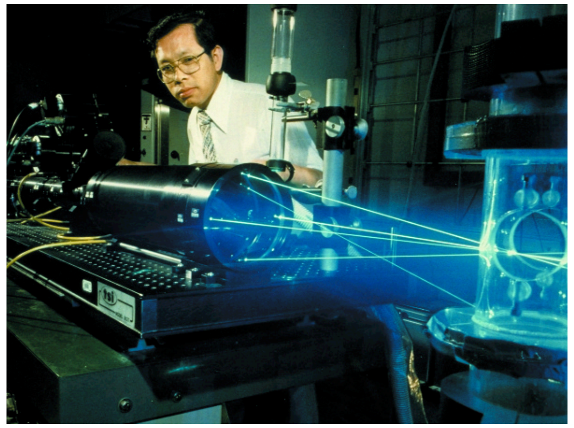
## Energy Today

Today's energy system—the supply, conversion, transport, and end-use of energy—is dominated by fossil fuels. Of the energy used in 1995 worldwide, 88 percent was supplied by fossil fuels and only a small fraction—12 percent—was provided by nonfossil energy sources such as nuclear, hydroelectric, solar, and wind power.

Although virtually all of global transportation needs are fueled by fossil energy, the electricity sector uses more diverse sources of energy. Approximately one-third of global electricity in1995 was generated using nonfossil energy.

Use of natural gas, another fossil fuel, is growing rapidly—both in direct uses and in electricity generation. Natural gas provided 19 percent of the world's energy in 1995, representing a larger percentage than all of the commercial nonfossil energy sources combined.

Countries around the world differ in the types of energy they use. This diversity in the energy mix is governed by differences in indigenous fuel resources, land area, climate, economy, and political standing vis-à-vis energy-rich neighbors. Traditionally, for example, China has been energy-independent, relying almost exclusively on its extensive coal resources to meet its internal energy requirements—although petroleum imports have begun to rise as the demand for transportation has increased. On the other hand, two of its neighbors, Korea and Japan, lack significant indigenous energy resources and import most of their energy supplies.



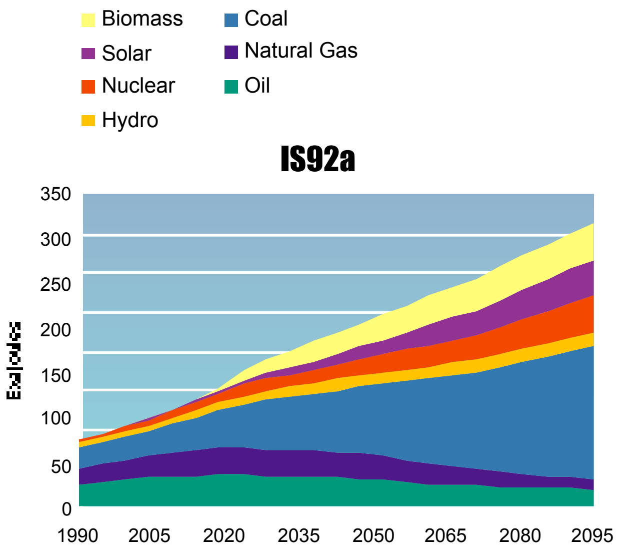
## Energy Tomorrow

Forecasting the future composition of the energy industry 100 years from now is a risky business. The only thing that is almost certain is that the future will prove different from any nontrivial predictions made today. On a regional basis, energy use will continue to be influenced by available energy resources, existing technologies, and the mix of energy services needed.

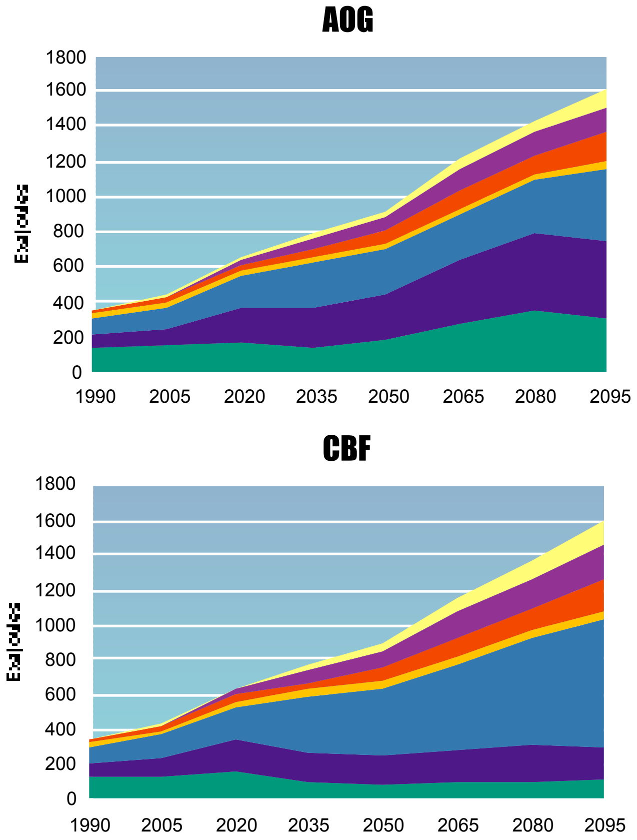
However, regional fuel choices also will be influenced by public policies, such as environmental regulations, energy subsidies in the form of low prices, and foreign investment in energy supplies, which are harder to project. Even the restructuring and privatization of electricity and natural gas markets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

To look forward a century, we consider again the four fundamental factors influencing future emissions: population growth, economic growth, energy intensity, and carbon intensity. If the past is any guide, the demand for energy services, which is a function of population growth, economic growth, and energy intensity, will increase dramatically. Given the current dominance of fossil fuels, future carbon intensity will be strongly influenced by the availability of fossil fuels over the next century and their price.

## Global Energy Use Today and Tomorrow



*Under the IS92a scenario, global energy use is projected to increase in the future. A key uncertainty that affects the evolution of this energy system is the future price and availability of oil and gas. This figure shows projected energy use under two future resource scenarios. In one plausible future, lower grades of oil and natural gas would become available at approximately current prices—the Abundant Oil and Gas (AOG) scenario. In another plausible future, liquid and gaseous fuels will have to be produced from coal and commercial biomass. In that case, which we call the Coal Bridge to the Future (CBF) scenario, the price of energy would be higher, resulting in lower overall demand.*



*Resulting fuels mixes for the two energy resource scenarios are similar for 2025, but very different for 2100. The scenarios are similar in 2025 because much of today's energy producing and using capital stock may still be operating in 2025, which limits change from the present, and because the resource constraints on oil and gas are just beginning in the CBF case. Both resource scenarios suggest major changes in the energy system over the next 100 years even in the absence of climate policies.*

## Fossil Fuel Availability

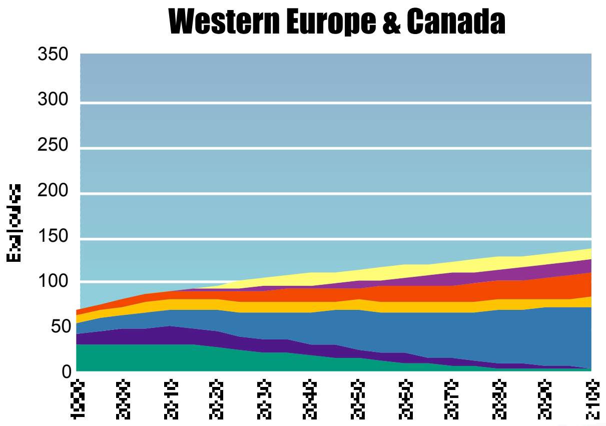
Energy resource surveys indicate that the world has more than enough fossil fuel resources to supply the energy needs of the 21st century. Coal dominates the fossil fuels that are readily available using current conventional methods of extraction.

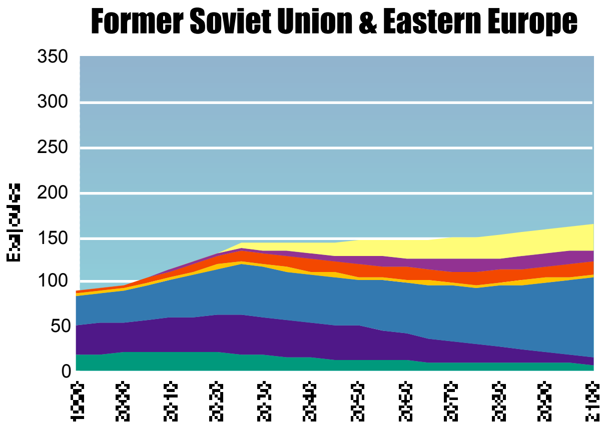
Most of the world's coal resources are located in a small number of countries. In 1998,

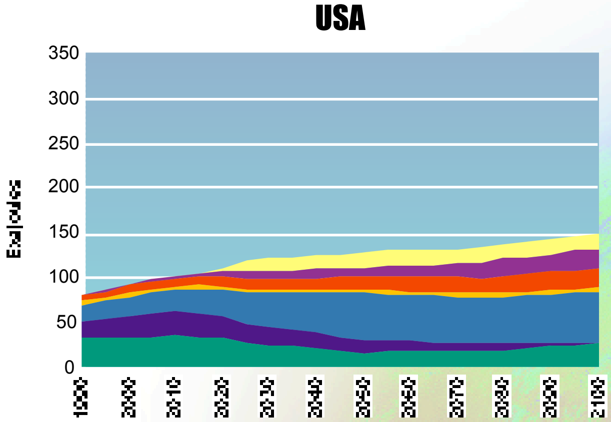
# Regional Energy Use Today and Tomorrow: Growth, Structural Change and Diversity

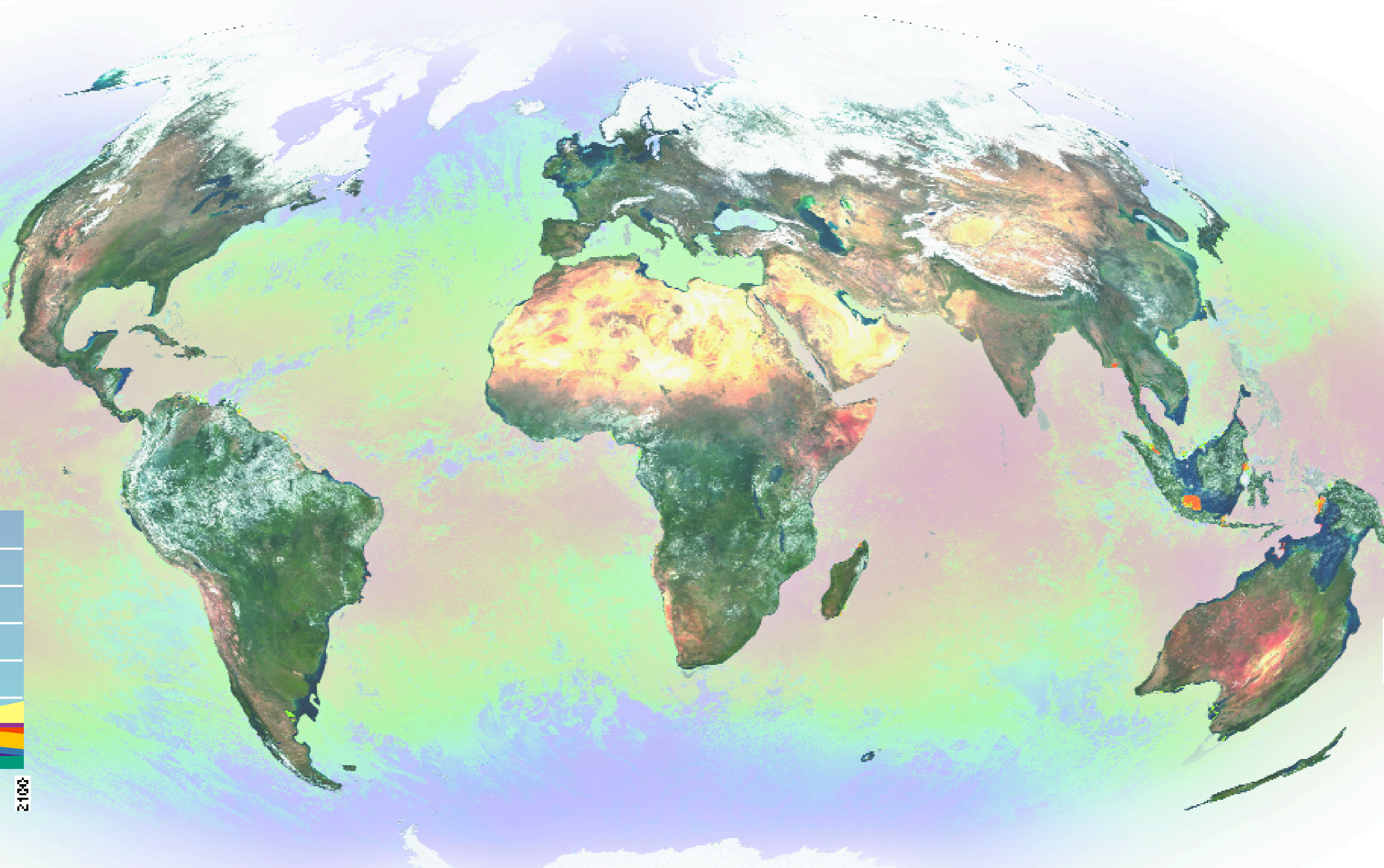
- 🟨 Biomass
- 🟪 Solar
- 🟥 Nuclear
- 🟧 Hydro
- 🟦 Coal
- 🟪 Natural Gas
- 🟩 Oil

