EXECUTIVE SUMMARY

The United States faces major energy-related challenges as it enters the twenty-first century. Our economic well-being depends on reliable, affordable supplies of energy. Our environmental well-being—from improving urban air quality to abating the risk of global warming—requires a mix of energy sources that emits less carbon dioxide and other pollutants than today's mix does. Our national security requires secure supplies of oil or alternatives to it, as well as prevention of nuclear proliferation. And for reasons of economy, environment, security, and stature as a world power alike, the United States must maintain its leadership in the science and technology of energy supply and use.

All of these energy-related challenges to the well-being of this country are made more acute by what is happening elsewhere in the world. The combination of population growth and economic development in Asia, Africa, and Latin America is driving a rapid expansion of world energy use, which is beginning to augment significantly the worldwide emissions of carbon dioxide from fossil fuel combustion, increasing pressures on world oil supplies, and exacerbating nuclear proliferation concerns. Means must be found to meet the economic aspirations and associated energy needs of all the world's people while protecting the environment and preserving peace, stability, and opportunity.

Improvements in energy technologies, attainable through energy research and development, are the key to the capacity of the United States to address—and to help the rest of the world address—these challenges.

Many of the energy R&D programs of the Federal government, which are primarily conducted by the Department of Energy (DOE), have been well focused and effective within the limits of available funding. But these programs, taken as a whole, are not commensurate in scope and scale with the energy challenges and opportunities the twenty-first century will present. (This judgment takes into account the contributions to energy R&D that can reasonably be expected to be made by the private sector under market conditions similar to today's.) The inadequacy of current energy R&D is especially acute in relation to the challenge of responding prudently and cost-effectively to the risk of global climatic change from society's greenhouse-gas emissions, of which the most important is carbon dioxide from combustion of fossil fuels. Much of the new R&D needed to respond to this challenge would also be responsive to the other challenges.

SYNOPSIS OF MAIN RECOMMENDATIONS

To close the gap between the current energy R&D program and the one that the challenges require, the Panel recommends strengthening the DOE applied energy-technology R&D portfolio by increasing funding for four of its major elements (energy end-use efficiency, nuclear fission, nuclear fusion, and renewable energy technologies) and restructuring part of the fifth (fossil fuel technologies). We also recommend better coordination between the Department's applied energy-technology programs and the fundamental research carried out in the program on Basic Energy Sciences; increased Department efforts in integrated analysis of its entire energy R&D portfolio and the leverage the portfolio offers against the energy challenges of the next century; targeted efforts to improve the prospects of commercialization of the fruits of publicly funded energy R&D in specific areas; increased attention to certain international aspects of energy R&D; and changes in the prominence given to energy R&D in relation to the Department's other missions, coupled with changes in how this R&D is managed.

Applied Energy-Technology R&D Recommendations

The overall budgets we propose for applied energy-technology R&D to the year 2003, based on analyses summarized in our main report and set out in more detail in its appendices, are summarized in Table ES.1. (The table provides these figures both in as-spent dollars, which are the usual currency of official budget planning, and in constant 1997 dollars, which are more informative about what is really happening to the size of the effort.)

The applied energy-technology R&D programs, which have been the main focus of the Panel's study and which are shown in Table ES.1, contain only part of the activities constituting DOE's congressional budget lines for "Energy R&D." Table ES.2 shows the relation, under the FY 1997 congressional appropriation and the FY 1998 DOE request, between the amount budgeted for the activities included in our "applied energy-technology R&D" category and the amounts budgeted for the other activities included under "Energy R&D" in the congressional budget lines. (Table ES-3 at the end of the Executive Summary provides more detail.)

The Panel was not able to review in detail the Basic Energy Sciences budget line (which includes research in materials science, chemistry, applied mathematics, biosciences, geosciences, and engineering that is not directed at the development of a particular class of energy sources), and it did not review at all the other "Energy R&D" budget lines shown in Table ES.2 (which contain mostly items that are either not very closely linked to advances in civilian energy technology or are not really R&D at all). Accordingly, we do not offer any recommendations about the future sizes of these budgets. We note, however, that because advances produced by research in the Basic Energy Sciences category provide an important part of the expanding knowledge base on which progress in applied energy-technology R&D in the public and private sectors alike depends, the Department may want to consider expanding its support for Basic Energy Sciences as the applied energy-technology R&D areas grow.

As indicated in Table ES.1, our proposals for the applied energy-technology R&D programs would increase spending in that category from $1.3 billion in 1997 to $2.4 billion in

2003, in as-spent dollars. In constant-dollar terms, the increase from 1997 through 2003 is 61 percent, amounting to an average real growth rate of 8.3 percent per year. The proposed figure for 2003 would return DOE's real level of effort in applied energy-technology R&D in that year to about where it was in FY 1991 and FY 1992.

Table ES.1: Recommended DOE Budget Authority for Applied Energy-Technology R&D

In millions of as-spent dollars

	1997 actual	1998 request	1999	2000	2001	2002	2003
Efficiency[a]	373	454	615	690	770	820	880
Fission	42	46	66	86	101	116	119
Fossil	365	346	379	406	433	437	433
Fusion	232	225	250	270	290	320	328
Renewables	270	345	475	585	620	636	652
TOTAL	1282	1416	1785	2037	2214	2329	2412

In millions of constant 1997 dollars

	1997 actual	1998 request	1999	2000	2001	2002	2003
Efficiency	373	442	584	638	695	721	755
Fission	42	45	63	80	91	102	102
Fossil	365	337	360	376	391	384	371
Fusion	232	219	237	250	262	281	281
Renewables	270	336	451	541	559	559	559
TOTAL	1282	1379	1695	1885	1998	2047	2068

[a] What is called "energy end-use efficiency" in this report and is abbreviated as "efficiency" in these tables appears as "conservation" in many budget documents.

Of the Panel's proposed increases in DOE's applied energy-technology R&D accounts, the largest in dollar magnitude is in the end-use-efficiency programs, in which annual spending in FY 2003 would reach $880 million, about $500 million more than in 1997 (as-spent dollars). This large increase is appropriate because of the high promise of advanced efficiency technologies for relatively quick-starting and rapidly expanding contributions to several important societal goals, including cost-effective reductions in local air pollution and carbon dioxide emissions, diminished dependence on imported oil, and reductions in energy costs to households and firms.

Improvements in energy efficiency reduced the energy intensity of economic activity in the United States by nearly one-third between 1975 and 1995, an improvement that is now saving U.S. consumers about $170 billion per year in energy expenditures and is keeping U.S. emissions of air pollutants and carbon dioxide about one-third lower than they would otherwise be.

Table ES.2: Relation of Applied Energy Technology R&D to "Total Energy R&D"

In millions of as-spent dollars.

	1997 actual	1998 request
APPLIED ENERGY TECHNOLOGY R&D	1282	1416
"Energy Research": Basic Energy Sciences[a]	641	661
"Energy Research": Other Non-Fusion	539	585
"Other Nuclear R&D"	216	255
"Other Conservation R&D"	177	234
TOTAL "ENERGY R&D" BUDGET LINES	2855	3151

[a] DOE's Office of Energy Research includes the Department's R&D on fusion energy, as well as Basic Energy Sciences and some other science and technology programs including biomedical and environmental research, research in computing, and science education. "Other Conservation R&D" includes the State and Local Partnership Programs and the Federal Energy Management Program (which are not really R&D at all), among other items. "Other Nuclear R&D" includes radioisotope power sources for spacecraft and isotopes for medical applications, among other items. The Panel included fusion in its analysis of applied energy-technology R&D (although, as noted in that analysis, much fusion R&D is in fact basic science).

Further major increases in efficiency can be achieved in every energy end-use sector: in transportation, for example, through much more fuel-efficient cars and trucks; in industry through improved electric motors, materials-processing technologies, and manufacturing processes; in residential and commercial buildings through high-technology windows, super-insulation, more efficient lighting, and advanced heating and cooling systems.

The second largest of the Panel's proposed increases is for renewable energy technologies, in which annual spending in FY 2003 would reach $650 million, nearly $400 million more than in 1997 (as-spent dollars). This increase makes sense in light of the rapid rate of cost reduction achieved in recent years for a number of renewable energy technologies; the good prospects for further gains; and the substantial positive contributions these technologies could make to improving environmental quality, reducing the risk of climate change, controlling oil-import growth, and promoting sustainable economic development in Africa, Asia, and Latin America.

Opportunities exist for important advances in wind-electric systems, photovoltaics, solar-thermal energy systems, biomass energy technologies for fuel and electricity, geothermal energy, and a range of hydrogen-producing and hydrogen-using technologies, including fuel cells. As in the case of the proposed increases in energy-efficiency R&D, the increased support for these renewable energy technologies would focus on areas where the expected short-term returns to industry are insufficient to stimulate as much R&D as the public benefits warrant.

Fusion R&D is proposed for the third largest increase; annual spending for it in FY 2003 would reach about $100 million more than the 1997 figure in as-spent dollars. In this scenario, fusion funding would reach by 2002 the $320 million figure recommended in the 1995 PCAST study of fusion energy R&D as a constant level of spending in as-spent dollars to be maintained

from FY 1996 onward. (This earlier PCAST recommendation did not prevail, and fusion funding fell instead from $369 million in FY 1995 to $232 million in FY 1997.)

The Panel judges this amount warranted for two reasons: (1) About $200 million per year of it would continue a very productive element of the country's basic science portfolio (comparing favorably in cutting-edge contributions and valuable spinoffs with other fields in that category); and (2) the rest is easily justified as the sort of investment the government should be making in a high-risk but potentially very-high-yield energy option for society, in which the size and time horizon of the program essentially rule out private funding.

DOE's R&D in nuclear-fission energy systems, which fell 12-fold in real terms between 1986 and 1997, would increase under our proposal from about $40 million per year in FY 1997 to about $120 million per year in 2003 (as-spent dollars), thereby returning in real level of effort to that of 1995. Nuclear fission currently generates about 17 percent of the world's electricity; if this electricity were generated instead by coal, world carbon dioxide emissions from fossil fuel consumption would be almost 10 percent larger than they currently are.

