CHAPTER 1
ENERGY CHALLENGES AND OPPORTUNITIES

Research and development is our Nation's investment in its own future. America's science and technology base may well stand as our most important renewable resource. The overarching public goal of U.S. R&D policy, of which energy R&D is a major component, must be to assure for future generations that our Nation's capacity to shape the future through scientific research and technological innovation is continually being renewed .

Final Report of the Task Force on Strategic Energy Research and Development, Secretary of Energy Advisory Board, U.S. Department of Energy, June 1995.[1]

Adequate, affordable energy supply and efficient energy use are indispensable ingredients of the economic well-being of individuals and nations. In the United States and worldwide, energy accounts for 7 to 8 percent of GDP and a similar share of international trade; global investments in energy-supply technology (oil refineries and pipelines, electric power plants and transmission lines, and so on) total hundreds of billions of dollars per year; and annual global expenditures on items whose energy-using characteristics are potentially important to their marketability (automobiles, aircraft, buildings, appliances, industrial machinery, and more) run into the trillions. When and where energy becomes scarce or expensive, recession, inflation, unemployment, and the frustration of aspirations for economic betterment are the usual results.

Energy is no less crucial to the environmental dimensions of human well-being than to the economic ones. It accounts for a striking share of the most troublesome environmental problems at every geographic scale—from wood smoke in Third World village huts, to regional smogs and acid precipitation, to the risk of widespread radioactive contamination from accidents at nuclear-energy facilities, to the buildup of carbon dioxide and other greenhouse gases (GHG) in the global atmosphere. The growth of energy use, driven by the combination of population increase and economic development, has pushed some of these problems to levels variously disruptive of human health, property, economic output, food production, peace of mind, and enjoyment of nature in many regions. And all of these aspects of human well-being could eventually be impacted over substantial areas of the planet by the kinds of global climatic changes widely predicted to result from continued buildup in the atmosphere of GHGs, most importantly carbon dioxide from fossil fuel combustion.

[1] SEAB (1995). This is the first paragraph of the final report of the Task Force. We agree wholeheartedly with this view—and with much else in that report—and we hope readers of our study will read that one, too.

The importance of energy to national economies and the circumstance that more than a quarter of total world energy supply (including more than half of the oil) is traded internationally make energy a national security issue as well as an economic and environmental one. Gaining or protecting access to foreign energy resources has been a contributing motivation in a number of major conflicts during the twentieth century and could be again in the twenty-first. Another national security dimension of energy is the danger that nuclear-weapons-relevant knowledge and materials will be transferred from civilian nuclear energy programs into national nuclear arsenals or terrorist bombs. Still another is the potential for large-scale failures of energy strategy with economic or environmental consequences serious enough to generate or aggravate social and political instability (this a concern not only in developing countries but also in industrialized ones that fall on hard times).

Improvements in energy technology and the widespread penetration of these improvements in the marketplace in the twenty-first century are badly needed to enhance the positive connections between energy and economic well-being and to ameliorate the negative connections between energy and environment and between energy and international security. Such improvements in technology can lower the monetary and environmental costs of supplying energy, lower its effective costs by increasing the efficiency of its end uses, reduce overdependence on oil imports, slow the buildup of heat-trapping gases in the atmosphere, and enhance the prospects for environmentally sustainable and politically stabilizing economic development in the many of the world's potential trouble spots.

Research and development (R&D) is the only systematic means for creating the needed technical improvements and, therefore, is a necessary (although not always sufficient) condition for improving the energy systems that are actually deployed. What is deployable today is the result of the energy R&D that was done in the past; what will be deployable in the future depends on the R&D that is being done now and that will be done tomorrow. It is important to understand, moreover, that while some kinds of energy R&D can bring quite rapid returns (such as research on finding oil and gas, or on improving the efficiency of electric lightbulbs), the time scales on which most kinds of energy R&D exert a significant influence on deployed energy systems are longer. This is related not only to the time required to complete the R&D but also to the long turnover times of most energy-supply and energy-end-use equipment: on the supply side, for example, three to five decades for electric power plants and oil refineries; on the end-use side, five decades or more for residential and commercial buildings, and a decade or more even for automobiles and household appliances.

These long time scales are one of the reasons that energy R&D is not and should not be left entirely to the private sector, even in a free-enterprise-based economic system such as that of the United States: It is in society's interest to investigate—as part of its strategy for preparing for an uncertain future—some high-potential-payoff energy alternatives for which the combination of a long time horizon for potential economic returns, uncertainty of success, and cost of the R&D makes this pursuit unattractive to private firms. Another rationale for a government role in R&D is that some of the most badly needed improvements in energy technologies relate to "externalities" (such as environmental impacts) and "public goods" (such as national security) that are not valued in the marketplace and hence do not generate the market signals to which firms respond. Still another is that the fruits of some kinds of R&D are difficult for any one firm or small group of firms to appropriate, even though these innovations may be highly beneficial to society as a whole. Finally, the structure of particular energy industries and markets may mask or dilute incentives for firms to conduct R&D from which they, their customers, and society as a whole would all greatly benefit.

The charge to the Panel from President Clinton, spelled out in a letter of January 14, 1997, from the President to his Science and Technology Advisor John H. Gibbons, was to

> *review the current national energy R&D portfolio and make recommendations to me...on how to ensure that the United States has a program that addresses its energy and environmental needs for the next century. The analysis should be done in a global context, and the review should address both near- and long-term national needs including renewable and advanced fission and fusion energy supply options, and energy end-use efficiency.*

Accordingly, the primary aim of this report is to review and recommend improvements in the program of energy R&D supported and coordinated by the United States Federal government, in relation to the energy challenges of the next century and in relation to the energy R&D roles likely to be played by the U.S. private sector, by the states, and by other countries. Within the Federal government, our principal focus is on the energy-technology R&D and fundamental energy-related science and technology programs[2] of the U.S. Department of Energy (DOE), which embody the great bulk of the Federal government's efforts toward development of improved energy technologies.

In the remainder of this chapter, the Panel's findings are presented, beginning with a description of the economic, environmental, and national security challenges likely to be posed by U.S. and world energy supply and demand in the decades ahead, together with a discussion, in general terms, of the leverage that energy R&D could offer against these challenges. Chapter 2 presents current and historical patterns of energy R&D funding by the Federal government, by state governments, by U.S. firms, and by other countries; it also treats the rationales and evolving circumstances affecting the role of government in energy R&D vis-à-vis that of the private sector—including lessons learned from the past few decades of experience with government energy R&D and the implications of recent trends in energy-industry restructuring.

Chapters 3 through 6 provide a closer look at DOE's energy R&D strategy and portfolio, based on the findings of Task Forces formed by the Panel to address the Department's R&D on energy-end-use technologies, fossil fuel technologies, nuclear energy technologies (fission and fusion), and renewable-energy technologies. This material reviews the major program elements within these four compartments of the Department's portfolio, evaluates their effectiveness and prospective leverage (and that of possible additional program elements) against the impending challenges and in the context of government's appropriate role, and makes recommendations about the content and budget of these programs for FY 1999 through FY 2003.

Chapter 7 then addresses issues that cut across the four compartments, including coordination among them, coordination between each of them and the Department's fundamental energy-related science and technology programs, methods for evaluating the entire portfolio in a comprehensive comparative framework, and other issues in the Department's management of its energy R&D.