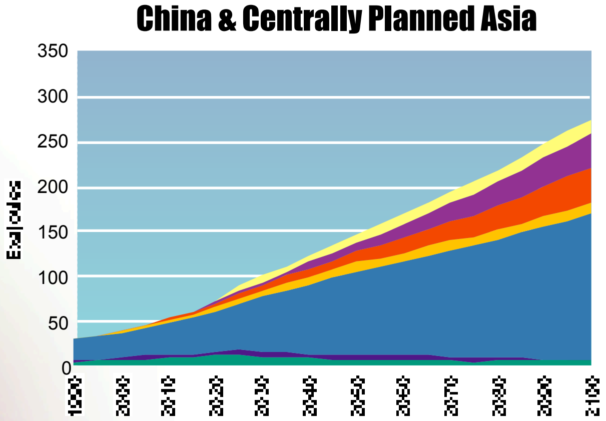
*Energy choices around the world will vary depending upon indigenous energy resources, energy and environmental policies, national security issues, and technical capacity. This graphic shows possible energy development paths for nine regions of the world for the IS92a scenario. The story overall is one of growth, fundamental fuel shifts, and significant diversity across regions.*

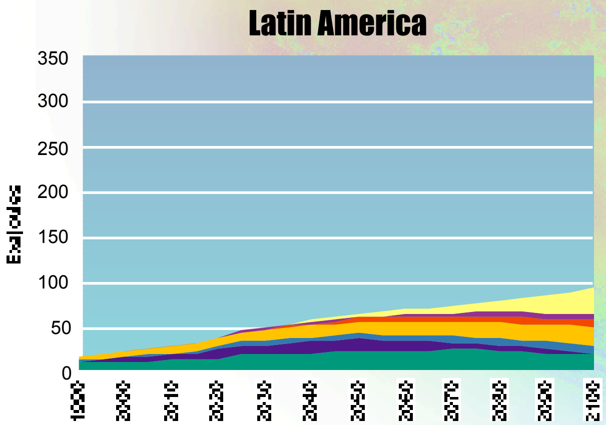

**Western Europe & Canada**

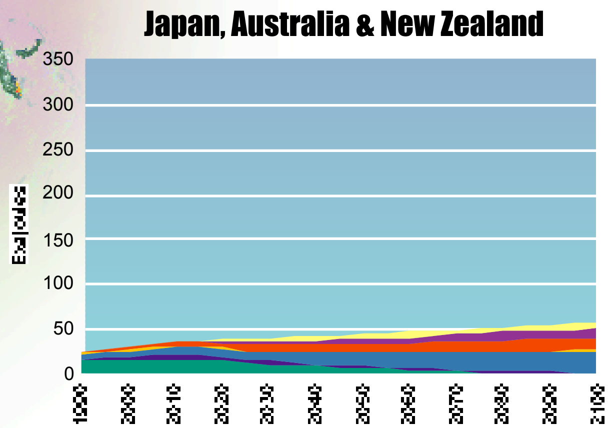

**Former Soviet Union & Eastern Europe**

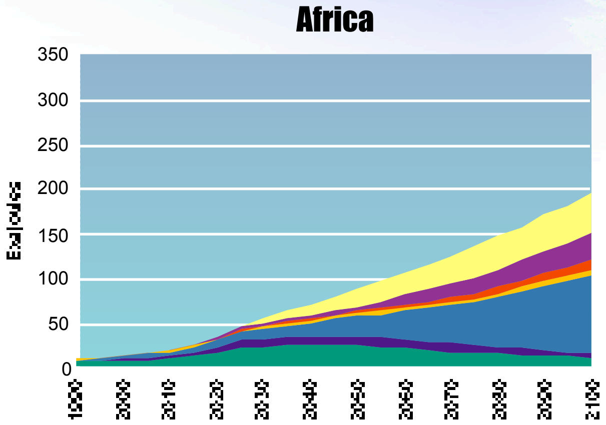

**USA**

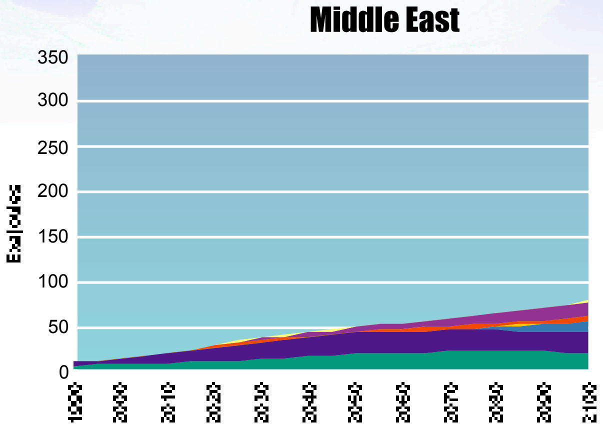


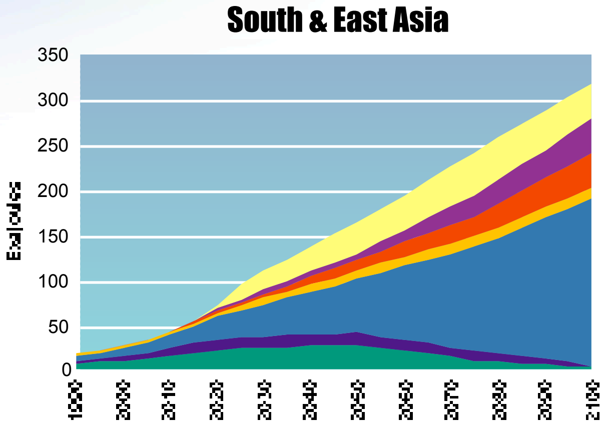

**China & Centrally Planned Asia**


**Latin America**


**Japan, Australia & New Zealand**


**Africa**

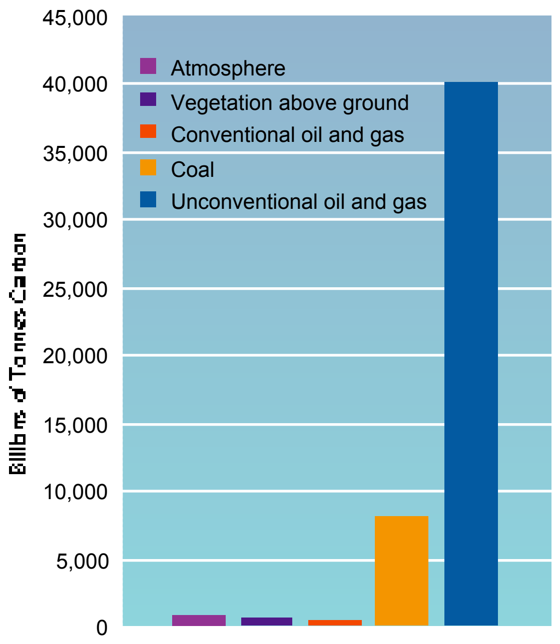

**Middle East**


**South & East Asia**

the United States, China, the former Soviet Union, and India produced 3,195 million short tons, or 63 percent, of the global total coal production of 5,043 million short tons. The United States, China, and the former Soviet Union possess the majority of the world's coal resources. Adding fewer than a dozen additional countries would account for more than 95 percent of the total coal resources.

Unconventional oil (including oil found in shales, tar sands, and heavy oils) and unconventional gas (including gas found in deep formations, tight seams, and clathrates) represent the bulk of the remaining energy resources. With anticipated technological improvement, even these currently unconventional sources are likely to become cost-competitive with nonfossil energy sources. Unconventional energy deposits are more evenly distributed among countries than conventional fossil resources are. For example, virtually every nation with a coastline has natural gas in the form of gas hydrates.

### Carbon Reservoirs and Fossil Fuel Resources



***Conventional coal resources are abundant enough to meet the world's energy needs for the $21^{st}$ century and beyond. The amount of carbon stored in conventional coal resources and in unconventional oil and gas is many times the amount currently stored in the atmosphere and in vegetation. If these resources are used in conjunction with current technologies, they could increase the concentration of carbon dioxide in the atmosphere significantly.***

Even if conventional oil and gas resources prove to be limited, coal resources are virtually unlimited. Increases in the cost of energy will be limited ultimately by the cost of transforming coal into liquids and gases—a cost that is relatively well understood. Fossil fuel energy therefore will be available and may well be cost-competitive for the next century and beyond.

## Changing the Energy System

Fundamental shifts in the energy system have occurred very slowly. They have been driven principally by the demand for new energy services and the availability of supply. Oil, which has been in use since at least the 1850s, did not surpass coal as the predominant global fuel until the 1960s. Its growth was very slow until transportation demand started to grow rapidly around the middle of the 20th century. Natural gas, which has been used in small amounts since the early 1800s, did not become a significant fuel source until seamless tubing became available in the 1940s, allowing for low-cost, long-range transport. Unlike oil, where the increased usage was driven by the demand for new energy services, the growth of natural gas occurred primarily because it is more cost-effective and cleaner than oil and coal.

Changes in energy use have been slow because the energy system is complex (involving myriad decisionmakers) and because it is capital intensive. A shift to a new fuel requires changes not only in investment and the technology to extract the fuel, but also in the technology to transport it, store it, convert it to useful forms, and distribute it to end-users, as well as changes in the end-use technology.

Fundamental changes in power generation can occur more rapidly because electric utilities can shift fuels without requiring any changes on the part of end-users, who are still receiving the same electricity, no matter what the fuel source is. In the 1970s and 1980s, nuclear power represented a large proportion of the additions in capacity. In the United States, natural gas, which in 1978 was outlawed for use in new electric generation due to perceived shortages, is currently the fuel of choice for capacity additions.

In any case, the speed of these transitions was limited not only by the availability of new technologies but also by the demand for new energy equipment. A new car is purchased when consumers decide they need to replace their old cars or need an additional vehicle; a new generating technology is employed only when it becomes cost-effective to replace the old plant or regulations force a change.

Completing a major transformation in the energy system takes time. Oil is expected to remain the leading global fuel for the next few decades. Achieving the fundamental revolution of the global energy system required to stabilize greenhouse gas concentrations will require multiple changes. For example, switching from petroleum to electricity, hydrogen, or another fuel for transportation will require designing and producing vehicles that use these fuels—and, more importantly, putting in place the complex supporting infrastructure.

### Four Long-Term Questions

The need for a major change in the energy system raises four long-term questions:

(1) Will different regions of the world require different energy systems and, if so, what are they?
(2) Specifically, what portfolio of new energy technologies is needed to build those systems?
(3) When will those new technologies be needed?
(4) Given the long time frame necessary to change the energy system, how do we make the transition away from carbon-emitting energy technologies?

Although the fundamental technology challenge is clear, the path forward is less apparent. In the chapters that follow, we begin the exploration of some of these questions.

# CHAPTER IV

# Technology Needs

Energy technology will play a critical role in future emissions, both with and without climate policies. The most frequently cited scenario of the future assumes substantial improvement in energy technology, which will require R&D breakthroughs. Stabilizing concentrations will require even greater technological change. Since technological change takes time, the nations of the world will need to start now. Technology research should focus on the two channels through which almost all energy flows: electricity generation and conversion of fossil fuels.

With substantial increases in the global demand for energy services expected over the next century, energy technology holds the key to effective limitation of greenhouse gas emissions. As described in the last chapter, carbon-based fuels and their associated technologies supplied 88 percent of the world's energy in 1995. Over the coming decades, technologies that are carbon-free will compete in the global marketplace with ever-improving fossil fuel technologies. How successfully they compete will determine future emissions.

The Intergovernmental Panel on Climate Change (IPCC) in 1992 developed six peer-reviewed descriptions of possible future emissions paths in a world with no climate policies. The one that is most often cited is the middle-of-the-range scenario, generally referred to as the IS92a scenario.

## Technology Assumptions in the IPCC IS92a Scenario

The IPCC's IS92a scenario assumes that significant technological change will take place under a "business-as-usual scenario," that is, a world without climate policy. The following are examples of the IPCC's energy technology assumptions:

- 75 percent of electricity in 2100 will be generated from nonfossil sources compared to roughly 33 percent in 1995.
- 57 percent of energy needs in 2100 will be supplied by fossil fuels—down from 88 percent in 1995.
- Biomass energy in 2100 will be used at a scale that exceeds the total global energy use in 1975.
- End-use efficiency in all sectors and regions will improve at 1 percent per year. This assumption implies a 45 percent improvement in energy efficiency in all sectors and regions by 2050.

The IS92a scenario assumes that population will double and moderate economic growth will continue, resulting in a 12-fold increase in the global economy during the 21st century. Combining this economic growth with the scenario's assumed shift toward more efficient use of energy (declining energy intensity) and toward carbon-free energy sources yields a 3-fold rise in emissions.