Fission's future expandability is in doubt in the United States and many other regions of the world because of concerns about high costs, reactor-accident risks, radioactive-waste management, and potential links to the spread of nuclear weapons. We believe that the potential benefits of an expanded contribution from fission in helping address the carbon dioxide challenge warrant the modest research initiative proposed here, in order to find out whether and how improved technology could alleviate the concerns that cloud this energy option's future. To write off fission now as some have suggested, instead of trying to fix it where it is impaired, would be imprudent in energy terms and would risk losing much U.S. influence over the safety and proliferation resistance of nuclear energy activities in other countries. Fission belongs in the R&D portfolio.

Energy from fossil fuels currently contributes 85 percent of U.S. annual energy use and 75 percent of the world's. These fuels will continue to provide immense amounts of energy through the middle of the next century and beyond, under any plausible scenario. We judge that DOE's current fossil-energy R&D program is about the appropriate size in relation to the array of relevant needs, opportunities, and likely continuing private sector fossil-energy R&D activities. Our proposed budget for DOE's fossil-energy R&D, which increases funding in as-spent dollars by about $70 million per year between 1997 and 2003, actually holds the real level of effort approximately level near its FY 1997 value of $365 million per year.

We do, however, recommend some changes in emphasis within this program. Specifically, we propose phasing out DOE's R&D on near-term coal-power technologies and promptly ending the funding for direct coal liquefaction, while increasing the Department's R&D on advanced coal-power programs, carbon capture and sequestration, fuel cells and other hydrogen technology, and advanced oil and gas production and processing. These changes are designed to increase the responsiveness of DOE's fossil energy R&D to the carbon dioxide and oil-import challenges (including technology-export opportunities that could favorably affect other countries' carbon emissions and oil imports while improving the U.S. balance of payments), and to improve the program's complementarity with (or help to stimulate) R&D efforts in the private sector.

Our recommendations for R&D initiatives in the efficiency, renewables, fusion, fission, and fossil fuel components of DOE's applied energy-technology portfolio are described in more detail later in this Executive Summary and are summarized, together with the budgets we propose for these efforts, in Table ES.3.

Recommendations on Crosscutting Issues

The Panel recommends that coordination between the Basic Energy Sciences program and the applied energy-technology programs be improved using mechanisms such as comanagement and cofunding.

We recommend that the Department make a much more systematic effort in R&D portfolio analysis: portraying the diverse characteristics of different energy options in a way that facilitates comparisons and the development of appropriate portfolio balance, in light of the challenges facing energy R&D and in light of the nature of private sector and international efforts and the interaction of U.S. government R&D with them.

After consideration of the market circumstances and public benefits associated with the energy-technology options for which we have recommended increased R&D, the Panel recommends that the nation adopt a commercialization strategy in specific areas complementing its public investments in R&D. This strategy should be designed to reduce the prices of the targeted technologies to competitive levels, and it should be limited in cost and duration.

The Panel recommends that the government and government/national-laboratory/industry /university consortia should engage strongly in international energy technology R&D and, where appropriate, development and commercialization efforts to regain and/or maintain the scientific, technical, and market leadership of the United States in energy technology.

We recommend that overall responsibility for the DOE energy R&D portfolio should be assigned to a single person reporting directly to the Secretary of Energy, and that, similarly, a single individual should be given the responsibility and authority for coordination of crosscutting programs between the applied-technology programs, reporting to the single person responsible for the overall R&D portfolio.

The Panel recommends that industry/national-laboratory/university oversight committees should work with DOE to provide overall direction to energy R&D programs, with DOE facilitating and administering the process; and we recommend that all DOE energy R&D programs undergo outside technical peer review every 1-2 years, while interim internal process-oriented reviews are reduced to a minimum.

Additional recommendations and discussion on crosscutting issues appear later in this Executive Summary.

RATIONALE FOR THE RECOMMENDATIONS

The rationale for the recommendations summarized above—and for others to be found in the more detailed treatment later in this Executive Summary—is presented in what follows in terms of the importance of energy to our national well-being, the evolution of U.S. and world energy supply and demand, the challenges this evolution poses to energy R&D, recent trends in public and private funding for energy R&D, and the implications of those trends (and the energy R&D status quo) for the prospects of meeting the energy and environmental challenges of the next century.

The Importance of Energy

The characteristics of the technologies available to this nation and others for energy supply and energy end-use are critical to our country's economic well-being, environmental quality, and national security:

- Economically, expenditures on energy account for 7 to 8 percent of gross economic product in the United States and worldwide and a similar fraction of the value of U.S. and world trade. Experience has shown that periods of excessive energy costs are associated with inflation, recession, and frustrated economic aspirations. Sales of new energy-supply technologies globally run in the multi-hundreds of billions of dollars per year.

- Environmentally, energy supply accounts for a large share of the most worrisome environmental problems at every geographic scale—from woodsmoke in Third World village huts, to regional smogs and acid precipitation in industrialized and developing countries alike, to the risk of widespread radioactive contamination from accidents at nuclear energy facilities, to the build-up of carbon dioxide and other heat-trapping gases in the global atmosphere.

- National security is linked to energy through the increasing dependence of this country and many others on imported oil, much of it from the politically troubled Middle East; through the danger that nuclear-weapons-relevant knowledge and materials will be transferred from civilian nuclear energy programs into national nuclear arsenals or terrorist bombs; and through the potential for large-scale failures of energy strategy with economic or environmental consequences serious enough to generate or aggravate social and political instability.

Scientific and technological progress, achieved through R&D, is crucial to minimizing current and future difficulties associated with these interactions between energy and well-being, and crucial to maximizing the opportunities. If the pace of such progress is not sufficient, the future will be less prosperous economically, more afflicted environmentally, and more burdened with conflict than most people expect. And if the pace of progress is sufficient elsewhere but not in the United States, this country's position of scientific and technological leadership—and with it

much of the basis of our economic competitiveness, our military security, and our leadership in world affairs—will be compromised.

Past, Present, and Projected Patterns of Energy Supply

The challenges and opportunities associated with the economic, environmental, and national security dimensions of energy have become what they are primarily as a consequence of the tremendous increase in energy use, and especially fossil fuel use, over the past century and a half. This increase, in which world energy use grew 20-fold between 1850 and 1995 and fossil fuel use increased more than 100-fold, arose principally from the combination of population growth and rapid economic development in the industrialized countries.

In contrast, by far the largest part of the *future* growth of world energy use is expected to take place in the currently less developed countries of Asia, Africa, and Latin America. Today, with nearly 80 percent of the world's population, these countries still account for only a third of the energy use. But if recent trends continue (the "business as usual" energy future), they will pass the industrialized countries in total energy use (and in carbon dioxide emissions) between 2020 and 2030, and their growth will be the primary driver of a doubling in global energy use between 1995 and 2030 and a quadrupling between 1995 and 2100.

Energy use in industrialized countries would continue to increase in a business-as-usual future, but not as rapidly as in the less developed countries and not as rapidly as in the past. A business-as-usual energy trajectory for the United States would entail increases in energy use, above the 1995 level, of about 40 percent by 2030 and nearly 75 percent by 2100.

The fossil fuels—oil, natural gas, and coal—accounted for 75 percent of energy supply worldwide in 1995. The remainder was nuclear energy (6 percent), hydropower (6 percent), and biomass fuels (13 percent, mostly fuelwood in developing countries), with wind, solar, and geothermal energy together contributing less than half a percent. The dominance of the fossil fuels would decline only slowly in a business-as-usual future: the world as a whole would still be obtaining perhaps two-thirds of all its energy needs from fossil fuels in 2030 and half or more in 2100. Fossil fuel resources are adequate to support such an outcome, albeit perhaps with higher dependence on coal than today, relative to oil and gas.

The United States obtained 85 percent of its energy from fossil fuels in 1995, nearly 40 percent from oil alone (of which half was imported). U.S. fossil fuel dependence, like that of the rest of the world, would decline only slowly in a business-as-usual future. U.S. oil imports, according to the "reference" forecast of the Department of Energy, would grow from 9 million barrels per day in 1995 to 14 million barrels per day in 2015 and continue to increase for some time thereafter.

The Challenge to Energy R&D

Improvements in energy technology can and must play a major role in reducing the costs, increasing the benefits, and alleviating the perils that a business-as-usual energy future without such improvements would be likely to entail.

Energy-technology improvements, achieved in the United States and then deployed here and elsewhere, could:

- lower the monetary costs of supplying energy;
- lower its effective costs still further by increasing the efficiency of its end uses;
- increase the productivity of U.S. manufacturing;
- increase U.S. exports of high-technology energy-supply and energy-end-use products and know-how;
- reduce over-dependence on oil imports here and in other countries, thus reducing the risk of oil-price shocks and alleviating a potential source of conflict;
- diversify the domestic fuel-supply and electricity-supply portfolios to build resilience against the shocks and surprises that an uncertain future is likely to deliver;
- reduce the emissions of air pollutants hazardous to human health and to ecosystems;
- improve the safety and proliferation resistance of nuclear energy operations around the world;
- slow the build-up of heat-trapping gases in the global atmosphere; and
- enhance the prospects for environmentally sustainable and politically stabilizing economic development in the many of the world's potential trouble spots.

The direct and indirect effects of the pursuit of improved energy technologies for these purposes through appropriately sized, tailored, and publicized R&D programs, moreover, will strengthen this country's science and technology base, bolster our research universities, build effective industry/government/university partnerships, help to stem the decline in enrollments of our most talented young people in science and engineering disciplines, and contribute to maintaining the global leadership and influence of the United States in relation to scientific and technological developments worldwide and their application to the betterment of the human condition.

Among all of these good reasons for adequately funded, suitably focused, effectively managed energy R&D, one is particularly demanding in what it requires of the R&D effort: the need to expand the array of energy technologies available for responding cost-effectively to the risk of global climatic change from greenhouse gases, most importantly carbon dioxide from fossil fuel combustion.