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[2] Fundamental energy-related science and technology programs are found primarily within the Office of Energy Research at the Department of Energy and include portions of Basic Energy Sciences, Computational and Technology Research, Biological and Environmental Research, and other programs. Although Fusion Energy is also within the Office of Energy Research and is primarily focused on fundamental science, it is examined separately here. The short-hand nomenclature "Basic Energy Sciences" (BES) and "Energy Research" are used interchangeably in this report to refer more formally to the range of fundamental energy-related science and technology programs at the Department of Energy, understanding that the bulk of these activities are within the Office of Energy Research and its Basic Energy Sciences Program.

U.S. AND WORLD ENERGY SUPPLY AND DEMAND

Understanding the challenges to energy R&D requires, first of all, an appreciation of recent and possible future trajectories of U.S. and world energy supply and demand.

In 1995, the 5.7 billion people then on the planet were using inanimate energy forms at a rate of about 420 quadrillion Btus (quads) per year, 75 percent of which was derived from fossil fuels. (See Table 1.1.) About two-thirds of the total supply went to the 1.2 billion people living in industrialized countries, and about one-third went to the 4.5 billion people living in developing countries.

The United States, with 4.6 percent of the world's population in 1995, accounted for about 22 percent of the energy demand. As indicated in Table 1.1, the dependence of U.S. energy supply on fossil fuels—almost 85 percent—was even greater than that of the world as a whole. Nearly 40 percent of U.S. energy supply in 1995 came from oil, half of it imported.

Table 1.1: World and U.S. Energy Supply, 1995[a]

	World	United States
Total Energy Use, Quads[b]	420	91
percent of which is oil	33	38
coal	22	22
natural gas	20	24
biomass fuels [c]	13	3
hydropower	6	4
nuclear	6	8
solar, wind, geothermal	<0.5	0.4

[a] Data from British Petroleum (1996), EIA (1996,1997a) and extrapolation of world biomass fuel estimates from Johannson et al. (1993).
[b] One quad = 1 quadrillion Btus = 1.055 billion gigajoules (1.055 exajoules).
[c] Biomass fuels are wood, charcoal, crop wastes, and manures.

Approximately 30 percent of the 1995 global primary-energy supply was used to make some 12.5 trillion kilowatt-hours of electricity, almost 80 percent of it used in the industrialized countries. As indicated in Table 1.2, the share of the United States alone in world electricity use is about 28 percent. As in overall energy supply, moreover, the United States is even more fossil fuel dependent for electricity generation than is the world as a whole. Coal alone accounts for half of U.S. electricity supply.

Table 1.2: World and U.S. Electricity Supply, 1995

	World	United States
Net Generation, TWh [a]	12,500	3,400
percent of which is fossil fuel	62	68
hydropower	19	9
nuclear	17	20
biomass and other	1	3

[a] TWh - terawatt-hours = billion kilowatt-hours. Figures include nonutility generation.

The pattern of energy end uses in the United States in the mid-1990s is shown in Table 1.3. The patterns are broadly similar in other industrialized countries (although nearly all use substantially less energy per person than the United States) and in the urban/industrial sectors of developing countries. These figures serve to underline the pervasive roles of energy in everyday life and economic activity, the widely distributed responsibility for the environmental impacts of energy supply, and the distribution of opportunities for energy savings through improved end-use efficiency.

The emergence, over the past century and a half, of the fossil fuel era in which we still live is chronicled for the world as a whole in Figure 1.1. Total energy use in 1995 was 20 times larger than in 1850, 4.5 times larger than in 1950. These tremendous increases arose principally from the combination of population growth and rapid economic development in the parts of the world now classified as "industrialized". In the United States, for example, energy use in 1995 was 40 times larger than in 1850 and 2.6 times larger than in 1950; and population growth and growth in energy use per person shared equally in producing the increases, both over the whole period and in the last half century.

Table 1.3: Energy End-Uses in the United States, Mid-1990s[a]

Sector and Energy Service	Percent of primary energy use
Residential buildings	12
of which space heating	50
water heating	20
air conditioning	5
appliances	25
Commercial Buildings	24
of which space heating	35
lighting	21
water heating	16
air conditioning	8
Transportation Fuel	26
of which passenger cars	55
truck freight	25
aircraft	7
Industry and Agriculture	38
of which fuel products	18
chemicals	15
primary metals	8
pulp and paper	8

[a] From EIA (1997a) and IEA (1997). The figures include both electric and nonelectric energy use, with electricity counted as the heat energy that would have been required to generate the electricity in a typical thermal generating station

Fossil fuels, which provided only 12 percent of world energy supply in 1850, accounted in 1995 for 75 percent of the 20-fold larger total supply. In the United States, fossil fuels were providing 85 percent of all energy use in 1995, having increased their energy contribution 350-fold since 1850. It was these tremendous increases in fossil fuel use that brought the absolute magnitude of world combustion to a level capable of materially affecting the composition of the atmosphere not only locally and regionally but globally. And it was the sixfold increase in oil use between 1950 and 1979 that put such immense

economic leverage in the hands of a few countries in the Middle East, which happen to sit on two-thirds of the world's resources of this extremely convenient and versatile fuel.

Under "business-as-usual" assumptions about the energy future, world energy demand in 2030 would be about twice as large—and in 2100 about 4 times as large—as the 1995 figure, and fossil fuel use would increase over these periods by nearly as much. These business-as-usual scenarios entail real rates of global economic growth averaging about 3 percent per year to 2025, falling gradually thereafter toward 2 percent per year, and with rates of decline of the energy intensity of economic activity (i.e., energy use per unit of real GDP) averaging 1 percent per year indefinitely. The fossil fuel intensity of world energy supply, measured as carbon per unit of energy, would decrease only slowly under business-as-usual at perhaps 0.2 to 0.4 percent per year. Fossil fuels would still be supplying about two-thirds of all the world's energy in 2030 and probably more than 50 percent in 2100; in that scenario, the rate of fossil fuel use would increase by 60 percent or more between 1995 and 2030 and by 160 percent between 1995 and 2100. World resources of fossil fuels are sufficient to support such increases, albeit probably with heavier reliance on coal than its 30 percent share of fossil energy in 1995.[3]

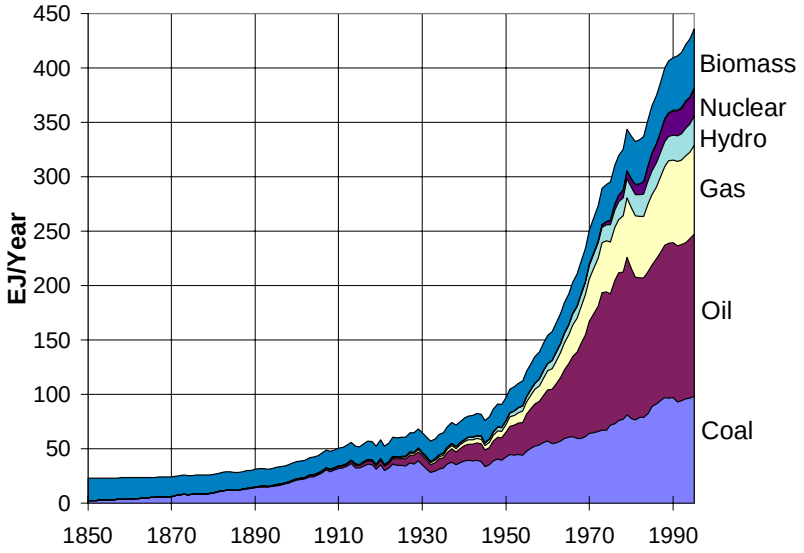

Figure 1.1: World primary energy supply from 1850 to 1995. Source: WEC (1995).