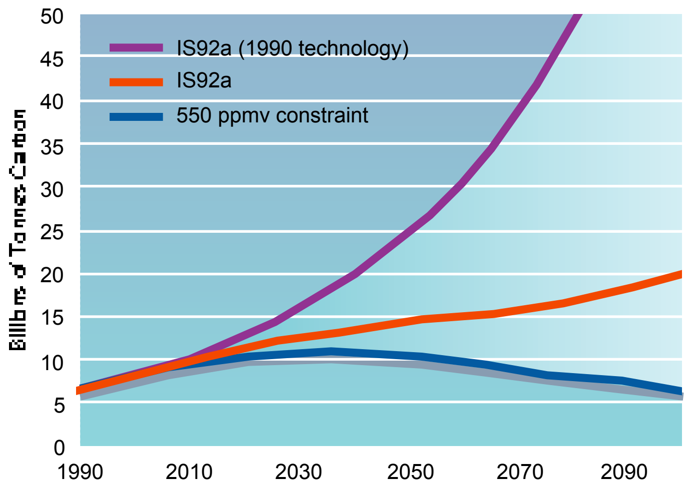
The IS92a scenario also assumes substantial improvements in the efficiency of power plants that use fossil fuels. At the same time, despite marked efficiency improvements in fossil technology, the scenario envisions a world in which carbon-free technologies such as wind, solar, biomass, nuclear, and hydropower will become sufficiently cheap relative to fossil fuels that they will supply 75 percent of global electricity by the end of the century, up from approximately a third in 1995. Overall, fossil fuels are assumed to supply 57 percent of energy needs in 2100, substantially down from the 88 percent share these fuels held in 1995.

In summary, the IPCC's central scenario assumes major improvements in technology that will require significant future research breakthroughs and fundamental shifts in the energy system toward carbon-free fuels. Some have questioned whether these technology assumptions are realistic or optimistic, but the more salient question is: "Even if we achieve the IPCC's assumptions, will that get us to stabilization?"

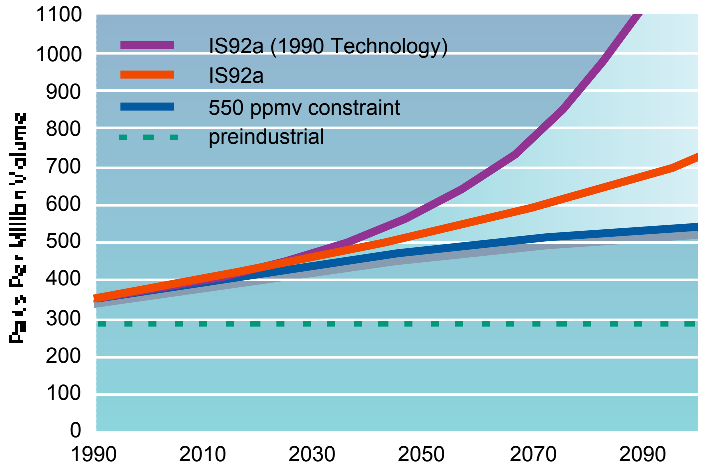
Technology is improving and can be expected to continue to change in a way that makes it possible for increasing amounts of wealth to be generated per unit of energy used, while enabling carbon intensity to fall as well. Yet, even under the advanced technology assumptions of IS92a, emissions will continue to grow.

## The Future With and Without Technological Change

### Carbon Emissions



### Carbon Dioxide Concentrations



***The middle curve in the first chart depicts the carbon dioxide emissions associated with the Intergovernmental Panel on Climate Change (IPCC) central scenario, denoted IS92a, and the middle curve in the second chart represents the concentrations in the atmosphere that result from these emissions. This IPCC "business-as-usual" scenario incorporates significant technological advances. In contrast, while the top curves assume the same population and economic growth as IS92a, they hold energy technology constant at its 1990 level. The difference between the upper and middle curves thus illustrates the technological improvement needed merely to achieve the IS92a emissions path with its corresponding impact on concentrations. The lower curves depict an emissions path and its corresponding concentration path consistent with a 550 parts per million volume (ppmv) concentration ceiling. The dotted line on the concentrations chart indicates the pre-industrial level of carbon dioxide concentrations (i.e., a level virtually unaffected by human activities).***

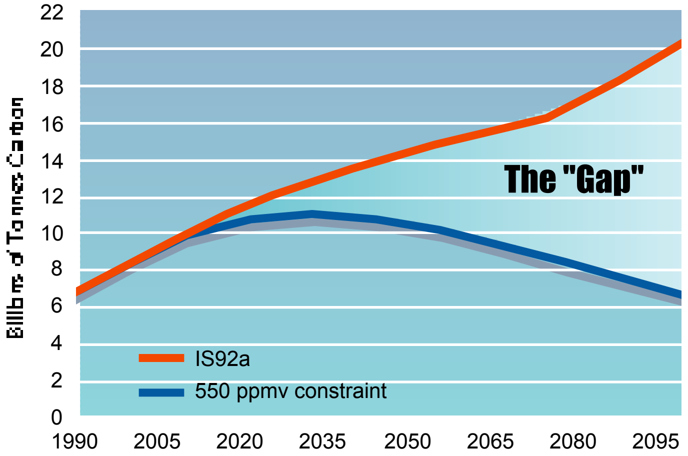
They will increase at a significantly slower rate than they would have without the technology developments envisioned by IS92a. Nevertheless, under the IS92a scenario, the concentration of carbon dioxide will rise to more than 700 ppmv by the end of the 21st century—nearly triple the preindustrial level—and will continue rising.

Thus, a gap emerges between the technologies that are anticipated to come into use under the IS92a scenario and those needed for stabilization. Substantial development of energy technologies is necessary to achieve the IS92a goals, and even greater development and deployment is needed to achieve stabilization.

## Changing Energy Technologies—Development and Deployment

Shifting the dominant fuels that run the energy system from wood to coal, oil, and natural gas took decades, even centuries. (See "Changing the Energy System" in Chapter 3.) The shifts were slow because of the time needed to research, develop, and deploy individual technologies, and because of the intricacies of the energy system.

## The Technology Gap



***The gap refers to the difference between future emissions based on IS92a technologies and an emissions path that would achieve a 550-ppmv concentration target. Achieving this stabilization emissions path would require even greater use of advanced technologies than is assumed in IS92a.***

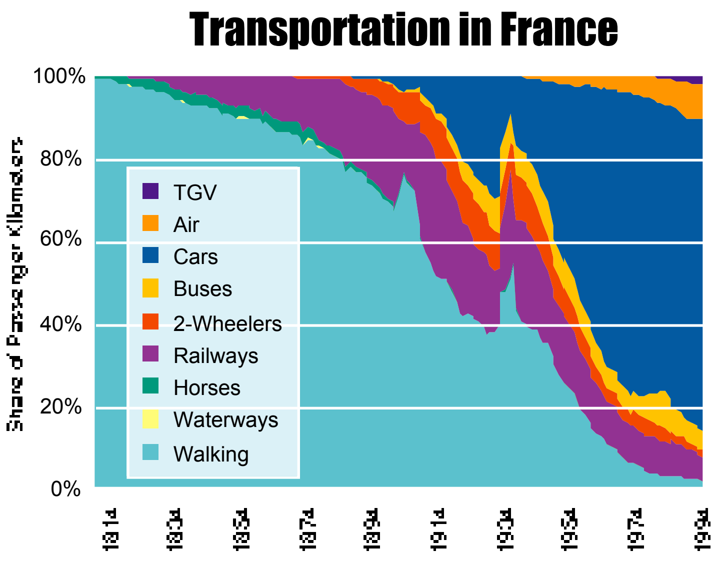
***R&D takes time.*** Innovation and demonstration can take decades before the new technologies become widely accepted and economically competitive. New technologies often vie for supremacy. For several decades, the internal combustion engine was only one of many options that competed to become the power plant of the automobile. A significant number of early cars were powered by electricity.

***Energy capital stock is often long-lived.*** Deployment of new technology can be slowed by the rate at which existing equipment is retired. Much of the technology and infrastructure that supplies our energy services is long-lived. It is not unusual for a power plant to be in service for more than 50 years, and the transmission and distribution infrastructure may be even longer-lived. Existing technologies will likely remain in place even if their operating costs are higher, because switching to newer technologies requires capital expenditures. Even in rapidly developing countries, new technologies may be slow to gain acceptance due to a limited capacity to install and maintain advanced, relatively high-priced technologies.

***Changing a single technology may require replacing an entire energy infrastructure.*** Changing an energy technology may require a complex changeover in the supporting infrastructure. The automobile, for example, was not an overnight success. A long series of investments in supporting technologies was needed. Roads had to be made auto-friendly. Fueling stations had to be designed and constructed. Roadside restaurants and other services had to be built.

In cases where broad changes in infrastructure are not required, the effect of improvements in technology can be much more rapid. For example, fuel switches in power generation can occur more rapidly than economy-wide switches in fuels because electric utilities can make the shift without requiring any changes on the part of end-users, who are still receiving the same electricity, no matter what the fuel source is.

End-use technology efficiencies can improve quite rapidly as well. For example, the average fuel economy of new US automobiles doubled between 1975 and 1985; the average electricity use of new refrigerators will have dropped by more than two-thirds by 2001, compared with the mid-1970s. However, the rate of improvement in overall energy efficiency is still limited by stock turnover. Government efficiency standards, direct financial incentives, and R&D (both public and private) were all needed to achieve a substantial slowing in the growth of US energy use. Partially as a result of these efforts, energy intensity in the United States fell 42 percent between 1970 and 1999, continuing a pattern of decline observed since the 1920s.



*In France, it took 50 years for the automobile's share of passenger transport to rise from 1 percent to 50 percent. The speed of change was limited by technology, societal preferences, and the time required to develop a supporting infrastructure of roads and gasoline stations.*

***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 institutions and strategies for spreading these capabilities.

In summary, developing new technologies, bringing them successfully to market, and improving them over time are processes that can consume years to decades. Since it will take time to achieve the fundamental changes to the energy system that are required to stabilize concentrations of greenhouses, we must start to develop the needed technologies now.

## Focusing the Search for New Technologies

Despite an increasing diversity of fuel sources and energy uses, the world's commercial energy still makes its way through two channels: electric power generation for stationary uses, and refining and processing for mobile uses.

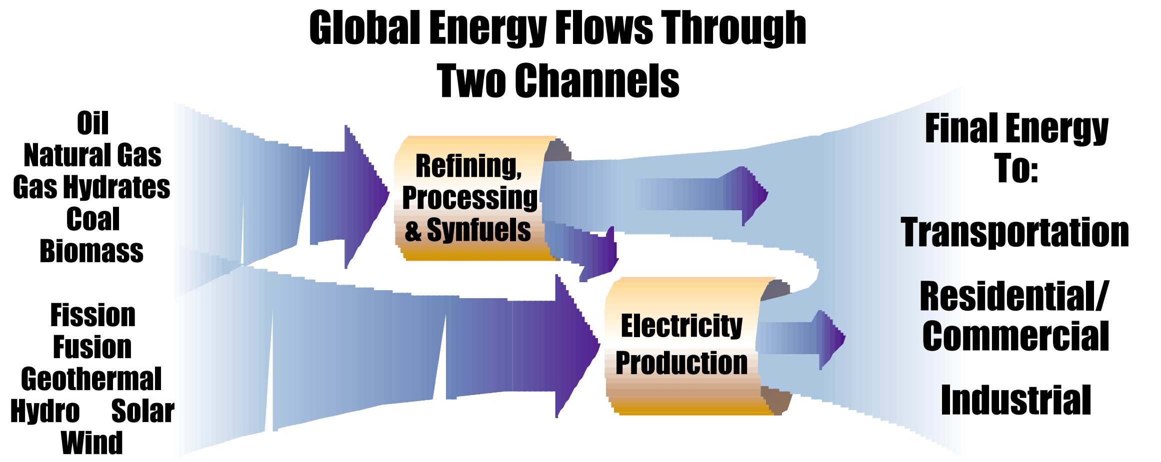
Stationary energy technologies such as power plants, industrial facilities, and office buildings often are large in scale. These stationary facilities can use boilers, large-scale turbines, and large electrical motors. They can use a variety of fuels, including oil, coal, natural gas, hydropower, and nuclear fuel.

Mobile energy technologies, on the other hand, are dominated by the internal combustion engine and have become restricted to oil as the power source. The technologies needed to support these end-uses include oil wells, ocean and land transport, refineries, and internal combustion engines.

The fact that almost all energy undergoes either conversion to electricity or refining and processing is important for developing a targeted technology strategy. Unless one of the channels becomes dominant in the future, a climate technology strategy has to address the technology needs of both types of energy flow.

And the technological needs of the two channels may be quite different. Approaches for taking carbon out of electricity production and distribution can be implemented without affecting end-use technologies. In other words, the same light bulb can be used whether the electricity is generated by a coal-fired power plant that has no carbon scrubbing technology or by a coal-fired power plant that does have carbon scrubbing. Conversely, approaches for taking the carbon out of transportation are likely to require not only changes to refining and conversion techniques, but also fundamental changes in automobiles, service stations, and the rest of the transport infrastructure.

The structure of the energy system thus gives us two areas to focus on, but it also gives us few clues about which technologies will be needed to fill the gap. The next section addresses this crucial question.



*Primary commercial energy flows through two channels to meet an ever-increasing array of end-use demands.*

# CHAPTER V

# Technology Portfolio

Development of new technologies and improvement in existing technologies can control the costs of stabilization. A broad portfolio of investments is needed to manage future 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 be broad to accommodate the diversity in regional technology needs and to address all major energy flows. R&D priorities should be revised periodically to reflect new knowledge.

Climate change is a complex issue that involves many countries, a number of decision-makers, and a myriad of possible responses. A strategy for addressing climate change will have several elements, of which technology is just one. From a technology perspective, managing the risks of climate change requires making investments in research projects that are most likely to improve our understanding of the roles that specific technologies might play in reducing the costs of stabilizing concentrations and in a broad-based portfolio of the technologies that are most likely to achieve that objective.