Many of the characteristics of this risk and of society's potential responses to it are subject to considerable uncertainty and controversy. These characteristics aspects include the pace at which climatic change may become more obvious as greenhouse-gas concentrations grow, the magnitude and geographic distribution of the ecological and human consequences of such change, and the impacts on the U.S. and world economies of various measures that might be undertaken to constrain carbon dioxide emissions.

If greenhouse-gas-induced climate change were to develop along the path deemed most likely in the latest assessment by the Intergovernmental Panel on Climate Change (IPCC), there would be a significant chance that changes in patterns of temperature, humidity, rainfall, soil moisture, and ocean circulation, plus increases in sea level, would be adversely impacting human well-being over substantial areas of the planet by some time in the twenty-first century. The IPCC assessment also indicates that slowing the build-up of carbon dioxide in the atmosphere will be very difficult to achieve, because of the upward pressure of population growth and economic aspirations on energy demand, the large energy contribution and long turnover time of the fossil fuel technologies that are the primary source of CO_2 emissions, and the long residence time of this gas in the atmosphere.

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

Notwithstanding these differences, however, the Panel members are in complete agreement about the implications of the climate-change issue for energy R&D strategy:

- First, there is a significant possibility that governments will decide, in light of the perceived risks of greenhouse-gas-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 therefore requires having in place an adequate energy R&D effort designed to expand the array of technological options available for accomplishing this at the lowest possible economic, environmental, and social cost.

- Second, 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 these technologies to reduce their 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, the possibility of a mandate to significantly constrain greenhouse-gas emissions is the most demanding of all of the looming energy challenges in what it requires of national and international energy R&D efforts.

- Third (and this finally is the *good* news about the greenhouse-gas issue), many of the energy-technology improvements that would be attractive for this purpose also could contribute importantly to addressing some of the other energy-related challenges that lie ahead, including reducing dependence on imported oil; diversifying the U.S. domestic fuel- and electricity-supply systems; expanding U.S. exports of energy-supply and energy-end-use technologies and know-how; reducing air and water pollution from fossil fuel technologies; reducing the cost and safety and security risks of nuclear energy systems around the world; fostering sustainable and stabilizing economic development; and strengthening U.S. leadership in science and technology.

Energy R&D Spending in Decline

Society's capacity to respond effectively to the challenges described above will be determined in large measure by the *output* of its energy R&D efforts (as well as by the success of measures undertaken to ensure that the output is effectively deployed), and the output of R&D efforts will be substantially affected (with variations depending on the efficiency with which the R&D is managed and conducted) by the *input*, that is, by R&D spending.

Nonetheless, while the challenges looming in the energy future of the United States and the world have been growing in recent years—or at least growing more apparent—expenditures on R&D have been declining. In the United States, this has been the case in both the public and the private sectors, although the decline in funding from the public sector has been considerably steeper than the decline in funding from industry. Government funding for energy R&D has also been falling in most other industrialized countries, with the conspicuous exception of Japan. (The Panel was not able to compile plausible estimates of trends in private sector R&D funding in other countries.)

By far the largest part of Federal funding for energy R&D (about 90 percent) comes from DOE. The Department's FY 1997 budget for applied energy-technology R&D was $1.28 billion, compared to $2.18 billion five years earlier, in FY 1992, and $6.15 billion twenty years earlier, in FY 1978 (all figures in constant 1997 dollars).

If one includes DOE's funding for Basic Energy Sciences, the energy R&D decline was from $6.55 billion in FY 1978 to $3.04 billion in FY 1992 to $1.92 billion in FY 1997. Thus, the decrease in the past 5 years was between 37 and 42 percent, depending on whether Basic Energy Sciences is included in the totals, and the decrease between 1978 and 1997 was between 3.4- and

4.8-fold. As a fraction of real GDP, DOE's 1997 spending for energy technology was less than half that of DOE's predecessor agencies 30 years earlier, in 1967, at the height of pre-oil-shock American complacency about energy supply and energy prices.

Although data for energy R&D in the U.S. private sector are less comprehensive than those for government spending, the most recent systematic study of energy-industry R&D trends found that the industry's spending for R&D fell 40 percent in real terms between 1985 and 1994, from $4.4 billion to $2.6 billion. The R&D spending of the 112 largest U.S. operating electric utilities fell 38 percent between 1993 and 1996 alone, and the R&D of the four U.S. oil firms with the largest research efforts approximately halved between 1990 and 1996.

There is evidence that Federal and private investments in R&D in general (that is, not for energy alone) tend to rise and fall together, rather than one's rising in compensation when the other goes down. State government funding of energy R&D in the United States, which was probably under $200 million in 1995, may follow electric-utility funding downward.

In the G-7 countries other than the United States and Japan, public sector energy R&D has fallen sharply, decreasing between 1984 and 1994 by more than 4-fold in both Germany and Italy, by about 6-fold in the United Kingdom, and by 2-fold in Canada. Public spending on energy R&D in France, for which 1984 figures were not available, was declining slowly between 1990 and 1995. Japan, however, increased its public sector energy R&D spending from about $1.5 billion in 1974 to $4.2 billion in 1980; by 1995, the figure was $4.9 billion, about twice as high as DOE's energy R&D spending (Basic Energy Sciences included) in that year.

Explanations and Implications of the Declines in Public and Private R&D

Many explanations for the overall downward trends in energy R&D in recent years suggest themselves. One important factor is surely low energy prices. World oil prices fell sharply after 1980, and in the 1990s they have been about where they were in the 1920s and in the 1950s (in inflation-corrected dollars); and natural gas prices in the United States are so low that no other means of electricity generation can compete with gas-fired combined-cycle power plants where gas is available. This situation discourages investment in the development of new energy technologies. The very large demonstration projects in fossil, nuclear, and renewable energy that accounted for much of the post-oil-shock increase in U.S. Federal energy R&D spending came to be regarded as costly anachronisms after prices fell again, and their cancellation was, for the most part, appropriate.

In addition, public sector spending on energy R&D has experienced downward pressure from overall budgetary stringency in government and from public and policymaker complacency attributable to low prices, no gasoline lines, and high confidence in the capacity of the United States and allied military forces to preserve access to Middle East oil. DOE has experienced particular budget-inhibiting scrutiny by critics of "big government," and its energy R&D spending has been further constrained from within by pressure from larger parts of the Department's budget (notably environmental cleanup and nuclear-weapons programs).

In the competitive environment of declining government spending on energy R&D, moreover, advocates of each energy option have tended to disparage the prospects of the other options, in hopes of gaining a greater share of the budget for their favorite. Thus, the energy community itself has formulated the arguments that budget-cutters have used to downsize energy R&D programs one at a time ("renewables are too costly," "fossil fuels are too dirty", "nuclear fission is too risky", "fusion will never work", "conservation means sacrifice"), with no coherent energy-community voice calling for a responsible portfolio approach to energy R&D—that is, an approach that seeks to address and ameliorate the shortcomings of all of the options.

The private sector, meanwhile, has been experiencing a paradigm shift driven by the increasing globalization of the economy, the revolution in information technology, the increasing power of shareholders and financial markets over corporate decisions, and deregulation and restructuring in important parts of the energy business. These factors have combined with low energy prices and the inherently low profit margins of commodity-based businesses to cause energy companies to place more emphasis on the short-term bottom line, to decrease risk taking on broad-based or long-range R&D projects, and to outsource their R&D to specialized R&D contractors (which may represent a part of private sector energy R&D that is *not* shrinking).

It is also possible, finally, that energy R&D in the private sector, the public sector, or both has become more efficient, in which case declining inputs (funding) need not mean correspondingly declining outputs (innovations that can be successfully marketed or that otherwise improve the human condition). The Panel hopes that this is so, although it is difficult to verify (partly because there are often significant time lags between the conduct of research and its effects on the actual flow of innovations, so that if outputs remained high while inputs fell this might be a temporary condition).

In any case, that the overall declines in both public sector and private sector funding for R&D are largely explainable, and that some of what has disappeared was not needed or effective, does not establish whether what remains is adequate in relation to current and future needs.

In the private sector, energy R&D has been an important engine of progress, enabling firms to improve their products and invent new ones, so as to increase their shares of existing markets, establish and penetrate new ones, and maintain or increase performance while reducing costs. Perhaps these benefits will flow in adequate measure from the new paradigm; but it is also possible that important parts of an industrial R&D system that has served our society extremely well for many decades are now being sacrificed for short-term gain. Concerns have been expressed that the trend toward decentralization of industrial R&D, for example, could erode the interconnectedness among people and among different bodies of knowledge that contributes much to technological innovation in the long term.

Public sector R&D funding has the responsibility for addressing needs and opportunities where the potential benefits to society warrant a greater investment than the prospective returns to the private sector can elicit. Such needs and opportunities relate to public goods (such as the national security benefits of limiting dependence on foreign oil), externalities (such as unpenalized and unregulated environmental impacts), and situations where lack of appropriability of the

research results, or the structure of the market, or the size of the risk, or the scale of the investment, or the length of the time horizon before potential gains can be realized dilute incentives for firms to conduct R&D that would greatly benefit society as a whole.

Needs for public sector R&D can increase over time if the public-goods and externality challenges grow or if changing conditions shrink the incentives of firms to conduct some kinds of R&D that promise high returns to society. We have said enough already to suggest that both things might recently have been happening. But the real test of whether the current portfolio of public energy R&D is adequate comes from asking whether the R&D programs in the portfolio are addressing, effectively and efficiently, all of the needs and opportunities where the prospects of substantial societal benefits are good and the prospective returns to the private sector are insufficient to elicit the needed R&D. The Panel has analyzed DOE's energy R&D portfolio in these terms.

ELABORATION OF FINDINGS AND RECOMMENDATIONS

We turn now to what we found, first in relation to the content of the portfolio's major energy-technology compartments—end-use efficiency, fossil fuel technologies, nuclear technologies (fission and fusion), and renewable energy technologies—and then in relation to crosscutting issues including the role of Basic Energy Sciences, portfolio analysis, commercialization considerations, international dimensions, and DOE management of its energy R&D programs.