By far the largest part of the future growth of world energy use, in contrast to the growth in the past 150 years, is expected to take place in the currently less developed countries of Asia, Africa, and Latin America that today, with nearly 80 percent of the world's population, still account for only a third of the energy use. Under business as usual, they will pass the industrialized countries in total energy use between 2020 and 2030 and in carbon dioxide emissions at about the same time. (Most of the less developed countries currently plan to power their industrialization primarily with fossil fuels, just as the countries of the North did before them.)

[3] For elaboration on the business-as-usual and other scenarios, the assumptions behind them, and the relation of their energy requirements to world resources, see Leggett et al. (1992), WEC (1993), and WEC (1995). For the case of the United States, see also EIA (1997b).

Business-as-usual forecasts for the United States center around sustained rates of growth of 2 percent per year for real GDP and a sustained rate of decline in energy intensity of 1 percent per year, yielding a 1 percent annual rate of growth in energy use. This would yield about a 40 percent increase in U.S. energy use between 1995 and 2030 and almost a 75 percent increase between 1995 and 2050. The share of U.S. energy supplied by fossil fuels actually increases over the next few decades under business as usual (to 88 percent in 2015 in the Energy Information Administration's 1997 "reference" case, for example), mainly because of projected nuclear-power-plant retirements.

ECONOMIC CHALLENGES IN OUR ENERGY FUTURE

The challenges posed by the energy future to the economic well-being of the United States include: controlling consumer costs for energy and energy-intensive products; reducing oil-import bills; and building international markets for U.S. energy technologies and other products.

Expenditures for energy—electricity and fuels—by individuals and organizations in the United States amounted in the mid-1990s to approximately $500 billion per year or about 7.5 percent of GNP. U.S. energy prices (when adjusted for inflation) are near their long-term historical levels—and very low compared to those of the 1970s and 1980s—but there is no guarantee that they will remain so. They could be driven up by increasing competition for world oil output, by manipulation of the world oil market, by political instability in the Persian Gulf, by environmentally motivated requirements to reduce emissions from fossil fuel combustion, and by other eventualities of both foreseeable and unforeseeable types.

As the oil-price shocks of the 1970s abundantly demonstrated, large and sudden energy-price increases produce not only immediate adverse effects in the form of erosion of purchasing power but also can drive the global economy into recession, at immense economic cost. High energy prices do even more damage to the poor than to the prosperous, because the poor spend a higher fraction of their income on energy, have smaller capacity to invest in energy-efficiency improvements, and are more vulnerable to recession.

The challenge to energy research and development in these connections is to provide additional energy-supply and energy-efficiency options that can reduce U.S. dependence on the imported oil supplies that are subject to sharp price increases, to develop options that can shrink the cost of reducing emissions from fossil fuels (which includes the possibility of replacing some fossil fuel use with nonfossil options less costly than those that would be available for this purpose today), and more generally to develop options that can "backstop" existing energy-supply technologies—that is, provide the possibility of substituting for them if their costs escalate beyond the cost of the backstop option.

U.S. oil imports in 1995 were a $60 billion item on the deficit side of this country's balance-of-payments ledger. DOE's reference forecast shows the U.S. oil-import bill reaching $108 billion per year (1995 dollars) by 2015, at which time this country will be importing 50 percent more oil than in 1995 (Figure 1.2). In this forecast, U.S. use of oil increases from 18 million barrels per day in 1995 to 22 million in 2015, while domestic production falls from 9 million to 8 million barrels per day.[4] Further, to reduce short-term vulnerability to another oil shock, the United States has invested roughly $20 billion in the Strategic Petroleum Reserve.[5] Clearly there is the possibility of a substantial economic benefit from

[4] And it could be worse: the reference forecast assumes significant improvements in vehicle efficiency and in the technology of domestic oil production that might not materialize. See EIA (1997b).
[5] This includes roughly $4 billion to build the Strategic Petroleum Reserve and $17 billion to fill it. CBO (1994).

energy R&D (or other measures) that could lead to reducing U.S. oil imports over the next 20 years to below the trajectory forecasted in DOE's reference case.

The third major U.S. economic stake in the energy future has to do with this country's capacity to sell both energy equipment and other products in international markets. With respect to energy equipment, the value of the world's energy-supply system today—the power plants, oil refineries, pipelines, drilling rigs, transmission lines, and so on—is in the range of $10 trillion at replacement cost. If the average lifetime of these facilities is 30 years, mere replacement of attrition in a system of constant size would entail investments of some $300 billion per year. To meet the business-as-usual projection of a doubling in energy use by 2025, however, the global energy system would need to double in size in the next 30 years, entailing an additional $300 billion per year in investments (assuming that the cost of a given quantity of energy-supply capacity does not change, which of course may not be true).

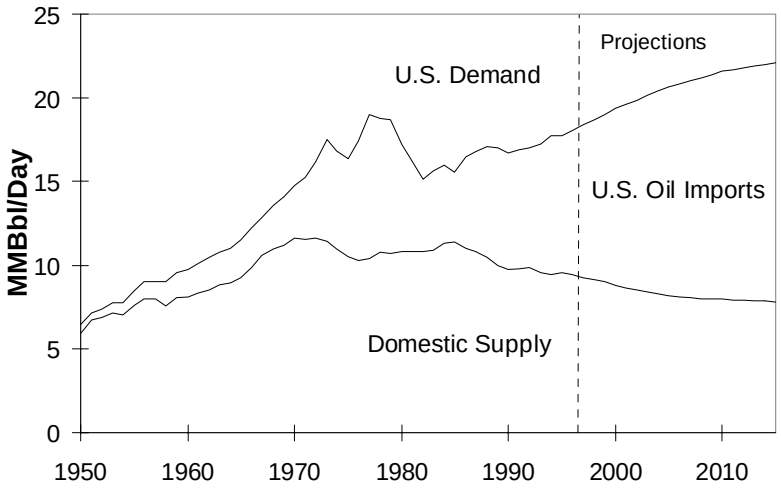

Figure 1.2: Past and projected U.S. oil imports, 1950 to 2015. Source: Historical data are from the Energy Information Administration *Annual Energy Review 1996*. Projections are based on the reference ("business-as-usual") forecast of the EIA *Annual Energy Outlook 1997*.

As a very rough estimate, in any case, the world market for energy-supply equipment and construction of energy-supply facilities over the next 30 years is going to be in the range of several hundred billion dollars per year. The world market for energy-using devices in which energy-use efficiency is an important attribute (such as trucks, automobiles, aircraft, refrigerators, air conditioners, and industrial process equipment) is even larger. The challenge for U.S. energy R&D in this connection is to develop energy technologies of sufficient attractiveness—in relation to those being offered by others—to maintain a substantial share of these immense markets (including the market in the United States, where if we are not diligent we could lose market share to, e.g., Japan, Germany, South Korea, and others). Part of this challenge, of course, is to shape some of our R&D to the economic and environmental needs of the most rapidly growing parts of the international market, such as China and India, rather than only developing energy options tailored for U.S. conditions.