A technology investment portfolio must accommodate several key uncertainties: uncertainties in climate science, uncertainties about future policies, technological uncertainty, and fundamental uncertainties about the energy resource base. In addition, a portfolio must be broad enough to include the range of technologies needed to address all major sources of carbon dioxide emissions and to reflect diverse regional technology preferences.

The important future uncertainties are formidable. For example, 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 for the next century or through only part of it. We will discover whether current concerns about nuclear power technology can be addressed. We will learn whether carbon capture and storage will be acceptable from both economic and environmental perspectives.

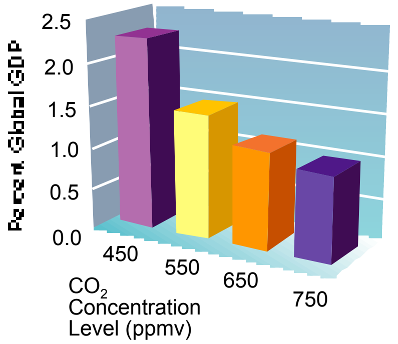
In the face of all these uncertainties, it is clear that society cannot adopt a plan today and follow it over the next 100 years. Actions can and will be modified as the decades pass. A global energy technology strategy will need to be adaptable. Society will need to act, then learn, and then act again.

## Technology Improvements 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 and developing flexible policy instruments (e.g., emissions trading) that will allow technological innovation to occur where it is most cost effective. Although efforts employing currently available technologies can slow the growth of emissions, considerable technology advancement is needed to reduce the cost of making these near-term emission reductions and the much larger reductions required to stabilize concentrations.

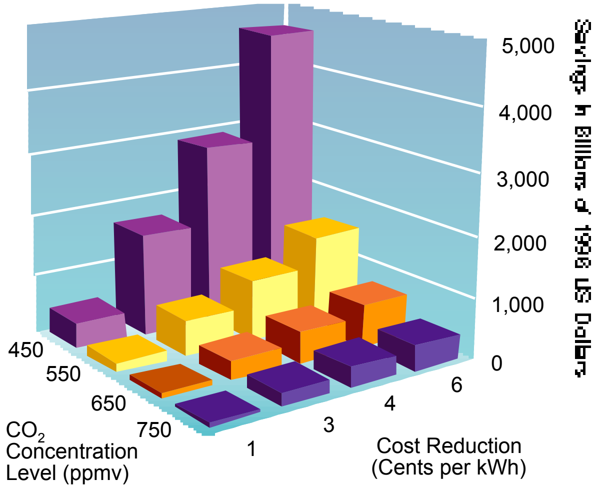
In the previous chapter, we presented two technology variants of the IS92a scenario: one with technology frozen at 1990 levels and the other incorporating the dramatically improved technologies assumed under the IPCC's IS92a scenario. The value of this technological improvement can also be estimated. For a 550 ppmv concentration target, the value of moving from 1990 technology to those assumed under IS92a is almost 1.5% of gross world product.

**Value of IS92a Energy Technology Improvement**



*The value of technology advances can be calculated by comparing the costs of stabilization with the IS92a technologies to the cost of stabilization with no technological advances. The value, expressed here in terms of present value of cost reductions divided by the present value of gross world product, is substantial for all concentration targets analyzed.*

**Value of Solar Photovoltaic Technology Improvement**



*The value of reducing the cost per kWh of solar photovoltaics from a reference value of 9 cents per kWh can be calculated for a range of stabilization targets, holding all other technologies at reference prices and efficiencies. The value of technology improvements in solar increases as the stabilization target tightens. This value pattern across targets would not necessarily hold for all technologies. Some technologies might have high value when only moderate reductions are required, but lesser value if more stringent reductions were required.*

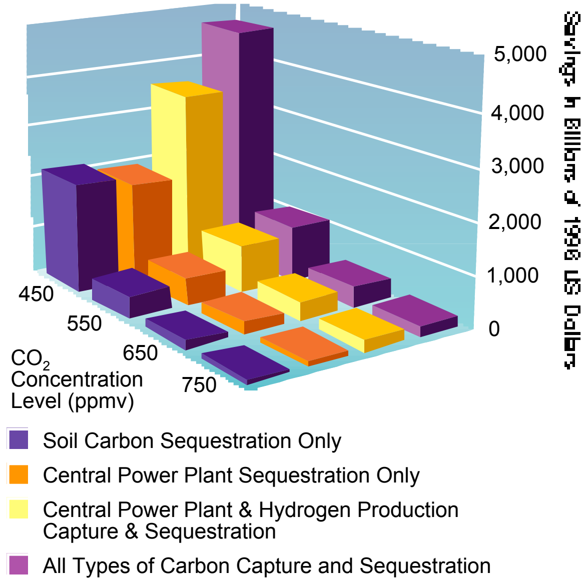
Improvements in the price and performance of currently commercial technologies can save literally trillions of dollars in the cost of addressing climate change. For example, if solar power could be developed that cost 3 cents per kilowatt-hour (a 6 cent per kWh reduction from the reference value of 9 cents and a price which is competitive with today's electricity sources), the global cost of stabilizing atmospheric carbon dioxide at 550 ppmv could be reduced by about $1.5 trillion. Clearly, failure to invest in the improvement of existing technologies that can reduce emissions, such as end-use efficiency, solar power, wind, biomass, nuclear, and hydropower, would increase the potential costs of stabilization substantially.

Similarly, successful investments in technologies that are not yet in widespread commercial use, such as those to sequester carbon by storing it in soils or to capture and store carbon from fuels or power plants, can save literally trillions of dollars in the cost of addressing climate change. Whenever a key technology is taken out of the portfolio, the cost of stabilization increases significantly. For example, the value of adding soil carbon sequestration to the complete suite of carbon capture and sequestration technologies available to stabilize at 450 ppmv is about $1.1 trillion. Removing all of the carbon capture and sequestration technologies more than triples the cost of stabilization for all concentration levels analyzed.

## A Technology Investment Portfolio

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.

**Value of Carbon Capture and Sequestration Technologies**



*The value of having carbon sequestration technologies available to help achieve stabilization can also be calculated. Calculations were made both for individual classes of technology and for combinations of these technologies. In combination, the individual technologies compete for market share so that the value of the combination is less than the sum of the values calculated for individual technologies. Integrated analysis like this is critical for assessing technology value.*

***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 resources.*** At present, we cannot forecast whether oil and natural gas resources will be confined to conventional sources because of technology limitations or whether technological advances will enable unconventional fossil resources to become accessible at prices comparable to current costs.

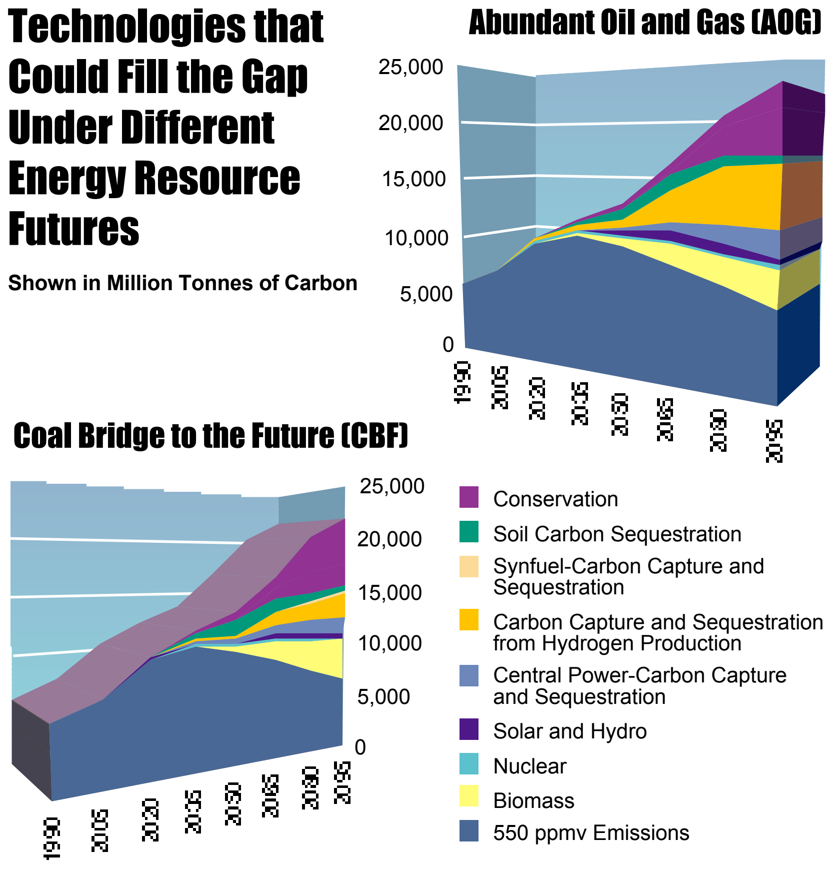
In one plausible future, lower grades of oil and natural gas would become available at approximately current prices—the Abundant Oil and Gas (AOG) scenario. In another plausible future, liquid and gaseous fuels will have to be produced from coal and commercial biomass. In that case, which we call the Coal Bridge to the Future (CBF) scenario, the liquid and gaseous fuel prices would be higher. The only difference between these plausible futures is whether coal, oil, or natural gas will be the most inexpensive fuel choices.

This uncertainty, however, drives important differences in the mix of technologies that are deployed to limit carbon dioxide emissions. Carbon capture and sequestration from hydrogen production would play a much smaller role in the CBF case, but biomass production would play a greater one.

The graphic shows a relatively small direct effect of energy conservation in the CBF case, but the indirect effect would be much larger in the form of reduced demand for energy services. Because end-use energy would be more expensive under the CBF scenario than under AOG, people would be motivated to implement a wide range of conservation measures. For example, since much of the end-use energy under the CBF model would be either electricity or synthetic liquid and gas derived from coal, conserving emissions at the point of use also avoids the additional emissions that would have occurred during the production of that secondary energy source (e.g., using less gasoline derived from coal).

## Technologies that Could Fill the Gap Under Different Energy Resource Futures

Shown in Million Tonnes of Carbon



*These figures illustrate the effect of energy resource uncertainty on the portfolio of technologies that could be used to reduce emissions from the IPCC's mid-range projection of the future to a 550 ppmv stabilization path. In the AOG future, conventional oil and gas remain available at approximately current prices. In CBF, energy prices increase leading to additional end-use efficiency improvements and to increased use of coal for the production of synthetic fuels. Technologies are chosen in the analysis based upon their relative prices and availabilities. These figures identify only the technologies chosen to reduce emissions from the IS92a path to a stabilization path. As noted earlier, substantial technology improvements are required to move from a 1990 technology path to the IS92a path.*

In summary, different possible energy resource futures argue for investing in a broad range of technologies.

***A broad portfolio can control 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 possibly be anticipated. The key challenge in exploring technological routes to a stabilization goal is to fund enough research to determine whether the approach is practical, yet be willing to terminate the research if neccessary. 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.

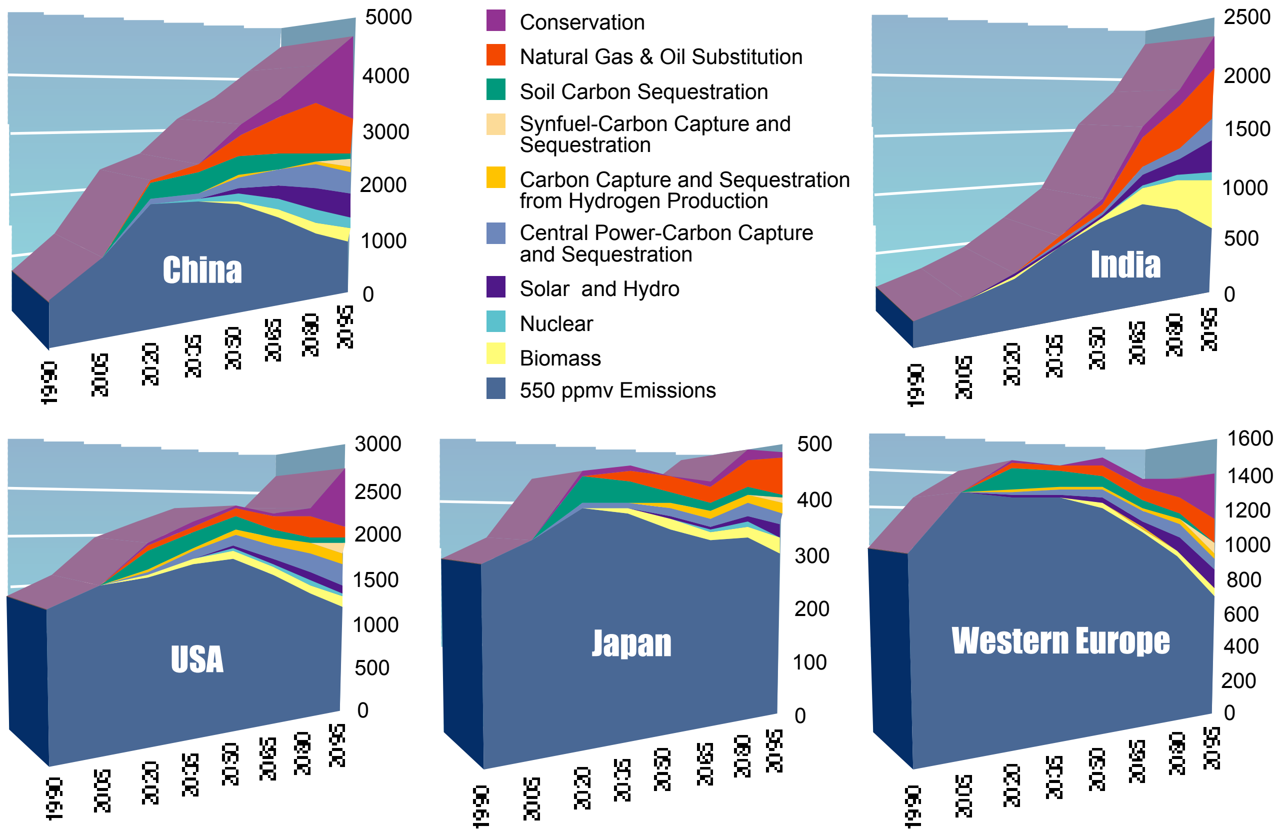
***A portfolio can meet the differing needs of key regions.*** Technology needs vary from one country and region to another. For example, India has considerable potential to produce modern commercial biomass, but China does not. China has significantly greater space heating needs than India. Neither country, both of which have rapidly growing economies and energy demands, faces exactly the same challenges as the United States, Europe or Japan, whose economies are more mature. 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 is 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.*** 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. Efforts to remove the carbon should focus on the two channels through which commercial energy flows – electricity generation and fuel refining and processing.