End-Use-Efficiency Technology

Between 1975 and 1986, the United States increased its energy efficiency by almost a third. This extraordinary achievement helped pull the country out of its two oil shocks and their attendant stagflation. Efficiency improvements now save U.S. consumers some $170 billion per year, and U.S. emissions of air pollution and CO_2 have been reduced by a third or more from their expected values.

Challenges and Opportunities

Those achievements are instructive as we look at future energy, economic, and environmental issues. Technological advances and investments in energy efficiency helped rescue the U.S. economy once, and gave the country decades of breathing room to deal with the energy problem. Many of these advances were made possible by DOE-sponsored R&D. Can a similar improvement be achieved in the years ahead?

The Panel believes it can. We find that investments in energy efficiency are generally the most cost-effective way to simultaneously reduce the risks of climate change, world oil-supply interruptions, and local air pollution, and to improve the productivity of the economy. We have reviewed technologies that can reduce energy use in automobiles by half or more; in motors and drive systems by half; and in buildings by over 70 percent. Many of these technologies are in their

infancy and require a serious R&D effort to make them commercially viable. Others are near market readiness, but need standards and incentives to ensure they spread rapidly.

Budget, Goals, and Initiatives

The Panel recommends that the R&D components of the DOE's energy efficiency budget grow steadily over the next 5 years, from $373 million to $755 million (constant 1997 dollars). The Panel has identified the following goals (some pre-existing, and some newly proposed here) for each of the sectors:

Buildings. To fund and carry out research on equipment, materials, electronic and other related technologies and work in partnership with industry, universities, and state and local governments to enable by 2010: (1) the construction of 1 million zero-net-energy buildings; and (2) the construction of all new buildings with an average 25-percent increase in energy efficiency as compared to a new building in 1996. Additional longer term research in advanced energy systems and components will enable all new construction to average 70 percent reductions and all renovations to average 50 percent reductions in greenhouse-gas emissions by 2030.

Industry. By 2005, develop with industry a more than 40-percent efficient microturbine (40 to 300 kW), and introduce a 50-percent efficient microturbine by 2010. By 2005, develop with industry and commercially introduce advanced materials for combustion systems to reduce emissions of nitrogen oxides by 30 to 50 percent while increasing efficiency 5 to 10 percent. By 2010, achieve a more than one-fourth improvement in energy intensity of the major energy-consuming industries (forest products, steel, aluminum, metal casting, chemicals, petroleum refining, and glass) and by 2020 a 20 percent improvement in energy efficiency and emissions of the next generation of these industries.

Transportation. By 2004, develop with industry an 80-mile-per-gallon production prototype passenger car (existing goal of the Partnership for a New Generation of Vehicles—PNGV). By 2005, introduce a 10-mpg heavy truck (Classes 7 and 8) with ultra low emissions and the ability to use different fuels (existing goal); and achieve 13 mpg by 2010. By 2010, have a production prototype of a 100-mpg passenger car with zero equivalent emissions. By 2010, achieve at least a tripling in the fuel economy of Class 1-2 trucks, and double the fuel economy of Class 3-6 trucks.

The R&D areas requiring increased funding to meet these goals have been identified. The Department has a sufficiently rich agenda, management expertise, history of success, and most important, potential for future contribution, to justify these increases.

Further Findings and Recommendations

The buildings program needs high-profile leadership from within the Administration, closer links with industry, and better mechanisms to distribute its research results. These elements could be brought together in the "Buildings for the 21st Century Initiative." The codes and

standards program needs to be expanded to give greater technical assistance to states and to speed internal progress.

The industries program is effective. It should be expanded to include more industries, and the crosscutting research—which develops technologies for use in many industries—should grow significantly.

Transportation research, most notably the PNGV, is extremely valuable. The PNGV program is insufficiently funded and cannot meet all its goals at current levels. It should be complemented by a "PNGV II" to augment efforts on long-term technologies, such as fuel cells, with extraordinary potential after 2005. PNGV also needs to give greater attention to air-quality issues, to ensure that technologies selected do not undermine national and state clean-air programs. The Administration must also develop new transportation policies that shift the auto fleet, over time, toward higher efficiency. And advanced vehicle development programs should be coordinated with alternative fuels programs to ensure they are complementary for transportation systems of the future.

R&D in the Department of Transportation should be reorganized around clear public interest goals, and Transportation's energy and environmental pursuits should be consonant with DOE's goals. The Department of Transportation should pursue more multimodal research and system optimization and should increase its focus on developing integrated transit systems with improved efficiency, to reduce urban congestion and enhance air quality. The Automated Highway System research needs to be thoroughly evaluated, key technical assumptions must be documented and peer-reviewed, and then the program should be reorganized around the public interest goals mentioned above.

Increasing energy efficiency has an extraordinary payoff. It simultaneously saves billions of dollars, reduces oil imports and trade deficits, cuts local and regional air pollution, and cuts emissions of carbon dioxide. DOE research, complemented by sound policy, can help the country increase energy efficiency by a third or more in the next 15 to 20 years.

Fossil-Energy Technology

Fossil fuels supply 85 percent of U.S. energy and 75 percent of all energy globally. They will continue to be essential to the energy economies of the United States and the world well into the twenty-first century. R&D on fossil fuel technologies is warranted to minimize the costs, impacts, and risks of this continuing reliance on fossil fuels and to exploit the opportunities it represents for U.S. industry and the U.S. economy.

Challenges and Opportunities

DOE Fossil Energy R&D programs are directed—appropriately in the Panel's judgment—at two important challenges: (1) reducing the environmental impacts (including CO_2 emissions) that constrain fossil fuel use; and (2) reducing the vulnerability of the economy to oil price shocks (caused by excessive dependence on imported oil and potential instabilities in the Middle East) by

helping ensure the availability of secure and affordable transportation fuels. In the process, the Department aims to maintain U.S. science and technology leadership in fossil fuel related fields.

Over the past two decades, enormous progress has been made in reducing the environmental impacts of fossil fuel use—particularly of coal use in electric power production—in cost-effective ways. This progress has partly been the result of DOE/industry collaborative R&D and the Clean Coal Technology Demonstration Program. DOE seeks to maintain this progress through pursuit of an idea called Vision 21, with the objective of economical coal and gas power and fuels technology with zero-to-small CO_2 emissions and very low emissions of other air pollutants. This is a most ambitious goal, requiring significant breakthroughs to achieve very high efficiencies of conversion to electricity (and fuels) and cost-effective methods for separating and sequestering CO_2.

In the United States, natural gas has become the fuel of choice for new electric generation because of its low cost, small environmental impacts, relatively small scale (yielding versatile siting and quick installation), and rapidly advancing turbine technology, and because of the competitive pressures of electric industry restructuring. This trend to natural gas is likely to continue for several decades and contributes positively to DOE's environmental objective, particularly by reducing CO_2 emissions to the extent that gas replaces coal.

As a consequence, the major markets for advanced coal power and fuels technologies will not be in the United States but in coal-intensive developing countries such as China and India, where gas is not widely available for these purposes. Providing attractive coal technologies that are much more efficient with greatly reduced CO_2 and other emissions contributes to DOE environmental objectives. For the United States to take advantage of this environmental opportunity, it must maintain technological leadership in coal power technologies and develop a strong international program including collaborative R&D, development, and commercialization activities. This will require a paradigm shift away from the current focus on the U.S. market and toward a focus on coal-intensive developing countries.

Relative to the challenge of ensuring secure and affordable transportation fuels, DOE R&D is developing and demonstrating technologies that can enhance domestic oil and gas production, diversify supply, and reduce the cost of converting natural gas (and coal, biomass, and waste) to clean fuels for transportation. Activities to enhance production include technology transfer to independent oil and gas producers to help bolster production from mature resources and high-risk R&D investments at the front end of the resource cycle for frontier provinces. The potential return to the government from taxes and royalties alone justifies the investment, not to mention reducing balance-of-payment imbalance and losses to the economy in the event of a future oil-price shock. It is good insurance both from the point of view of oil dependence and for the climate change issue because of the importance of natural gas as a transition fuel during the next century.

Budget, Goals, and Initiatives

The Panel's analysis of these challenges and opportunities leads us to recommend that the Fossil Energy budget remain at about the current level in constant dollars but with a significant reorientation and new initiatives aimed at Vision 21, gas as a transition fuel, and a comprehensive transportation fuel R&D strategy.

Coal and Gas Power and Fuels. The Panel endorses Vision 21 as the long-term objective and recommends reorientation of DOE R&D priorities toward it. This should include continued emphasis to improve efficiency of the combined cycle using high temperature fuel cells, development of advanced gasification technologies (for coal, biomass, or waste) for the flexible production of power and clean transportation liquid fuels (ultimately hydrogen and separated CO_2). It should also include initiating a science-based CO_2-sequestration program in cooperation with the US Geological Survey, industry, and universities, with an annual budget rising to $20 million dollars or more in 2003. Hydrogen may prove to be the transportation fuel of the future if fuel cells become the power source of choice for vehicles, and fossil fuels are the likely least expensive route to hydrogen assuming sequestration is practical.

Phaseouts. As part of this reorientation, the Panel recommends that the Department terminate: (1) direct liquefaction of coal, because it does not fit Vision 21; (2) the solid fuels and feedstocks program, directing the funding instead toward a comprehensive, science-based program to reduce hazardous air emissions from existing and future coal power plants; and (3) the Low Emissions Boiler System program. It should phase out near-term clean-coal programs that do not contribute to Vision 21 or to providing much better low-CO_2-emissions technology choices for developing countries.

Oil and Gas Production and Processing. Because of its importance as a transition fuel for the United States in controlling CO_2 emissions, the Panel recommends more intense effort on natural gas production and processing, including a major initiative for DOE to work with USGS, the Naval Research Lab, Mineral Management Services, and the industry to evaluate the production potential of methane hydrates in US coastal waters and worldwide. The resource is very large indeed, in the range of 100,000 to 1,000,000 Tcf (trillion cubic feet). This research might well interface with hydrogen-production and CO_2-sequestration efforts with CO_2 hydrates as the sequestered state of the gas.