With respect to the capacity of the United States to sell other products in international markets, the connection to energy R&D is through the links between suitable energy technologies and economic growth. Adequate supplies of economically affordable and environmentally tolerable energy are an essential

ingredient of increased economic prosperity around the world. To the extent that U.S. energy R&D can contribute to this end, it will be building potential markets for all of the products that the United States might like to export.

ENVIRONMENTAL CHALLENGES IN OUR ENERGY FUTURE

Energy is perhaps the most intractable part of the planet's environmental problems, both because the impacts of energy systems are the dominant drivers of many of the most troublesome environmental problems at every geographic scale from the local to the global and because the energy-system characteristics that cause these problems are often costly and time-consuming to change. Environmental concerns, similarly, may well prove to be the heart of the energy problem, in the sense that environmental constraints and the costs of coping with them, much more than resource scarcity or the monetary costs of energy technology other than those arising from environmental considerations, may turn out to be the most important considerations in society's choices about how much energy should be supplied from what sources.

At the local level, the most pervasive and difficult environmental problems include acute air pollution, both in the outdoor environment of the world's cities (to which problem the hydrocarbons and particulates emitted in burning fossil and biomass fuels are invariably major contributors, albeit not the only ones) and in the indoor environment of poorly ventilated dwellings in both the urban and rural sectors of developing countries (where coal, fuelwood, charcoal, crop wastes, and dung are burned for heating and cooking). The latter problem is, in light of the combination of extremely high pollutant concentrations and large numbers of women and children exposed to them during a high proportion of the hours of the day, quite clearly an even more consequential problem for global public health than is the outdoor air-pollution problem.[6] Among the world's many local water-pollution problems, those produced by coal-mine drainage, oil-refinery emissions, oil spills from pipelines and tankers, and leakage into groundwater from underground fuel-storage tanks (this last problem one of the most pervasive contributors to putting toxic-waste sites on the Superfund list) are prominent contributions from the energy sector.

Energy-related environmental problems at the regional level include air-basin-wide smogs from the interaction of hydrocarbons and nitrogen oxides and acidic hazes and fogs fed by varying combinations of nitrogen and sulfur oxides. The associated hazards include damage to crops and forests as well as to public health; the culprits are mainly fossil fuels burned in vehicles and power plants. Emissions of oxides of nitrogen and sulfur are also the primary sources of acid precipitation, arguably the dominant form of regional water and soil pollution in areas where soils and surface waters are poorly buffered (a description that applies to tens of millions of square kilometers of the world's land area), with potential impacts on forest health, fish and amphibian populations, nutrient cycling, and mobilization and uptake of toxic trace metals.

At the global level, the emission of heat-trapping carbon dioxide gas from fossil fuel combustion is the largest contributor to the possibility that amplification of the atmosphere's "greenhouse effect" by human activities will significantly change the global climate. (Other important contributors to the buildup of GHGs include carbon dioxide added to the atmosphere by deforestation; methane emanating from agriculture, waste disposal, and fossil fuel production and use; nitrous oxide from agriculture and industrial processes; halocarbons from a variety of industrial processes and products; and tropospheric ozone resulting mainly from emissions of carbon monoxide, nitrogen oxides, and various hydrocarbon compounds.)

[6] Smith (1987,1993).

The evidence is compelling that the global composition of the atmosphere with respect to these heat-trapping gases has already been significantly influenced by human activities, but there has been uncertainty and controversy about whether the imprint of GHG-induced climate change is already discernible in the complex patterns of global temperature, precipitation, cloudiness, oceanic circulation, and so on, all of which are subject to substantial natural variability (which is visible in both the recent and the geologic record). Considerable uncertainty and controversy have also surrounded estimates of the pace at which climatic change will become more pronounced as GHG concentrations continue to grow and about the magnitude and geographic distribution of the physical, ecological, and human consequences.

In the face of growing concerns and continuing controversies about the potential magnitude of this problem and what to do about it, the World Meteorological Organization and the United Nations Environment Programme jointly established, in 1988, the Intergovernmental Panel on Climate Change (IPCC), with a mandate to "(i) assess available scientific information on climate change, (ii) assess the environmental and socioeconomic impacts of climate change, and (iii) formulate response strategies." The First Assessment Report of the IPCC was completed in August 1990 and served as the principal technical input to the negotiation of the United Nations Framework Convention on Climate Change, which was completed at the 1992 Earth Summit in Rio de Janeiro. The Framework Convention, which was signed in Rio by President George Bush and came into force in March 1994, after ratification by 164 nations (including ratification by the United States Senate), included a commitment by the industrialized countries to seek to reduce their emissions of carbon dioxide and other GHGs to 1990 levels by the year 2000. The Framework Convention is described in more detail in Box 1.1.

The IPCC followed up its 1990 "First Assessment" with supplemental assessments in 1992 and 1994 and a major "Second Assessment" completed in 1995 and published in 1996.[7] (Altogether some 2,000 scientists and other specialists from more than 40 countries have served as authors and reviewers of the 17 volumes of exposition and analysis issued by the IPCC through 1996.) Among the principal findings of the 1995 assessment were that:

- "the balance of evidence suggests a discernible human influence on global climate";
- the increase in mean global surface air temperature between 1990 and 2100 under a mid-range emissions scenario would probably fall between 2.2 and 6.5 degrees Fahrenheit;
- "regional temperature changes could differ substantially from the global mean value";
- the warmer temperatures will lead to an increase in sea level (with a "best estimate" for the mid-range scenario of about one-and-a-half feet by 2100, continuing to increase thereafter), an "increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days", and "a more vigorous hydrological cycle";
- "climate change is likely to have wide-ranging and mostly adverse impacts on human health, with significant loss of life";
- "boreal forests are likely to undergo irregular and large-scale losses of living trees because of the impacts of projected climate change";

[7] See IPCC (1990,1992,1994,1996).

- agricultural productivity "is projected to increase in some areas and decrease in others, especially the tropics and subtropics"; and

- "climate change and the resulting sea-level rise can have a number of negative impacts on energy, industry, and transportation infrastructure; human settlements; the property insurance industry; tourism; and cultural systems and values".

The 1995 Assessment also emphasized that many uncertainties remain and called particular attention to the possibility of "surprises" arising from the nonlinear nature of the climate system. And it presented further analyses indicating, as previous IPCC assessments and the work of others have also done, that rapid reductions in the rate of increase of GHG concentrations in the atmosphere will be very difficult to achieve. This is because of the upward pressure of population growth and economic aspirations on energy demand, the large energy contribution and long turnover time (years to decades) of the fossil fuel-burning equipment that produces the largest GHG emissions, and the long residence times of these gases (decades to centuries) in the atmosphere. (See Box 1.2.)

Box 1.1: The UN Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) is the first binding, international legal instrument that deals directly with the threat of climate change. Since its enactment at the 1992 "Earth Summit" in Rio de Janeiro, the Convention has been signed by the United States and 164 other nations (plus the European Union). It came into force on 21 March 1994.

Signatory countries have agreed to take action to realize the goal outlined in Article 2 of the Convention, namely the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." To achieve this, all Parties to the Convention, both developed and developing, are committed under Article 4 to adopt national programs for mitigating climate change; to promote the sustainable management and conservation of GHG "sinks" (such as forests); to develop adaptation strategies; to take climate change into account when setting relevant social, economic, and environmental policies; to cooperate in technical, scientific, and educational matters; and to promote scientific research and exchange of information.