## Technologies that Could Fill the Regional "Gaps"

Shown in Millions of Tonnes Carbon



*These figures illustrate one possible portfolio of technologies for moving from the IPCC's mid-range projection of the future to an emissions path leading to stabilization of concentrations at 550 ppmv. Five regions are presented. These regions represent the majority of today's emissions of carbon dioxide and are projected to represent the majority of emissions for the foreseeable future. The estimates are provided by the Global Energy Technology Strategy Program's regional collaborators. The top line in each region denotes regional emissions under the IS92a scenario. The gray regions denote the emissions paths that minimize the cost of achieving a concentration target of 550ppmv. Emission reductions are made where most economic, with no regard to the critical issue of who pays for these reductions. These figures highlight the technologies needed to reduce emissions from the IS92a path to a stabilization path. As noted earlier, substantial technology improvements are required to move from a 1990 technology path to the IS92a path.*

Improvements in the efficiency of energy use are critical. As we have learned over the last three decades, 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.

The next focus is to limit the free venting of carbon from the energy that is needed. Investments to develop technologies for reducing emissions from electric generation need to focus on non-fossil systems to generate power as well as carbon capture and sequestration technologies that could allow the continued use of fossil fuels.

Removing carbon from transportation will require fundamental changes in personal vehicles, possibly so that they operate on carbon-free fuels such as hydrogen. Shifting to hydrogen as a fuel would require the development of methods to produce large amounts of hydrogen without venting carbon to the atmosphere. A new transport system also would require new fuel transport and storage technologies and the development of a fueling infrastructure.

## Reassessment of Technology Investment Priorities

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 the concentration target chosen to meet the Framework Convention's ultimate goal 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 key 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.

## Technologies That Fill the Gap

A series of global and regional analyses conducted by the Global Energy Technology Strategy Program have assessed literally hundreds of technologies that may help fill the technology gap. If resources were unlimited, it would make sense to invest in all of those technologies. Given that funding is limited, however, a detailed analysis of specific R&D paths is needed to determine those of greatest importance.

As demonstrated above, it is critical to continue to fund the improvement of currently commercial technologies that can help reduce carbon emissions. The rapid development and deployment of these technologies are required in order to achieve the IS92a, "business as usual," scenario and to prepare for the next step of achieving stabilization.

Of the technologies that are not currently commercial, the GTSP analyses identify three technology paths that currently merit substantially increased R&D investment to determine more clearly their future potential:

- Carbon sequestration technologies
- Low carbon-emitting methods to produce hydrogen in combination with improved hydrogen storage and fuel cells
- Carbon capture, transport and storage technologies

***Carbon sequestration technologies.*** The overall purpose of these technologies is to retain or store carbon in plants, soils, and oceans and to develop energy sources that balance the uptake and release of carbon, for example, by producing energy from plants. Some of these technologies have additional benefits such as restoring degraded lands. Others enlarge the suite of options for producing energy regionally, such as electricity and liquid fuels from biomass.

To develop current carbon sequestration technologies will require an increase in our understanding of the carbon cycle and the mechanisms by which carbon is sequestered. Research and development is needed to design processes to convert biomass to electricity and liquid fuels efficiently and at low cost.

***Hydrogen-based Transportation.*** Fuel cells might power vehicles with greater efficiency and lower emissions than conventional engines. Vehicular fuel cells currently are being commercialized, but the onboard fuel used is projected to be either methanol or a liquid hydrocarbon. As long as vehicular fuel cells are fed by carbon-based fuels, they will not reduce carbon dioxide emissions sufficiently to achieve stabilization. If the carbon associated with hydrogen production were captured and sequestered, fuel cells would be much more effective in stemming the carbon dioxide emissions from transportation —illustrating the interdependent nature of the technologies within the R&D portfolio.

Alternatively, hydrogen fed fuel cells could be an important non-emitting source of energy if the hydrogen were produced from non-carbon energy sources such as fission, fusion, or solar electricity. To complement ongoing R&D in fuel cells, basic research into the most efficient ways to produce, distribute and store hydrogen is needed.

***Carbon capture, use, and storage.*** Current scientific research suggests that sustained basic R&D today could result in effective technologies to capture and store carbon on a scale that would significantly help mitigate climate change. Carbon capture, use, and storage technologies would allow the continued use of fossil fuels but would prevent carbon from being released to the atmosphere. Technologies to remove carbon dioxide from combustion flue gases are already operational at small scale, but are expensive.

The primary question is what to do with the captured carbon dioxide. Some of it has commercial value. Since the early 1970s, carbon dioxide has been used in mature oil fields to enhance recovery of oil. The gas is injected into old reservoirs (sometimes alternating with water to increase the pressure and the flow of oil). Other commercial uses include enhancing the production of coal bed methane and increasing the production of urea, methanol, and soda ash.

A large percentage of the captured carbon dioxide could be stored in geological formations such as deep saline aquifers, depleted natural gas and oil reservoirs, and coal seams. Carbon capture and storage are new technologies, and many questions remain to be addressed through geologic, energy, and environmental research.

Based upon our analyses, these three technology paths are ones that are currently under-funded relative to their potential contribution to atmospheric stabilization. They all deserve R&D priority today, but these priorities should be revisited on a regular basis.

## Challenges for Today’s Commercial Energy Technologies

Individuals, companies, and countries consider a range of factors when making energy technology choices. Economics is very important, but environment, safety, energy security, national security, and other factors also affect investment decisions. Four key categories of existing commercial technologies face unique challenges over the coming decades that research can help to address:

**End-use efficiency**. End-use efficiency has played and will continue to play a critical role in limiting carbon dioxide emissions. Key issues facing energy efficiency technologies include technological improvement and creating products that consumers will embrace.

**Hydroelectric generation**. Hydroelectric generation supplied about 6 percent of global energy in 1995. There is considerable hydroelectric capacity around the world that has not been developed. Key challenges for hydroelectric generation include concerns about the environmental impacts associated with new and existing facilities and long-distance transmission since many remaining hydro resources are far from population centers.

**Nuclear**. Nuclear energy also supplied 6 percent of global energy in 1995. Nuclear energy, however, faces several critical challenges that research might help address: concerns about safety, the final disposition of radioactive wastes, and nuclear weapon proliferation, along with basic issues about its capital costs in an era of electric industry restructuring.

**Renewables**. Renewables contributed only a small amount of the global commercial energy supply in 1995. The challenges for renewables include cost, intermittent availability (for solar and wind), emissions (for biomass resources) and regional availability. Technology improvements are needed to reduce costs, and advances in storage and long-distance transmission can help address the availability issues.

In summary, 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 carbon management technology system to re-optimize the portfolio. The need for new technology is clear, and guiding principles for determining research priorities are starting to emerge. The question that also must be answered is how are we doing in developing the technologies needed to manage the risk of climate change.

# CHAPTER VI

# Research and Development

Dramatic improvements in conventional energy technologies will be required just to keep atmospheric carbon dioxide concentrations from exceeding three times pre-industrial levels. Fundamentally new technologies will be required to stabilize concentrations of greenhouse gases at lower levels at a reasonable cost. The needed improvements in conventional technologies have not yet been realized, and the development of fundamentally new technologies is not being supported at any significant level.

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The research and development challenge presented by climate change is novel. The scope extends beyond traditional energy R&D into agricultural and environmental science and technology. A great deal of integration will be required throughout the innovation process, coordinating knowledge gained from basic research and fundamental science and applying it to the development of commercial applications and technology deployment.

Large-scale, integrated technologies, such as those required for atmospheric stabilization, do not simply appear in the marketplace. Because of their scale, it will take several decades to achieve significant commercial application. Integration will require focused efforts during all stages of the innovation process to achieve the necessary technological breakthroughs. Continuous commitments of resources by government, industry, and universities over decades will be needed to reduce the cost of new technologies and ensure environmental acceptability.

During the past two centuries, investments in research and development have greatly improved the performance of conventional energy production and end-use technologies. But support for energy R&D has been episodic and driven largely by changes in energy markets and by political dynamics. For example, periods of low energy prices coupled with market and policy uncertainty are characterized by low and declining energy R&D efforts by both the public and private sectors. Conversely, during periods of sustained high energy prices, energy R&D efforts tend to increase in quantity, if not efficiency. In order to produce the fundamentally new technologies needed to stabilize greenhouse gas concentrations, a much more concerted and consistent R&D effort will be required.

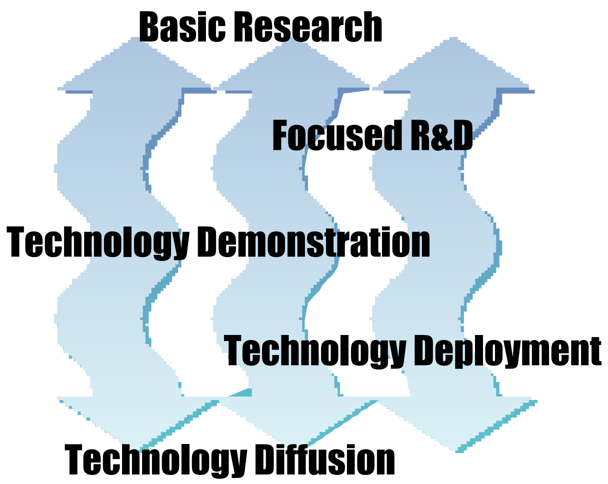
# The Innovation Process

Technology innovation is a continuous process with several definable but overlapping stages. Technology development aimed at a specific goal requires investment and coordination at all stages. It is critical to engage both the public and private sectors in the effort in a way that recognizes the unique strengths and weaknesses of each. This chapter describes the stages of the innovation process required to address the climate goal and highlights the overlapping and interlocking roles of the public and private sectors.

***Basic research.*** At the front end of innovation, fundamental science is critical to building the knowledge necessary for new technology discoveries. The benefits of investments in basic research are difficult to quantify. National governments view investment in fundamental science as necessary to maintain their national security and economic and environmental well-being. For this reason, governments are often the principal supporters of basic research.

For the most part, governments will have to take the lead in funding basic research needed to address climate change because of the diffuse private benefits of that kind of expenditure and the long delays between discovery and application. Although a broad basic research program is consistent with the need to support innovation, some fields are particularly in need of emphasis, either because of cost or technical feasibility. Clearly, carbon management areas such as advanced fuels processing, carbon or hydrogen separation, biosequestration, and geological storage would benefit from advances in the biological, computational, materials, and molecular sciences, to name just a few.

## Stages from Innovation to Use



***Technology innovation consists of a web of definable but overlapping stages. Breakthroughs or barriers encountered in any of the stages should inform activities in the other stages.***

***Applied research and development.***
Applied research is designed to turn the knowledge derived from basic science into useful products and applications such as biomass cropping systems, photovoltaic cells, hydrogen storage, fuel cells, battery technology, carbon capture and storage technologies, and highly efficient, low-emission vehicles. Each of these practical applications involves the integration of a number of different disciplines and frequently generates new questions and scientific puzzles requiring yet more basic discoveries. Once applied research indicates that a practical application has a chance of succeeding in the marketplace, market-focused technology development is required to justify substantial investments in the new technology.