Transportation Fuels Strategy. The Panel recommends that DOE develop a comprehensive transportation fuels strategy, beginning with an analysis of the potential for technologies to increase the price elasticity of oil supply and demand including the impact of substitutes. This effort should include, for example, R&D focused on reducing the cost of producing transportation fuels from natural gas and work on indirect liquefaction of coal and biomass. Such an effort is supportive of Vision 21 and may improve its flexibility for combined fuel and power generation, including eventually producing hydrogen for central or distributed use with CO_2 sequestering.

Nuclear Energy Technology

Nuclear energy can be generated by fission (the splitting of a nucleus) or by fusion (the joining of two nuclei). Neither fission nor fusion reactions generate greenhouse gases or the air pollutants that produce urban smogs and regional acid precipitation. Fission power currently provides about 17 percent of the world's electric power, with 442 nuclear power reactors operating in 30 countries and 36 more plants under construction. Fusion power requires much additional work in the quest to make the fusion reaction self-sustaining and to design and build practical fusion power plants; the most optimistic timetable for fusion to reach commercialization is another half century. But the potential benefits of fusion are so large that fusion R&D is an important component of current energy R&D portfolios in the United States and internationally.

Challenges and Opportunities: Fission

Several problems compromise fission's potential as an expandable energy source today and into the future: disposal of spent nuclear fuel; concerns about nuclear weapons proliferation; concerns about the safe operation of plants; and uncompetitive economics. But given the projected growth in global energy demand as developing nations industrialize, and given the desirability of stabilizing and reducing GHG emissions, it is important to establish fission energy as a widely viable and expandable option if this is at all possible. A properly focused R&D effort to address the problems of nuclear fission power—economics, safety, waste, proliferation—is therefore appropriate. World leadership in nuclear energy technologies and the underlying science is also vital to the United States from the perspective of national security, international influence, and global stability.

Although the United States has the largest number of operating reactors of any country in the world, the outlook is that no new nuclear plant will be built in this country in the next 10 to 20 years. The decline of nuclear power in the United States has resulted from many factors: a sharp drop in annual electricity consumption growth rates, low gas prices and improved efficiency of gas-fired combined-cycle plants, rapid escalation of nuclear plant construction costs, the unresolved problems of waste disposal and storage, and concerns about proliferation and safety. These factors, combined with the upcoming deregulation of the electric utilities, may lead to early shutdown of operating nuclear plants in the United States.

Budget, Goals, and Initiatives: Fission

Based on its analysis of the potential and problems of fission power, the PCAST Energy R&D Panel recommends that nuclear fission R&D be increased from $42 million in FY 1997 to $119 million in FY2003 (as-spent dollars). Included in these totals throughout the period is about $6 million per year for university programs, including fellowships and fuel support for university reactors. The Panel makes the following further observations and recommendations about the fission R&D effort:

<u>Operating Reactors</u>. Extending the operation of nuclear plants will make it easier to meet GHG emission goals. The Panel recommends that DOE work with its laboratories and the utility

industry to develop a program to address the problems that may prevent continued operation of current plants. We recommend such a program be funded at $10 million per year, to be matched by industry.

Nuclear Energy Research Initiative. DOE should establish a new program—the Nuclear Energy Research Initiative—funded initially at $50 million per year and increasing by FY 2002 to $100 million per year (as-spent dollars), which would competitively select among proposals by researchers from universities, national laboratories, and industry to address key issues affecting the future of fission energy including: proliferation-resistant reactors or fuel cycles; new reactor designs with higher efficiency, lower-cost, and improved safety to compete in the global market; lower-output reactors for use in settings where large reactors are not attractive; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste. This approach is in contrast to the traditional style of directed research of the DOE Nuclear Energy program (in which the program office defines the topics, milestones, and scope) and follows instead a model along the lines of the Environmental Management Science Program (EMSP).

Coordination. DOE should improve coordination and integration among the eight DOE program offices sponsoring R&D applicable to fission energy.

Challenges and Opportunities: Fusion

The objective of DOE's fusion energy sciences program is to develop the scientific and technological basis for fusion as a long-term energy option for the United States and the world. The fusion R&D program is strongly centered in basic research and supports the important field of plasma science. Results and techniques from fusion plasma science have had fundamental and pervasive impact in many other scientific fields, and they have made substantial contributions to industry and manufacturing. Since 1970, fusion power in experiments has increased from less than 0.1 watt to more than 10 megawatts.

The nation's fusion energy research program has received three major reviews since 1990, the most comprehensive being the 1995 study by the PCAST Panel on the U.S. Program of Fusion Energy Research and Development (PCAST-95). PCAST-95 recommended an annual budget of $320 million. In FY 1996, Congress reduced the fusion budget by about one-third and directed DOE to restructure its fusion energy program. The present funding level of $230 million is too low in the view of the PCAST Energy R&D panel; it allows no significant U.S. activity relating to participation in an international program to develop practical low-activation materials; reduces the level of funding for the design of the International Thermonuclear Experimental Reactor (ITER); forced an early shutdown for the largest U.S. fusion experiment; and canceled the next major U.S. plasma science and fusion experiment. It also limited the resources available to explore alternative fusion concepts.

Budgets, Goals, and Initiatives: Fusion

Based on its analysis of the potential of fusion power and the challenges and opportunities in this field, as just described, the PCAST Energy R&D Panel recommends that fusion R&D

funding be increased from its annual level of $232 million in the FY 1997 appropriation to reach $320 million per year by FY2002 (as-spent dollars). This would restore fusion R&D funding to the level which the 1995 PCAST study of fusion-energy R&D recommended be maintained from FY 1996 onward.

The Panel reaffirms support also for the specific elements of the 1995 PCAST recommendation that the program's budget-constrained strategy be based on three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion experiment focused on the key next-step scientific issue of ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems. The Panel makes the following further observations about the fusion R&D effort:

International Collaborations. The U.S. program should establish significant collaborations with both the JET program in Europe and the JT-60 program in Japan. Such collaboration should provide experience in experiments that are prototypes for a burning plasma machine, such as ITER, and that can explore driven burning plasma discharges.

ITER. The Panel judges that the proposed 3-year transition between completion of the Engineering Design Activity and an international decision to construct is reasonable and that the ITER effort merits continued U.S. involvement. It would be helpful to all parties in the ITER enterprise if at least one of the parties would express, within the next year or two, its intention to offer a specific site for ITER construction by the end of the 3-year period. Clearly, one major hurdle to ITER construction is its total project cost, most recently estimated to be $11.4 billion, with the host party expected to fund a substantial share. If the parties agree to move forward to construction, the United States should be prepared to determine, with stakeholder input, what the level and nature of its involvement should be. The Panel believes that if no party offers to host ITER in the next three years, it will nonetheless be vital to continue without delay the international pursuit of fusion energy. A more modestly scaled and priced device aimed at a mutually agreed upon set of scientific objectives focused on the key next-step issue of burning plasma physics may make it easier for all parties to come to agreement.

Renewable Energy Technology

Renewable energy technologies (RETs) can provide electricity, fuels for transport, heat and light for buildings, and power and process heat for industry. These technologies generally have little or no emissions of greenhouse gases, air pollutants, or other environmental impacts. RETs can also offset imports of foreign oil and offer important economic benefits; for example, growing biomass energy crops on excess agricultural lands would increase farm income while potentially allowing a reduction in Federal farm income support programs.

Challenges and Opportunities

The primary challenge facing RETs today is relatively high unit costs, but remarkable progress has been over the past two decades. Costs of energy from RETs such as wind turbines

and photovoltaics (PVs) have come down by as much as 10 times. Much further progress is expected, to the extent that RETs could become major contributors to U.S. and global energy needs over the next several decades. The Shell International Petroleum Company, for example, projects that by 2025 renewable energy sources could contribute to global energy one-half to two-thirds as much as fossil fuels do at present, with new renewable sources (excluding hydropower and traditional biomass) accounting for one-third to one-half of total renewables.

Much of the global market growth for RETs, as well as for total energy, will take place in developing countries. The small scales and modularity of most RETs are well matched to energy technology needs in developing countries. Also, the inherent cleanliness of most RETS will have a special appeal, making it possible to reduce environmental problems without resorting to complex regulatory controls as is done for conventional energy systems.

Budget, Goals, and Initiatives

In light of the remarkable progress already made in many areas of DOE's Renewable Energy program, the good prospects for further gains, and the substantial potential impacts renewables could have in addressing the multiple challenges posed to the energy system in the United States and worldwide, the Panel believes that the Renewable Energy R&D Program should be substantially expanded, from annual spending of $270 million in FY 1997 to a level of about $650 million in 2003 (as-spent dollars), with goals that include the following:

Wind. Reduce by 2005 wind electricity costs to half of today's costs, so that wind power can be widely competitive with fossil-fuel-based electricity in a restructured electric industry, through R&D on a variety of advanced wind turbine concepts and manufacturing technologies.

Photovoltaics (PV). Pursue R&D that would lead to PV systems prices falling from the present price of $6,000/kW to $3,000/kW in 5 years, to $1,500/kW by 2010, and to $1,000/kW by 2020. R&D activities should include assisting industry in developing manufacturing technologies, giving greater attention to balance of system issues, and expanding fundamental research on advanced materials.

Solar Thermal Electric Systems. Strengthen ongoing R&D for parabolic dish and heliostat/central-receiver technology with high temperature thermal storage, and develop high-temperature receivers combined with gas-turbine based power cycles; goals should be to make solar-only power (including baseload solar power) widely competitive with fossil fuel power by 2015.

Biopower. Enable commercialization, within ten years, of advanced energy-efficient power-generating technologies that employ gas turbines and fuel cells integrated with biomass gasifiers, building on past and ongoing R&D for coal in such configurations, and exploiting the advantages of biomass over coal as a feedstock for gasification. These technologies could be widely competitive in many developing country markets and in U.S. markets that use biomass residues or use energy crops in systems that derive coproducts from biomass.