The UNFCCC also establishes more specific obligations for developed countries, which have agreed to seek to reduce their emissions of carbon dioxide and other greenhouse gases to 1990 levels by the year 2000. The OECD countries, in particular, are also committed to facilitate the transfer of financial and technological resources to developing countries, beyond that already available through existing development assistance. The Convention requires developed countries to take the lead in adopting measures to combat climate change, recognizing that they are mainly responsible for historic and current emissions of GHGs, and that developing countries will need assistance to meet the treaty's obligations.

A Conference of the Parties to the UNFCCC scheduled for Kyoto in December 1997 will attempt to reach agreement on a Protocol to the Convention codifying commitments for reductions in GHG emissions after the year 2000. The position on such reductions that will be taken at the Conference by the United States has not been settled at this writing.

SOURCE: UNEP (1997).

Of course, the work of the IPCC to date will not be the last word on the issue of GHG-induced climate change. Some members of the research community think the IPCC's projections of future climate change and its consequences are too pessimistic, while others think they are too optimistic. Some contend that adaptation to climate change would be less difficult and less costly than trying to prevent the change; others argue that a strategy combining prevention and adaptation is likely to be both cheaper and safer than one relying on adaptation alone. Within the PCAST Energy R&D Panel there are significant differences of view on some of these questions.

What is more significant for the purposes of this report, however, is that the Panel is in complete agreement about the implications of the climate-change issue for energy R&D strategy, as follows:

- because there is a significant possibility that governments will decide—in light of the perceived risks of GHG-induced climate change and the perceived benefits of a mixed prevention/adaptation strategy—that emissions of greenhouse gases from energy systems should be reduced substantially and soon, prudence requires having in place an adequate energy R&D effort designed to expand the array of technological options relevant to accomplishing this at the lowest possible economic, environmental, and social cost;

- because of the large role of fossil fuel technologies in the current U.S. and world energy systems, the technical difficulty and cost of modifying them to reduce carbon dioxide emissions, their long turnover times, their economic attractiveness compared to most of the currently available alternatives, and the long times typically required to develop new alternatives to the point of commercialization, this possible GHG-reduction mandate is the most demanding of all of the looming energy challenges in what it requires of national and international energy R&D efforts.

Of course, ameliorating the environmental problems caused by energy supply will be partly a matter, in many circumstances, of putting in place appropriate combinations of incentives and regulations that effectively incorporate environmental costs into the decision-making calculus of energy producers and consumers alike. But improvements in energy technology itself are an essential part of any sensible strategy for addressing environmental problems, providing a means to alleviate the economic burdens and inefficiencies that would be associated with imposition of stringent environmental regulations in the absence of technological advances.

This, then, is the wider environmental challenge to energy R&D: to provide energy options that can substantially ameliorate the local, regional, and global environmental risks and impacts of today's energy-supply system, that can do so at affordable costs and without incurring new environmental (or political) risks as serious as those that have been ameliorated, and that are applicable to the needs and contexts of developing countries as well as industrialized ones (and the sooner the better). It is a big order.

Box 1.2: IPCC Emissions Scenarios and Their Implications

According to the IPCC, world emissions of carbon dioxide from fossil fuel burning amounted to about 6 billion metric tons (tonnes) of contained carbon per year in 1990. (It is customary to keep track of the emissions in terms of their carbon content rather than their total mass, in order to facilitate comparisons with other stocks and flows in the global carbon cycle in which the carbon may be in a variety of different chemical compounds.) The emissions of carbon dioxide from tropical deforestation amounted to about 1.5 billion tonnes per year, with an uncertainty of plus or minus a billion tonnes. The IPCC assumes that rates of tropical deforestation will gradually

decline over the next century, thus becoming even smaller in relative importance compared to the fossil fuel CO_2 emissions.

Also taken into account in the IPCC analysis and its scenarios for future emissions possibilities are the other anthropogenic GHGs—methane, tropospheric ozone, nitrous oxide, and halocarbons—and anthropogenic particulate matter in the atmosphere that partly offsets the heat-trapping effect of the GHGs by screening out incoming sunlight. The IPCC found that, as of the mid-1990s, buildups of the non-CO_2 GHGs had added about 75 percent to the heat-trapping effect that would have resulted by then from the buildup of CO_2 alone; but the IPCC's best estimate of the effect of increasing particle concentrations was that these had approximately cancelled the effect of the increases in non-CO_2 GHGs. In the IPCC "medium" scenario designated IS92a, increases in the effects of atmospheric particles over the next 100 years continue to roughly counterbalance the effects of increases in the non-CO_2 GHGs, so that the net increase in the heat-trapping effect over this period is about what would be expected from the CO_2 buildup alone.

The IS92a scenario is based on a World Bank "medium" population forecast in which world population reaches 11.3 billion by the year 2100. The scenario assumes that real economic growth worldwide averages 2.9 percent per year from 1990 to 2025 and 2.0 percent per year from 2025 to 2100. It also assumes that the energy intensity of economic activity (energy per unit of real GDP) declines at 1.0 percent per year from 1990 to 2100 and that the carbon intensity of energy supply (kilograms of carbon emitted in CO_2 per unit of energy supplied) decreases at 0.2 percent per year over this whole period. The result is that global carbon emissions increase from 7.4 billion tonnes per year in 1990 to 20 billion tonnes per year in 2100, and the cumulative carbon emissions between 1990 and 2100 amount to about 1500 billion tonnes.

The carbon content of the atmosphere in 2100 under the IPCC IS92a scenario would be some 1500 billion tonnes or about 715 parts per million of CO_2 by volume (ppmv), two and a half times the preindustrial level, and still rising steeply. (Only about half of the 1500 billion tonnes of carbon added between 1990 and 2100 would have remained in the atmosphere, the rest having been taken up by the oceans and by vegetation according to the IPCC's carbon-cycle model.) This is the scenario for which the IPCC obtained the surface-temperature and sea-level-rise estimates mentioned in the text. Because of the thermal lag time of the oceans and the continuing melting of polar ice under warmer conditions, the IPCC noted, both temperature and sea level would continue to rise after 2100 even if the growth of atmospheric CO_2 were halted at that point.

The magnitude of the challenge of stabilizing the CO_2 content of the atmosphere, if society decides to do so, is illustrated in the IPCC 1995 Assessment by presentation of emissions trajectories that would be able to achieve stabilization at several different concentrations ranging from 450 to 1000 ppmv. (The preindustrial concentration was about 280 ppmv; today's is 365 ppmv.) These trajectories can be characterized by the cumulative emissions they entail between 1990 and 2100 (although of course what happens after that also matters). The results can be summarized as follows:

To stabilize concentrations at (ppmv):	450	550	650	750	1000
By about the year:	2075	2125	2175	2200	2375
Cumulative emissions, 1990-2100 would need to be in the range of (billion tonnes of carbon):	630-650	870-990	1030-1190	1200-1300	1400
And the peak emissions (billion tonnes of carbon per year) and the year of their occurrence would be:	9.5 in 2012	11 in 2030	12.5 in 2050	13.5 in 2060	15 in 2075

The IPCC's IS92a "medium" scenario, with cumulative emissions of 1500 billion tonnes of carbon between 1990 and 2100 and annual emissions of 20 billion tonnes of carbon per year in 2100, is clearly above even the highest of these stabilization trajectories.