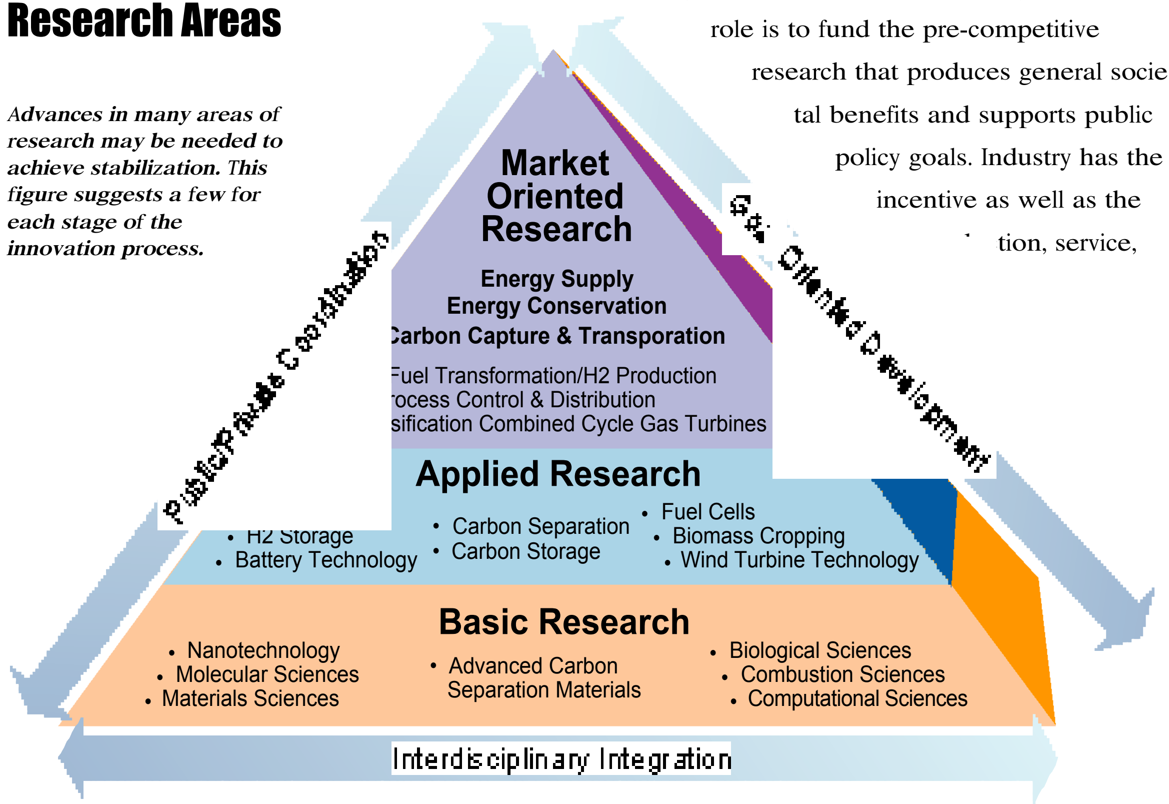
***Commercialization.*** In the process of introducing a new technology to the marketplace, experience leads to improvements and adaptation, sometimes requiring developments in the supporting infrastructure. Diffusion of a new technology reveals new applications and requirements based on economic and technical performance and productivity standards. The new applications suggest new goals to guide further technology development.

## Innovation –
## An Iterative Process

Successes and failures in one stage of the innovation process often stimulate refocused efforts in other stages. For example, successes in fundamental materials science can suggest new approaches for developing commercial fuel cells or photovoltaics or carbon scrubbers. Conversely, failure to develop cost-effective processes for manufacture can reduce a fundamental breakthrough to an interesting scientific note or stimulate a completely different innovation. The various stages of the innovation process inform, guide and stimulate each other.

In the context of climate change, this iterative aspect of the innovation process underscores the importance of reviewing the climate technology strategy on a regular basis. This review process is sometimes described as act, then learn, then act again.

## Illustrative Technology Research Areas



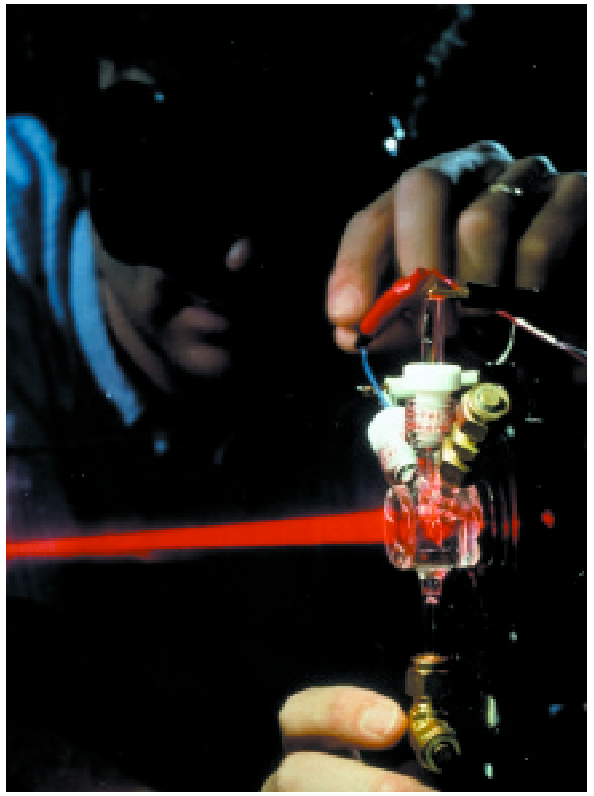
***Advances in many areas of research may be needed to achieve stabilization. This figure suggests a few for each stage of the innovation process.***

## Public and Private Roles in Innovation

Agreement is widespread that government's role is to fund the pre-competitive research that produces general societal benefits and supports public policy goals. Industry has the incentive as well as the tion, service, and marketing skills needed to take a new product or technology from the laboratory to the marketplace. Consequently, industry takes on greater R&D responsibility as the product moves closer to commercialization and technology issues begin to involve the manufacture of specific products for competitive markets.

Private industry tries to complement and leverage the public energy research portfolio. And the public R&D agencies are increasingly looking to industry for market guidance. Despite successes such as the search for clean coal technologies and the efforts made by the Partnership for a New Generation of Vehicles in the US, coordination between public and private sectors can be and will have to be significantly improved to address the climate technology development issues.

Achieving the public sector goal of stabilizing the atmosphere at a reasonable cost requires a dramatic improvement in existing commercial technologies, plus development and deployment on a global scale of new technologies that do not yet have a commercial market. Clearly defining the roles of the public and private sectors in addressing this complex issue appears to be impossible, but the general principles provide guidance. Atmospheric stabilization is a public goal, and both the programs needed to spur technology innovation and the necessary basic research are the responsibility of the public sector. Deployment remains a primary responsibility of the private sector.

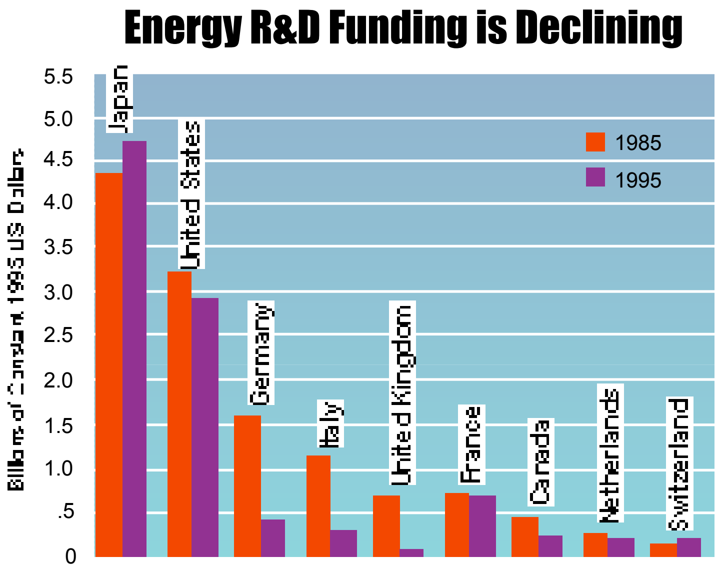


Significant consultation, planning, and coordination between the public and private sectors will be required to develop the required new technology and integrate it with existing conventional energy technologies. These sectors will have to integrate research in many different fields of science and technology and throughout the three stages of the innovation process: basic research, applied research, and commercialization. Together they must create a goal-oriented technology development program that links basic research to the needs of applied research, and supports practical development and deployment.

## Global Investments in Energy Research and Development

How then are we doing in terms of developing the new technologies needed to manage the risk of climate change? Data on energy research and development are difficult to locate, compile and interpret. However, the findings from an extensive Pacific Northwest National Laboratory study of R&D funding are not encouraging.

Every year, the public and private sectors devote billions of dollars to energy R&D, representing a significant investment. Still, those billions represent only a small fraction of the global economy and of the world's total investments in R&D. We have been able to document less than $15 billion annually invested in the development of improved energy technologies by the world's governments and private firms. Although the US commitment is one of the world's largest, it represents less than 0.05 percent of US gross domestic product and less than 2 percent of all R&D conducted in the US. Private energy R&D investments in the US, United Kingdom and Netherlands represent less than 1 percent of total sales for utilities as compared to a 3 percent R&D to sales ratio for US industry and 8-10 percent investment rates for R&D leaders such as the pharmaceutical, computer and communications industries.



***Total public funding of energy research in the OECD is falling. Although Japan's outlays increased slightly, US spending declined and leading European nations reduced their funding dramatically.***

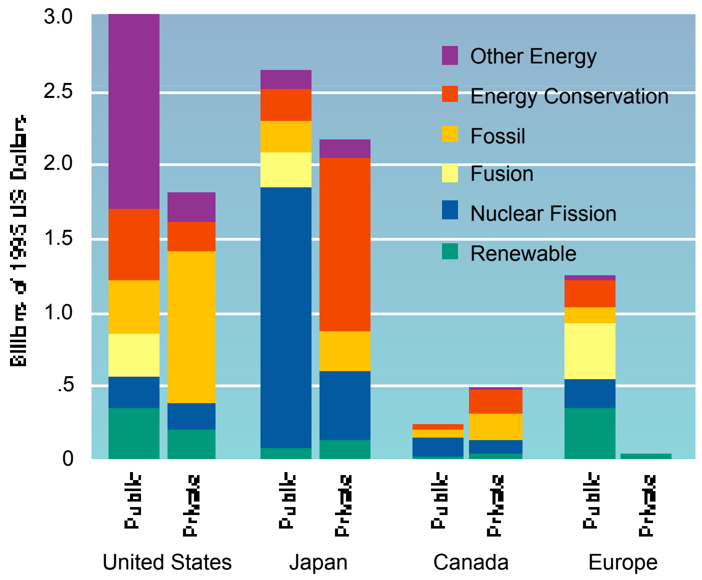
***Resources for energy R & D are declining.*** Resource commitments are an imperfect yardstick for measuring the benefits of energy R&D. Nevertheless, it may be significant that almost 96 percent of the industrialized world's public energy R&D is conducted in only nine developed nations.

Moreover, data from 1985 to 1995 suggest that both public and private investments in energy R&D are clearly declining. Between 1985 and 1995, public sector investment by the nine Organisation for Economic Co-operation and Development (OECD) countries that undertake such research decreased by 23 percent in real terms. More recent data points to a continuation of these reductions.

The United States and Japan together finance approximately 75 percent of global energy R&D. Investment by the US government fell by 23 percent from 1985-1998. During the same period, private sector investments in energy R&D in the US declined 67 percent in real terms. These reductions equate to nearly $3.5 billion less spent per year in 1998 than in 1985. Programs designed to create new advanced environmentally preferred electric generation technologies have been particularly hard hit by these reductions.

The reasons for these declines range from governmental budgetary pressures to low energy prices, greater competition in energy markets, and market uncertainty brought about by efforts to create more competitive energy markets. Some argue that reduced funding is a poor measurement of progress, since the R&D process may simply have become more efficient in recent years. In the context of the magnitude of the challenge posed by climate change, however, these investment figures suggest reason for concern.

### Energy R&D Portfolios of Selected OECD Countries in 1995



*The composition of documented energy investments varies widely between public and private sectors within countries and also varies widely across countries. To simplify the figure, an aggregate portfolio is presented for the European Union and its member countries (Germany, the United Kingdom, the Netherlands and Italy).*

The Japanese government's R&D spending actually grew between 1985 and 1998 by 1 percent. Looking behind the numbers, moreover, reveals that Japan's nuclear fission and fusion programs comprised approximately 75 percent of its public R&D portfolio. Japanese private sector energy R&D investments in electric power generation technologies have recently begun to decline modestly as Japan moves to create a more competitive energy market.

The trends were even more pronounced in European nations. In Germany, Great Britain, and Italy, public sector investments in energy R&D declined anywhere from 75-90 percent between 1985 and 1995. Where data are available for these country's private sector energy R&D investments, there is evidence that programs designed to create new, lower carbon emitting generation technologies are suffering in this funding environment.