Geothermal Energy. Continue work on hydrothermal systems and reactivate R&D on advanced concepts, giving top priority to high-grade hot dry-rock geothermal; this technology offers the long-term potential, with advanced drilling and reservoir exploitation technology, of providing heat and baseload electricity in most areas.

Biofuels. Accelerate core R&D on advanced enzymatic hydrolysis technology for making ethanol from cellulosic feedstocks, with the goal that, between 2010 and 2015, ethanol produced from energy crops would be fully competitive with gasoline as a neat fuel, in either internal combustion engine or fuel cell vehicles; coordinate this development with the biopower program so as to co-optimize the production of ethanol from the carbohydrate fractions of the biomass and electricity from the lignin using advanced biopower technology.

Hydrogen. Carry out R&D on hydrogen-using and -producing technologies; coordinate hydrogen-using technology development with proton-exchange-membrane fuel-cell vehicle development activities in the Department's Energy Efficiency program. Give priority in hydrogen-production R&D to co-optimizing the production of hydrogen from fossil fuels and sequestration of the CO_2 separated out during the production process, in collaboration with the Fossil Energy program.

Hydropower. To sustain and increase over 92,000 MW of hydro capacity, additional R&D is needed to provide a new generation of turbine technologies that are less damaging to fish and aquatic ecosystems. By deploying such technologies at existing dams and in new low-head, run-of-river applications, as much as an additional 50,000 MW could be possible by 2030.

Crosscutting and Other Programs. Crosscutting programs that should be strongly supported include Resource Assessment, International Programs, and Analysis. In addition, R&D is needed on energy storage, electric sytems, and systems integration.

Further Findings and Recommendations

The Panel believes that there are good prospects that these goals can be realized with the combination of an expanded R&D effort and appropriate demonstration and commercialization initiatives. The DOE program has demonstrated remarkable gains in technology performance and cost reductions and has laid the foundation for large further gains. The R&D effort should be intense over the course of the next decade, with much more emphasis than at present in DOE program on both core applied research and development and fundamental research directed to serving needs identified in the programs.

For technologies that continue to show promise, R&D budgets should be sustained at the elevated levels for several years (the number varying with the technology) until the technologies become established in the market, the industry has sufficient revenues from these RET markets to shoulder a greater share of needed continuing R&D, and government's role can be reduced to supporting mainly long-term R&D. For both wind power and biopower, most of the principal R&D goals could be met in a decade or less; for these technologies, Federal R&D budget support

could thereafter begin to decline. For other technologies, it will take longer, but in nearly all cases principal program goals should be achievable in less than 20 years.

Crosscutting Issues

In what follows, we elaborate briefly our findings and recommendations relating to four sets of issues that cut across the applied energy-technology R&D programs discussed above: the relation of DOE's Basic Energy Sciences program to applied energy-technology R&D; analysis of the portfolio as a whole and the leverage it offers against the energy challenges faced by the nation and the world; considerations related to commercialization of the fruits of R&D; and certain international aspects of R&D.

Links Between Applied Energy Technology R&D and Basic Energy Sciences

The Panel's review of DOE energy R&D activities identified many areas where technological advance could be accelerated if more attention were given to fundamental questions identified in these programs. Examples include better understanding of reactions at the interface of electrodes and electrolytes in fuel cells, the capacity of carbon nanostructures for hydrogen storage, the chemistry and fluid dynamics of CO_2 storage in saline aquifers, the physics of thin-film photovoltaic materials, and many others. The Panel found that linkages between the Basic Energy Sciences (BES) programs (where such issues are investigated) and the applied energy-technology programs (where the findings could be put to use) need to be strengthened in many cases.

While the technology programs do benefit today from the growing body of fundamental knowledge being generated under BES programs, they would benefit much more if BES were to address specific questions identified as important in these programs. The Panel recommends that BES allocate additional resources to support fundamental research activities addressing needs of the technology programs. This could be facilitated by mechanisms such as co-management and co-funding with—or budget sign-off by, or re-routing budgets through—the applied energy-technology programs.

Our recommendation that BES direct some of its resources to serving these needs might raise concerns that the creativity of basic science will be lost if it is constrained by premature thought of practical use, and that applied research invariably drives out pure, if the two are mixed. What is being sought here, however, is not to redirect BES resources to applied research. The technology programs support applied research but give little attention to addressing fundamental questions such as the above. The net effect of this recommendation should be to expand, not diminish, the portfolio of fundamental research activities within the limits of overall budget constraints. In light of the growing interest among policy planners in harnessing science for the technological race in the global economy, the allocation of some BES resources to the development of fundamental research programs that would serve the energy technology programs should add to the political appeal of supporting basic research generally.

Portfolio Analysis and Leverage

Developing the appropriate degree of diversity and balance in the Department's overall energy R&D portfolio is difficult. Technologies have many different attributes—cost (of the R&D to develop them and of the technologies themselves, once they are developed), performance, risk, return, potential contributions over time to energy and environmental goals, and others. How can one fairly evaluate the many R&D alternatives and select an R&D portfolio that best meets our national goals and needs? No single quantitative measure can encompass the range of relevant attributes. One technology may have substantial environmental benefits, a second may contribute more to national security, a third may have only modest benefits but have low risks and costs to develop.

The Panel has worked hard at exploiting and refining various ways to portray the diverse characteristics of different energy options in a way that facilitates comparisons and the development of an appropriate portfolio balance in light of the challenges facing energy R&D and in light of the nature of private sector and international efforts and the interaction of U.S. government R&D with them. We have made some progress, but a much larger and continuing effort in this direction by the Department of Energy itself is called for. (In saying this we echo one of the strongest recommendations of the 1995 Secretary of Energy Advisory Board report on Strategic Energy R&D—a recommendation that alas has so far borne little fruit.) Such analyses should be done on a regular basis as national needs and R&D options and opportunities change. We recommend that DOE regularly and systematically conduct—with external peer review—a portfolio analysis across the breadth of R&D options and to use this as an input to overall program planning.

The potential overall impact of the sector-by-sector energy R&D portfolio developed by the Panel can be illustrated by some simple "back-of-the-envelope" analyses. Examples for oil imports and carbon emissions are schematically shown in figures ES.1 and ES.2; details of these highly simplified projections are provided in Chapter 7. For clarity, only a few, highly aggregated sets of technologies are shown.

Consider oil imports. Under business-as-usual conditions, U.S. oil imports could increase from 8.5 million barrels per day at a cost of $64 billion dollars in 1996 to nearly 16 million barrels per day at a cost of $120 billion (assuming $20 dollars per barrel) in 2030. With continued R&D to increase domestic production from marginal oil supplies, an aggressive ethanol program (based on cellulosic biomass, not corn), and rapid development and penetration of the market by PNGV and light- and heavy-duty truck technologies, we estimate that this import could be reduced to something on the order of 6 million barrels per day oil import demand in 2030, as illustrated in Figure ES.1. Estimates of this sort are necessarily highly approximate, since they depend not only on the somewhat unpredictable pace of R&D successes but also future market conditions and measures taken to speed market penetration under whatever those conditions are; nonetheless, such "ballpark" estimates give at least a rough indication of the magnitude of the challenge the nation faces and size of the opportunity to address it with the stronger R&D program outlined here.

Potential impact on carbon dioxide emissions (customarily measured in tons of carbon contained in the emitted CO_2) is clearly also a crucial element of a portfolio's leverage against the energy-related challenges of the next century. Figure ES.2 illustrates, in a highly stylized and schematic way, how the factors most germane to an analysis of leverage against CO_2 emissions can be portrayed in a single diagram: the length of time until a new technology is ready to begin penetrating the market, the cost of the R&D effort needed to get to that point, and the rate at which the technology could penetrate the market (reflected in the diagram as the rate of increase in avoided CO_2 emissions) after that time. (With some modification such a diagram could also show the effect, on the potential for emissions avoidance, of the different sizes of the various energy-supply or end-use markets being penetrated.)

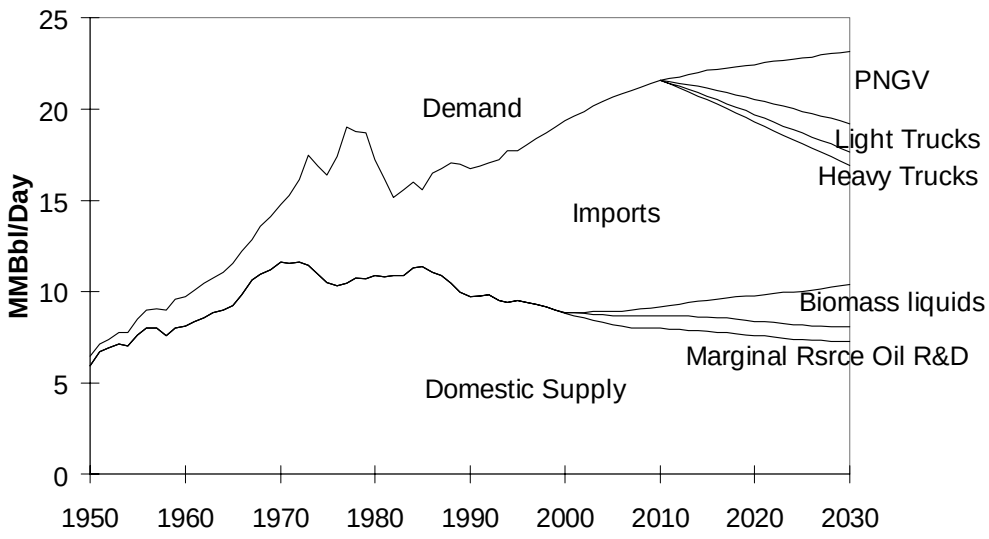

Figure ES.1: Potential reduction of U.S. oil imports by selected advanced technologies. Historical data and baseline projections from Energy Information Administration (EIA). Vehicle efficiency improvements assume R&D completed by 2004 and commercial production is underway by 2010, with straight-line penetration to 100 percent of the market by 2030. Improvements entail roughly 60 percent reductions in fuel intensity for cars and light trucks, 40 percent for heavy trucks. Contributions from R&D to exploit marginal domestic resources are based on DOE projections. Biomass liquids estimate is based on an aggressive program to produce ethanol from cellulosic biomass. Many other technological possibilities are not shown.