To illustrate the size of the challenge that would be associated with emissions-reductions trajectories of the sort being debated in the course of preparations for the December 1997 Kyoto Conference of the Parties to the U.N. Framework Convention on Climate Change (UNFCCC, see Box 1.1), consider what the numbers above imply for the case in which the stabilization target for atmospheric CO_2 is 550 ppmv, about twice the preindustrial level. This would require that cumulative emissions between 1990 and 2100 be less than two-thirds those in the IS92a "medium" scenario; and it would require that emissions begin to decline after peaking no higher than about 11 billion tonnes of carbon per year around 2030.

The difficulty of doing this becomes particularly apparent when one views it in terms of the roles of the industrialized and developing countries. In 1990, the industrialized countries were emitting about 4.5 billion tonnes of carbon per year from fossil fuel burning (three quarters of the world total, amounting to 3.6 tonnes per inhabitant of these countries). The less developed countries were emitting 1.5 billion tonnes (amounting to about 0.37 tonnes per capita). The industrialized countries agreed in 1992, as part of the UNFCCC, to seek to constrain their year-2000 carbon emissions to 1990 levels, but few are on a track toward achieving this. For example, U.S. carbon emissions in 1997 will be about 9 percent above those in 1990.

If the industrialized countries were now willing and able to return to their 1990 carbon emissions levels by 2010—a decade after the initial UNFCCC target—and if they were further willing and able to reduce these levels by 10 percent per decade thereafter, then staying on a trajectory toward stabilizing atmospheric CO_2 concentrations at 550 ppmv would still require that per capita emissions in the less developed countries in the global peak-emissions year of 2030 should not exceed 1 tonne of carbon per year. (This assumes that emissions from deforestation have been eliminated by 2030 and that the population of the less developed countries is about 7.5 billion at that time, consistent with the "medium" World Bank projection.) Even more challenging, in light of the economic aspirations of the less developed countries and their expectations of relying heavily on expanded fossil fuel use to meet those aspirations, is that their per capita emissions would need to fall quite sharply *after* 2030 (as would those in the industrialized nations) in order to stay on this 550 ppmv stabilization trajectory.

NATIONAL SECURITY CHALLENGES IN OUR ENERGY FUTURE

The most demanding national security challenges associated with energy are three: minimizing the dangers of conflict over access to oil and gas resources; controlling the links between nuclear energy technologies and nuclear-weapons capabilities; and avoiding failures of energy strategy with economic or environmental consequences capable of aggravating or generating large-scale political instabilities.

The proposition that states may go to war over access to resources is solidly rooted in history. Although there are few instances in international affairs in which a single factor explains everything, it is clear that in this century access to energy resources has more than once been a significant motivator of major conflict. Certainly this was a factor in the aspirations of Germany and Japan leading up to World War II; and few would doubt that control of Kuwaiti oil was one of Saddam Hussein's primary goals in invading Kuwait, or that denying him this was one of the primary goals of the U.S.-led coalition in throwing him out. The Persian Gulf, which remains one of the world's more unstable regions politically, today accounts for half of all the world's oil exports, and according to DOE's reference forecast, this figure is likely to reach 72 to 75 percent by 2015. Although exact allocations of the purposes of military spending are not possible, the widely repeated estimates that a quarter or more of the $270 billion per year U.S defense budget is attributable to the need to be prepared to intervene in the Middle East are probably not far wrong.[8]

[8] This sum cannot be simplistically attributed entirely to protection of access to Middle East oil, however, for there are other geopolitical reasons for U.S. concern with this region.

The complexity of the international security dimensions of world oil is likely to increase with the rapid growth of developing countries' presence in the oil market. China, for example, shifted from being a net exporter to a net importer of oil in late 1993, was importing some 600,000 barrels per day by late 1996, and could easily be importing 3 million barrels per day by 2010 and 10 million barrels per day by 2025 (more than the United States is importing today). It would be surprising if oil-import-dependency of these magnitudes did not affect Chinese foreign and military policy, including, perhaps, growing vigor in pressing potentially problematic territorial claims extending to the southern rim of the South China Sea (a region thought to have considerable undersea oil and gas resources).

To say that growing tensions and potential problems for the national security interests of the United States and its allies are likely to arise from intensifying competition for world oil and gas supplies is not to recommend that the United States and other nations pursue energy independence, which is neither feasible nor, in today's multiply interdependent world, even desirable. But it *is* desirable to try to limit the tension-producing potential of overdependence on imports (especially on imports from regions of precarious political stability)—as well as the tension-producing potential of resources of disputed ownership—by working to diversify sources of supply of oil and gas (including domestic supplies in the major importing regions), to develop further the non-oil-and-gas sources of portable fuels and electricity, and to increase the efficiency of energy end use. Clearly, energy R&D has roles to play in all of these connections although, equally clearly, it is not the only leverage point.

Expansion of the use of nuclear energy could provide a partial answer to the import-dependence, air-pollution, and climate-change liabilities of fossil fuels, but it carries significant national security liabilities of its own in the form of the difficult-to-manage linkages between nuclear energy technology and nuclear weaponry. The key point is that while any major country determined to acquire nuclear weapons could choose to do so without resorting to civilian nuclear energy facilities for help, nuclear energy does bring together skills and technologies that could ease the path to weaponry (and lower its cost); and approaches to nuclear energy that involve the use of highly enriched uranium or the separation and recycle of plutonium provide particularly direct routes to weapons—including by theft of these materials by agents of radical states lacking their own nuclear technology, by terrorists, or by middlemen feeding an international black market.

The scale of the global nuclear energy enterprise has grown much more slowly than was widely forecast a few decades ago, partly because of slower-than-expected growth in the electricity sector overall, partly because of nuclear energy's particular problems at the intersection of cost and reactor-safety concerns, and partly because of wider public worries about radioactive-waste management and nuclear weapons proliferation. Growing attention to the climate-change liabilities of fossil fuels might help produce a resurgence of interest in expanding nuclear power, but the size of any such expansion is likely to be very limited unless concerns about cost, safety, wastes, and proliferation are convincingly addressed. All of these issues are challenges not only to the management and regulation of nuclear energy, but also to R&D.

Perhaps the most fundamental and enduring source of conflict in the world is material deprivation or the threat of it. Accordingly, it may well be that the most fundamental and enduring links between energy and international security are those in which energy decisions (or the absence of them) either ameliorate or aggravate widespread economic or environmental impoverishment or the threat of them. Because affordable energy is an indispensable ingredient of material prosperity, it is not hard to see that this energy-economy-security connection must be taken seriously. In light of what is now known or suspected about the potential for widespread damage to human well-being from energy-related environmental impacts—especially, perhaps, from GHG-induced global climate change (with its possible effects on water availability, agricultural output, fisheries yields, forest productivity, disease patterns, sea-

level rise, flows of environmental refugees arising from all of these, and disputes about blame and responsibility)—the energy-environment-security connection increasingly must be taken seriously as well.

On the basis of all of the energy-security linkages just described, a plausible argument can be made that the security of the United States is at least as likely to be imperiled in the first half of the next century by the consequences of inadequacies in the energy options available to the world as by inadequacies in the capabilities of U.S. weapons systems. It is striking that the Federal government spends about twenty times more R&D money on the latter problem than on the former.