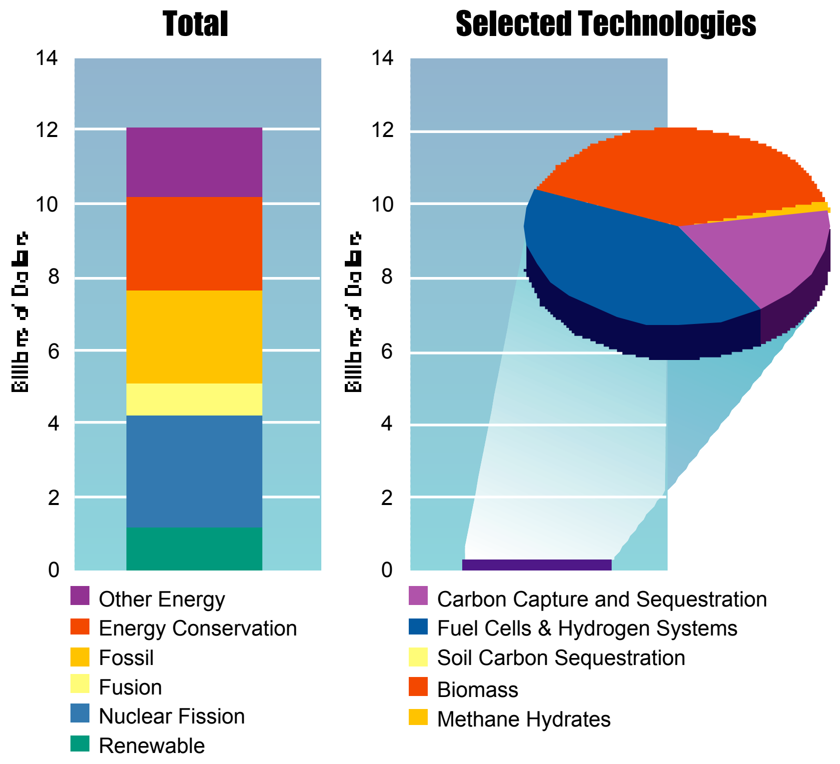
***Energy R & D is uncoordinated.*** At the national level, another trend that is cause for concern is the investment of public and private resources in different energy technologies, reducing the potential to leverage limited resources. As governments throughout the industrialized world deregulate their gas and electric utility sectors, they are creating an incentive system that encourages private energy R&D to focus increasingly on short-term, proprietary projects. At the same time, the government energy R&D sector is trying to create programs (often with the hope of private sector cost sharing) to deal with broad and diffuse public benefit issues. In this environment, the challenge is to determine the appropriate roles for public and private entities in creating the needed, new technologies.

Similarly, at the international level, coordination between nations is minimal. Climate change is a global problem. Yet governments are missing opportunities to meet their national requirements and global needs by cooperating internationally in funding and conducting R&D. Cooperation and coordination are essential to make best use of society's limited resources for addressing the climate issue.

***Energy R&D is not climate-focused.*** Finally, in almost every major area of energy R&D, research programs focus on short- and medium-term applications rather than on the fundamental knowledge that will be required to develop advanced technologies. For example, in some of the analyses presented earlier, 60 percent of the reductions required to fill the global emissions “gap” just a few decades from now come from increased use of biomass and carbon sequestration. Fuel cells, hydrogen systems, and methane hydrates also figure to be important technologies in filling the global technology gap. Yet these technologies receive less than 2.5 percent of the global investment going into energy research and development.

The recent trends in energy R&D spending stand in stark contrast with the technology needs to manage the risk of climate change. If this funding trend continues, the likelihood of realizing the technologies embodied in the IS92a scenario goes down. Accordingly, the likelihood of stabilizing concentrations declines even farther. The following section describes actions that will be required to stabilize concentrations of greenhouse gases in the atmosphere.

### Global Energy R&D Investments in 1995



*Only 2.5 percent of the global energy R&D investment is targeted at a suite of new technologies that could play a significant role in stabilization. This is not to say that continued investment in other critical emission-reducing technologies is not important, but rather to emphasize the need to understand more clearly the true potential of these new technologies.*

# CHAPTER VII

# Conclusion

The Global Energy Technology Strategy Program concludes: (1) energy technology advances are critical to achieving the ultimate objective of the Framework Convention on Climate Change, the stabilization of concentrations of greenhouse gases in the atmosphere, (2) current energy R&D investments are inadequate to meet this technological challenge, and (3) a global energy technology strategy will help achieve the needed technology advances, complements other global or regional climate policies, and is robust in the face of future uncertainties. As an initial step forward, we identify key elements to guide the development of a technology strategy.

The Global Energy Technology Strategy Program combines technical analyses from Battelle and research collaborators around the world with the expertise of a diverse group of senior representatives from the public and private sectors and from nongovernmental organizations. This chapter characterizes the fundamental challenge that the climate issue poses for the energy sector, summarizes the findings from analyses conducted over the past three years, and puts forward recommendations for policymakers to consider in devising a technological response to the climate issue.

## The Challenge

The future evolution of the energy system is central to the climate issue. Emissions of carbon dioxide from the energy sector comprise the largest human contribution to greenhouse gases in the atmosphere. If historic trends continue, future population and economic growth will outpace improvements in energy efficiency, resulting in continuing growth in the demand for energy.

Currently, fossil fuels provide approximately 88 percent of the world's energy and are dominant throughout the global economy. Fossil fuel use dominates every major sector. Fossil fuels provide 97 percent of the energy for the transportation system and approximately 65 percent of the world's electricity, although nuclear and hydroelectric generation are responsible for nearly a third of the electric power supply. With continued growth in energy demand, future fuel and energy technology choices will be a key determinant of the magnitude of future human influence on the climate.

The ultimate goal of the Framework Convention on Climate Change—the stabilization of concentrations of greenhouse gases in the atmosphere—requires that global carbon emissions peak and ultimately decline to zero. Moving from an energy system dominated by technologies that freely vent carbon dioxide to the atmosphere to one that significantly limits carbon dioxide emissions requires a fundamental change in technology choices. Meeting that challenge, while controlling cost, requires major innovations that increase the efficiency of energy use, remove obstacles to the wider use of current carbon-free energy technologies, and lead to the development and deployment of new technologies that are not currently deployed in the market at an appreciable level.

This technological innovation must accommodate important uncertainties. Uncertainties exist in many key areas: the concentration level ultimately required to achieve the objective of the FCCC and other aspects of climate science, global and regional technology needs, the future price and availability of fuels, and the structure of regional and international policies adopted to address climate change.

A diverse technology investment portfolio can address these, and potentially other, uncertainties. A broad array of technology development pathways spurred by research and development investments can provide society with the flexibility to respond to changing conditions while accommodating evolving circumstances. This does not imply that every investment in energy research and development will succeed. There will be failures. However, a broad portfolio, frequently revisited to minimize losses in unproductive areas of inquiry, provides insurance against multiple potential outcomes in science and policy and can address diverse regional technology needs.

The technological challenge in stabilizing greenhouse gas concentrations is clear. Society can address this challenge. However, if recent trends in global energy research and development funding are not reversed, meeting the challenge will be exceptionally difficult. Global investments in energy research and development are declining. Japan's commitment increased modestly since the 1980s; the US effort has declined over the same time period, and the public investments in energy research and development by the European Union have declined precipitously.

In addition, it is not clear that climate change is playing an important role in determining R&D investment priorities. For example, minimal investments are being made in new technologies that may play an important role in stabilizing concentrations in the long term. It will be difficult, if not impossible, to develop technologies capable of addressing the climate issue unless society makes a commitment to research and development commensurate with the objective of the FCCC.

What follows are elements of a strategic vision that are important to improving the performance of existing technologies and developing the new generation of technologies that will be needed to stabilize concentrations of greenhouse gases in the atmosphere.

# Key Findings

**Stabilizing concentrations of greenhouse gases in the atmosphere requires fundamental change in the energy system.**

- *Energy is central to the climate change issue.* Carbon dioxide emissions from the production and consumption of fossil fuels are the largest contributor to human emissions of greenhouse gases. Fossil fuel resources are abundant, and, if used in conjunction with present energy technology, have the potential to increase the concentrations of greenhouse gases in the atmosphere substantially.
- *If present trends continue, carbon dioxide emissions from energy will continue to grow.* The influences of future population growth and economic development on the demand for energy services are likely to exceed currently projected improvements in energy intensity and the ongoing transition to less carbon-intensive fuels. However, trends are not destiny—a global technology strategy could help change the present course.
- *In order to stabilize concentrations of greenhouse gases in the atmosphere, global carbon emissions must peak during the 21st century and then decline indefinitely.* This can occur only if lower carbon-emitting technologies are deployed worldwide.

**Technology breakthroughs are essential both to stabilize greenhouse gas concentrations and to control costs.**

- *Although incremental technology improvements are essential, they will not lead to stabilization.* Even with significant improvements in the performance of existing commercial technologies, the concentration of carbon dioxide in the atmosphere would grow to more than 2.5 times pre-industrial levels by 2100.
- *Technology breakthroughs can reduce the cost of greenhouse gas stabilization dramatically*. Technological advances can reduce the annual cost of stabilizing atmospheric concentrations of greenhouse gases by at least 1-2 percent of global world product. The savings will depend upon the concentration target and the level of technology improvement.
- *It is time to get started.* The energy system is capital-intensive, and the development and deployment of new technologies can take decades. Given the lead-time necessary to develop and deploy new technologies with their associated systems and infrastructure, we must begin the process without delay.

**A portfolio of technologies is necessary to manage the risks of climate change and to respond to evolving conditions.**

- *A diversified portfolio accommodates future uncertainties.* Changing scientific knowledge and economic conditions, combined with uncertainty in the resource base, requires a diversified initial portfolio of technology investments. Portfolio investment priorities will evolve over time as these uncertainties evolve or are resolved.
- *A broad portfolio can control costs.* A portfolio encompassing a broad suite of technologies can lower the costs of stabilization significantly. However, the public and private sectors cannot fund every idea. Technology investment priorities must be established to reflect available funding.
- *A broad portfolio can meet the differing needs of key regions.* Countries will need and employ different technologies based on their geography, indigenous resources, and economic, social, and political systems.
- *A flexible portfolio can accommodate alternative policy responses to the climate issue.* A technology portfolio complements a wide range of possible national and international policies, including trading, taxes, and other policies and measures.
- *A broad portfolio also can reflect the diversity of the energy system.* Technologies are needed to improve the efficiency of energy use, develop non-carbon energy sources, and limit the free venting of carbon from the fossil energy that will continue to be burned.

**Current investments in energy research and development are inadequate.**

- *Energy research and development outlays are declining.* Both public and private sector investments in energy research and development have declined significantly since the 1980s.
- *Energy research and development expenditures are unfocused and poorly coordinated.* Neither public nor private sector investments are adequately focused on the technologies that could be critical for stabilizing concentrations in the long term. Among the few governments with national energy research and development programs, investments are poorly coordinated and fail to take advantage of possibilities for joint, complementary, or specialized research.
- *Terrestrial sequestration, hydrogen, and carbon capture, use, and storage technologies* potentially play an important role in stabilizing concentrations, but are currently funded at minimal levels.

# Recommendations

**Emissions limitations and controlling costs complement a technology strategy.**

- *Emissions limits are needed to stabilize concentrations.* Without such limits, individual nations have little incentive to reduce greenhouse gas emissions. It is unlikely that the required technologies to achieve stabilization will be developed and deployed if there is not any value placed on developing such technologies.
- *Controlling the costs of stabilization is necessary*. The costs of stabilizing concentrations of greenhouse gases are uncertain and are distributed unevenly across generations, nations, and sectors of the economy. Better definition and control of these costs is critical to achieving societal consensus to take action.

**Increase global investments in energy research and development.**

- *Increase investment in energy research and development to improve the performance of existing technologies and to develop the next generation of technologies that are required to stabilize greenhouse gas concentrations.* A fundamental restructuring of the energy system will be extremely difficult without significant investments in energy research and development.
- *Develop dedicated long-term funding sources for energy research and development to support the necessary technology transformation.* Climate change is a 21st

century problem. Long-term challenges often are given inadequate attention in annual processes that allocate resources. Dedicated funding sources for energy research and development would ensure that adequate resources are available to develop and implement a technology strategy.

- *Direct investments to specific technologies that have significant potential to substantially reduce greenhouse gas emissions over the long term.* A fraction of research and development efforts are being applied towards a suite of new technologies that could play a key role in reducing greenhouse gas emissions. Additional resources should be devoted to these new technologies. This support should not come at the expense of improving currently available technologies that have the potential to reduce emissions.
- *Build broad-based public support by communicating the climate and ancillary benefits of energy research and development.*

**Improve the implementation and performance of energy research and development.**

- *Incorporate climate change when revisiting current energy research and development priorities.* Current energy R&D portfolios should be revisited to ensure that they incorporate climate change as a key priority.
- *Better coordinate the roles of the public and private sectors in the research and development process to reflect their specific strengths.* Both sectors have key roles to play in all stages of energy research and development but their emphases should reflect their primary capabilities. For example, agreement is widespread that government support of basic research and fundamental science is essential to build knowledge for technological breakthroughs, while industry plays a greater role as technology moves closer to market.
- *Fund all stages of the innovation process from basic research to market deployment of the most promising technologies.* Fundamental breakthroughs are likely to be derived from successes in basic research in fields such as biology, combustion, computing, and materials science. Funding of basic research will be required to provide this foundation. Resources will also be required as these technologies move closer to demonstration and to market.
- *Establish long-term goals and near-term milestones for technological performance to drive progress and to maximize returns on technology investments.* Resources often become locked into supporting certain technologies regardless of performance. Given the challenges in addressing climate change, policy-makers must establish processes that ensure this does not occur.
- *Design flexible research and development programs to allow for the shifting of resources to accommodate new knowledge and conditions, particularly when sufficient technological progress is not being achieved.* The future is uncertain. A technology strategy must adapt to changed circumstances.

**Reflect the international nature of the research challenge.**

- *Develop and coordinate international and national energy technology research and development strategies to take advantage of national scientific strengths and regional needs.* Investment portfolios of nations that invest in energy research and development should be adjusted and coordinated to support more promising technologies consistent with national interests and objectives.
- *Provide assistance to key developing countries to build their technical and institutional capacities for implementing energy research and development programs effectively and for deploying advanced technologies.* Key developing countries require the capability to conduct energy research and development and successfully deploy advanced technologies. Without eventual deployment of advanced energy technologies in the developing world, stabilization of greenhouse gases is not achievable.