The Panel has not been able, in the time available for this study, to complete the sorts of analyses that would be necessary to specify the relevant market-entry points, associated research investments, and plausible penetration rates—and the uncertainty ranges associated with all of these—with any confidence. Figure ES.2 is based on very approximate understandings of needed research investments and market-entry points developed in the course of our study, and on crude guesses about penetration rates (which were uniform across the technologies shown, in the absence of the sort of analysis that would be required to do this in a differentiated way). What can be said in favor of this very rough and preliminary depiction of potential leverage is that (a) it

illustrates what we believe DOE should be doing in the way of portfolio analysis, with a much larger analytical effort behind it than they or we have mustered until now, and (b) the timing and magnitudes of the conceivably achievable avoided carbon emissions shown in the diagram are roughly consistent with what other major recent studies of the potential of new technologies for this purpose have found.

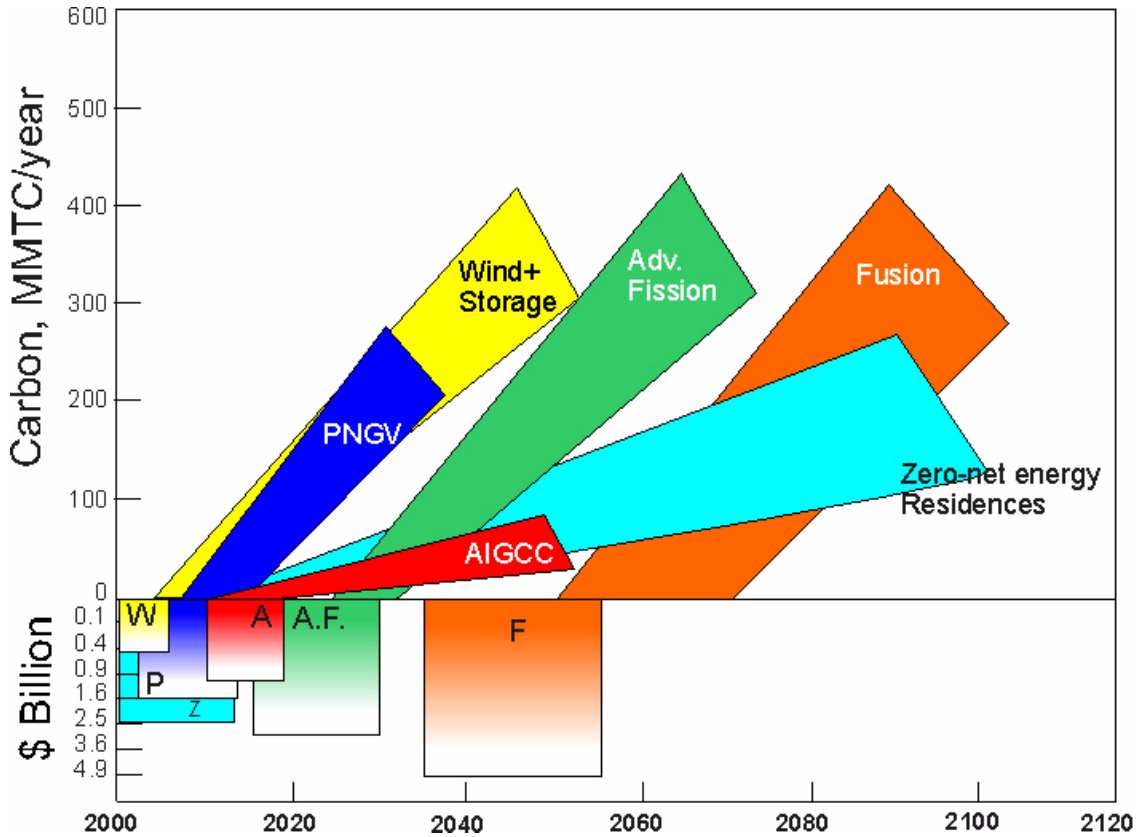

Figure ES.2: Schematic portrayal of R&D portfolio analysis of carbon-reduction potential. This drawing depicts an approximate range of times when a technology might be available for commercial use—where the shaded wedges touch the time-axis; the potential carbon savings as the technology penetrates the market—depicted by the shaded wedges indicating a range of penetration rates; and the approximate cost of the R&D to develop these technologies to commercialization—depicted by the squares at the bottom of the drawing, which have areas proportional to the discounted present value of the R&D costs. The width of the wedges and shading in the boxes depict uncertainty in these estimates. Maximum slopes of penetration-rate wedges are based on 100 percent capture of the market for new units and specified turnover times for old units: 15 years for cars, 40 years for electric power plants, 80 years for residential buildings. For simplicity, carbon intensities of the various sectors are assumed to be frozen at 1995 levels. Funding estimates are for applied technology development only; they do not include fundamental science research. Funding for buildings includes commercial buildings, for which carbon savings are not shown. Large, long-term R&D programs assume international collaborations. With refinement and more nuanced analysis behind it, such an approach to illustrating the leverage of an R&D portfolio versus time and investment could be very informative.

Figure ES.2 shows mostly technologies that would not begin penetrating markets until after 2010. They offer large emissions-avoidance potential, but only well into the next century. (Of course, the point of increasing R&D investments in appropriately targeted areas is to move forward the date at which such technologies can begin penetrating their markets.) Options that could have an impact by 2010 are not shown here but have been separately examined by DOE in a recently released report; these earlier-impacting options necessarily depend largely on R&D that has already been done.

Commercialization Considerations

To achieve the sorts of impacts illustrated schematically in Figures ES.1 and ES.2 would require more than R&D in many cases.. New technologies face the chicken-and-egg problem of generally having high costs, and thus being limited to low market volumes, but needing large market volumes to drive costs down. Making this transition is difficult given the low costs of energy today and given that the public benefits of new energy technologies—notably environmental quality and national security—are generally not valued in the market. Industry-led, public-private collaborations in demonstration and commercialization of new energy technologies can be an appropriate way to address this difficulty in ways that ensure that R&D programs are appropriately targeted and market relevant and that the benefits of the public investment in R&D are realized in market penetration rates commensurate with the sum of the private and public benefits of such penetration.

After consideration of the market circumstances and public benefits associated with the energy-technology options for which we have recommended increased R&D, the Panel recommends that the nation adopt a commercialization strategy in specific areas complementing its public investments in R&D. This strategy should be designed to reduce the prices of the targeted technologies to competitive levels, and it should be limited in cost and duration. The Panel does not make a recommendation as to the source of funds for such an initiative. We do believe, however, that such a commercialization effort should be designed to be very efficient in allocating funds to drive prices down, minimally disruptive of energy/financial systems, and temporary.

International Aspects

Markets for many new energy supply technologies will be very limited in the United States for the next decade or two due to slow growth in demand and the availability of low cost natural gas; most of the growth in world energy production and use and in carbon emissions will take place in developing countries. For the United States to maintain scientific, technological, and market leadership in these critical energy technologies, it will be essential for public R&D and demonstration and commercialization programs to broaden their scope to directly address international energy issues, including both collaborative R&D and market competition. This can provide us as well as our partners substantial economic and environmental benefits.

The Panel recommends that the government and government/national-laboratory/industry /university consortia should engage strongly in international energy technology R&D and

demonstration and commercialization efforts to regain and/or maintain the scientific, technical, and market leadership of the United States in energy technology. This should include increased R&D—particularly in collaboration with developing countries, temporary support for D&C activities where appropriate, and responses to foreign export promotion activities where necessary.

DOE Management of Its Energy R&D Programs

The necessity of linking fundamental research with applied R&D and with demonstration and commercialization, the increasing complexity of R&D efforts, globalization of R&D and technology markets, heightened global market competition, and other evolving factors in the energy field have several important implications for energy R&D management. The complexity and technical demands of R&D require increased industry/national-lab/university peer review and technical oversight and direction of R&D programs. Linkages require improved coordination.

Better communications can enable reduced administrative procedures and management overheads, and can improve coordination by pushing these responsibilities down to the operational level. Efficient use of resources requires careful establishment of R&D targets and timelines, and ongoing measurement of progress. Although DOE has been making some efforts in these areas and some programs are beginning to establish effective models that can be applied more broadly, in general these factors need to be better addressed in DOE energy R&D management.

To address these management issues, and above all to increase the efficiency with which public dollars invested in energy R&D yield the results that the national interest requires, the Panel offers the following specific recommendations:

- Overall responsibility for the DOE energy R&D portfolio should be assigned to a single person reporting directly to the Secretary of Energy; similarly, a single individual should be given the responsibility and authority for coordination of crosscutting programs between the applied-technology programs, reporting to the single person responsible for the overall R&D portfolio.

- Industry/national-laboratory/university technical oversight committees should work with DOE to provide overall direction to energy R&D programs, with DOE facilitating and administering the process;

- All R&D programs should undergo outside technical peer review every 1 to 2 years, but interim internal process-oriented reviews should be reduced to a minimum.

- DOE staff technical skills should be strengthened by training, targeted hiring, and by systematically rotating external technical (and managerial) staff through DOE as senior professionals with significant responsibilities for all aspects of program management.

- Lead laboratories should be named and laboratories should be treated by DOE as integrated entities, not as collections of projects independently controlled from DOE headquarters.

- Industry/laboratory/university partnerships should conduct the energy R&D that is funded by DOE, in most cases.

- The national laboratories should be encouraged to perform work for clients other than DOE, inside and outside the government, as appropriate, and processes for doing this should be streamlined.

- DOE staff procedures for energy technology programs should be reviewed in detail, and staff levels adjusted accordingly.