THE LEVERAGE OF ENERGY R&D AGAINST THE CHALLENGES

As indicated throughout the foregoing discussion of the challenges connected with the future of U.S. and world energy supply, improvements in energy technology through R&D will be indispensable in making these challenges manageable. Improved energy technologies are needed, for example: to help keep the monetary costs of energy supply at levels that neither stifle economic growth nor put the energy requirements of a decent existence out of reach of the poor; to help avoid overdependence on imports of oil and natural gas from regions of high potential for political instability and loss of world access to these resources; to help reduce the environmental risks and impacts of energy supply, including especially the emissions from energy systems of climate-altering GHGs; and to help ensure that nuclear energy technologies deployed in various parts of the world in the decades ahead are both as safe as practicable and as resistant as practicable to diversion or theft of their nuclear materials for use in weapons.

But how much can energy R&D contribute to the achievement of these aims, as a function of time and in relation to the sums invested in the R&D? It is difficult, indeed impossible, to offer any precise answers to this question, not least because the answers depend strongly on the outcomes of the R&D, which (by the nature of such activity) cannot be predicted in detail. Even if one could predict the rates of technological improvement that would result from R&D, moreover, this would not in itself provide much information about the rates at which these innovations would reach the marketplace, nor about the rates at which, once in the marketplace, they would alter the composition of the stocks of energy-conversion and energy-end-use equipment. (It is changes in these stocks, plus any accompanying changes in the producer and consumer behavior that affect how the stocks are used, that determine, finally, what changes occur in how much energy is used, in what forms, at what costs, and with what environmental impacts.)

In order for energy R&D to make the contributions that are needed and expected from it, then, requires not only devoting adequate resources to such R&D, allocating these resources sensibly among the array of potentially promising focuses, and managing the R&D intelligently so as to get as much potentially useful innovation out of the process as practicable; it also requires attention to overcoming the barriers that can impede the penetration, into the marketplace, of the innovations that R&D produces. Such barriers include lack of knowledge, by prospective users, of the innovations and their benefits; lack of infrastructure for marketing the new technologies; lack of financing for purchasers; lack of a means to achieve sufficient initial market penetration to get the cost-reducing benefits of mass production and learning; and inappropriate subsidies for (or, equivalently, failure to internalize the environmental and other social costs of) the older technologies with which the innovations must compete.

Firms that depend on the application of innovation for their competitiveness tend to be aware of these barriers, and they take steps to overcome them. Governments, which conduct or sponsor R&D that is deemed to be in society's interest but not likely to be conducted or sponsored by the private sector, are often less attentive to the barriers impeding the flow of the resulting innovations into the marketplace. "Enabling" policies that may be necessary and appropriate for overcoming the barriers to society's

capturing the benefits of government-funded energy-technology R&D are discussed in this report in Chapters 3-7. The point to be emphasized here is that predicting the leverage of energy R&D against the challenges described above requires making assumptions not only about what innovations a given R&D program is likely to produce but also about the nature and effectiveness of the enabling policies that are implemented to accelerate the penetration of the worthwhile results into the marketplace. Indeed, the impact on the energy system of the innovations that emerge from R&D will also be affected by policies besides those explicitly intended to affect this (including, for example, tax policies, public-utility-regulatory policies, and so on) and by factors that are partly to largely outside the realm of policy to influence at all, such as the rate of discovery of inexpensive natural gas resources and the rates of growth of national economies.

These complexities of predicting the leverage of energy-technology R&D notwithstanding, there are nonetheless two classes of studies that can provide some insight, however imperfect, into the magnitude of the impact from R&D that might be possible. The first consists of studies of rates of technological improvement, rates of penetration of these improvements into the energy system, and resulting consequences (for patterns of energy supply, economic costs and benefits, and environmental conditions) that have occurred in the energy sector in the past. The other class of studies consists of those combining understanding of what has occurred in the past with hypotheses or educated guesses about what will happen in the future (in outcomes of R&D and in the policies and other circumstances that will affect the diffusion of these) in order to generate scenarios of how innovation could influence the energy future.

In the category of historical data, one can look at rates of improvement in the performance of: the best precommercial technologies of particular types (reflecting mainly the accomplishments of R&D); the best technologies currently on the market (which may reflect, in addition to R&D, the success of other kinds of efforts to overcome the barriers to commercialization); the average technologies currently being sold (which may reflect a still wider array of factors); and the average technologies currently in society's stock of the particular type of equipment (which embodies, in a way, a running record of the recent history of innovation and its success at penetrating the market, integrated over the turnover time of the type of technology in question). The measures of performance tracked in such studies may focus on technical efficiency, economic cost, environmental emissions, or other indices. Still another historical approach is to attempt to determine, using statistical approaches to sort out the contributions of the various factors, the economic rate of return to past investments in R&D.

The evidence from all of these historical approaches supports the proposition that the leverage of R&D, against the challenges now facing the energy system, is likely to be large. Presented in Table 1.4, by way of illustration, are recent rates of improvement in the performance of various energy technologies—measured in terms of the average characteristics of new units and in terms of the average characteristics of all of the units in the stock—as well as recent rates of decline in the energy and carbon intensities of entire economies. Most of the rates of improvement fall in the range of 1.5 to 3 percent per year, corresponding to "doubling" or "halving" times (time periods needed to improve performance twofold) ranging from 23 to 46 years; the highest rate shown, 5 percent per year, would double performance in 14 years.

Of course, experiencing a particular rate of improvement over a period of time does not ensure that this rate will persist over a longer time; in some of the cases shown in Table 1.4, in fact, the rate of improvement dropped sharply after the indicated period. The improvement in the efficiency of coal-fired electric power plants effectively ceased after 1960, for example, both because energy costs of pollution control for such plants were tending to offset efficiency gains elsewhere in the plant, and because the extra construction costs of making plants of the prevailing type still more efficient could not be offset by the savings in fuel costs that would result.

On the other hand, rates of improvement of specific technologies (such as incandescent lightbulbs or fossil fueled power plants based on steam cycles) are of no use in predicting the "surprises" that R&D may bring in the form of entirely new approaches to the same problems (such as fluorescent bulbs or fossil fueled power plants based on fuel cells) that can drastically improve performance. Aggregate historical measures such as energy intensity or carbon intensity in whole economies do capture the past effects of such revolutionary developments, however. With due attention to these complexities, the rates of improvement shown in Table 1.4 can be taken as roughly indicative of what has been achievable in periods when technological possibilities, the technical skills to exploit them, and incentives to do so were all present.

Table 1.4: Annual Rates of Improvement in Energy-Technology Performance

Technology & Measure	Time Period	Annual Rate[a]	Reference
Average New Technologies in the Marketplace			
New car fuel intensity normalized to vehicle weight (liters per 100 km and 100 kg), U.S.	1973-1983	-3.7%	IEA (1997, p.21)
New car fuel intensity normalized to vehicle weight (liters per 100 km and 100 kg), France	1980-1993	-2.0%	IEA (1997, p.21)
Residential space-heating intensity for new gas-heated houses (MJ per square meter and degree-day), U.S.	1954-1989	-1.6%	IEA (1997, p.151)
Electricity intensity of average refrigerator sold (kWh per year per cubic foot), U.S.	1972-1993	-2.0%	IEA (1997, p.160)
Electricity intensity of average room air conditioner sold (kWh per million Btu), U.S.	1972-1993	-5.0%	IEA (1997, p.160)
Average of All Deployed Technologies			
Fuel intensity of electric-utility fossil fueled electricity generation (MJ per kWh), U.S.	1920-1960	-3.0%	Census (1975)
Fuel intensity of all cars on the road (liters per 100 km for the fleet), U.S.	1973-1993	-2.1%	IEA (1997, p.21)
Energy intensity of space heating for all housing (MJ per square meter and year), U.S.	1973-1992	-2.6%	IEA (1997, p.153)
Electricity use of all refrigerators in households (kWh per refrigerator per year), U.S.	1973-1992	-1.2%	IEA (1997, p.30)
Energy intensity of steel production (GJ per tonne), U.S.	1970-1990	-1.4%	IEA (1997, p.217)
Energy intensity of all economic activity (GJ per constant dollar of GDP), U.S.	1920-1970 1970-1990	-1.0% -1.9%	Census (1975) EIA (1997)
Carbon intensity of all economic activity, corrected for structural change (grams C per constant dollar of GDP), U.S.	1970-1990	-1.9%	IEA (1997, p.43)
Carbon intensity of all economic activity, corrected for structural change (grams C per constant dollar of GDP), France	1976-1991	-3.7%	IEA (1997, p.43)

[a] Note that a rate of decline of 2 percent per year in an index (e.g., energy intensity, cost of energy, emissions per unit of output) will, if it persists, halve the index in 35 years; a rate of decline of 4 percent per year will halve it in 18 years.