## Next Steps

These findings and recommendations demonstrate the importance of technology in addressing climate change and provide general principles for moving forward. These results will be actively communicated to all global climate change stakeholders, and particularly those involved in the international discussions. However, they are only a beginning. With the assistance of our steering group, funders, and international collaborators we have identified general future directions, which will be refined as we move forward.

### Refine the Technology Strategy

The Program's first three years provided a range of important insights and raised important new questions. In the next three years, we plan to refine and enhance these analyses by expanding and deepening our international collaborations, by examining in more detail the special issues facing the transportation sector, and by conducting additional analyses to improve understanding of the value of specific technologies.

### Extend the Technology Strategy

The first phase of the Global Energy Technology Strategy Program focused on carbon dioxide emissions from the energy sector. In the next phase, the Program will broaden its scope to examine the roles of other greenhouse gases and additional categories of carbon sinks in the climate issue. We will examine both projected trends and possible technological responses.

### Investigate Implementation Issues

Key recommendations from the first phase of the program emphasize the need for sustained funding of research and development and for improved coordination of research efforts. In the next phase of the Program, we will engage our team of international collaborators to explore some of these issues in more depth. We will also begin to consider the myriad of issues associated with the deployment of new technologies in developing countries.

### Communicate

Through briefings, periodic reports and the existing website (http://gtsp.battelle.org), the program will continue to communicate insights gained through collaborative research on the technological and policy pathways that governments, businesses, institutions, and individuals can take to minimize the risks of human interference with the climate system.

# Notes

The analyses in this document utilized MiniCAM, an integrated assessment model developed at Battelle in collaboration with scientists in the geographic regions included in the model. The model, its use in developing the technology strategy, and the future scenarios, “Abundant Oil and Gas (AOG)” and “Coal Bridge to the Future (CBF),” are described in the following publications:

Edmonds, J. and M. Wise. 1998. Exploring a technology strategy for stabilizing atmospheric $CO_2$. *Economics Energy Environment.* Fondazione Eni Enrico Mattei, Venice.

Edmonds, J., M. Wise, H. Pitcher, R. Richels, T. Wigley and C. MacCracken. 1997. An integrated assessment of climate change and the accelerated introduction of advanced energy technologies: an application of MiniCAM 1.0. *Mitigation and Adaptation Strategies for Global Change* 1, 311-339.

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

## Figure References

### Chapter 1

The Future With and Without Technological Change. Sources: Pepper et al. (IS92a); Battelle (IS92a(1990 technology)); WRE 1996 (550 PPMV constraint).
Energy R&D Funding is Declining. Source: Dooley 1998.

### Chapter 2

Factors Driving Emissions. Sources: Data for population, gdp per capita, energy intensity and carbon intensity from sources listed later in this chapter.
Distribution of Global Greenhouse Gas Emissions in 1989. Source: Wuebbles and Edmonds 1991.
Emissions Trajectories Consistent with Various Atmospheric $CO_2$ Concentration Ceilings. Source: WRE 1996.
Global Carbon Emissions. Source: CDIAC website.
Carbon Dioxide Concentrations. Source: CDIAC website.
Global Population. Source: IIASA website (history); Pepper et al. 1992 (projections).
Economic Growth Per Capita. Source: Worldwatch Institute (1999); Pepper et al. 1992 (projections).
Global Energy Intensity. Source: IIASA website (history); Pepper et al. 1992 (projections).
Carbon Intensity. Source: Grubler and Nakicenovic 1996 (history); Pepper et al. 1992 (projections).
Fossil Fuel Carbon Emissions. Source: Pepper et al. 1992 (projections).

### Chapter 3

Global Energy Production and Consumption. Source: IIASA web site.
Global Energy Use Today and Tomorrow. Source: Pepper et al. 1992; Battelle analysis.
Regional Energy Use Today and Tomorrow. Source: Pepper et al. 1992.
Carbon Reservoirs and Fossil Fuel Resources. Source: Watson et al. 1996; Edmonds and Reilly 1985.

### Chapter 4

The Future With and Without Technological Change. Source: Pepper et al. 1992 (business-as-usual); WRE 1996 (550 case); Battelle analysis (1990 technologies).
The Technology Gap. Source: Battelle analysis.
Transportation in France. Source: IIASA website.

### Chapter 5

Value of IS92a Energy Technology Improvement. Source: Battelle analysis.
Value of Solar Photovoltaic Technology Improvement. Source: Kim et al. 2000.
Value of Carbon Capture and Sequestration Technologies. Source: Edmonds, et al. 1999.
Technologies that Could Fill the Gap Under Different Energy Resource Futures. Source: Battelle analysis.
Technologies that Could Fill the Regional Gaps. Source: Battelle analysis (US, Japan, Europe); Battelle analysis in coordination with the China Energy Research Institute (China), Indian Institute for Management analysis (India).

### Chapter 6

Energy R&D Funding is Declining. Source: Dooley 1998.
Energy R&D Portfolios of Selected OECD Countries in 1995. Source: Dooley 2000.
Global Energy R&D Investments in 1995. Source: Dooley 2000.

## Figure Sources

CDIAC [Carbon Dioxide Information Analysis Center]. http://cdiac.esd.ornl.gov/
Dooley, J.J. and P.J. Runci. 2000. “Developing Nations, Energy R&D, and the Provision of a Planetary Public Good: A Long-Term Strategy for Addressing Climate Change.” *The Journal of Environment and Development.* Vol. 9, No. 3, September 2000. pp. 216-240.
Dooley, J.J. 1998 (June). “Unintended Consequences: Energy R&D in Deregulated Market.” Energy Policy. pp. 547-555.
Edmonds, J., Dooley, J., and S.H. Kim. 1999. “Long-term energy technology: needs and opportunities for stabilizing atmospheric $CO_2$ concentrations,” in *Climate change policy: practical strategies to promote economic growth and environmental quality.* American Council for Capital Formation, Center for Policy Research, Washington, DC.
Edmonds, J. and J. Reilly. 1985. *Global energy: assessing the future.* Oxford University Press, New York.
Grubler, A. and N. Nakicenovic. 1996. Decarbonizing the global energy system. *Technological Forecasting & Social Change* 53(1):97-110.
IIASA [International Institute for Applied Systems Analysis]. http://www.iiasa.ac.at/
Kim, S., C. MacCracken, and J. Edmonds. 2000. “Solar energy technologies and stabilizing atmospheric $CO_2$ concentrations,” *Progress in Photovoltaics* Special Issue.
Pepper, W.J., J. Leggett, R. Swart, J. Wasson, J. Edmonds and I. Mintzer. 1992. *Emissions scenarios for the IPCC: an update – assumptions, methodology, and results.* Geneva: Intergovernmental Panel on Climate Change.
Watson, R.T., M.C. Zinyowera and R.H. Moss (eds). 1996. *Climate change 1995: impacts, adaptations, and mitigation of climate change: scientific-technical analyses.* Cambridge University Press, Cambridge.
Worldwatch Institute 1999. *Vital Signs.*
WRE [Wigley, T.M.L., R. Richels and J. Edmonds]. 1996. Economic and environmental choices in the stabilization of atmospheric $CO_2$ concentrations. *Nature* 379(6562):240-243.
Wuebbles, D.J. and J. Edmonds. 1991. *Primer on greenhouse gases.* Lewis Publishers, Chelsea, MI.

## For Further Reading

Benedick, R. 2000. “Contrasting approaches: the ozone layer, climate change, and resolving the Kyoto dilemma.” In *Global biogeochemical cycles in the climate system,* E-D Schulze, et.al. (eds). Academic Press, San Diego.
Benedick, R. 1998. *Ozone Diplomacy – New Directions in Safeguarding the Planet.* Enlarged edition. Harvard University Press, Cambridge, MA and London.
Benedick, R. 1998(November). “Auf dem falschen Weg zum Klimaschutz?” *Universitas - Zeitschschrift für Interdisziplinäre Wissenschaft* 629.
Benedick, R. 1998. “How to salvage the Kyoto Protocol.” Resources for the Future, *weathervane*. www.rff.org.
Benson, S.M., W. Chandler, J. Edmonds, J. Houghton, M. Levin, L. Bates, H. Chum, J. Dooley, D. Grether, J. Logan, G. Wiltsee and L. Wright. 1999. Assessment of basic research needs for greenhouse gas control technologies. In *Greenhouse gas control technologies,* P. Riemer, B. Eliasson and A. Wokaun (eds). Elsevier Science Ltd.
Dooley, J., J. Edmonds and M.A. Wise 1999. The role of carbon capture and sequestration in a long-term technology strategy of atmospheric stabilization. In *Greenhouse gas control technologies,* P. Riemer, B. Eliasson and A. Wokaun (eds). Elsevier Science Ltd.
Edmonds, J. 1999. “Beyond Kyoto: toward a technology greenhouse strategy,” *Consequences* 5(1):17-28.
Edmonds, J. 1999. “Future agreements.” In *Economic impact of mitigation measures,* Pan, J., N. van Leeuwen, H. Timmer and R. Swart. (eds). CBP, The Hague, The Netherlands.
Edmonds, J. 1998. “We need some new ideas.” *Climatic Change* 38: 129-132.
Edmonds, J., Dooley, J., and S.H. Kim. 1999. “Long-term energy technology: needs and opportunities for stabilizing atmospheric $CO_2$ concentrations,” in *Climate change policy: practical strategies to promote economic growth and environmental quality.* American Council for Capital Formation, Center for Policy Research, Washington, DC.
Edmonds, J., S. Kim, C. MacCracken, R. Sands, and M. Wise. 1998. *Return to 1990: the cost of mitigating United States carbon emissions in the post-2000 period.* PNNL-11819, Pacific Northwest National Laboratory, Washington, DC.
Edmonds, J., J.M. Roop and M.J. Scott. 2000. *Technology and the economics of climate change policy.* Pew Center on Global Climate Change, Washington, DC.
Edmonds, J., Y. Shi and K. Storck 1999. *Mid- and long-term strategies for technology deployment to address climate change in China.* PNWD-3005. Pacific Northwest National Laboratory, Washington, DC.
Edmonds, J., and M. Wise. 1999. “Exploring a technology strategy for stabilizing atmospheric $CO_2$.” In *International environmental agreements on climate change.* Kluwer Academic Publishers.
Edmonds, J., and M. Wise. 1999. “Resource endowment and mitigation costs.” In *Climate change policy in Germany and the United States.* German-American Academic Council Foundation.
Edmonds, J., and M. Wise. 1998. “Building backstop technologies and policies to implement the Framework Convention on Climate Change.” *Energy & Environment Special Issue—Climate Change Policy in Western Europe and the USA* 9(4) 383-97.
Izaurralde, R.C., N.J. Rosenberg, and R. Lal. 2000. Mitigation of climatic change by soil carbon sequestration: issues of science, monitoring and degraded lands. *Adv. Agron.* 70:1-75.
Kim, S., C. MacCracken, and J. Edmonds. 2000. “Solar energy technologies and stabilizing atmospheric $CO_2$ concentrations,” *Progress in Photovoltaics* Special Issue.
Kinzey, B., M. Wise and J. Dooley. 1998. *Fuel cells: a competitive market tool for carbon reductions.* PNNL-SA-29809. Washington, DC.
Logan, J., J. Edmonds and J. Kejun. 1999. *China economic and environmental modeling workshop: proceedings.* PNWD-SA-4619. Pacific Northwest National Laboratory, Washington, DC.
Rosenberg, N.J., R.C. Izaurralde and E.L. Malone. 1999. *Carbon sequestration in soils: science, monitoring, and beyond.* Proceedings of the St. Michaels Workshop, December 1998. Battelle Press, Columbus, OH.
Sands, R.D., T.Y. Jung and S. Jo. In press. Second Generation Model for Korea. In *Energy and environment models for Korea,* H. Lee and T.Y. Jung (eds).
Schock, R.N., W. Fulkerson, M.L. Brown, R.L. San Martin, D.L. Greene, and J. Edmonds. 1999. *How much is energy R&D worth as insurance?* UCRL-JC-131205. Lawrence Livermore National Laboratory.
Shukla, P.R. 1999. *Technology strategy for India: modeling and analysis of energy and carbon mitigation.* Indian Institute of Management, Ahmedabad, India.

## For More Information

The Global Energy Technology Strategy Program's website provides access to the technical papers that form the basis of the analyses presented in this report. References for the Global Energy Technology Strategy Addressing Climate Change may be found on the website: http://gtsp.battelle.org.

## Project Coordinators

Dr. James A. Edmonds
Battelle
901 D Street, SW, Suite 900
Washington, DC 20024
202-646-5243 (tel)
202-646-5233 (fax)
jae.edmonds@battelle.org

Dr. John F. Clarke
Battelle
901 D Street, SW, Suite 900
Washington, DC 20024
202-646-5280 (tel)
202-646-5233 (fax)
john.clarke@battelle.org

### Acknowledgment

This document represents the collective effort of many individuals. In addition to the members of the Steering Group and the principal authors listed inside the front cover, we would extend special thanks to Dale Heydlauff and Gilbert Jersey for their assistance in developing the Program recommendations and in reviewing document drafts.

This document was designed and produced by Melody Warford and Paul Grabhorn. Norah Davis created the initial draft document and edited the later versions. The result of their efforts is self-evident. We thank them for their excellent work and for their after-hours efforts to get this document finished on time.

Jae and John

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