CONCLUDING OBSERVATIONS AND ONE MORE RECOMMENDATION

Funding and managing the energy R&D needed to help address the energy challenges and opportunities of the next century are tasks not for the Federal government alone but for all levels of government, for industry, for universities, for the nonprofit sector, and for a wide variety of kinds of partnerships among entities in these different categories. The Panel's charge was to review Federal energy R&D, but we have been attentive to the ways in which the role of the government relates to and interacts with the roles of the other sectors. Our recommendations aim to focus the government's resources on R&D where high potential payoffs for society as a whole justify bigger R&D investments than industry would be likely to make on the basis of its expected private returns, and where modest government investments can effectively complement, leverage, or catalyze work in the private sector.

The funding increases we are proposing for Federal energy R&D, in order to better match the combined energy R&D portfolio of the public and private sectors to the energy-related challenges and opportunities facing the nation, appear quite large when expressed as percentage increases in some of the particular DOE programs that would be affected. But the increase in annual spending—amounting altogether to an extra billion dollars in 2003, compared to that in 1997, for R&D on all the applied energy-technology programs together—is equal to less than a fifth of one percent of the sum that U.S. firms and consumers spent on energy in 1996; and it would only bring the Department of Energy's spending on applied energy-technology R&D back to where it was in 1992, in real terms. The potential returns to society from this modest investment are very large. They can be measured in energy costs lower than they would otherwise be, oil imports smaller than they would otherwise be, air cleaner than it would otherwise be, more diverse and more cost-effective options for reducing the risk of global climate change than we would otherwise have, and much more.

If this is such a good case, why hasn't it been made and accepted before now? Actually the case has been made often before, by energy experts and by studies like this one. It has not been entirely heeded for a variety of reasons, most of them discussed above and many of them

perfectly understandable. But perhaps the most important reason that the government today is not doing all that it should in energy R&D is that the public has been lulled into a sense of complacency by a combination of low energy prices and little sense of the connection between energy and the larger economic, environmental, and security issues that people *do* care very much about. In a way the low priority given to energy matters is reflected even in the Department of Energy itself, where energy is only a modest part of the Department's array of missions and there is no official responsible for all of the Department's energy activities and those alone.

What we have here is thus, in part, an education problem. There needs to be more public discussion and a growing public understanding of why energy itself—and therefore energy R&D—is important to the well-being of our nation and the world. In this the scientific and technological community has an obvious role to play, and we hope this report will be seen as a positive contribution to that. But the Federal government, led by the President, also has an important educational role to play, reflected in what is said and in what is done. As the last of the recommendations in this report, which was commissioned by the President, we therefore offer the following:

> We believe the President should increase his efforts to communicate clearly to the public the importance of energy and of energy R&D to the nation's future, and that he should clearly designate the Secretary of Energy as the national leader and coordinator for developing and carrying out a sensible national energy strategy, which of course includes not only energy R&D but much else.

* * * *

Table ES.3: Recommended DOE Applied Energy-Technology R&D Initiatives and Budget Authority (in Millions of as-spent dollars)

PROGRAM[a]	R&D Activities, Initiatives, and Budget Changes	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
Efficiency: Buildings	Building System Design and Operation: advanced sensors; smart controls; automated diagnostics; and whole-building optimization and design tools.	24	33	38	48	60	72	84
	Building Equipment and Materials: advanced materials; advanced energy-efficient HVAC, lighting, windows, appliances, office equipment, etc.; and insulation initiative.	27	37	57	72	85	98	111
	Codes and Standards: for efficient appliances and buildings; technical assistance.	12	21	25	25	25	25	25
	Crosscutting Activities: technology roadmapping and partnership development with industry following the model of the DOE Industries of the Future program.	--	--	20	25	30	35	35
	Other: management and planning, and other activities.	18	20	20	20	20	20	20
	Subtotal	81	111	160	190	220	250	275
Efficiency: Industry	Industries of the Future: advanced technologies for energy intensive industries—aluminum, cement, chemicals, forest products, glass, metal casting, refining, steel, agriculture—and for emerging energy-intensive industries following technology roadmaps.	46	56	65	75	85	95	110
	Crosscutting Activities: advanced microturbines (40-200 kW), sensors, motor drive systems, and materials; work with DOE/OUT on biomass Integrated Gasification Combined Cycle.	38	38	70	80	90	95	100
	Technology Access: innovation grants; industrial assessments, "Climate Wise," and motors.	25	37	40	40	45	45	50
	Other: management and planning, and other activities	7	8	10	10	10	10	10
	Subtotal	116	139	185	205	230	245	270
Efficiency: Transport	PNGV: better emissions controls for light diesels; hybrid vehicles; and system integration.	105	129	100	100	100	100	75
	PNGV II: fuel cells, microturbines, advanced energy storage, and system integration.	--	--	75	85	100	100	125
	Advanced Heavy Vehicles: efficient diesels, diesel pollution reduction, and hybrids.	20	18	30	40	50	55	60
	Advanced Materials: high-temperature/high-strength materials to reduce weight 25%.	33	31	35	40	40	40	45
	Technology Deployment: clean cities program, alternative fuel vehicles, and other activities.	11	17	20	20	20	20	20
	Other: management and planning, and other activities.	7	9	10	10	10	10	10
	Subtotal	176	204	270	295	320	325	335
Fossil Energy	Coal Power: end Low Emission Boiler System, phase out near-term clean-coal activities, and accelerate R&D on advanced power systems.	86	84	79	90	87	88	82
	Coal Fuels: end direct liquefaction and solid fuels and feedstocks R&D; develop science-based hazardous air emissions program.	16	16	9	12	15	16	16
	Gas Power: strengthen solid-oxide fuel-cell R&D and other advanced research.	97	78	92	92	83	74	70
	Oil and Gas Production and Processing: maintain oil programs for marginal resources; strengthen gas production and processing R&D; and increase advanced research.	70	77	86	94	107	110	113
	Carbon Sequestration: strengthen science-based carbon sequestration program.	1	2	10	11	17	23	22
	Methane Hydrates: develop science-based program with industry, Federal agencies, and the Navy to understand the potential of methane hydrates worldwide.	0	0	5	5	11	11	12
	Hydrogen Manufacture/Infrastructure: conduct R&D on hydrogen production from fossil fuels.	0	0	1	2	6	6	7
	Technology/Oil Price Elasticities: analyze technologies to reduce cost of oil shocks.	0	0	1	1	1	1	0
	Developing-Country Technologies: conduct collaborative R&D with other countries.	0	0	1	2	6	6	6
	Other: management and planning; environmental restoration; cooperative R&D, etc.	95	89	95	97	100	102	105
	Subtotal	365	346	379	406	433	437	433

PROGRAM[a]	R&D Activities, Initiatives, and Budget Changes	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
Nuclear Fission	Operating Reactors: R&D to address problems that may prevent continued operation of existing reactors.	4	25	10	10	10	10	10
	Nuclear Energy Research Initiative: competitively select among proposals by researchers from universities, national laboratories, and industry that address issues including proliferation-resistant reactors or fuel cycles, new reactor designs with higher efficiency, lower cost, and improved safety; low-power reactors; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste.	0	0	50	70	85	100	103
	Education: university research reactors and other support.	4	6	6	6	6	6	6
	Other: advanced light water reactor and reactor concepts.	34	15	0	0	0	0	0
	Subtotal	42	46	66	86	101	116	119
Nuclear Fusion	Plasma Science: conduct research on fundamental plasma science; develop fusion science and technology and plasma confinement innovations; and pursue fusion energy science and technology as a partner in international efforts.							
	Subtotal	232	225	250	270	290	320	328
Renewable Energy	Biomass Fuels: strengthen feedstock development; advance enzymatic hydrolysis and other conversion technologies in integrated power and fuel systems.	28	38	58	76	94	97	99
	Biomass Power: develop biomass materials handling equipment; integrated gasification combined cycles; biogasification-fuel cell systems; and small gasification-engine systems.	28	38	63	86	89	91	93
	Geothermal: strengthen hydrothermal research; reactivate R&D on advanced resources; expand advanced drilling R&D; and increase R&D on reservoir testing and modeling.	30	30	42	49	50	51	52
	Hydrogen: reorient near-term demonstrations and launch initiative with DOE Fossil Energy on innovative hydrogen production from fossil fuels with sequestration.	15	15	16	16	17	17	17
	Hydropower: develop “fish-friendly” turbines and low-head run-of-river turbines; analyze coupling of hydropower to intermittent renewables.	1	1	4	8	11	11	12
	Photovoltaics (PVs): accelerate basic PV science; develop laboratory scaleup to first-time manufacturing; and support engineering science for large-volume, low-cost production.	60	77	105	130	133	137	140
	Solar-Thermal: strengthen power tower and dish-stirling, esp. optical materials and solar manufacturing initiative; launch initiative on advanced high-temperature receivers.	22	20	32	43	44	46	47
	Wind: accelerate R&D on lightweight adaptive systems, direct-drive variable speed generators, hybrid systems, and system integration—including with storage; wind technology manufacturing initiative; fundamental work on materials, and computational aerodynamics.	29	43	53	65	66	68	70
	Systems and Storage: energy storage, esp. for system integration with intermittents.	32	46	51	54	55	57	58
	Solar Buildings: R&D in efficient and passive whole-building design and design tools; building integrated PVs and thermal systems; and initiative on low-cost solar water heaters and others.	3	4	6	9	9	9	9
	International: applications-specific systems integration and development, and field studies; collaborative R&D and training; technical assistance; and technical/policy analysis.	1	7	11	13	13	14	14
	Resource Assessment: integrated assessments across all resources; further development of geographic information systems; and collaborative R&D with developing nations.	0	0	5	5	6	6	6
	Analysis: systematic analyses of technologies, system integration, markets, and policies.	0	0	4	5	6	6	6
	Other: management and planning; renewable energy production incentive; other.	21	26	25	26	27	26	29
	Subtotal	270	345	475	585	620	636	652
SUBTOTAL		1282	1416	1785	2037	2214	2329	2412

[a]Activities should be done through various partnerships between industry, national laboratories, universities, and Federal/state agencies, as appropriate.