The time required to improve the performance of a whole sector of deployed energy-supply or end-use technologies (say, fossil fuel electricity generation or residential lighting) tends to be longer than would be suggested by looking at historical and potential rates of improvement of the best-extant precommercial and commercial technologies of the relevant types. This is because the "sectoral improvement time" depends not only on how rapidly improvements in the sector's constituent technologies materialize, but also on the time required for the improved technologies to come to dominate the market for new units and on the

time required for new units to replace a substantial fraction of society's total stock of this type of equipment (the "turnover" time). Table 1.5 shows some typical turnover times for energy-conversion and energy-end-use technologies, which illustrate why transforming the performance of whole energy systems takes decades—even when the rate of innovation in technology is high.

Still another way to address the issue of the leverage of energy R&D against the challenges of the future is to study the rates of return to investments in such R&D, based on historical data. There has been a considerable number of such studies for R&D in general and a smaller number for energy R&D. Although this approach is beset with analytical difficulties and the results are sometimes controversial, most such studies find the rates of return to be high. Indeed, most analysts of these matters contend that a substantial fraction of the total productivity growth in industrial societies is attributable to technological innovation, hence to R&D. Studies of the returns to R&D in specific firms and industries have typically shown rates in the range of 20 to 30 percent per year. Societal rates of return—considering not only the private benefits captured by firms that do R&D but also benefits that accrue to society as a whole—are typically found to be higher, averaging 50 percent per year according to one recent review.[9] Studies of the returns to energy R&D have been generally consistent with these findings.[10]

Table 1.5: Turnover Times for Energy Supply and End-Use Technologies

Technology	Turnover Time
Incandescent light bulbs	1-2 years
Industrial process equipment	3-20
Home appliances	5-15
Oil and gas drilling rigs	5-20 [a]
Oil Refineries	10-30 [a]
Electric power plants	30-50 [a]
Residential and commercial buildings	50-100 [a]

[a] Although the turnover time for these large installations runs into the decades, some of their subsystems may be replaced on a shorter time scale.

A related but future-oriented approach is to try to develop quantitative estimates of the potential value of energy R&D as "insurance" against eventualities that are uncertain but would have very high costs if they occurred in the absence of improved energy options that could reduce the costs. This approach entails making judgments about the probabilities of specific eventualities (such as an oil-import cutoff or a government decision that GHG-emissions must be sharply reduced) and about the likely effectiveness of technological improvements generated by R&D in reducing the costs of these eventualities. Such judgments are difficult and, inevitably, debatable. It is worth noting, nonetheless, that one recent analysis along these lines found that, for a range of assumptions, the insurance value of energy R&D in relation to

[9] Nadiri (1993).

[10] A number of both the general and the energy-specific studies of returns to investments in energy R&D are discussed in the Secretary of Energy Advisory Board's study of two years ago on strategic energy R&D (SEAB 1995). See also Dooley (1996) and Chapter 8 of the National Science Board's **Science and Engineering Indicators 1996** (NSB 1996). Note that a high aggregate return to investments in a sector of energy R&D does not ensure that individual R&D projects in that sector will yield high returns in the future. It is precisely in the nature of research that returns to investments in individual projects cannot be predicted. Indeed, that some individual research projects fail to yield any gain to society should not be considered a lapse on the part of researchers or their managers, since any program of research in which everything succeeds is not exploring the frontiers. It is for this reason that Frosch (1995) has argued that returns to research should *only* be calculated for whole programs, dividing the benefits from the program by the investments made in it, rather than for individual projects.

possible oil-price-shocks and GHG-reduction mandates would justify higher Federal investments in such R&D than are being made today.[11]

Finally, several recent, major studies have addressed the potential of improved technologies of energy supply and end use for reducing CO_2 emissions at the national and global levels. These studies have approached the issue of GHG mitigation from different perspectives and with different assumptions underlying their analyses, but they are in general agreement that it would be possible, with the help of improved technologies for increasing energy-end-use efficiency and decreasing the carbon emissions from energy supply, to reduce future CO_2 emissions to much less than expected under business as usual while maintaining economic growth at close to business-as-usual rates. Some of the relevant features of four of these studies are compared in Table 1.6.

Table 1.6: Projected Rates of Technical Improvement in Recent CO_2 Studies.

Study	**Period**	**Real GDP** annual rate of change	**Energy Intensity** annual rate of change	**Carbon Intensity** annual rate of change	**Carbon Emission** annual rate of change	**Largest supply-side contributors to carbon reductions**
U.S. Studies						
DOE (1997) [a]	1997-2010	1.9%	-1.7%	-0.9%	-0.8%	natural gas, biomass
ASE (1997) [b]	1990-2010	2.2%	-1.9%	-0.7%	-0.5%	natural gas, biomass
World Studies						
WEC (1995) [c]	1990-2050	2.2%	-1.4%	-1.1%	-0.3%	biomass, natural gas
IPCC (1996) [d]	1990-2050	3.3%	-2.5%	-1.5%	-0.7%	biomass, natural gas

[a] DOE (1997) was prepared for the Department of Energy by a group of five national laboratories.
[b] ASE (1997) was performed by a group of five nongovernmental organizations.
[c] WEC (1995) was a joint effort of the World Energy Commission and the International Institute of Applied Systems Analysis.
[d] IPCC (1996) refers to the LESS scenarios (Low CO_2-emission Energy Systems) in the Report of Working Group II to the IPCC Second Assessment.

Without endorsing any particular scenario as the "right" one for the energy future of the United States or the world, the Panel notes that these recent studies all derive their conclusions about the feasibility of significantly constraining CO_2 emissions from assumptions about rates of technological change in the energy field that are not inconsistent with what has been achieved in the past when possibilities and incentives for innovation were both present. It is worth noting also that the studies all found that advanced energy technologies for the power-generation, buildings, industry, and transportation sectors that are available for implementation in the short term could achieve significant energy savings and reductions in GHG emissions over the next decade or so. But these technologies are the result of past investments in energy R&D programs. In the longer term, as these studies all point out, further improvements in energy efficiency, emissions characteristics, and indeed other features of an energy mix responsive to the full range of energy challenges that the next century will pose can occur only through further investments in energy R&D. If too little is put into this R&D "pipeline" now, too little will come out later, when a continuing stream of innovations will be required.

[11] Schock et al. (1997).

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